

École polytechnique de Louvain

A Framework for Engineering Gesture-Based User Interfaces Using the Leap Motion Controller

Development and Applications

Author: **Arthur SLUYTERS**

Supervisor: **Jean VANDERDONCKT**

Readers: **Suzanne KIEFFER, Sébastien LAMBOT**

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Abstract

The continuous improvement of gesture-sensing technologies by sensors, wearable devices, and computer vision is fostering a shift towards more natural user interfaces taking benefit of these technologies. After mastering 2D gesture recognition on contact-based interactive surfaces, researchers and practitioners are turning their focus of interest to contact-less gestures performed in mid-air interaction spaces. The Leap Motion Controller has become a ubiquitous device for capturing contact-less mid-air gestures that led to numerous projects and applications. Since the Leap Motion comes with an Application Programming Interface, the development of gesture-based user interfaces is primarily achieved by hand programming in an opportunistic way, thus impeding maintainability, portability, and compatibility. To satisfy these software quality properties, we conduct a target literature review in Leap Motion gesture recognition to develop a framework for engineering gesture-based user interfaces captured by a Leap Motion that preserves these properties. Its generic and flexible software architecture accommodates several configurations for gesture recognition, testing, and benchmarking of gesture recognizers, as well as the deployment of interactive applications with Leap Motion gesture-based user interfaces. We illustrate the development process on DICOM Viewer, an application for browsing medical images by gestures. Then, we perform a benchmarking of implemented gesture recognizers. Then, we deploy a large-size, real-world application in the context of the Large User Interface (LUI), a project launched by MIT Media Lab. Finally, we present a plan for evaluating the framework and an application deployed based on it and we discuss the benefits and shortcomings of this work before suggesting some future avenues.

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Chapter 1

Introduction

1.1 Context of the Problem

For decades, people have been exposed to futuristic user interfaces (UIs), mostly through Sci-Fi movies and series. They have seen their favorite characters ditch the classic keyboard-mouse-screen trio in favor of a more high-tech combination of gestures, wall screens, and holograms, with gesture interaction as the primary modality of interaction [48,56].

The continuous improvement of motion-sensing technologies by sensor input and/or computer vision [27,68] is fostering a shift towards more natural UIs taking benefit of these technologies. After mastering 2D gesture recognition [110,111,119,122] on touch-enabled, surface computing [133], researchers and practitioners are turning their focus of interest to 3D motion gestures performed in mid-air interaction spaces [136]. For example, to establish some continuum from 2D to 3D gestures [10], a “touch+air” gesture [12] initiates a 2D gesture captured on a surface and terminates it with a mid-air gesture, or vice versa in “air+touch” [26].

Although long perceived as a distant dream, motion-tracking technology has become more affordable at the beginning of this millennium. As a result, it has already been used in various mainstream applications, such as the Nintendo Wii, released in 2006, which came with a literally “game-changing” controller that combined accelerometers with an infrared sensor to determine its position in space. In 2010, Microsoft released Kinect, a device composed of depth sensors and cameras that captured the position of various body parts. Coupled with an Xbox 360, it provided a gesture-based gaming experience to the consumers

Released in 2012, the Leap Motion Controller (LMC) focused on precisely tracking the positions of hands and their fingers, to navigate through computer interfaces. Other motion-sensing devices include smart rings [42] and wired gloves [40], but their impact on the consumer market was not as significant as the previous examples. Since its inception, the Leap Motion Controller has initiated a very large amount of projects in mid-gesture recognition and interactive applications equipped with a gesture-based UI [58].

The LMC captures raw gestures from its sensor and makes them available through a Application Programming Interface (API) available in various languages, such as C++, Java, Python, and JavaScript [70]. Therefore, developing a gesture-based UI based on the LMC requires extensive, manual programming [108] in one or many of these languages [85], which are challenging to master for advanced UIs [101]. It turns out that most projects and applications, if not all, have followed different hand-crafted, fit-to-purpose, opportunistic practices to develop their UI. This manual practice largely impediments three fundamental ISO/IEC 25010 software quality properties [50]: compatibility, maintainability, and portability, along with some of their sub-properties:

1. *Compatibility*: “degree to which a product, system or component can exchange information with other products, systems or components, and/or perform its required functions while sharing the same hardware or software environment”. This characteristic is composed of the following sub-characteristics [50]:
 - *Co-existence*: “degree to which a product can perform its required functions efficiently while sharing a common environment and resources with other products, without detrimental impact on any other product”. For the LMC, there is no common environment raising the level of abstraction with respect to gesture raw data to leverage the development of corresponding applications.
 - *Interoperability*: “degree to which two or more systems, products or components can exchange information and use the information that has been exchanged”. For the LMC, various projects and applications partially or totally use all data provided by the LMC API and store them in different formats that are not interoperable.
2. *Maintainability*: “degree of effectiveness and efficiency with which a product or system can be modified to improve it, correct it or adapt it to changes in environment, and in requirements”. This characteristic is composed of some of the following sub-characteristics [50]:
 - *Modularity*: “degree to which a system or computer program is composed of discrete components such that a change to one component has minimal impact on other components”. For the LMC, it is unsure to what extent the software architecture implemented is structured into adequate layers and modules to guarantee this sub-property.
 - *Reusability*: “degree to which an asset can be used in more than one system, or in building other assets”. Due to inconsistencies, existing LMC implementations are not reusable for another application. In our review, we did not identify any architecture that is reused from one project to another.
 - *Modifiability*: “degree to which a product or system can be effectively and efficiently modified without introducing defects or degrading existing product quality”. It is unclear how existing LMC implementations could be subject to any modification, if any, that would support new gesture recognition.
 - *Testability*: “degree of effectiveness and efficiency with which test criteria can be established for a system, product or component and tests can be performed to determine whether those criteria have been met”. Beyond the testability of existing LMC-based implementations, most studies report their own results for gesture recognition, with little or no comparison to others.
3. *Portability*: “degree of effectiveness and efficiency with which a system, product or component can be transferred from one hardware, software or other operational or usage environment to another”. This characteristic is composed of the following sub-characteristics [50]:
 - *Adaptability*: “degree to which a product or system can effectively and efficiently be adapted for different or evolving hardware, software or other operational or usage environments”. LMC-based applications are often tied to a particular usage environment and are rarely adaptable to another, such as for another context of use (*i.e., different users, platforms, and environments* [16]).
 - *Installability*: “degree of effectiveness and efficiency with which a product or system can be successfully installed and/or uninstalled in a specified environment”. Part perhaps for Java and JavaScript which are multi-platform programming languages,

LMC-based implementations can only be installed in some particular environment, such as C# for MS Windows and Objective-C for MacOS. These setups cannot be transferred to another platform.

- *Replaceability*: “degree to which a product can replace another specified software product for the same purpose in the same environment”. LMC-based applications usually implement one gesture recognition technique that cannot be replaced by another one. Even more, multiple recognition techniques cannot be combined.

1.2 Mission Statement

1.2.1 Statement

In order to address the aforementioned shortcomings affecting compatibility, maintainability, and portability of LMC-based UIs, the central objective of this master thesis is to **develop a framework for engineering gesture-based UIs of interactive application using the LMC**. The framework should be generic enough to explicitly address the three software quality properties and their corresponding sub-properties.

1.2.2 Working Hypotheses

During this thesis, we assume the following working hypotheses:

- H1.** *Device and platform specifications*: the framework should facilitate the deployment of gesture-based UIs based on the LMC [70] only, for mid-air gesture interaction [58], and should be employed on multiple computing platforms, and not only one with a specific operating system. We pose the hypothesis of working in JavaScript. Other similar devices are not considered.
- H2.** *Environment specifications*: the LMC-based UI will be used in an in-door, stable environment with the appropriate lighting conditions. Non-wearable, contact-less input sensing devices, such as the LMC, are better suited to the environment than wearable, contact-based devices, such as an interactive surface.
- H3.** *Target audience*: the framework is aimed at facilitating the development life cycle of LMC-based UIs for the developer and the designer.
- H4.** *End-users’ aspects are out of scope*: although usability is also specified in ISO/IEC25010 as another important quality property, it will not be addressed in this thesis in computer science. Consequently, no particular assumption is made about end-users, their profiles, or their abilities. Other ISO properties such as security, functionality are also beyond the scope of this thesis.

1.2.3 Research Method

Our research method is structured according to the software development process, which is usually divided into six phases according to the following definitions inspired by the IEEE Standard Glossary of Software Engineering Terminology [49]):

1. *Requirements analysis*: studying user needs to arrive at a definition of system or software requirements.

2. *Design*: creating and documenting designs for the architecture, the software components, the interfaces, and the data.
3. *Implementation*: translating the design into a software component.
4. *Testing*: checking whether or not the system is meeting our expectations.
5. *Deployment*: delivering the product to the customer.
6. *Maintenance*: modifying the system after the delivery to correct faults, improve performance or other attributes, or adapt to a changing environment.

In the context of this thesis, we will mostly consider the first three steps (from requirements to implementation) in the development of the framework, the fourth step (testing) through running a benchmarking in LMC-based gesture recognition and the fifth step (deployment) through deploying two LMC-based applications: a small-size DICOM viewer and a large-size application for manipulating multimedia contents on wall screens in the context of the Large User Interface (LUI) project [89] managed by The MIT Media Lab¹.

1.3 Overview of the Thesis

To reach the central objective assigned to this thesis, the manuscript is structured as follows.

Chapter 2 explores previous work related to this objective by describing the LMC, by conducting a targeted literature review in the area of LMC-based projects, applications, and recognition techniques and by performing a comparative analysis of gesture recognizers that are relevant for the context.

Chapter 3 covers the first three stages: the requirements engineering, the design, and the implementation phases for the framework for engineering LMC-based UIs. In particular, the pipeline software architecture, its underlying unified form for gesture representation, and the implemented gesture recognizers will be described. It will end up illustrating the development process for DICOM Viewer, a small-size application for browsing medical images by gesture, in order to address the phase of deployment. This application gives rise to a first framework instantiation.

Chapter 4 addresses the phases of testing and deployment by setting up the framework in a configuration useful for performing a benchmarking of implemented recognizers on two challenging Leap Motion datasets. This application gives rise to a second framework instantiation.

Chapter 5 also addresses the phase of deployment for developing a gesture-based UI for the LUI project for browsing multimedia objects on wall screens. This application gives rise to a third framework instantiation.

Chapter 6 briefly discusses an experimental plan for evaluating the framework and an application deployed thanks to this framework, such as the LUI project. It also summarizes the benefits and shortcomings of the work in light of the three properties: compatibility, maintainability, and portability.

Finally, Chapter 7 overviews the contributions of this thesis and suggests some future avenues to this work, given its existing shortcomings.

¹This work is part of a larger collaboration project between MIT and UCLouvain in the context of an MIT-UCL MISTI Fund “Large User Interface” project (see <https://www.media.mit.edu/projects/large-user-interface-with-gesture-and-voice-feedback/overview/>) lead by Prof. Pattie Maes on the MIT side and by Prof. Jean Vanderdonckt on the UCLouvain side, under contract #200278.

Chapter 2

Related Work

After introducing the Leap Motion Controller (LMC) and presenting its capabilities in Section 2.1, this chapter is structured as follows from the most general to the most specific: Section 2.2 overviews general research and development performed based on the LMC, Section 2.3 explains some template-based gesture recognizers that are specifically adapted to stroke gesture recognition, and Section 2.4 describes the typical gestures and gesture sets used with the LMC in existing projects and applications.

2.1 The Leap Motion Controller

The Leap Motion Controller (LMC) is a small ($80 \times 30 \times 13mm$) device that connects to a computer via its USB port. It is composed of two near-infrared cameras which allow it to track motion in a cone-shaped zone extending about $60cm$ from the base of the device (see Figure 2.1). It provides motion tracking data in the form of a skeleton. According to [128], it manages sub-millimeter ($0.2mm$) accuracy for static gestures, and falls to $1.2mm$ for dynamic gestures. The manufacturer advertises a typical frame rate of about $120Hz$.

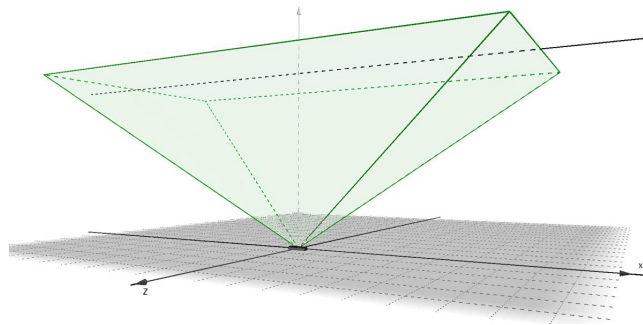


Figure 2.1: Field of view of the Leap Motion Controller (adapted from [69]).

The Leap Motion Software Development Kit (SDK) is available for many programming languages, including Javascript, Python, and C++ [85]. However, only the last version of their LeapC API, as well as their integration for Unity and Unreal Engine built on this API, are still actively supported. The API transforms raw data acquired from the hand gesture into **Frame** objects. Several properties exist for each frame [101]: the palm position, its normal form and its velocity (Figure 2.2, left), the hand direction, the position, the direction, and the speed of the five fingertips (*i.e.*, the thumb, the index, the middle, the ring, and the pinky), and the arm direction (Figure 2.2, right).

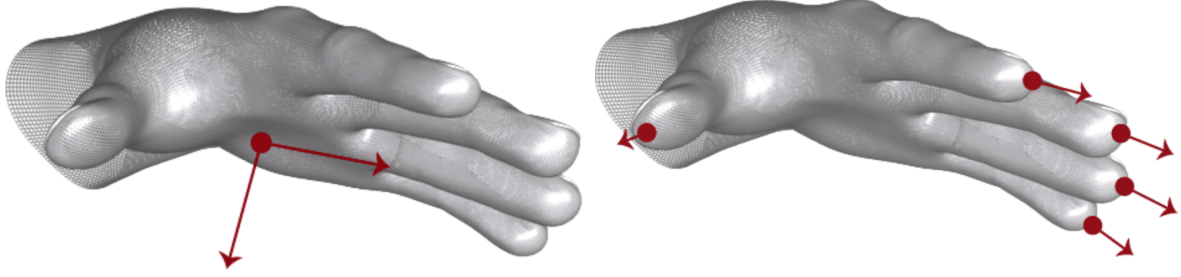


Figure 2.2: Leap Motion data: palm tracking (left), fingertips (right) [70].

There are two main types of LMC-based hand gestures: *static gestures*, where the pose of the hand(s) entirely conveys the meaning of the gesture; and *dynamic gestures*, which consist of a sequence of hand poses in time. Continuous gesture recognition consists of both gesture segmentation (*i.e.*, extracting a gesture from a continuous stream of data) and gesture recognition. Some recognition algorithms work directly from raw sensor data (*e.g.*, images), whereas other work from skeleton data (*i.e.*, a series of body joints and their position, speed, etc.). We do not consider here methods for extracting a skeleton from raw sensor data. Because of its design, the Leap Motion Controller suffers from a few issues:

- Accuracy decreases when parts of the hand are hidden from the sensor. As such, some intricate hand poses might not be picked up correctly, such as in self-occlusion.
- The interaction zone is quite small because of the sensor’s limited field of view. The LMC is thus mostly limited to hand gestures, as opposed to other devices such as the Kinect, but which are much more sophisticated and less specifically tailored for hand recognition.
- The controller might sometimes mistake one hand for another. For instance, it might detect two left hands instead of separating the left hand from the right hand.

2.2 LMC-based Gesture Recognition: Research and Development

We conducted a Targeted Literature Review (TLR), which is a non-systematic, in-depth, and informative literature review, that keeps only the references maximizing rigorousness and relevance while minimizing selection bias [67]. The relevant references obtained may be more limited than in a Systematic Literature Review (SLR) [54], but stems for a knowledgeable selection of high-quality, easy-to-identify references on 2D stroke gesture recognition, as opposed to an all-encompassing list of somewhat relevant references. This applies to LMC gesture recognition, where the literature is very abundant [39,44].

3D gesture recognition is a huge field of research and development given the proliferation of devices, wearable or not, the human limbs considered for gesturing, and the techniques used for recognition. We refer to the literature for a more extensive survey, such as to [27] for 3D hand gesture recognition (a complex three-step process involving hand detection, hand tracking, and recognition [93]) and more recently to [136] for a systematic literature review. They found that the main techniques used between 2016 and 2018 are: general purpose toolkits (*e.g.*, [129]), Artificial Neural Networks (ANN), Convolutional Neural Network (CNN), Recurrent Neural Network (RNN), k -Nearest Neighbor (k -NN [37], *e.g.*, [125]), decision tree classifier, Support Vector Machine (SVM), Hidden Markov Model (HMM), Dynamic time warping (DTW, *e.g.*, [111]), Naive Bayes classifier, Linear discriminant analysis (LDA, *e.g.*, [97]), Principal

Component Analysis (PCA), Deep Learning (*e.g.*, DeepGRU [77]), etc. A common pattern identified in this portion of the literature is the overfitting in the data sets for artificial intelligence and machine learning algorithms: they exhibit excellent accuracy (usually superior to 90%) and performance (usually inferior to 100 msec., a usual threshold for system response time [87]), but they are entirely optimized for a given dataset, thus leaving little or no space for keeping the same performance if the dataset is changed. This occurs when samples and/or classes need to be modified, thus leading to a re-training of the algorithm, although this is now achievable in almost real-time. For example, when a system-defined gesture should be replaced by a user-defined gesture in a dataset, a re-training may be required.

Based on this TLR, we identified a series of significant gesture recognition techniques used in research and development that are exploiting the LMC.

Neto *et al.* [86] present two ANNs to spot and classify static hand gestures in a continuous stream of data from wired gloves. The two ANNs are arranged in series, where the first one focuses on spotting communicative gestures, while the second one is trained to detect transition (non-communicative) gestures. The authors claim that their method achieves high accuracy with a short training time of about 10 to 15 minutes.

Marin *et al.* [80] combine features extracted from a Microsoft Kinect’s depth map with features provided by a Leap Motion Controller to achieve higher accuracy than with either of these 2 devices alone. They use a multi-class SVM classifier to classify extracted gestures and manage to reach 91.3% accuracy. They improved their initial solution by using data from the Leap Motion Controller to help extract data from the Kinect device [81]. This approach increases performance as well as accuracy, which now reaches 96.5%. The authors also measure the impact of replacing the multi-class SVM by a Random Forest. It results in faster training times at the cost of slightly worse accuracy (94.7%). The authors claim that their system can provide real-time performance, even on low-end computers.

Bhuyan *et al.* [9] propose a vision-based approach for sign language recognition. They highlight the challenges of gesture segmentation in a continuous data stream. These challenges include handling coarticulation (the fact that a gesture is influenced by those preceding and following it) and transition gestures (non-gestural movements between gestures). Their solution uses Conditional Random Fields (CRFs) instead of HMMs because are better at detecting gestures when there is coarticulation.

Avola *et al.* [8] use a stack of four RNNs to recognize sign language from skeleton data acquired using a Leap Motion Controller. They achieve 96% accuracy on a custom dataset of 12 dynamic and 18 static gestures.

Kratz & Back [59] show that it is possible to accurately determine the execution phases (*i.e.*, the start, middle, and end) of pre-segmented gestures recorded with a smartphone’s IMU (Inertial Measurement Unit, a combination of a gyroscope, accelerometer, and magnetometer). They used a multi-class SVM, but suggest that it may be possible to determine the same phases in unsegmented data using HMMs.

Alon *et al.* [4] propose a framework to handle spatial (work out the position of the hand in an image) and temporal (determine the start and end of a gesture) gesture segmentation, as well as gesture recognition in a continuous video sequence. Instead of requiring a pause between two consecutive gestures, their framework determines gesture boundaries by finding intervals of the input sequence that seem to match with one of the gesture class. The authors show two possible applications of their framework: real-time recognition of digit gestures, and a system that helps users find a specific sign within a video containing continuous signing in ASL.

Krupka *et al.* [65] show the basics of what later became Microsoft Prague [95]. It is an SDK that developers can use to add hand-gesture interaction to any application. Gestures are

represented as finite-state machines (FSMs), whose transitions can be either hand poses, hand motions, or other gestures. Hand poses are described as sets of constraints, while hand motions are a sequence of 2D “motion building blocks” that can be attached to specific parts of the hand. A gesture is recognized if the user performs the action sequence represented by its FSM. There is no need for training data, as gestures are entirely defined using their description language. Using this method, they achieve 96% recognition rate on a set of 12 gestures. At the moment, their SDK runs exclusively on Windows 10 and supports only three depth cameras: the Kinect v2 as well as the F200 and SR300 Intel RealSense cameras. It is unclear whether they will ever update it to support cheaper devices such as the LMC.

2.3 Template-Based Gesture Recognizers

Several algorithms recognize 2D stroke gestures [138] by adopting a *template matching* [14]: they compare a *candidate gesture* against pre-recorded *template gestures* gathered by *gesture classes* in a *training set* that was used to train the recognizer beforehand. This assumes calculating a (dis-)similarity distance between the candidate gesture and template classes.

We consider these recognizers in this work because they are quick and easy to implement, while still delivering a high enough recognition rate, albeit usually lower than what can be achieved with more advanced techniques. Although they were initially reserved for 2D unistroke gestures, we will consider them later on for generalizing them to 3D LMC-based gestures.

GrandMa, Rubine’s recognizer [97], creates a vector of 13 geometric features for each template and candidate, which is classified with respect to gesture classes by a linear evaluation. This offers a high recognition accuracy for a low computational cost, manual opportunistic programming is no longer required, and its understanding is simple and facilitated by a geometric interpretation. These three advantages form a common motto for several other recognizers.

Wobbrock *et al.* present their **\$1 recognizer** [133], a 2D unistroke gesture recognizer specifically designed to be used in prototyping environments. It can fit in about 100 lines of code and can recognize gestures with as few as one template per gesture class. Candidate gestures first go through a four steps preprocessing: (1) spatial resampling; (2) approximate angular alignment; (3) non-uniform scaling; and (4) translation. The algorithm then iteratively searches for the optimal angle between the candidate gesture and each template using Golden Section Search, and the template with the lowest Euclidean distance is returned. Due to its simplicity, it does have a few caveats. It is limited to 2D unistroke gestures and cannot recognize 1D gestures (*e.g.*, lines) because of its non-uniform scaling. Furthermore, it is rotation, scale, aspect-ratio, space, and time-independent, which may cause problems in some situations, such as when distinguishing ovals and circles, or gesture execution speed is important.

Anthony & Wobbrock’s **\$N** and **\$N-protractor** recognizers [5,6] address most of \$1’s weaknesses. They add support for 2D multistroke gestures by connecting the strokes of a gesture to form a single unistroke gesture. Because a gesture’s strokes may be performed in different orders and directions, both algorithms automatically generate all the permutations of a template gesture’s strokes. This approach allows the designer to provide only one template for each multistroke gestures but significantly increases time and space complexity. The impact on time complexity is partially mitigated by the simple and fast comparison algorithm, as well as by 2 optimizations proposed by the authors, which can reduce the number of comparisons by up to 90% without any negative impact on accuracy. Another improvement compared to \$1 is the support for 1D gestures (*e.g.*, lines): 1D gestures are automatically recognized and scaled uniformly to preserve aspect ratio, while 2D gestures are still scaled non-uniformly.

\$N\$-protractor replaces the iterative search for the best angular alignment of \$N\$ by an approach based on inverse cosine distances. This significantly increases its recognition speed compared to \$N\$, with a negligible impact on its accuracy. Both recognizers are scale and position-independent and suffer from a high drop in performance when the number of templates and the number of strokes per template increases. Finally, because both algorithms connect strokes to form a single unistroke gesture, there may be collisions between symbols (*e.g.*, “z” and “=”).

Vatavu *et al.*’s **\$P\$ recognizer** [121] try to overcome \$N\$ and \$N\$-protractor’s memory explosion problem. Instead of considering a gesture as a sequence of strokes, it represents them as a “time-free cloud of points”. This approach considerably reduces memory usage, as the recognizer does not need to store each permutation of the multistroke gestures. However, it loses the ability to distinguish gestures according to their direction (*e.g.*, it cannot distinguish “swipe up” from “swipe down”).

The \$Q\$ recognizer [122] improves \$P\$ with several algorithmic revisions: the classification of multi-stroke gestures is faster when the size of the training set is large. Aligned with the accuracy of \$P\$, \$Q\$ is announced as the fastest recognizer of the \$-family. Other variants to the \$-family also exist, such as Quick\$ [94], 1F [117], SHARK [64], SHARK2 [63], and 1c [45].

More recently, G-Gene [19] declaratively models stroke gestures like DG3 [35] for recognizing a stroke in real-time, as a whole or for its parts, with an accuracy comparable to offline methods already after a few segments of the stroke.

Vanderdonckt *et al.* [115] present **!FTL** as an alternative to \$1\$ and \$P\$. It is a vector-based 2D multistroke gesture recognizer that converts resampled gesture points into a series of pairs of vectors called “shapes” and computes the Local Shape Distance (LSD) between each pair of shapes in sequence to assess how two gestures are dissimilar. Its accuracy is comparable to \$P\$, but four times faster. !FTL has not been compared to \$Q\$ in terms of speed, though.

Both Kratz and Rohs’ **\$3** and **Protractor3D** recognizers [60,61] attempt to recognize gestures regardless of their orientation, although they use different techniques to align the performed gesture with the templates. The former rotates input gestures independently from the templates while the latter finds the rotation of the input gesture that minimizes the Euclidean distance to each template. Both recognizers then return the template with the lowest Euclidean distance to the input gesture.

Caputo *et al.*’s **3 cent recognizer** [18] is based on the same idea of comparing sampled trajectories as Kratz and Rohs’ recognizers, but it assumes that gestures are always performed in the same orientation. According to the authors, this allows their recognizer to be significantly faster and more accurate. However, it requires each gesture to be defined precisely, with a fixed direction and orientation. They find that classification stays very accurate with as few as 10 sampling points and that a gesture can be recognized before its completion, as accuracy stays about the same even if classification is performed on only the first 60% of the gesture.

Taranta *et al.*’s **Jackknife** [111] is a general-purpose algorithm that can recognize dynamic gestures from continuous streams of data produced by a variety of devices, including touchscreens and 3D sensors. In the spirit of the \$-family recognizers, it manages high recognition rates with limited training. However, unlike them, it uses DTW (Dynamic Time Warping) to measure the distance between two templates. It supports unsegmented data by using a sliding-window approach, combined with an automatically determined rejection threshold to avoid false positives.

Celebi *et al.* [24] achieve a 36% gain in accuracy compared to classical Dynamic Time Warping by using a distance function that assigns a different weight to each body joint, depending on its relevance in the recognition of this gesture class.

Vatavu *et al.* [118] study the impact of gesture dimensionality (*i.e.*, the number of sampling points for each gesture frame) and bit cardinality (*i.e.*, the precision of the measurements) on

the execution speed and accuracy of 3D Nearest Neighbors classifiers. They observe that, past a certain threshold, higher dimensionality and bit cardinality do not lead to significantly higher recognition rates. By carefully selecting the values for gesture dimensionality and bit cardinality, it is thus possible to significantly reduce execution speed while still reaching (almost) peak accuracy. They also note that accuracy generally increases with the number of training samples, but decreases with the size of the gesture set.

2.4 LMC Gesture Sets

From the Targeted Literature Review conducted in Section 2.3, a series of LMC-based gesture sets has been identified, which enables us to perform a comparative analysis of gestures that are typically, frequently manipulated by LMC-based UIs. Among them, we highlight two significant ones that will be used later on.

For example, the **SHREC2019** dataset [17] served as a benchmarking for the Eurographics 2019 SHape Retrieval Contest (SHREC) track on online gesture recognition to detect command gestures from hands' movements in a virtual reality context. The proposed dataset is topical due to its recency. The emergence of this periodic contest in the field of computer graphics results in the indexation of this dataset as a reference dataset. This dataset consists of 195 3D trajectories performed by 13 participants with the whole hand. Each trajectory contains a sequence of 3D points and quaternions designating one of five iconic gestures: "Cross" (X), "Circle" (O), "V-mark" (V), "Caret" (/ \), and "Square" ([]).

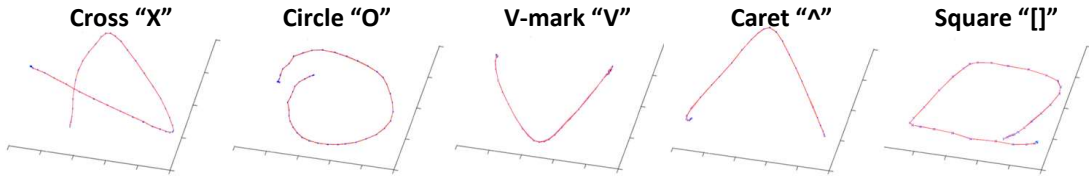


Figure 2.3: The **SHREC2019** dataset [17].

The **3DTCGS** dataset [18] is employed to test the classification performance of the *3 cent* [18] recognizer on interface command gestures. Data were provided in a segmented form which makes them easier to exploit during experimentation for the classification task. This dataset contains gestures of varying complexity (Figure 2.3), ranging from the simplest (*e.g.*, a "3D swipe") to the most complex one (*e.g.*, a "3D spiral" is challenging because it can be drawn in a co-planar way or with varying depth). Some other gestures follow a similar trajectory, but with a different direction (*e.g.*, "left-swipe" *vs.* "right-swipe", "arc3Dleft" *vs.* "arc3Dright"), which is considered for testing the direction-invariance property. Each subject produces one sample per gesture which makes the user-independent evaluation particularly challenging. Authors asked participants to issue short iconic gestures with the dominant hand forefinger. The gathered data consist of 347 sequences of 3D coordinates. These data are combined with a timestamp, describing 26 gesture classes performed by 14 subjects and recorded with a Leap Motion. They are clustered in five categories (Figure 2.4): semi-circular arcs (*i.e.*, "arc3Dleft", "arc3Dright"), symbols drawn in a 3D space (*i.e.*, "caret", "check", "curly-bracket-left", "curly-bracket-right", "delete", "pigtail", "square-bracket-left", "square-bracket-right", "star", "v", "x"), Simple geometric figures (*i.e.*, "left-swipe", "right-swipe", "circle", "rectangle", "zig-zag"), 3D polygonal chains (*i.e.*, "poly3Dxyz", "poly3Dxzy", "poly3Dyxz", "poly3Dzyx", "poly3Dzxy", "poly3Dzyx"), and a 3D spiral.

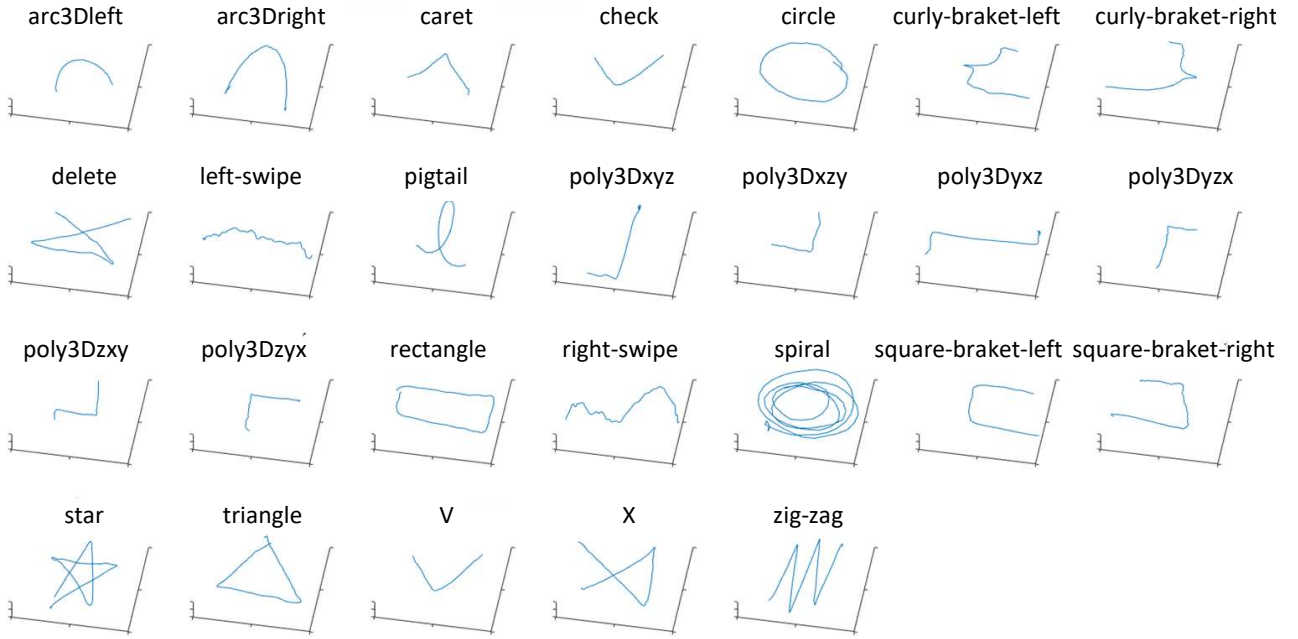


Figure 2.4: The **3DTCGS** dataset [18].

2.5 Summary

Apart from the recognizers adopting a template matching, such as the recognizers belonging to the $\mathcal{S}$ -family, most of them are too complex for incorporating them into a generic framework. Indeed, besides their intrinsic computational complexity, most of them require intensive training before they can be used to recognize a given set of gestures. Furthermore, adding a new gesture to an existing gesture set requires re-training the recognizer. Being able to add custom gestures without having to re-train the recognizer is a desirable property, as the literature shows that recognizers' accuracy is better with user-dependent gestures [118]. We retain template-based approaches (Section 2.2) because, contrarily to others, they provide the means for satisfying the ISO/IEC properties selected in Section 1.1:

- *Modifiability*: such recognizers can easily accommodate any change in the gesture set: adding a new template or a gesture class, removing a template or a class, or modifying them do not alter the algorithm and do not require complete re-modeling, re-training or pre-processing, apart those concerned by the local modifications.
- *Reusability*: such recognizers can be reused straightforwardly in various configurations of LMC-based gestures without modifying their code.
- *Replaceability*: such recognizers are interchangeable as they pretty much work on the same gesture representation, apart from their format. Thus, replacing a recognizer by another one does not affect the entire framework or recognition.
- *Adaptability*: such recognizers are directly adapted to the current gesture set without needing to perform calibration, tweaking, or parametrization to adapt to a new context.
- *Modularity*: thanks to the incremental development that introduced variations of recognizers based on previous versions, each recognizer can be implemented into a single module and variations can be created on top of them without affecting the overall architecture.

Chapter 3

Framework Development

Chapter 2 identified a series of recognition techniques targeting the LMC. Most of them are built and tested for one specific application and/or for a single context of use, making it hard for developers to (re-)use these techniques in another application or context of use. In order to address the ISO quality properties defined in Section 1.1, this third chapter describes our framework¹ for engineering LMC-based gesture UIs as follows: Section 3.1 defines its requirements, Section 3.2 describes its software architecture, and Section 3.3 illustrates how the framework can be used to develop a small application.

3.1 Requirements

To leverage the shortcomings of work related in LMC-based recognition, the framework should satisfy the ISO/IEC 25010 [50] quality properties selected in Section 1.1 as follows:

1. Compatibility

- *Co-existence*: the framework should be able to work properly alongside other applications that are also using the LMC.
- *Interoperability*: aside from supporting a variety of gesture sets, the framework should use a standardized format for skeleton-based gesture sets.

2. Maintainability

- *Modularity*: the framework should be composed of independent modules with clear, separate roles.
- *Reusability*: the framework should allow front-end developers to add gesture support to any application easily.
- *Modifiability*: the framework should allow developers to add new, more powerful modules (*e.g.*, recognizers) to the framework without modifying their application or the other modules.
- *Testability*: the framework should provide a reliable way to compare the accuracy of gesture recognizers.

3. Portability

- *Adaptability*: the framework should be quickly configurable to the needs of a specific user, application, and system.
- *Installability*: the framework should be multi-platform and relatively easy to install.
- *Replaceability*: developers should be able to replace any module in the framework, such as changing a recognizer or a gesture set.

¹The framework was developed in collaboration with Bastien Nothomb [112]. Appendix A details the distribution of the work between the two of us.

3.2 Software Architecture

We designed the framework as an intermediate layer between an application and a sensor. Isolating the UI from the recognizer and the sensor makes it easy for a developer to write a new application without focusing on the recognition techniques. In the same way, switching the sensor with another one (*e.g.*, going from an LMC to a Kinect device), or using a different recognizer should not force developers to modify their application.

We chose JavaScript as the programming language for four main reasons: (1) it is an expressive, powerful, and cross-platform language that enables applications to run directly in a web browser without requiring any setup; (2) it is used in many domains of applications, ranging from games to virtual reality, thus opening the range of potential applications; (3) some gesture recognizers that are candidates for incorporation and extension in our framework are available in this language; and (4) it is a popular language, with a lot of highly maintained libraries.

Following Pree’s notation [92], the framework can be divided into two parts: frozen and hot spots. Frozen spots are its “fixed” parts. They are the same for all of its instances. On the other hand, hot spots are generic parts that can be easily modified to better suit the context of use. Because it both provides a selection of predefined components (black box) and allows developers to write new components that better suit their needs (white box), the framework can be considered as gray-box. In the remainder of this section, we describe the overall software architecture of the framework: its frozen and hot spots, as well as how it can be configured to suit the needs of a specific context of use [16].

3.2.1 Overview

Figure 3.1 shows the overall architecture of the framework. Messages sent across the modules are the following:

1. Raw data from the sensor.
2. A standardized frame from the sensor (see Section 3.2.2).
3. A **Sample** object (see Section 3.2.2).
4. A JavaScript object with three properties: (1) the type of gesture, *i.e.*, static or dynamic; (2) the name of the gesture; and (3), data from the analyzer if the gesture is static.
5. A WebSocket message of type **data**, containing frames, static and dynamic gestures.
6. A WebSocket message of type **operation** (see Section 3.2.2).

When initialized, the **frame-processor** loads one gesture set to train the classifier and another for the recognizer. Depending on its configuration, it can train them directly with all of the gestures or only when requested by the application.

Each time the **sensor-interface** produces a frame, it does two things: (1) transmit raw sensor data to the WebSocket server, which is then forwarded to the **app-interface**; and (2) send a standardized frame to the **frame-processor** which then attempts to classify the pose (*i.e.*, static gesture) performed by the user. Depending on the type of pose, two things can happen: (1) the frame is forwarded to the **analyzer** if the application previously informed the framework that it wants to handle the pose; or (2) the frame is sent to the **segmenter**. In the first case, the pose and extracted data are sent to the application. In the second one, if the **segmenter** determines that the user has performed a gesture, it sends the gestural data to the **recognizer**. If it recognizes a gesture, it sends its name to the application.

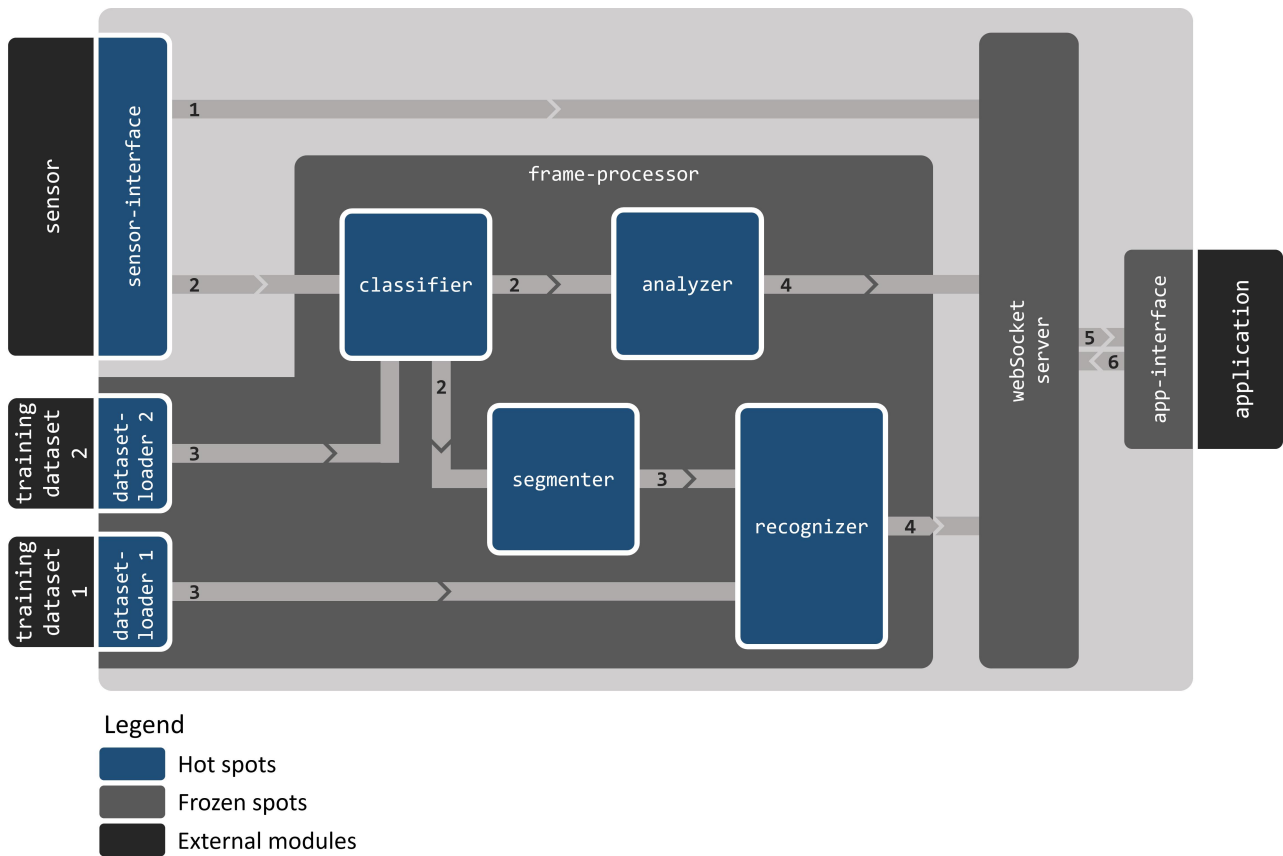


Figure 3.1: Software architecture of the framework.

3.2.2 Frozen Spots

Some parts of the framework are fixed and standardized to maximize reusability across multiple projects, at the cost of lower flexibility. Their source code is available in [Appendix F.1.1](#).

Frame

The `frame.js` module represents a standardized frame from the sensor. One frame contains skeleton data extracted from the sensor at one particular point in time. All frames have the following format:

```

1 timestamp: integer - milliseconds since the Epoch
2 hasLeftHand: boolean
3 hasRightHand: boolean
4 articulations: array of Articulation objects
5   label: string - e.g., "rightPalmPosition"
6   points: array of Point objects
7     x: float
8     y: float
9     z: float
10    t: integer - milliseconds since the Epoch

```

The key-value system allows developers to easily add or remove articulations, depending on the context of use (*e.g.*, the LMC only provides forearm articulations, while other sensors, such as the Kinect, could provide articulations of the whole body).

Gestures and Gesture Sets

Figure 3.2 depicts the UML V2.5 [15] Class diagram of the modular data structure used in the framework. Any dataset can be used in the framework. They just need to be converted into **GestureSet** objects. A **GestureSet** object can contain samples (also known as templates) of two types: (1) **PoseData**, for static gestures; and (2) **StrokeData**, for dynamic gestures. **PoseData** objects consist of a single frame that represents a hand pose. On the other hand, **StrokeData** objects can comprise of multiple paths, where a path corresponds to the trajectory of a specific articulation (*e.g.*, the tip of the right index). Paths are in turn composed of a series of strokes. Paths are in turn composed of a series of strokes.

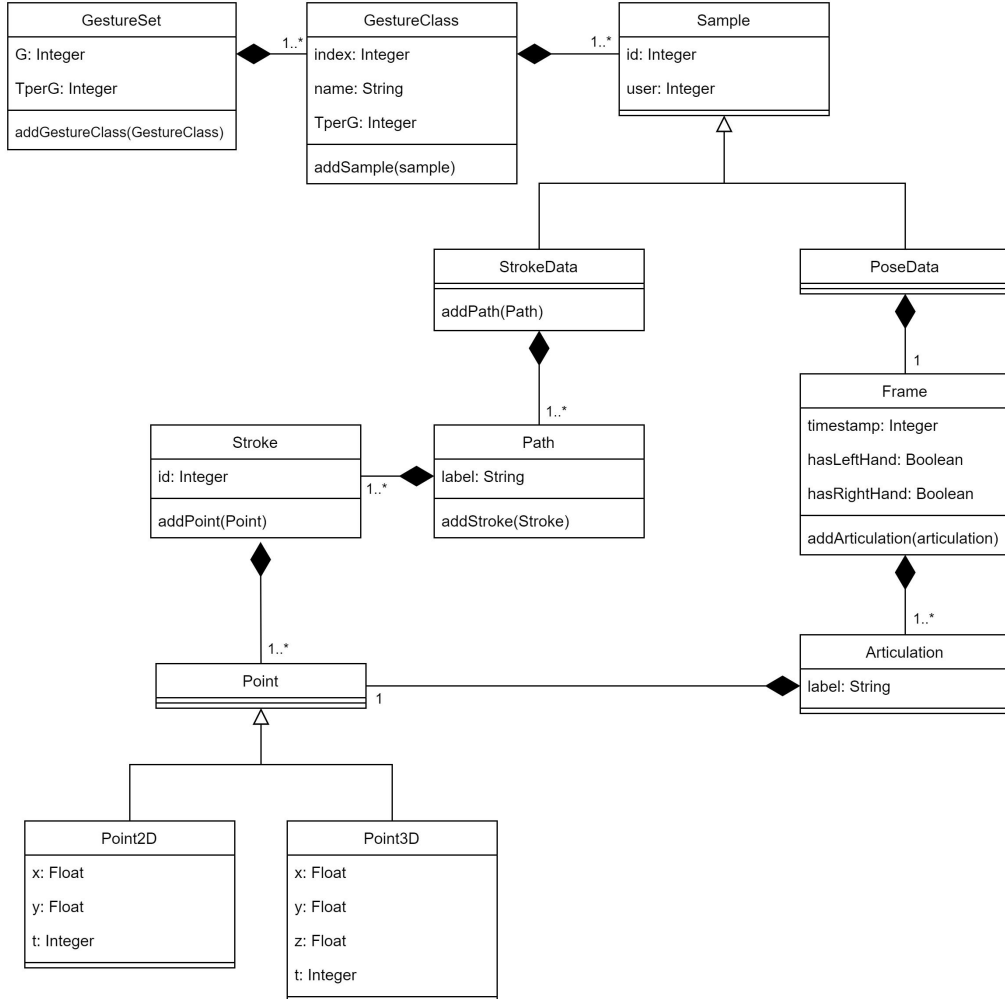


Figure 3.2: UML V2.5 Class Diagram of the Framework.

WebSocket Server

`index.js` is the main module of the framework. It loads the framework configuration and initializes the sensor module (see 3.2.3). It also sets up a WebSocket server, used to both receive and send messages to the client application. In the current version of the framework, clients only send **operation** messages to the server. There are four types of operations: `addGesture`, `addPose`, `removeGesture` and `removePose`. These messages allow the client application to control which gestures and/or poses should be recognized by the framework, which improves recognition accuracy. The server only sends **data** messages to the client application. Their payload can be of three types: `frame`, `gesture`, or `pose`.

Frame Processor

The `frame-processor.js` module is at the core of the framework, as it coordinates most of the modules to extract data from sensor frames and determine whether the user is performing a pose or a gesture. For more information, see Section 3.2.1 and Figure 3.1.

Application Interface

The `app-interface.js` module is used as an interface between the application and the recognition framework. It contains the `GestureHandler` class, which has the following methods:

- `onFrame(callback)`: execute the callback each time a frame is received from the sensor. This can be used to display the position of the fingers on the screen in real-time.
- `onGesture(gesture, callback)`: execute the callback each time the (dynamic) gesture is detected. This can be used by an application to associate an action with a specific gesture.
- `onEachGesture(callback)`: execute the callback each time any gesture is detected. This can be used to perform an action regardless of the gesture performed.
- `removeGestureHandler(gesture)`: remove the callback associated to the gesture.
- `onPose(pose, callback)`: execute the callback each time the pose (*i.e.*, static gesture) is detected. This can be used to execute a “continuous” action while the pose is detected (*e.g.*, rotate an image depending on the rotation of the hand).
- `removePoseHandler(pose)`: remove the callback associated to the pose.
- `disconnect()`: disconnect from the gesture recognizer.

Once instantiated, a `GestureHandler` object regularly attempts to connect to the gesture recognition server using WebSocket. Using WebSocket allows the server to directly push data, such as frames, gestures, or poses, to the client. Because the client does not need to regularly poll data from the server, there is less delay between an action and its effect on the UI.

3.2.3 Hot Spots

The framework is composed of six different types of interchangeable modules. Any instance of the framework must be composed of one module of each type, but “placeholder” modules are provided for situations where a module is not necessary. This section describes, for each type of module, their role, and the methods that they have to implement. The abstract classes are available in Appendix F.1.2, while the source code of the modules that we have implemented can be found in Appendix F.2 to F.7.

Sensors

Sensor modules serve as an interface between the framework and a physical sensor (*e.g.*, an LMC or a Kinect device). Every sensor has to extend the `AbstractSensor` class and implement its two methods:

- `loop(callback)`: this method transforms frames from the sensor into a standardized format. Each time it receives a frame from the sensor, it executes the callback with the standardized frame as an argument.
- `stop()`: stop processing frames from the sensor.

For the moment, we provide a module for the LMC that calls the Leap Motion API to fetch frames at regular intervals (their duration is adjustable in the configuration file).

Datasets

Dataset modules transform a dataset into a standardized format compatible with the framework (see Figure 3.2). They only need to contain one method:

- **loadDataset(name, directory)**: this method takes the name of the dataset and the path to the directory where it is stored. It returns a **GestureSet** object representing the dataset.

Classifiers

Classifier modules determine the hand pose of the user. They have to extend the **AbstractClassifier** class, which contains three methods:

- **addPose(name, frame)**: add a frame corresponding to a pose to the training set of the classifier.
- **removePose(name)**: remove a pose from the training set of the classifier.
- **classify(frame)**: determine the name of the pose that corresponds to the frame given as argument.

We have implemented two 3D pose classifiers:

- **\$P^3+**. A 3D version of Vatavu’s $\$P+$ algorithm [119]. It is position, direction, and scale-invariant, but not rotation invariant. It is described in more details later in this section.
- **GPSDa**. Proposed by Prof. Paolo Roselli², **GPSDa** is a position, scale, direction and rotation invariant recognizer. Static gestures, also called hand poses, are represented as *Point a-Shapes*. The Point a-Shape $PS_{P,a}$ of a static gesture P is the list of the normalized reciprocal a-distances between each pair of points, arranged in non-decreasing order. If
 - $P = (P_1, \dots, P_N)$, where $P_i = (x, y, z)$, is the list of 3D points of gesture P ;
 - $|P_i - P_j| = \sqrt{(P_i.x - P_j.x)^2 + (P_i.y - P_j.y)^2 + (P_i.z - P_j.z)^2}$ is the Euclidean distance between points P_i and P_j ;
 - $B_P = \frac{1}{N} \sum_{i=1}^N P_i$ is the barycentre of the points of P ;
 - $MD_{P,B,a} = \frac{1}{N} \sum_{i=1}^N |P_i - B_P|^a$ is the mean a-distance between the points P_i and their barycentre B_P .

Then, the Point a-Shape of gesture P is defined as:

$$PS_{P,a} = \text{Sort} \left(\left(\frac{|P_i - P_j|^a}{MD_{P,B,a}} \right)_{1 \leq i < j \leq N} \right) = (\sigma_{P_1}, \dots, \sigma_{P_{\frac{N(N-1)}{2}}})$$

The Global Point Shape a-Distance (GPSD) between a gesture G and a template T can now be defined as:

$$GPSD_{G,T,a} = \sum_{h=1}^{\frac{N(N-1)}{2}} |\sigma_{G_h} - \sigma_{T_h}|$$

Note that a is a parameter that impacts recognition sensibility. Gesture recognition is a two steps process. The recognizer first computes the Point a-Shape of the gesture. Then, for each template, it calculates the GPSD between the template and the gesture and returns the template which minimizes it.

²This method is proposed by Prof. Paolo Roselli, Lecturer at Université catholique de Louvain and Senior Research Associate, Università di Rome “Tor Vergata”, and implemented for the first time in the context of this framework.

Analyzers

The role of an analyzer module is to extract data from a frame after a pose has been recognized. This data is then sent to the application, along with the pose that was recognized. Every analyzer has to implement the two methods of the **AbstractAnalyzer** class:

- **analyze(frame)**: extract and return relevant information from a frame.
- **reset()**: reset the internal state of the analyzer.

We provide one module of this type, **basic-analyzer**. It extracts four values from each frame: (1) **rotation**, the rotation of the hand compared to the previous frame; (2) **pinch**, the ratio of the distances between the index and the thumb of the current and the previous frames; (3) **translation**, the displacement of the palm compared to the previous frame; and (4) **thumbVector**, a 3D vector that gives the orientation of the thumb.

Segmenters

The role of segmenters is to determine if a set of frames consists of a gesture. If the set corresponds to a gesture, it sent directly to the recognizer. Each segmenter must extend the **AbstractSegmenter** class and implement its two methods:

- **segment(frame)**: process a frame and return a **StrokeData** object if the frame marks the end of a gesture.
- **notifyRecognition()**: notify the segmenter that a gesture has been recognized. The segmenter can use this information to avoid unintended gestures that could occur due to coarticulation between two subsequent gestures.

We designed three different segmenters that each have their pros and cons. Please note that this list is non-exhaustive, as gesture segmentation [62] is a deep and interesting problem which could be the subject of an entire thesis.

- **Left-hand segmenter**. This segmenter uses the presence of the left hand in the sensor's field of view to trigger the buffering of frames. As soon as the user removes his left hand, it sends the collected gesture data to the recognizer. This method is easy to implement and usually provides accurate segmentation, as users can directly tell the framework when they are performing a gesture. However, it prevents them to use their left hand for other tasks and makes accurate recognition of two-handed gestures more difficult.
- **Zoning segmenter**. This approach is conceptually very similar to the left-hand approach. Frames from the sensor are buffered while at least one hand is within a 3D zone in space, delimited by a set of boundaries. If both hands leave the zone, or if the buffer is full, the gesture data is sent to the recognizer. In this approach, gestures can be performed with either one hand or both hands, without requiring both of them to be free at all times. However, the size of the bounding box limits the range of movement. If it is too small, users might not be able to perform gestures accurately. On the other hand, if it is too large, unintended gestures might be picked up by the segmenter.
- **Window segmenter**. This segmenter attempts to overcome the limitations of both the zoning and the left-hand segmenters. It uses a fixed-size buffer called the window. Each time a new frame is received, it is pushed in the window, while the oldest frame is removed. Every fixed number of frames, the buffered gesture data is sent to the recognizer. Because it does not impose a limit on the range of motion and does not require both hands to be available at all times, this approach might seem like the best of both worlds. However, it

still suffers from a few issues, some of which can be alleviated at some cost. First, its fixed window size limits the maximum duration of the gestures. Second, because it regularly sends sets of frames to the recognizer, regardless of whether they represent an intended gesture, it causes more CPU strain and may cause the detection of unintended gestures. We introduce two changes to fix this issue: (1) the segmenter waits for some time before forwarding gestural data to the recognizer after a gesture is detected; and (2) it does not forward the data if the amplitude of the movement is below a certain threshold.

Recognizers

Recognizer modules are very similar to the classifiers. Their role is to determine the name of the gesture performed by the user. Recognizers should implement the three methods of `AbstractRecognizer`:

- `addGesture(name, sample)`: add a gesture to the training set of this recognizer.
- `removeGesture(name)`: remove a gesture from the training set of this recognizer.
- `classify(sample)`: determine the name of the gesture that corresponds to the sample given as argument.

We have implemented six 3D gesture recognizers:

- **3 cent.** An optimized 3D port of Wobbrock *et al.*'s $\$1$ [133] by Caputo *et al.* [18]. As opposed to the other recognizers presented in this section, it only supports single-stroke gestures. To recognize a gesture, it first applies a three-step pre-processing: (1) resample the gesture to a fixed number of equidistant points; (2) scale the gesture uniformly to a standard unit length; (3) translate the centroid of the point cloud to the origin, *i.e.*, $(0, 0, 0)$. Then, it computes the distance between this gesture and each template, as the sum of the squared distances of corresponding points. It returns the template with the shortest distance. This recognizer is position and scale-invariant, but neither rotation nor direction invariant.
- **$\$P^3$.** An implementation of Vatavu *et al.*'s $\$P$ [121] that supports 3D gestures. To support multi-stroke gestures while keeping memory usage and execution time low, gestures are represented as unordered sets of points, called *point clouds*. Gesture recognition happens in two phases: normalization and cloud-matching. The normalization process is similar to other $\$$ -family algorithms and is divided into three steps: (1) resample the gesture to a fixed number of equidistant points; (2) scale the gesture uniformly to keep its shape; (3) translate the centroid of the point cloud to the origin, *i.e.*, $(0, 0, 0)$. The cloud-matching phase matches a gesture's point cloud to the point cloud of each template by associating each point from the template to exactly one point from the gesture. It then computes the resulting distance, as the sum of Euclidean distances between all pairs of matching points, and returns the template that minimizes it. This recognizer is position, direction, and scale-invariant, but not rotation invariant.
- **$\$P^3+$.** A more accurate version of $\$P^3$, adapted from Vatavu's $\$P+$ [119]. It brings two key improvements to $\$P$: (1) each point from the template can now be matched to more than one point of the gesture; (2) the distance between a gesture and a template takes into account the connections between consecutive points (in the form of their turning angles). This recognizer has the same invariance properties as $\$P^3$.
- **$\$P^3+X$.** A variation of $\$P^3+$, with partial direction invariance. In the context of large UIs, gesture direction may be key to telling two gestures apart (*e.g.*, swipe left vs. swipe right). However, true direction invariance may reduce accuracy for gestures that may be

performed in any direction, such as letters or symbols. To maximize accuracy, $\$P^3+$ keeps track of conflicting templates, *i.e.*, templates that represent the same gesture but drawn in different directions. Gesture recognition is similar to $\$P^3+$. However, depending on the template that is returned, two scenarios can happen: (1) the template is not marked as “conflicting”, it is thus returned directly; (2) the template is marked as “conflicting”, the direction of the gesture is compared with each conflicting template and the closest one is returned. This recognizer is position and scale-invariant, partially direction invariant, but not rotation invariant.

- **$\$Q^3$.** A 3D version of Vatavu *et al.*’s $\$Q$ [122], which achieved a 46X speedup on average over $\$P$ with no loss of accuracy. It brings two major changes to $\$P^3$: (1) early abandonment of templates, as soon as the distance becomes greater than the current shortest distance; (2) each point cloud has a $16 \times 16 \times 16$ 3D look-up table (LUT), where each location (x, y, z) contains the index of its closest point. Using look-up tables, a lower bound of the distance between a gesture and a template can be computed with a time complexity of $O(n)$. If this lower bound is greater than the current shortest distance, it does not need to compute the exact distance. This recognizer has the same invariance properties as $\$P^3$.
- **Jackknife.** A general-purpose 3D gesture recognizer [111] that supports any number of articulations. Unlike most of the dollar-family recognizers, it represents gestures as time-series. It uses the nearest neighbor approach, where it compares a gesture to each template, and returns the closest one. Unlike the recognizers described before, Jackknife uses *dynamic time warping* to measure the distance between a template and a gesture. However, it applies a series of correction factors to take into account differences in gesture scale and span. As a result, this recognizer is both position and scale-invariant, but neither direction nor rotation invariant.

3.2.4 Configuration File

The `config.js` file is used to configure different aspects of the framework so that it suits the needs of an application. For most hot spots, developers can simply select which module they want to use and set its options. The following example shows how one can configure a recognizer, but it works similarly for sensors, classifiers, analyzers and segmenters. A configuration file is shown in Appendix F.1.3.

```

1  config.recognizer = {
2      module: P3DollarPlusXRecognizer,
3      options: {
4          palmThreshold: 50,
5          fingerThreshold: 15,
6          samplingPoints: 16,
7          articulations: palms.right,
8      }
9  }
```

Configuring datasets is slightly different. There is no `options` field but the framework offers three parameters: `useCustomTemplatesPerClass` and `templatesPerClass` control the number of templates that are used to train the recognizers, whereas `aggregateClasses` is used to combine and rename gesture classes, as well as select only a subset of the gesture set.

```

1 config.datasets.gesture = {
2     directory: __dirname + "/datasets/gesture",
3     loader: LeapMotionDatasetLoader,
4     name: "guinevere",
5     useCustomTemplatesPerClass: true,
6     templatesPerClass: 16,
7     aggregateClasses: [
8         { name: "rhand_uswipe", classes: ["swipe_index_up", "swipe_palm_up"] },
9         { name: "rhand_dswipe", classes: ["swipe_index_down"] },
10        { name: "rhand_lswipe", classes: ["swipe_index_left"] },
11        { name: "rhand_rswipe", classes: ["swipe_index_right"] },
12        { name: "rindex_airtap", classes: ["tap"] },
13    ]
14 }

```

3.3 Use-Case: the DICOM Viewer

3.3.1 Overview

During an operation, surgeons often have to look at medical images of the patient. However, keeping computer controls sterilized is difficult and it is not always possible to have another person dedicated to the manipulation of images. Bastien Nothomb's DICOM viewer [112] aims at solving these issues by bringing gestural interaction into the operating room. It uses our framework to allow surgeons to view and manipulate DICOM images without any contact (see Figure 3.3).

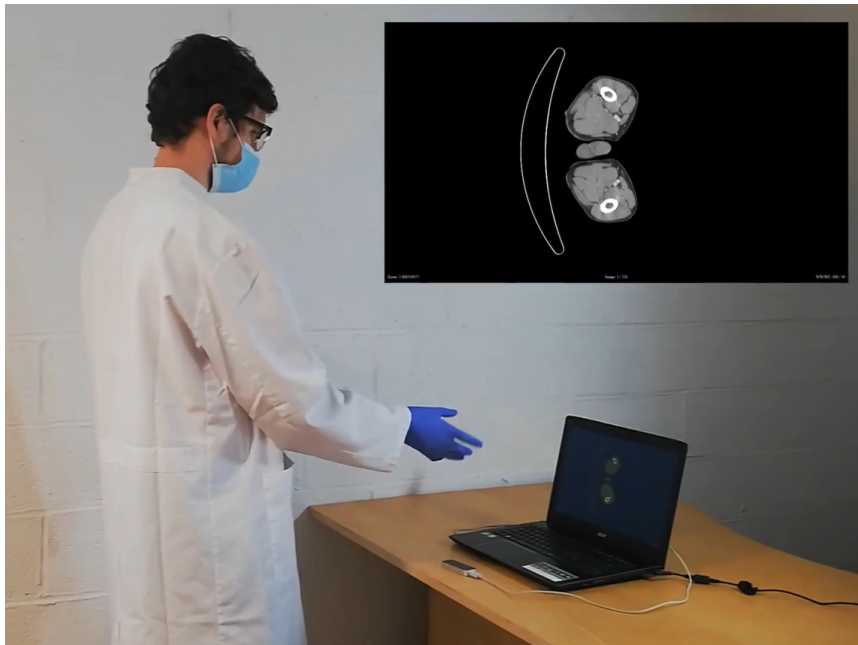


Figure 3.3: The DICOM application.

The application is still a prototype but it already offers a wide range of functionalities. In its current state, it shows a list of DICOM “studies” corresponding to one patient. Each study corresponds to an examination of the patient, which can contain one or more images. Surgeons

can navigate from one study to the next using “swipe” gestures. Within a study, multiple actions are possible, such as manipulating the image or moving to the previous/next one. See Table 3.1 for the complete list of supported actions.

3.3.2 Gesture Set

Table 3.1 shows the gestures associated with each of the 14 actions supported by the current version of the DICOM viewer. The 14 actions and their corresponding gestures were selected based on a gesture elicitation study by Madapana *et al.* [76].

Category	Action	Gesture
Studies navigation	Next study	Swipe left
	Previous study	Swipe right
Image animation	Forward	Swipe up
	Backward	Swipe down
Image manipulation	90° rotation clockwise	Turn invisible button clockwise
	90° rotation anti-clockwise	Turn invisible button anti-clockwise
	Zoom in	Pinch out
	Zoom out	Pinch in
	Increase contrast	C shape w/ the left hand, swipe up w/ the right hand
	Decrease contrast	C shape w/ the left hand, swipe down w/ the right hand
	Pan up	Open hand in up direction
	Pan down	Open hand in down direction
	Pan left	Open hand in left direction
	Pan right	Open hand in right direction

Table 3.1: Gesture set of the DICOM application.

3.3.3 Configuration and Efficacy of the Framework

Figure 3.4 shows the configuration of the framework for the DICOM viewer. The **classifier** and **analyzer** modules are not needed because all of the 14 supported gestures are dynamic. It is configured with the **Jackknife recognizer**, as it reaches high accuracy, even on a large number of gesture classes [111].

The number of lines of code (LOC) of the application was greatly reduced by the use of the framework. In its current state, the DICOM viewer fits into 375 LOC. Without the framework, this number would possibly double to about 770 LOC. Indeed, by taking a look at the source code of the framework, we can observe that, together, the modules that are used in this instantiation are comprised of 397 LOC, distributed into:

- 106 LOC to connect to the LMC and extract data in the correct format;
- 115 LOC to load the gesture dataset;
- 82 LOC for the zoning segmenter;
- 94 LOC for the Jackknife recognizer.

Overall, using the framework has enabled both substantial time-savings and a significant reduction in the complexity of the application.

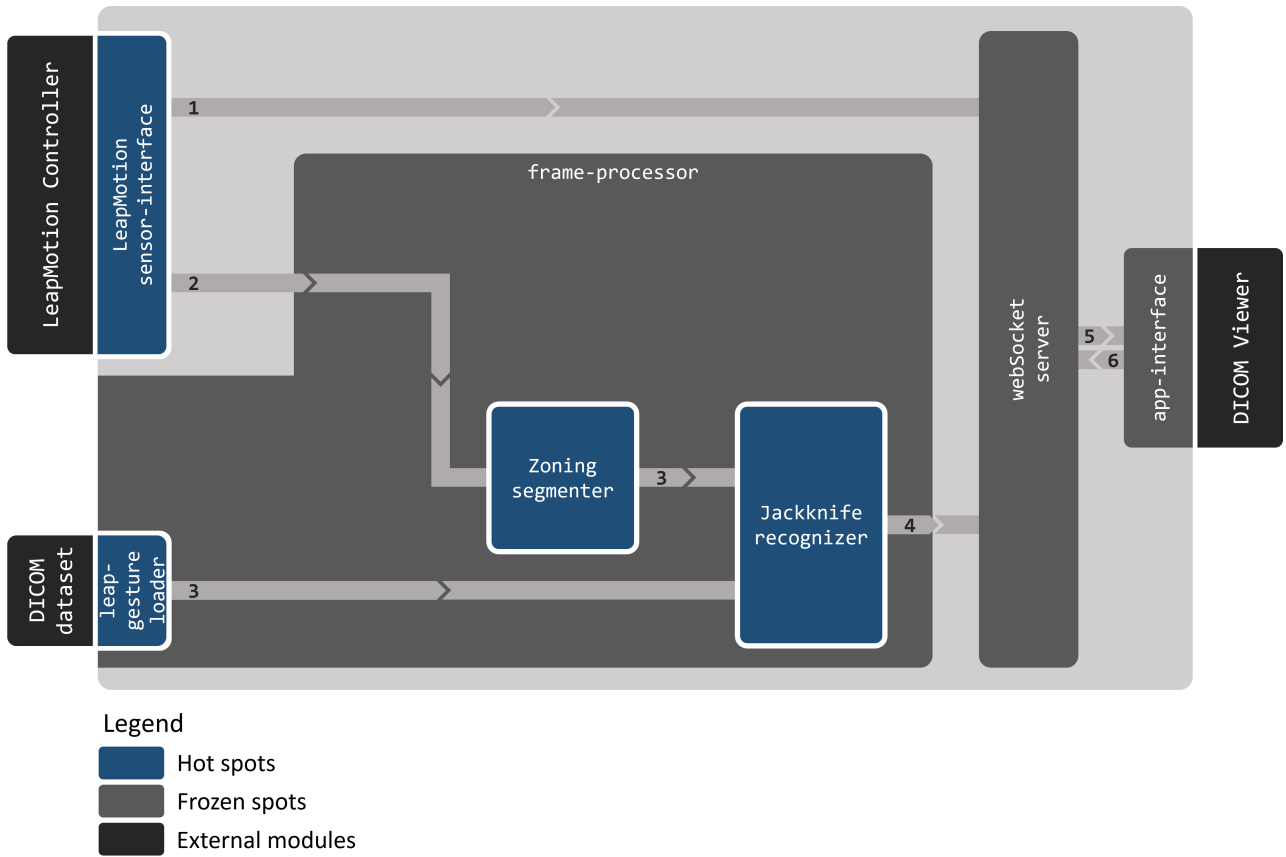


Figure 3.4: Configuration of the framework for the DICOM application.

3.4 Conclusion

This chapter presented the complete development process of the framework for gesture recognition. It first laid out a series of requirements to be satisfied by the framework, based on three ISO/IEC 25010 [50] quality properties. It then detailed its architecture: the gesture recognition pipeline and the modules that were implemented. All of this led up to a first instantiation of the framework, in the form of a small-scale application: the DICOM viewer. Next, chapters 4 and 5 will showcase two larger-scale applications of the framework.

Chapter 4

Benchmarking of Recognizers

The framework for engineering LMC-based UIs introduced in Chapter 2 was illustrated on a first, small-scale application, the DICOM viewer (Section 3.3). This chapter presents a second application of this framework that is different from developing a gesture-based UI: a benchmarking of gesture recognizers. Section 4.1 describes the configuration of the framework, the recognizers, and the evaluation procedure used for this purpose. The results are then summarized and discussed in Section 4.2.

4.1 Benchmark

4.1.1 Benchmarking Tool

The software architecture of the framework (see Figure 3.1) allows configuring modules for a variety of purposes, such as, obviously, developing a gesture-based UI for an interactive application with an LMC, but also for other purposes, such as testing a particular recognizer against one or many gesture sets, testing a particular gesture set across recognizers, and designing gestures for the LMC by managing gesture sets. In particular, benchmarking recognizers is aimed at comparing the overall behavior of several recognizers on several gesture sets to identify which one is the most accurate in terms of recognition rate and the most efficient in terms of execution time. For this purpose, a benchmarking module is integrated into the framework to compare both static and dynamic gesture recognizers with limited effort (Figure 4.1). Similarly to the gesture recognition part, it holds a configuration file that allows testers to select and configure a series of recognizers and gesture sets. As this chapter focuses exclusively on dynamic gesture recognizers, only the bottom part of the pipeline shown in Figure 4.1 is used.

4.1.2 Recognizers

In addition to the $\$P^3$, $\$P^3+$, and $\$Q^3$ recognizers implemented and described in Section 3.2.3, we also incorporated in the framework four recognizers developed by [Nathan Magrofuoco](#) and [Mehdi Ousmer](#), thus demonstrating adaptability, a sub-factor of compatibility.

Rubine3D

Inspired by the iGesture framework [105], Rubine3D is a feature-based recognizer that combines a set of three individual 2D Rubine recognizers [97], one for each plane XY , YZ , and ZX . 3D trajectories are projected onto the three planes by transforming each of their points to the

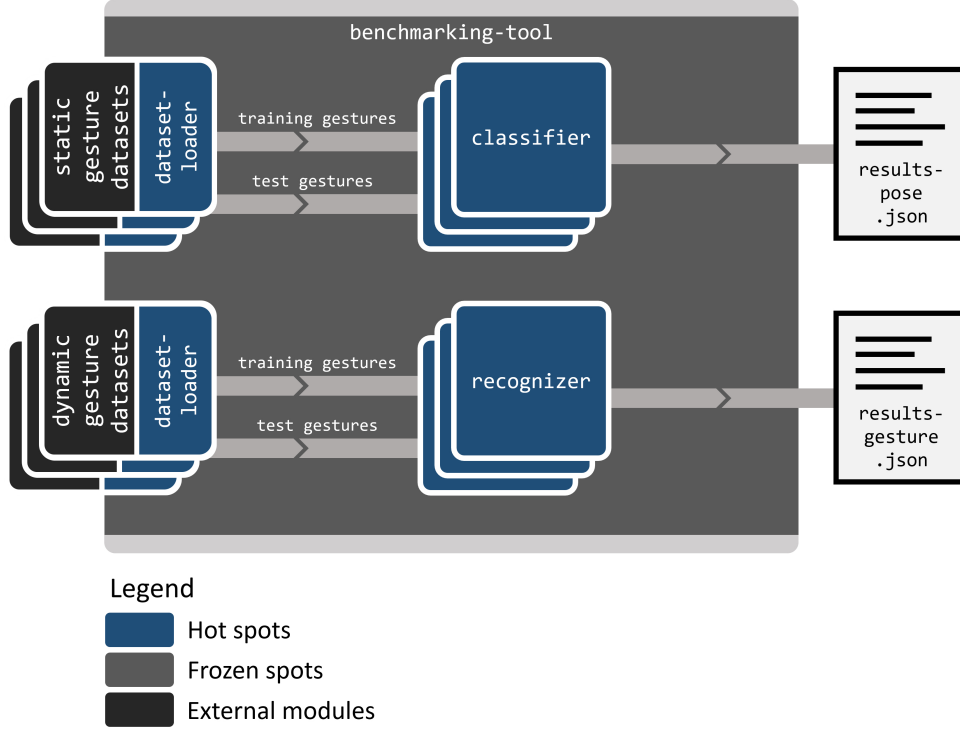


Figure 4.1: Configuration of the framework for the benchmarking of recognizers.

three coordinate system planes (XY, YZ, ZX). If $M(i, j, h)$ is a point of the 3D trajectory, then $P(i, j)$, $Q(j, h)$, and $R(h, i)$ are the 2D point coordinates of the projection onto (XY, YZ, ZX).

Before it can recognize 3D trajectories, Rubine3D has to pre-process the training templates. Each template is first projected onto the three planes. Then, for each plane, the recognizer compute weights for the features of each gesture class in five steps: (1) the raw data is pre-processed by scaling and filtering its points; (2) the 13 original features ($f_1, \dots, f_{13}$) defined by Rubine [97] are computed for each template; (3) from these features we compute the mean feature vector and the covariance matrix of each gesture class; (4) we compute the common covariance matrix and its inverse matrix; and (5) we estimate the weights for each gesture class from the inverse matrix. Once Rubine3D is trained, there are several steps to determine the possible class of a candidate gesture. The gesture is first projected onto each plane and three feature vectors are extracted from the three projections. For each projection, we return the gesture class that maximizes the similarity score (computed by combining the weights of the gesture class with the feature vector of the gesture). The results from the three projections are then merged using a heuristic inspired by iGesture. If the three projections return the same gesture class, it is designated as the final result. Otherwise, if there are two or three different classes, we compute the similarity score of these classes for the three planes. The scores of each plane are weighted ($W_{XY}=0.4, W_{YZ}=0.3, W_{ZX}=0.3$) to factor in the relative difficulty of producing gestures in that specific plane [114]. We return the gesture class which maximizes the sum of the three similarity scores.

Rubine-Sheng

Rubine-Sheng (RS) is a 3D recognizer inspired by Rubine. It supports 3D gestures by adding three new features proposed in the AdaBoost recognizer [104] to Rubine’s existing 13 features. Aside from this difference, it is extremely similar to its 2D counterpart for both the pre-processing of the templates and gesture recognition.

$\$F$

The $\$F$ recognizer adds $\$P+$'s flexible cloud matching [119] to $\$P^3$. As for most $\$$ -recognizers, the points of the candidate and the templates are resampled to equidistantly-spaced points, scaled within a unit box, and translated so their centroid is at the origin $(0, 0, 0)$. The template with the lowest dissimilarity score is considered as the best matching template for the candidate. As opposed to $\$P^3$, $\$F$'s cloud matching is flexible, as points can be matched to more than one point. It consists of matching the points from the first cloud with their closest point from the second cloud, then matching the points from the second cloud that have not been matched yet with their closest point in the first cloud.

FreeHandUni

The FreeHandUni (FH) recognizer is derived from Vatavu *et al.*'s Free-Hand recognizer [32], which extends the $\$P$ 2D gesture recognizer [121] to support 3D hand gestures. FreeHandUni is adapted to meet our need for recognizing the unipath character of 3D trajectories by replacing the hand pose structure with a 3D point structure (x, y, z) . With this modification, FreehandUni corresponds to an improvement of $\$P^3$, using a flexible cloud matching based on a one-to-many alignment between points [119]. The pre-processing stays the same but the matching process is more flexible: each point of the template cloud is matched with the closest point from the candidate cloud, then the remaining points from the candidate cloud are matched with the closest point from the template cloud. It returns the gesture class with the lowest dissimilarity score. FreeHandUni is different from $\$F$ in that the early abandoning is not implemented, to align the computational complexity to $\$P^3$.

4.1.3 Experiment

We evaluated the seven resulting recognizers, the three that we implemented, and the four that we integrated via their configuration files, in the traditional user-independent procedure [5,6,119,121].

Design

Our study was within-subjects with two independent variables:

1. RECOGNIZER: nominal variable with 7 conditions, representing the various recognizers implemented for recognizing 3D trajectories: $\$P^3$, $\$P^3+$, $\$Q^3$, $\$F$, FH (FreeHandUni), $R3D$ (Rubine3D), and RS (Rubine-Sheng).
2. DATASET: nominal variable with 2 conditions, representing two datasets *i.e.*, SHREC2019 [17] and 3DTCGS [18]. Both datasets are described in Section 2.4.

Procedures and Quantitative Measures

We compute the *recognition rate* (the ratio of positive recognitions divided by the total number of trials) and the *execution time* (the time for pre-processing a candidate gesture and determining its result class in milliseconds) for the 7 (RECOGNIZER) $\times$ 2 (DATASET) = 14 basic configurations following the typical method used in the literature to evaluate recognizers [3,5,6,121,122,133].

We compare the recognizers in a *user-independent scenario*, *i.e.*, we evaluate the recognition on gestures produced by different users than the templates used to train the recognizers. The 14 basic configurations defined above are further refined depending on two parameters: (1) N , the number of resampling points ($N \in \{4, 8, 16, 32, 64\}$); and (2) T , the number of templates per

gesture chosen from all users to train the recognizers. This second parameter varies according to the dataset: $T=\{1, 2, 4, 8, 16\}$ for SHREC2019 and $T=\{1, 2, 4, 8, 11\}$ for 3DTCGS. Furthermore, $R3D$ and RS require at least two templates to be instantiated as they cannot compute weights if the number of samples is too small [106]. As such, we defined $T=\{2, 3, 4, 8, 16\}$ (*resp.*, $T=\{2, 3, 4, 8, 11\}$) for $R3D$ and RS for the SHREC2019 dataset (*resp.*, the 3DTCGS dataset).

The testing procedure for a recognizer is straightforward. First, one “testing” template is randomly selected for each gesture class from all participants. Then, a training set is generated by randomly choosing T templates for each gesture class for all users. These templates should be different from the templates previously selected for the testing. Finally, the recognizer is trained on the resulting training set. Each time a candidate is positively recognized, an internal counter is incremented. This operation is repeated 100 times for each T . In the end, the number of recognized gestures is averaged to get the recognition rate and format it as a percentage for each N for each recognizer. Overall, we performed $2 \text{ (DATASET)} \times 5 \text{ (resampling values } N) \times 5 \text{ (values for } T) \times 100 \text{ (repetitions)} \times 7 \text{ (RECOGNIZER)} = 35,000$ recognition trials.

4.2 Results

4.2.1 Recognition Rate

Figure 4.2 plots the recognition rates for all recognizers on the SHREC2019 and 3DTCGS datasets with the individual rates obtained in the upper part and the global (aggregated) rates in the bottom part to summarize the results. To be consistent in the presentation style, we systematically use the same type of chart presented in [122], with the same design. Next, we summarize the results for the SHREC2019 dataset. We do not summarize the results for 3DTCGS as they are quite similar. The only major differences compared to SHREC2019 are that the recognition rates increase faster with T and that the global recognition rates are better for $R3D$ ($\tau=74.48\%$ instead of $\tau=52.51\%$) and RS ($\tau=68.80\%$ instead of $\tau=40.82\%$).

- $\$P^3+$ turns out to be the most accurate recognizer in all conditions ($N=\{4, 8, 16, 32, 64\}$) in terms of absolute values for all values of T . When $N=64$, $\$P^3+$ is almost joined by $\$Q^3$, thus suggesting that $\$Q$ exhibits a better accuracy when the amount of templates is increasing. The more points are included for each template, the more accurate $\$Q^3$ becomes as it is the case for $\$Q$ [122]. $\$P^3+$ is appropriate for gestures with high sampling, even with a low number of templates (*e.g.*, $\tau=80.00\%$ with $T=4$, increasing above 90%).
- $\$P^3+$ is significantly more accurate than all other recognizers. We computed Student’s t test for two paired samples since the samples were the same. There was a very highly significant difference in the global recognition rates for $\$P^3+$ ($M=86.94\%$, $SD=15.00\%$) and all the other conditions (all with $df=2499$ and $p^{***}<.001$):
 $\$F$ ($M=79.36\%$, $SD=18.08\%$), $t=18.74$, with a Cohen’s $d=.37$ for a small effect [29];
 $\$Q^3$ ($M=79.36\%$, $SD=18.60\%$), $t=18.67$, with a Cohen’s $d=.37$ for a small effect [29];
 FH ($M=79.28\%$, $SD=18.51\%$), $t=18.20$, with a Cohen’s $d=.36$ for a small effect [29];
 $\$P^3$ ($M=78.10\%$, $SD=19.20\%$), $t=21.13$, with a Cohen’s $d=.42$ for a small effect [29];
 $RD3$ ($M=52.51\%$, $SD=32.24\%$), $t=52.35$, with a Cohen’s $d=1.05$ for a large effect [29];
 RS ($M=40.82\%$, $SD=30.22\%$), $t=73.61$, with a Cohen’s $d=1.47$ for a very large effect [102].
 These results suggest that using the $\$P^3+$ recognizer has a positive effect on global recognition rates. This is also confirmed by the values obtained by a one-way ANOVA with Tukey’s HSD post-hoc analysis: the between-group analysis also returned a very highly significant effect ($SS=11036.5$, $df=6$, $F=1444.58$, $p^{***}<.001$).

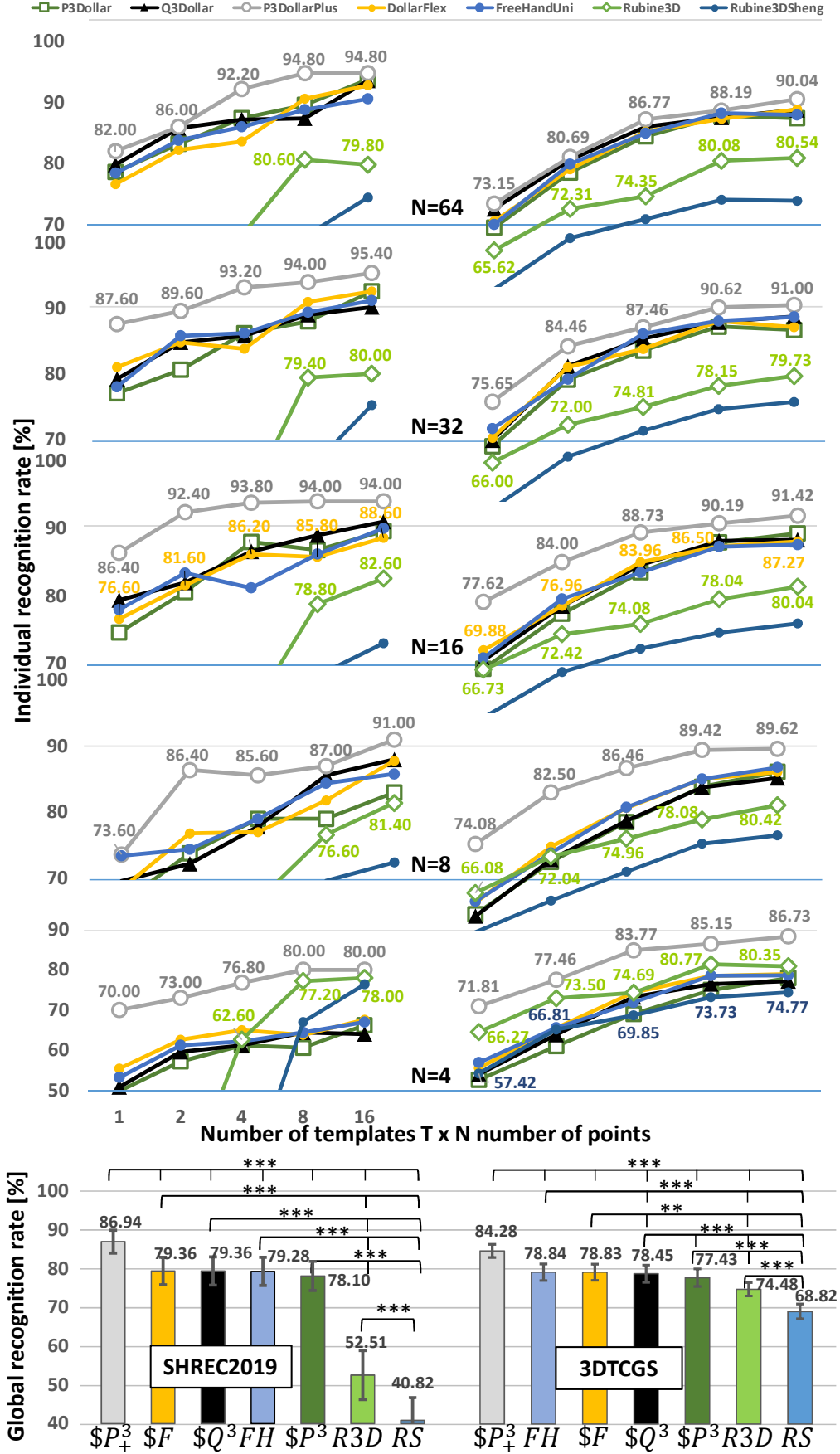


Figure 4.2: Recognition rates of all recognizers for two datasets (left: SHREC2019 [17], right: 3DTCGS [18]): individual rates (top) for $N=4, \dots, 64$ (top) and global rates (bottom) $\forall N$ ($p^{***} \leq .001$). Error bars show a confidence interval with $\alpha=.05$.

- $\$P^3+$ could accommodate gestures with low sampling: already with one template on four points ($N=4, T=1$), it benefits from a reasonable rate of $\tau=70\%$, the lowest value for this recognizer in all configuration. When $N=4$, better to have at least 8 points to reach a rate of $\tau=80\%$. When the number of points reaches 8 ($N=8$), two or more templates are admissible to get a rate of at least ($\tau=86\%$). This observation seems to confirm the observation that for $\$$ -family members, a sampling of 8 points already gives acceptable results [118]. When $N \geq 16$, one template is already enough and there is no need to go up to 16, even if the best rate is obtained when $N=32$ with $\tau=95.40\%$.
- Apart from $\$P^3+$, all other $\$$ -like recognizers display a global rate of $\tau \geq 78\%$. Their differences are very light: they remain included in the same envelope with similar rates and progression when $N \nearrow, T \nearrow$, and the curves are almost superimposed all the time.
- Although $\$P^3$ returned the lowest global rate of all $\$$ -like recognizers, the one-way ANOVA did not return any significant difference between them, but all of them are always significantly more accurate than $RD3$ and RS .
- Regarding the two feature-oriented recognizers, Rubine3D (R3D) is always more accurate than its counterpart Rubine-Sheng (RS) in all conditions. A Student's t test for two paired samples revealed a very highly significant difference in the global recognition rates for $RD3$ ($M=52.51, SD=32.20$) and RS ($M=40.82\%, SD=30.22\%$): $t=20.16, df=2499, p^{***}<.001$, with a Cohen's $d=.40$ representing a small effect. Both exhibit an acceptable rate only when $N \geq 8$. Below this threshold, they are not useful. Surprisingly, when $N=4$, $RD3$ and RS outperform other $\$$ -like recognizers, apart from $\$P^3+$, when $T \geq 4$. After that, they are completely surpassed.
- Rubine-Sheng is the least accurate recognizer in almost all conditions as it is outperformed by all other recognizers tested. Therefore, computing more geometric features for a 3D trajectory does not help much, and keeping the original features in the three planes is enough to outperform Rubine-Sheng.
- If we assume that a human-acceptable rate of $\tau \geq 90\%$, the ideal cases are all when $T=16$ for all conditions.

4.2.2 Execution Time

We now investigate the recognizers' efficiency based on their execution time (computed as the sum of the pre-processing time plus the recognition time for each candidate) for different configurations. Figure 4.3 plots the execution time of each recognizer on the SHREC2019 and 3DTCGS datasets. We summarize the results for the SHREC2019 dataset:

- Overall, Rubine3D ($M=.047, MD=.044, SD=.013$) and RubineSheng ($M=.017, MD=.015, SD=.006$) have the lowest and the most constant times in all configurations. On the contrary, the $\$$ -like recognizers are the most time-consuming: $\$F$ ($M=.289, MD=.088, SD=.490$) is the fastest recognizer among them, followed by $\$P^3+$ ($M=.363, MD=.094, SD=.649$), FreeHandUni ($M=.492, MD=.111, SD=.956$), $\$Q^3$ ($M=3.005, MD=1.623, SD=3.005$) and $\$P^3$ ($M=4.798, MD=.668, SD=10.224$). This difference suggests that feature-based recognizers (*i.e.*, $RD3$ and RS) and template-based ones (*i.e.*, $\$P^3$, $\$P^3+$, $\$Q^3$, $\$F$, and FreeHandUni) are not influenced by the same parameters.
- RubineSheng is the fastest recognizer in most N and T conditions, except in the case where $N=4$ and a reduced number of templates are provided to the recognizer ($T \leq 4$).
- The times of all $\$$ -like recognizers increase while the number of points and the number of templates grow.

- $\$Q^3$ is the slowest recognizer for $N=4, 8$. Other curves are under the $\$Q^3$ one but from $N=16$, $\$P^3$ execution times increase quickly and exceed the execution time of $\$Q^3$ for $T=16$ ($t_{\$P^3}=2.196$ ms, $t_{\$Q^3}=1.853$ ms) and it occurs even quicker for $N=32$ and $N=64$, where $\$P^3$ exceeds $\$Q^3$ immediately after $T=4$, resp., $T=2$.
- RS is three-time faster than $RD3$: the ratio of their averaged execution times is $\frac{t_{RS}}{t_{RD3}}=2.82$. This ratio makes sense considering that $RD3$ computes 39 features of the candidate (3 times 13 features for the three planes XY , YZ , and ZX) while RS computes 16 features once.
- For these feature-oriented recognizers, the candidate is pre-processed, its features are extracted and multiplied by pre-computed weights of each class, then summed. The candidate's class is designated by the larger sum resulting from this calculation, which confirms the constant time for the recognition, only influenced by the number of classes in the dataset.
- The $\$F$, $\$P^3+$, and FreeHandUni have short execution times compared to other $\$$ -like recognizers. $\$F$ and $\$P^3+$ are better than FreeHandUni ones, this variation is caused by the early abandoning for the two recognizers.
- Knowing that 100 ms is the limit for a user to feel that a system is operating in real-time [87], the execution times for all the conditions for this dataset are fortunately under this limit.

The overall picture remains the same for the 3DTCGS dataset: the execution times increase for all the recognizers and conditions, which pushes the $\$P^3$ over the limit of 100 ms. This increase is due to the higher number of classes and samples per class in the dataset (26 classes compared with 5 gestures for SHREC2019). We observe a rapid increase of the $\$P^3$ curve which surpasses the $\$Q^3$ just after $T=4$ for $N=8$.

4.3 Conclusion

This chapter showed that, in addition to the development of gesture-based UIs, the framework can also serve more general purposes such as comparing gesture recognizers. This benchmarking compared the accuracy and execution time of seven recognizers (*i.e.*, three that were described in Section 3.2.3 and four that were integrated into the framework for this specific application) on two challenging gesture sets that were used in gesture recognition contests. The modular architecture of the framework makes it easy to vary the benchmarking configuration, by adding or removing recognizers, changing datasets, or selecting a subset of gestures from a dataset. It is thus possible to obtain other similar configurations for testing a particular recognizer against various gesture sets, a particular gesture set across a series of recognizers, and for benchmarking several recognizers against several gesture sets.

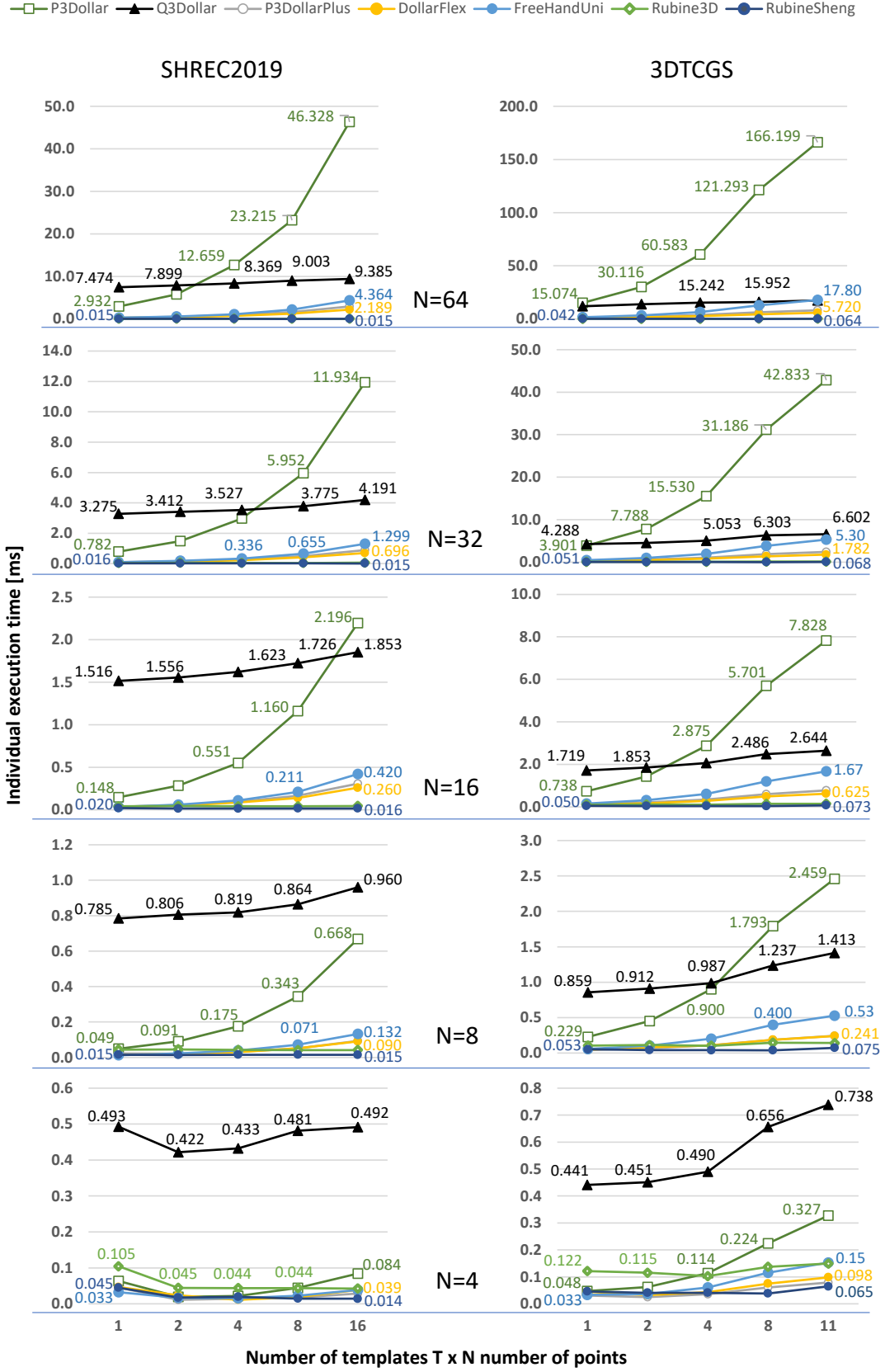


Figure 4.3: Execution times of all recognizers for two datasets (left: SHREC2019 [17], right: 3DTCGS [18]): individual times for $N=4, \dots, 64$.

Chapter 5

The Large User Interface Project

This chapter presents a third case study of using the framework for engineering gesture-based UIs to a large-size application: the Large User Interface project. This chapter is composed of four parts. Section 5.1 first gives an overview of the LUI project, the rationale behind it, and its current state. Then, Section 5.2 describes how we designed a suitable gesture set by applying a gesture elicitation study for the application while Section 5.3 is dedicated to finding the most appropriate recognizers for this gesture set. Finally, Section 5.4 details how we used the framework to implement a complete gesture-based UI for the LUI project.

5.1 Project Overview

The [Large User Interface](#) (LUI) project [89] managed by The MIT Media Lab¹ is aimed at allowing people to naturally interact by gesture to manipulate multimedia contents on a large display, such as a wall display or a tabletop. As multimedia contents, such as pictures, videos, and maps, are probably the most common elements that are widely manipulated by the largest amount of users [36], an intuitive and accessible gesture-based UI could quickly be adopted by a significant part of the population. This project is mainly developed by [Vik Parthiban](#) at MIT as such: “LUI is a scalable, multimodal web-interface that uses a custom framework of non-discrete, free-handed gestures and voice to control modular applications with a single stereo-camera and voice assistant”.

5.1.1 Rationale

As large displays have become more and more accessible in the last few years, input methods such as the classic keyboard-and-mouse combo or TV remotes have become increasingly ill-suited to the task. In this context, the objective of LUI’s creators is to provide a UI that is easy to control through both gestures and voice commands, while being “easily installed and deployed on any large screen surface” [89]. When designing the system, they defined the three following design guidelines:

1. *Accessible*: the system should be both cheap and easy to set up and to use.
2. *Extensible*: apps should be simple to add, modify, and remove from the system.

¹This work is part of a larger collaboration project between MIT and UCLouvain in the context of an MIT-UCL MISTI Fund “Large User Interface” project lead by [Prof. Pattie Maes](#) on the MIT side and by [Prof. Jean Vanderdonckt](#) on the UCLouvain side, under contract #200278.

3. *Non-discrete*: to avoid latency, the system should support non-discrete methods of interaction.

5.1.2 Current State

The system is built using the popular ReactJS framework to provide a reactive UI that can be easily modified. Each application, such as the *Photos* or the *Videos* applications, consists of one separate module. As such, writing new apps is easy as developers only have to focus on one module, which contains all of their application’s code. In its current version, the LUI project is composed of only four major modules, including two applications, forming the functional core of the LUI project:

- *Welcome screen* (Figure 5.1a): the entry point of the LUI project. From this screen, one can only go to the app menu.
- *App menu* (Figure 5.1b): a list of all the applications. Clicking on an application opens it.
- *Videos app* (Figures 5.1c and 5.1d): a list of YouTube videos, organized into multiple pages. Each video can be selected and viewed in full-screen. From the full-screen mode, users can play/pause the video, or go to the previous and next ones in the list.
- *Photos app* (Figures 5.1e and 5.1f): a list of pictures, organized into multiple pages. As in the *Videos* app, each photo can be selected and viewed in full-screen, and one can browse through the photos directly from the full-screen mode.

Four other applications are also available, but they have been disabled in the latest version of the project. For this reason, we do not describe them here.

The hypothesis of this chapter consists of the availability of the functional core of the aforementioned modules, for which a gesture UI should be developed based on the LMC. The JavaScript code corresponding to this functional core has been made available by Vik Parthiban in the context of the MISTI project.

5.2 Designing an Appropriate Gesture Set

Designing a good gestural interface requires some insight regarding potential users’ preferred gestures for interacting with the application. A great way of gathering such insight is to perform elicitation studies, *i.e.*, experiments in which users are asked to associate their preferred gestures to a series of actions (called referents) in a controlled environment.

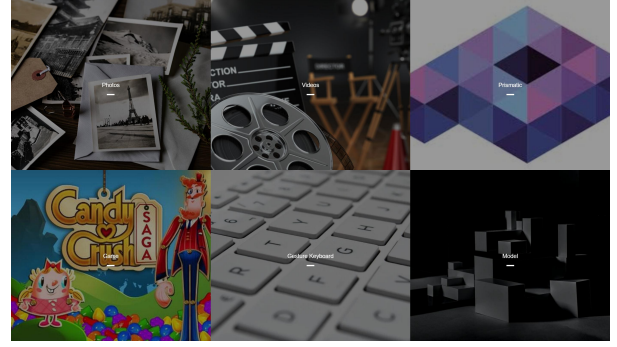
The remainder of this section is divided into five parts. Section 5.2.1 briefly describes two preliminary gesture elicitation studies (GESs) that were conducted to explore user-defined gestures and highlights their shortcomings. Then, Section 5.2.2 details the updated procedure used for a more recent, updated, GES and Section 5.2.3 reports its results. Section 5.2.4 explains how, based on these results, we created a gesture set for the LUI project. Finally, Section 5.2.5 classifies the gestures of the new gesture set according to Aigner *et al.*’s taxonomy [2].

5.2.1 Preliminary Gesture Elicitation Studies

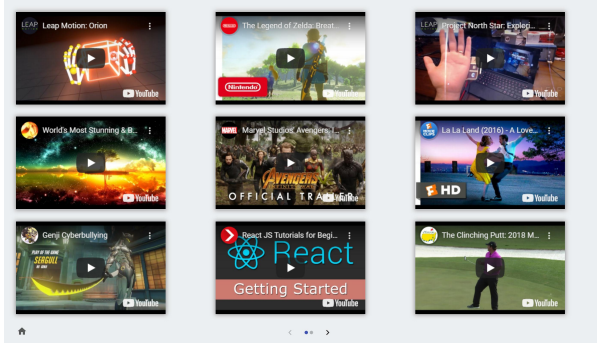
The LMC comes with five system-defined gestures, *i.e.*, “swipe right/left/up/down”, and “Explode”, that are accessible through a programmatic way that does not satisfy our software quality properties. These system-defined gestures, as well as designer-defined gestures, are not always easy to remember by end users [84], who often prefer to rely on their own user-defined gestures. To explore which gestures would be preferred by LUI end-users, two preliminary GESs



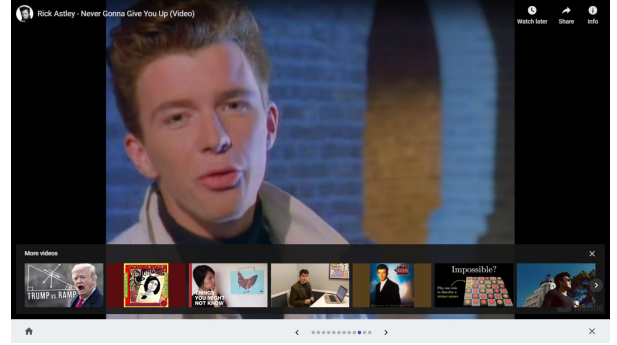
(a) Welcome screen



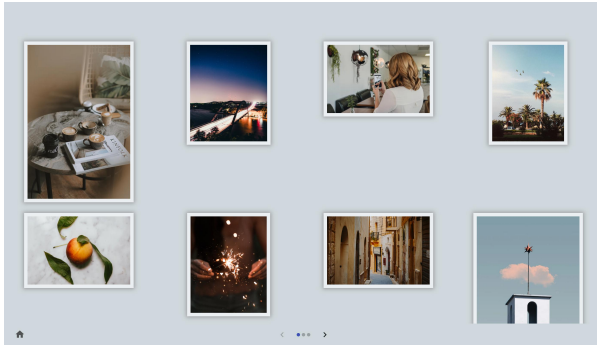
(b) App menu



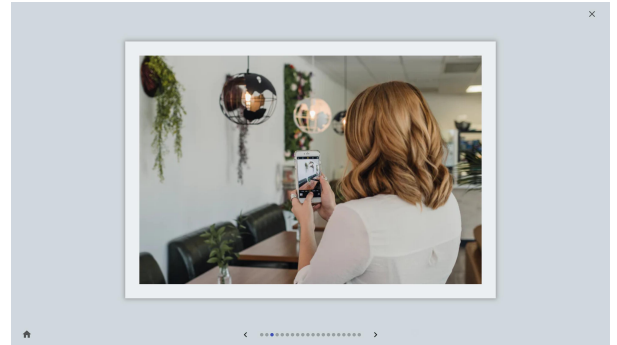
(c) Videos app (list view)



(d) Videos app (full-screen)



(e) Photos app (list view)



(f) Photos app (full-screen)

Figure 5.1: Screenshots of the LUI application.

were conducted in 2019 following the general methodology (*e.g.*, [32,42,124,131,133]) to collect users' preferences for mid-air gesture input for browsing through respectively photos and videos.

Gesture Elicitation Studies [32,124,132] are popular for investigating users' preferences for gesture input in a variety of contexts of use [99,121,125,132]. For instance, Wobbrock et al. [132] reported users' preferences for multi-touch input on interactive tabletops. Zaiți et al. [125,137] addressed mid-air gesture input to control a TV set. The result consists of a characterization of users' gesture input behaviors with valuable information for designers, practitioners, and end-users regarding the consensus among participants (which is computed as an *agreement* or *coagreement rates* [32,124,132]), most frequent (thus, generalizable across users) gestures for a specified task, and insights into users' conceptual models for performing tasks. The most recent formalization of the elicitation method proposed both repeated measures [124] and between-subjects [32] experimental designs. See [126] for a survey of GESs.

In the rest of this section, we briefly describe the setup of the two preliminary GESs and highlight some of their shortcomings.

Setup

In both experiments, participants were installed at a desk and faced a laptop, which showed them referents. For each of these referents, they had to propose a suitable gesture, *i.e.*, a gesture that fits the referent well while being easy to perform and remember. There were no constraints on the participants' choices of gestures, with the exception that a given gesture could not be assigned to more than one referent. The order of the referents was randomized per participant.

Because we did not have a Kinect or LMC at our disposal for the experiment, participants were asked to perform their gestures in mid-air in front of the laptop, as if it was able to register their hand gestures (see Figure 5.2). Participants' fine motor skills and creativity levels were evaluated before the experiment, and a short questionnaire was administered after the experiment to give us an insight into the system's user satisfaction.

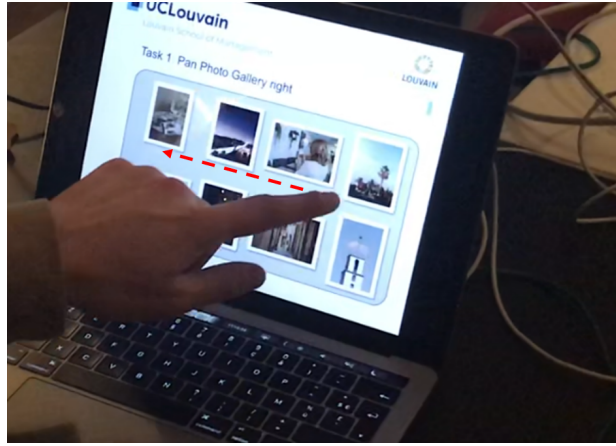


Figure 5.2: Snapshot from the GES showing a participant performing a mid-air gesture.

Observations and Possible Issues

When analyzing the results of both GESs (details are available in Appendix B), we identified the following shortcomings:

- *Unrealistic setup*: the experiment's setup may have impacted participants' choice of gestures. For instance, in the *photo-browsing* experiment, participants were situated very close to the screen with the visualization of the referents, to the point where some of them physically touched it while performing gestures. This may have encouraged them to propose more "touch-oriented" gestures.
- *Unique gestures requirement*: requiring participants to assign a different gesture for each referent sometimes forced them to propose less-than-ideal gestures, *e.g.*, if they had already assigned their preferred gesture to another referent.
- *Unclear visual indications*: some visual indications of the referents did not provide a clear idea of what the meaning of the represented action was. Designing clear visualizations for each referent could help participants propose more suitable gestures and speed up the elicitation process.
- *Too many referents*: some participants complained about the high number of referents (*resp.*, 27 and 31 for the *photo-browsing* and *video-browsing* experiments), which greatly increased the duration of the experiment. Reducing the number of referents could ensure that participants stay focused throughout the experiment.

- *Too complex referents*: some referents referred to complex actions, which combined multiple concepts at once while providing insufficient details (*e.g.*, “search photos within the gallery by criteria”, implies both a “search” and a “select a criteria” action). Such referents should be clarified and/or divided into multiple smaller referents.

5.2.2 New Gesture Elicitation Study

This section details a new GES that was performed in collaboration with [Nathan Magrofuoco](#). Due to the confinement measures imposed by the Belgian government during the COVID-19 outbreak, we reached a smaller number of participants than expected.

Addressing the Shortcomings of the Previous Experiments

This new experiment mostly follows the same protocol, inspired by Gheran *et al.* [42], as the two preliminary GESs mentioned above. However, it was slightly modified in an attempt to address their shortcomings. First, both the number of referents and their complexity have been drastically reduced. Second, the setup of the new experiment has been modified to be more realistic. The screen is now further away from the participants, and the LMC can record their hand motions. Finally, participants are encouraged but not required to find a unique gesture for each referent.

Participants

Twenty-three (23) participants (6 female), aged between 18 and 56 years old ($M=27.1$, $SD=10.2$ years), volunteered for the study. Their occupations include students and employees, mostly in IT, art, and engineering. All but two of the participants had never used an LMC, but all of them regularly used a computer. Only one participant did not frequently use a smartphone. 95.7% of the participants (22/23) were right-handed.

Apparatus

Compared to the two previous elicitation studies, the setup is much closer to the expected context of use of the system. The experiment relied on three main devices: the LMC to capture the mid-air gestures proposed by the participants, a smartphone to record their touch gesture propositions, and a large screen to display the referents. A laptop computer was also used to control the display and record the gestures captured by the LMC using a custom tool that we developed (see Appendix C).

Design

The experiment has three independent variables. Two of them are within-subjects variables: the REFERENT and the INTERACTION METHOD.

The REFERENT is a nominal variable with 18 conditions. Each condition represents a common task to perform in multimedia environments, such as in a music player, a video gallery or a PowerPoint presentation: (1) previous; (2) next; (3) enable fullscreen; (4) disable fullscreen; (5) zoom in; (6) zoom out; (7) volume up; (8) volume down; (9) rotate 90° clockwise; (10) rotate 90° anti-clockwise; (11) play; (12) pause; (13) like; (14) dislike; (15) fast forward 5 seconds; (16) rewind 5 seconds; (17) enable subtitles; and (18) disable subtitles. The number of conditions has been reduced compared to the previous experiments by combining similar referents in different contexts and dropping the most uncommon actions.

The INTERACTION METHOD is a nominal variable with 2 conditions: (1) touch gesture; and (2) mid-air gesture.

The last variable, the PROPOSITION SEQUENCE, is between-subjects. It has 2 conditions: (1) for each referent, the participant first proposes a touch gesture and then a mid-air gesture; and (2) for each referent, the participant first proposes a mid-air gesture and then a touch gesture.

In the context of this thesis, we will only focus on participants' mid-air gesture propositions.

Task

Participants were installed at a desk and faced a large screen situated at a few meters on the opposite side of the desk. The LMC was positioned in front of them, and a smartphone was placed on their right. Each participant was presented with a series of referents in a randomized order. For each one of these referents, participants were asked to propose both a touch and a mid-air gesture that fit the referent, in an order determined randomly at the start of the experiment. Participants' thinking time was measured for each touch and mid-air gesture proposition. There were no constraints on the participants' choices of gestures. After each gesture proposition, the participants estimated the goodness-of-fit of their proposition on a Likert scale from 1 (very unsatisfied) to 5 (very satisfied).

Measures

We employed the following measures, taken from Gheran *et al.* [42], to evaluate and understand users' preferences for gestures detected by the LMC:

1. We computed agreement rates (AR) for each REFERENT using the formula of Vatavu and Wobbrock [124] (p. 1327), as follows:

$$AR(r) = \frac{\sum_{i < j} \delta_{i,j}}{n \cdot (n - 1) / 2} \quad (5.1)$$

where n is the number of participants from which gestures are elicited, and $\delta_{i,j}$ evaluates to 1 if the i -th and j -th participants are in agreement over referent r and to 0 otherwise.

2. THINKING-TIME measures the time, in seconds, needed by participants to propose a gesture for a given referent.
3. GOODNESS-OF-FIT represents participants' subjective assessment, as a rating between 1 and 5, of their confidence about how well the proposed gestures fit the referents.

5.2.3 Results

We collected a total number of 414 mid-air gesture proposals from 23 (participants) $\times$ 18 (referents) conditions. We then clustered these gesture propositions into 102 groups of similar gestures. For this clustering, we distinguished between gestures according to their direction (*i.e.*, the same gestures performed in different directions are considered different) but grouped similar gestures performed with different poses together (*e.g.*, swiping with a flat hand is considered the same as swiping while pointing the index finger). In the rest of this section, we analyze the consensus between participants' gesture proposals, as well as its relation with thinking time and goodness of fit.

Referent	AR	Most frequent	Second most frequent
1. <i>Previous</i>	.498	Swipe right	Swipe left
2. <i>Next</i>	.498	Swipe left	Swipe right
3. <i>Enable fullscreen</i>	.273	Bring hands further apart	Pinch out
4. <i>Disable fullscreen</i>	.146	Bring hands closer	Pinch in
5. <i>Zoom in</i>	.320	Pinch out	Bring hands further apart
6. <i>Zoom out</i>	.300	Pinch in	Bring hands closer
7. <i>Volume up</i>	.478	Swipe up	Rotate a knob clockwise
8. <i>Volume down</i>	.316	Swipe down	Rotate a knob anti-clockwise
9. <i>Rotate 90° clockwise</i>	.830	Rotate a knob clockwise	N/A
10. <i>Rotate 90° anti-clockwise</i>	.830	Rotate a knob anti-clockwise	N/A
11. <i>Play</i>	.190	Tap with the index finger	Draw the “play” symbol
12. <i>Pause</i>	.166	Tap with the index finger	Swipe down with two fingers
13. <i>Like</i>	.751	Thumbs up	N/A
14. <i>Dislike</i>	.751	Thumbs down	N/A
15. <i>Fast-forward 5 seconds</i>	.087	Swipe right twice	Swipe left
16. <i>Rewind 5 seconds</i>	.095	Swipe right	Swipe left twice
17. <i>Enable subtitles</i>	.032	Swipe up	Swipe forward
18. <i>Disable subtitles</i>	.028	Swipe down	Swipe backward

Referents with agreement rates above average are highlighted in blue.

Table 5.1: First and second most frequent gesture proposals for each referent.

Consensus Between Proposed Gestures

Figure D.1 shows the agreement rates obtained for each REFERENT. Overall, agreement rates are quite high, between .028 and .83 ($M=.366$, $SD=.268$). These results fit within the reported agreement rates in the literature of gesture elicitation; see Vatavu and Wobbrock [124] (p. 1332) that summarize agreement rates of 18 studies. According to the recommendations of Vatavu and Wobbrock [124] to interpret the magnitudes of agreement rates, most of our results fall inside the high consensus (.300 – .500) category.

These results were confirmed by Kendall’s coefficient of concordance:² $W=.564$ ($\chi^2(26)=220.454$, $p<.0001$). As Kendall’s coefficient is related to the average of Spearman correlation coefficients between pairs of rankings [51] (p. 276), we can interpret the magnitude of its effect as large (*i.e.*, close to .500) according to Cohen’s suggested limits for interpreting effect sizes.

Gestures’ Goodness of Fit

Participants rated their gesture proposals with numbers from 1 (poor fit) to 5 (excellent fit) to denote their confidence in the goodness of fit of their proposals. Overall, participants were satisfied with their gesture propositions as shown by the high average goodness of fit ($M=4.21$, $SD=0.88$). GOODNESS-OF-FIT correlated significantly with the AGREEMENT-RATE (Pearson’s $r_{(N=18)}=.711$, $R^2=.505$, $p=.00094$): referents that reached high agreement rates were assigned gestures that were rated a good fit. Figure D.2 shows this relationship between the goodness of fit and agreement rates.

²Kendall’s W is a normalization of the Friedman statistic used to assess the agreement between multiple raters with a number ranging between 0 (no agreement at all) and 1 (perfect agreement).

Thinking Time

The average thinking time was usually quite low ($M=6.15$ s, $SD=9.12$ s). Figure D.3 shows the relationship between thinking times and agreement rates per REFERENT. THINKING-TIME correlated significantly with AGREEMENT-RATE (Pearson’s $r_{(N=18)} = -.620$, $R^2=.384$, $p=.006$): the agreement rate decreased for longer thinking times. A few referents showed considerably higher than average thinking times: disable subtitles, enable subtitles, and skip backward 5 seconds. The reason behind this could be that these referents represent tasks that participants are less likely to perform regularly on their devices.

5.2.4 Choice of Gestures

In the previous sections, we elicited users’ preferred gestures for a series of actions related to the LUI project. However, one would be ill-advised to use these gestures directly, as gestures with the highest agreement rate may not always be the most appropriate ones for a given system. In this section, we assign an appropriate gesture to each action, by taking into account both the results of the elicitation study as well as possible hardware and software limitations.

Table E.1 presents, for each action, its assigned gesture, as well as a justification for this choice. In general, we tried to assign symmetric gestures to symmetric actions (*e.g.*, the “flick left” and “flick right” gestures to resp. the “next” and “previous” referents) in an attempt to increase the memorability of the gestures. We also avoided using the same gesture for two different actions that could occur in the same context to avoid any conflict between them.

The “fast-forward” and “rewind” gestures could be swapped based on users’ preferences. Indeed, some users may prefer the swiping motion to correspond to them physically moving the video forward or backward. In this case, “swipe left” would be associated with the “fast-forward” action. On the other hand, others may associate this same swiping motion to moving a pointer on a timeline. In that case, “swipe left” would be associated with “rewind”. Here, we chose to keep the first option, as it seemed more popular.

Figure E.1 shows, for each referent, a representation of its assigned gesture. Please note that, due to both a low consensus among the participants and their comparatively low interest compared to the other referents, we chose to discard two of the referents present in our latest GES: “enable subtitles” and “disable subtitles”.

5.2.5 Gesture Taxonomy

We now characterize the gestures from our newly defined gesture set, following Aigner *et al.*’s taxonomy [2]. This step will prove extremely useful later to configure the framework and determine the most appropriate gesture recognition algorithms. According to Aigner *et al.*, gestures can be divided into five main types [2]:

- *Pointing*: gestures that indicate objects and directions.
- *Semaphoric*: hand poses and movements used to convey a specific meaning (which is often unrelated to the gesture). They can be further divided into three categories: static, when the meaning is entirely conveyed by the hand pose; dynamic, when the temporality of the gesture is important; and strokes, which are simpler as they only consist of single stroke hand motions.
- *Pantomimic*: gestures that imitate a real-life task, such as opening an invisible bottle.
- *Iconic*: gestures that communicate information about objects or entities (*e.g.*, sizes, shapes, or paths). They can be further divided into two categories: static when all the information

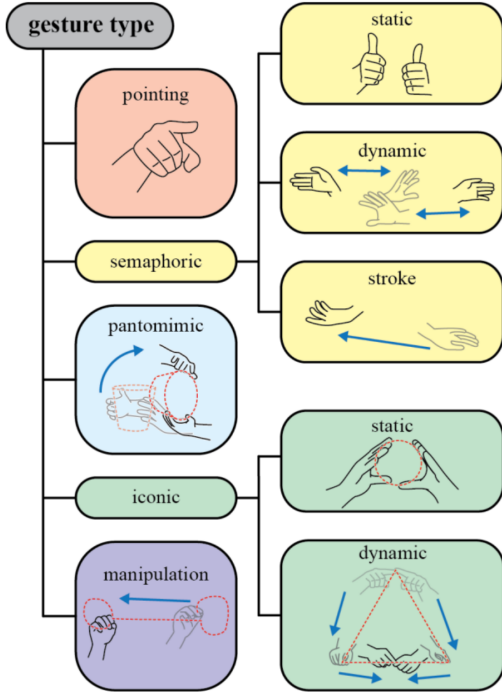


Figure 5.3: Aigner *et al.*'s classification of gestures [2].

Action	Gesture	Category
<i>Previous</i>	Flick right	Stroke semaphoric
<i>Next</i>	Flick left	Stroke semaphoric
<i>Enable fullscreen</i>	Tap	Pointing
<i>Disable fullscreen</i>	Flick up	Stroke semaphoric
<i>Zoom in</i>	Pinch out	Manipulation
<i>Zoom out</i>	Pinch in	Manipulation
<i>Volume up</i>	Swipe up	Manipulation
<i>Volume down</i>	Swipe down	Manipulation
<i>Rotate clockwise</i>	Rotate a knob clockwise	Manipulation
<i>Rotate anti-clockwise</i>	Rotate a knob anti-clockwise	Manipulation
<i>Play</i>	Tap	Stroke semaphoric
<i>Pause</i>	Tap	Stroke semaphoric
<i>Like</i>	Thumbs up	Static semaphoric
<i>Dislike</i>	Thumbs down	Static semaphoric
<i>Fast-forward</i>	Swipe left	Manipulation
<i>Rewind</i>	Swipe right	Manipulation

Table 5.2: Gesture classification according to Aigner *et al.*'s taxonomy.

is conveyed by a hand pose; and dynamic, such as movements that describe paths or shapes.

- *Manipulation*: gestures used to manipulate objects in a short feedback loop. The effect of the gesture on the object is perceived while the user is performing it, with only a very short latency.

Table 5.2 classifies each of the 16 selected gestures according to Aigner *et al.*'s taxonomy. One can observe that, depending on the context, the *tap* gesture may belong to two different categories. In the case of the *enabling fullscreen* action, *tap* also acts as a selection method, as users first need to hover their finger above the correct element before executing the gesture. In this context, it belongs to the *pointing* category. For the other actions, only the stroke motion is important, and *tap* is thus *stroke metaphorical*.

Eight of the 16 gestures are classified in the *manipulation* category, as they are used to directly modify or interact with content. For instance, the size of an image should change proportionally to the thumb-index distance when the user is performing a *pinch in* or *pinch out* gesture. Using the gesture recognition framework, we can support these gestures, as well as the two *static semaphoric* gestures, by combining a **classifier** and an **analyzer** module.

Finally, five gestures are considered as *stroke semaphoric*, and one as *pointing*. Recognizing them could prove tricky, as the framework first needs to correctly separate them from parasitic hand motions (*i.e.*, perform gesture segmentation). Thus, in addition to a **recognizer** module, we also need to use a **segmenter** module. Furthermore, as strokes mostly differ in their direction, we should avoid using direction-independent recognizers.

5.3 Finding the Most Appropriate Gesture Recognizers

This section is aimed at determining the most appropriate recognizers for the gesture set that we defined in the previous section. It first describes the testing procedure and then summarizes the results.

5.3.1 Procedure

We ran the benchmark on a computer running Windows 10 Home (version 1909), equipped with a Core i7-8750H CPU running at 2.20 GHz and 16 GB of DDR4-2667MHz RAM. We tested the dynamic and static gesture recognizers separately. All the recognizers are detailed in Chapter 3 but Table 5.3 summarizes their invariance properties.

Recognizer	Type of invariance			
	Position	Scale	Rotation	Direction
3 cent	✓	✓	✗	✗
\$P ³	✓	✓	✗	✓
\$P ³ +	✓	✓	✗	✓
\$P ³ +X	✓	✓	✗	✗/✓
\$Q ³	✓	✓	✗	✓
Jackknife	✓	✓	✗	✗
GPSDa	✓	✓	✓	✓

Table 5.3: Invariance properties of the recognizers.

The dynamic gesture recognizers were tested on pre-segmented gestures acquired from four participants (one of them is the author of this thesis). Each participant repeated the gestures four times, giving a total of 16 templates per gesture class. There are four gesture classes, corresponding to those needed for the LUI application. We fixed N , the number of resampling points to 16, which is a reasonable value for the type of algorithms tested here [118]. There are two parameters: (1) $A \in \{1, 6\}$, the number of articulations (Figure 5.4); and (2) $T \in \{1, 2, 4, 8\}$, the number of training templates. Testing a recognizer is straightforward. For each value of A and T , and for each gesture class, we repeat the three following steps 1000 times: (1) select a random testing template from the gesture set; (2) train the recognizer using T randomly selected templates produced by different users than the testing template (user-independent testing); and (3) attempt to recognize the testing template.

We tested the pose classifiers on a custom gesture set containing five types of poses acquired from one participant (the author of this thesis). Each pose was performed in various orientations and scales, which results in more than 1000 templates per class. There are two parameters: (1) $A \in \{6, 16\}$, the number of articulations (see Figure 5.4); and (2) $T \in \{1, 2, 4, 8, 16, 32, 64\}$, the number of training templates. Please note that we fixed the a parameter of *GPSDa* to 0.70. The testing process is similar to the one described above, except for the second step. For each value of A and T , and for each gesture class, we repeat the three following steps 1000 times: (1) select a random testing template from the gesture set; (2) train the recognizer using T randomly selected templates, produced by the same user as the testing template (user-dependent); and (3) attempt to recognize the testing template.

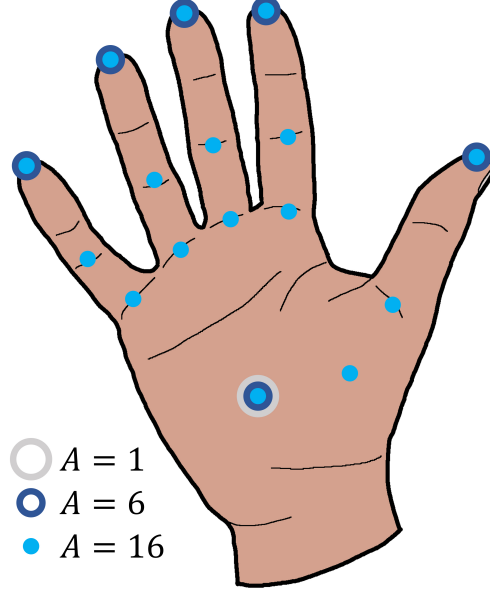


Figure 5.4: Articulations used in the benchmarking.

5.3.2 Results

We first summarize the results for dynamic gesture recognizers. The recognition rates of the recognizers for each gesture class are condensed in Table 5.4.

Recognizer	Gesture class				Global accuracy		
	Flick up	Flick left	Flick right	Tap	Mean	SD	Time
3 cent ($A=1$)	100.0%	96.6%	100.0%	100.0%	99.2%	1.7%	1.05ms
$\$P^3$ ($A=1$)	100.0%	67.8%	69.6%	100.0%	84.4%	18.1%	0.41ms
$\$P^3$ ($A=6$)	95.6%	93.0%	77.5%	99.8%	91.5%	9.7%	0.46ms
$\$P^3+$ ($A=1$)	100.0%	61.3%	53.4%	100.0%	78.7%	24.8%	0.05ms
$\$P^3+$ ($A=6$)	99.9%	86.5%	78.2%	100.0%	91.2%	10.7%	0.09ms
$\$P^3+X$ ($A=1$)	100.0%	99.4%	99.5%	100.0%	99.7%	0.3%	0.06 ms
$\$P^3+X$ ($A=6$)	99.8%	86.8%	78.6%	100.0%	91.3%	10.5%	0.09ms
$\$Q^3$ ($A=1$)	100.0%	63.9%	37.4%	100.0%	75.3%	30.5%	0.88ms
$\$Q^3$ ($A=6$)	100.0%	82.4%	72.5%	100.0%	88.7%	13.6%	0.93ms
Jackknife ($A=1$)	100.0%	100.0%	100.0%	100.0%	100.0%	0.0%	0.05ms
Jackknife ($A=6$)	100.0%	100.0%	100.0%	100.0%	100.0%	0.0%	0.11ms

Recognizers with a global accuracy higher than 98% are highlighted in blue.

Table 5.4: Recognition rates of each dynamic recognizer, for $T=8$.

- The highest recognition rates are achieved with 8 training templates ($T=8$) but all recognizers reach at least 75% of their best recognition rate with only one template. *Jackknife* ($A=1$ and $A=6$) and *3 cent* even manage to reach more than 95% accuracy, at respectively 100.0% and 95.6%.
- With only one training template ($T=1$), *Jackknife* ($A=1$ and $A=6$) achieves 100% accuracy over all gesture classes while being as fast as $\$P^3+$ and $\$P^3+X$.
- Direction-independent recognizers are not suited for the LUI application, as our benchmark confirms that they cannot correctly differentiate between the “swipe left” and “swipe right”

gestures (see Figure 5.5a). However, we noted that increasing the number of articulations generally improves their recognition rates for these symmetric gestures.

- On this gesture set, $\$P^3$ is slightly more accurate than $\$P^3+$ for both $A=1$ and $A=6$. However, $\$P^3+$ executes between 5 and 8 times faster.
- $\$P^3+X$'s partial direction-invariance does not provide any benefits over $\$P^3+$ when $A=6$. However, it manages a $>20\%$ gain in accuracy when $A=1$. Figure 5.5 shows the confusion matrices of $\$P^3+$ and $\$P^3+X$.

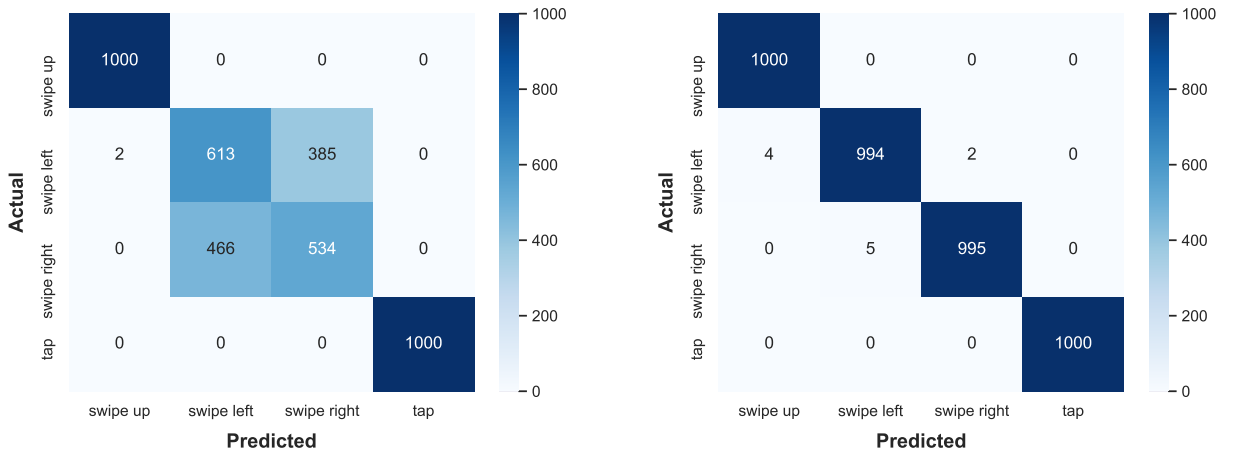
Then, we summarize the results for static gesture recognizers (or pose classifiers). Their recognition rates for each gesture class are condensed in Table 5.5.

- The accuracy of $\$P^3+$ decreases when going from 6 to 16 articulations, while the opposite is true for $GP\text{SDa}$.
- $GP\text{SDa}$'s execution time is comparable to $\$P^3+$ with 8 training templates. However, it becomes faster as the number of templates increases. With 64 templates, $GP\text{SDa}$ is twice as fast as $\$P^3+$.
- Both $\$P^3+$ (6 articulations) and $GP\text{SDa}$ (16 articulations) reach $>90\%$ accuracy with only 8 training templates.
- With 6 articulations and 64 training templates, $\$P^3+$ reaches 99.6% accuracy, while $GP\text{SDa}$'s accuracy is lower at 97.1%.
- With 16 articulations and 64 training templates, both recognizers reach $>98\%$ accuracy with (*resp.* 98.7% and 99.3% for $\$P^3+$ and $GP\text{SDa}$).

Recognizer	Gesture class					Global accuracy		
	Flat	Point	Pinch	Grab	Thumb	Mean	SD	Time
$\$P^3+$ ($A=6$)	98.9%	100.0%	99.5%	99.6%	100.0%	99.6%	0.5%	0.07ms
$\$P^3+$ ($A=16$)	99.5%	99.4%	99.3%	98.3%	100.0%	99.3%	0.6%	0.35ms
$GP\text{SDa}$ ($A=6$)	98.6%	97.8%	96.2%	97.3%	95.6%	97.1%	1.21%	0.02ms
$GP\text{SDa}$ ($A=16$)	99.7%	98.3%	97.4%	99.7%	98.4%	98.7%	1.0%	0.18ms

Recognizers with a global accuracy higher than 98% are highlighted in blue.

Table 5.5: Recognition rates of each static recognizer, for $T=64$.



(a) $\$P^3+$ ($A=1$)

(b) $\$P^3+X$ ($A=1$)

Figure 5.5: Confusion matrices for $\$P^3+$ and $\$P^3+X$ ($N=8$).

5.4 Implementation

In the previous sections, we designed and characterized a gesture set for the LUI project. In this section, we describe how we configured the framework to suit the needs of this application. Then, we detail how we modified LUI to incorporate the gesture recognition framework.

5.4.1 Framework Configuration

Figure 5.6 gives an overview of the configuration of the framework. Next, we justify the most important configuration choices.

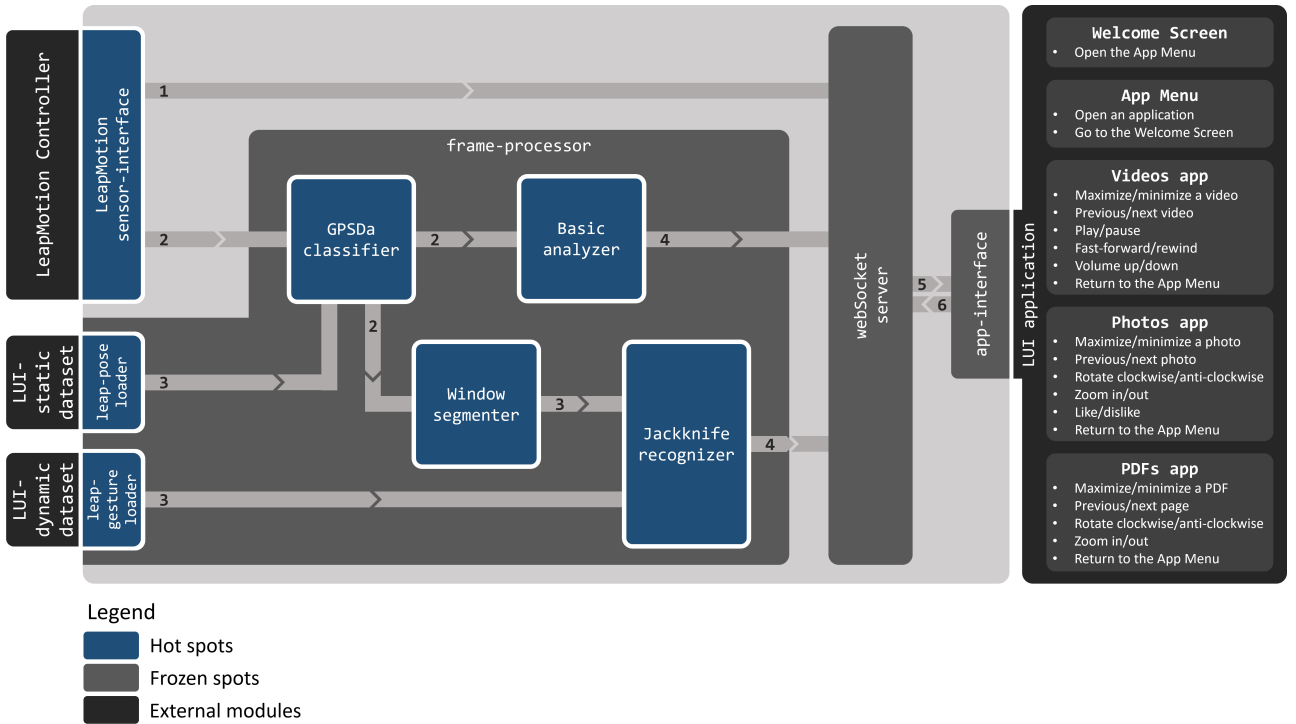


Figure 5.6: Configuration of the framework for the LUI application.

Classifier

We selected the *GPSDa* classifier with 16 articulations and $A=0.80$ over $\$P^3+$ for two reasons: (1) thanks to its rotation invariance it seems to more accurately classify hand poses under bad conditions (*e.g.*, in case of self-occlusion), especially for the *rotate (anti-)clockwise* actions; and (2) it executes faster, which allows us to train it using more templates and decreases latency. It is trained using 100 random templates for each one of the five poses (flat, point, pinch, grab, and thumb).

Recognizer

From the results in Section 5.3, we selected the *Jackknife* recognizer. It is both fast and accurate, which allows us to keep latency at a minimum with no trade-off on recognition accuracy. We use the window-segmenter configured with a window of 300ms for gesture segmentation and train the recognizer with 16 randomly selected templates per gesture.

Miscellaneous

To match the screen refresh rate of most devices and reduce CPU usage, we fixed the frame-rate of the sensor to 60fps.

5.4.2 Modifications to the Project

Figure 5.7 shows the gestures that we have implemented in each module of the LUI project. Most of the changes that are required to add a gestural interface to a module (*e.g.*, the *videos* or *photos* apps) are located in two methods: `componentDidMount()` and `componentWillUnmount()`. In this section, we only show how we modified the *photos* application as we applied similar changes to the other modules. Furthermore, to demonstrate that adding a new component to LUI is still an easy task, we also created a PDF visualizer application.

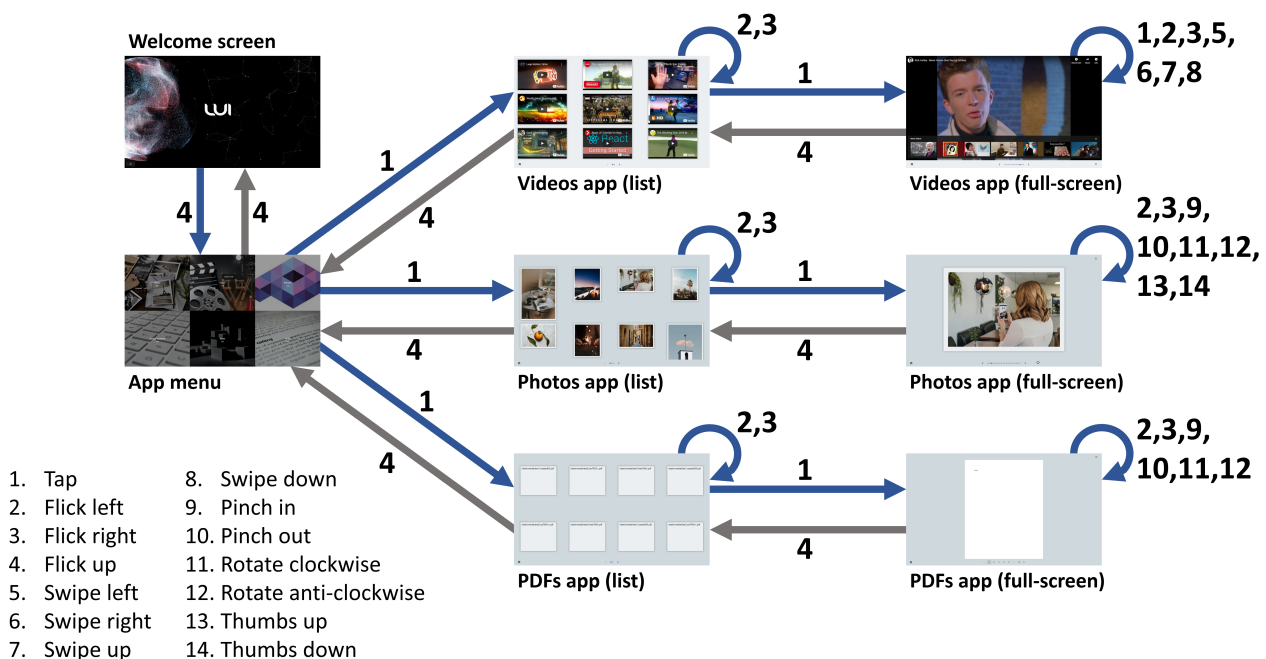


Figure 5.7: Diagram of the gestures available at any point in the LUI project.

- *Connect to the gesture recognition framework* (line 1): to connect to the framework, we simply instantiate a `GestureHandler` object in the `componentDidMount()` method. Once instantiated, it regularly attempts to establish a connection with the framework.
- *Display the position of the hand* (line 13): we use the `GestureHandler`'s `onFrame()` method to update the position of the hand displayed on the screen every time the framework sends a new frame.
- *Show when a gesture is recognized* (line 2): using the `onEachGesture()` method, we can temporarily change the color of the fingers displayed on the screen each time any dynamic gesture is recognized.
- *React to dynamic gestures* (lines 3, 4, 5, 9): we defined *handler* functions for the four types of dynamic gestures using the `onGesture()` method.
- *React to static gestures* (lines 6-8 and 10-12): because static gestures are only used in full-screen mode, we dynamically add and remove *handlers* using *resp.* the `onPose()` and `removePoseHandler()` methods.

- *Disconnect from the framework* (line 14): when the application is closed, we call the `disconnect()` method to close the connection with the framework properly.

```

componentDidMount() {
  let gestureHandler = new GestureHandler(); // 1
  this.gestureHandler = gestureHandler;

  gestureHandler.onEachGesture(function (gesture) { // 2
    this.setState({ pause: 4 });
  }.bind(this));

  gestureHandler.onGesture("rhand_lswipe", function () { // 3
    this.props.handleSwipe("left");
  }.bind(this));

  gestureHandler.onGesture("rhand_rswipe", function () { // 4
    this.props.handleSwipe("right");
  }.bind(this));

  gestureHandler.onGesture("rhand_uswipe", function () { // 5
    let clicked = this.state.clicked;
    if (clicked !== -1) {
      gestureHandler.removePoseHandler("grab"); // 6
      gestureHandler.removePoseHandler("pinch"); // 7
      gestureHandler.removePoseHandler("thumb"); // 8
      clicked = -1;
      this.setState({ clicked });
    }
    this.props.handleSwipeUp();
  }.bind(this));

  gestureHandler.onGesture("rindex_airtap", function () { // 9
    var { clicked, hovered } = this.state;
    if (clicked === -1 && hovered !== -1) {
      gestureHandler.onPose("grab", function (data) { // 10
        this.props.handleRotate(data.rotation);
      }.bind(this));
      gestureHandler.onPose("pinch", function (data) { // 11
        this.props.handlePinch(data.pinch, data.translation);
      }.bind(this));
      gestureHandler.onPose("thumb", function (data) { // 12
        let thumbUp = data.thumbVector[1] > 40;
        let thumbDown = data.thumbVector[1] < -40;
        if (thumbUp) {
          this.props.handleThumb(true);
        }
        if (thumbDown) {
          this.props.handleThumb(false);
        }
      }.bind(this));
      clicked = hovered;
    }
  }

```

```

        this.props.handleClick(clicked);
        this.setState({ clicked: clicked, hovered: -1});
    }
}.bind(this));

this.gestureHandler.onFrame(function (frame) { // 13
    if (frame.fingers.length !== 0) {
        this.setState({ hand: true });
    } else {
        this.setState({ hand: false });
    }
    this.traceFingers(frame.fingers);
}.bind(this));

this.timer = setInterval(() => {
    if (this.state.pause > 0) {
        this.setState({ pause: this.state.pause - 1 });
    }
    if (this.state.hand) {
        var { clicked, hovered } = this.state;
        if (clicked == -1 && !this.state.amiclicked) {
            hovered = this.checkHover();
            this.setState({ hovered });
            this.props.handleHover(hovered);
        }
    }
}, 100);
}

componentWillUnmount() {
    clearInterval(this.timer);
    this.gestureHandler.disconnect(); // 14
}

```

5.5 Conclusion

This chapter presented a third illustration of developing an LMC-based gesture UI for a real-world, large-scale project, *i.e.*, the LUI project. For this purpose, two preliminary gesture elicitation studies were conducted for photo and video browsing in order to explore a set of potential user-defined gestures for a series of actions on photos and videos. Based on these preliminary results, a new gesture elicitation study was conducted with an updated experimental protocol to come up with the final gesture set corresponding to the LUI actions. A benchmarking of implemented gesture recognizers on this new dataset was then conducted to determine the most appropriate gesture recognizers and to configure them for a fully running gesture-based UI. This chapter completes a series of three illustrations of how the framework can be used for developing, testing, and benchmarking LMC-based UIs.

Chapter 6

Evaluation

In Chapter 3, we developed a framework for engineering gesture-based UIs using the LMC and we subsequently illustrated it through three use cases, including a real-world, large-scale one, the LUI project (Chapter 5). Therefore, any evaluation could be conducted at two levels: (1) at the level of an LMC-based application developed using this framework by gathering input from end-users; and (2) at the level of the framework itself with input from developers and designers.

Regarding the first level, although the hypothesis H4 (Section 1.2.2) specifies that end-users' aspects are out of scope, we still want to sketch a plan for evaluating a gesture-based UI. As such, in Section 6.1, we propose a plan for evaluating the LUI-project, that can be generalized to evaluate any other gesture-based UI. Regarding the second level, based on hypothesis H3, Section 6.2 addresses the evaluation of the framework with input from developers and designers, gauges the quality of the framework, and determines whether it meets the requirements defined in Section 3.1.

6.1 At the Level of a Gesture-Based User Interface With the Framework

When designing UIs, it is crucial to always keep users in mind [87,88] through usability or user experience. As such, ensuring that they are satisfied with the gestural interface is a crucial part of the development process of any interactive application in general as well as for any gesture-based UI in particular, whether it is using an LMC or not.

Usability, as an ISO 25010 [50] software quality property, is defined as¹: “the degree to which a product or system can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use.” While *effectiveness* should evaluate how the UI supports users in completing actions accurately and *efficiency* should evaluate how end-users can perform tasks quickly through the UI, *satisfaction* should capture the subjective satisfaction with which end-users are carrying out their tasks.

We are not aware today of any method for evaluating a gesture-based UI either in general or in particular for the LMC. All that we know is a very specific adaptation of the SUS scale into a Gesture Usability Scale (GUS) [130], which added to the System Usability Scale (SUS) [13] five questions related to a gesture-based UI. These items assess the perceived reliability, performance, and compliance with the end-user's expectations, and not the usability or user experience. Later, they present a model considering accuracy, fatigue, naturalness, and gesture duration. In the area of gesture-based games, Winckler *et al.* [107] surveyed ten usability evaluations to conclude

¹See <https://iso25000.com/index.php/en/iso-25000-standards/iso-25010?limit=3&start=3>

that generic questionnaires were the most used instruments (used in 70% of the evaluations), followed by interviews (30%), and observation and video recording (20%).

Rico *et al.* [96] also confirm that no such evaluation method exists today that is particularly tailored to gesture-based UI, but mention several aspects subject to evaluation, such as memorability [84], social acceptance, and usability or user experience. However, identifying the right set of properties to properly evaluate a gesture-based UI remains an open question, especially when this set is potentially large and covers system aspects as well as end-users' aspects.

Therefore, defining and validating an overall method for evaluating the usability or the user experience of gesture-based UI would represent a significant contribution that is beyond the scope of this thesis. Equally important is to assess to what extent the ecological validity of the evaluation method will be covered, which could be assessed through the ECOVAL framework [52], and the process model to be followed for applying usability engineering. Kieffer *et al.* [53] classify user experience process models into five categories. In the absence of such an evaluation method and such a process, this section sketches a plan for evaluating the user satisfaction of the LUI gesture-based UI described in Chapter 5.

6.1.1 Plan for Evaluating User Satisfaction

To evaluate user satisfaction, we create a series of scenarios. Each scenario comprises of three elements: (1) a name, which represents its goal; (2) a context; and (3) a series of steps to perform to reach this goal. The scenarios represent actions that potential users of the system are likely to perform, and they cover most of the functionalities that we have implemented. We defined eight scenarios:

1. Open an application.

- Context: you are looking at the *welcome screen* and you want to open the *Videos* app.
- Steps: (1) enter to the *app menu* by doing a “flick up” motion; (2) hover your hand above the *Videos* app; (3) “tap” to open it.

2. View a picture.

- Context: you are currently looking at the home screen of the *Photos* app, you find a picture that you like and want to view it in full-screen.
- Steps: (1) go to the second page of the gallery with a “flick left” motion; (2) hover your hand above the picture that you like; (3) “tap” to view it in full-screen.

3. Manipulate a picture.

- Context: you are looking at a picture in full-screen when a detail suddenly picks your interest. You decide to manipulate the picture to see it better.
- Steps: (1) rotate the picture by 90° clockwise with a “grab” gesture; (2) zoom in on a detail of the image using a “pinch” gesture.

4. “Like” some pictures.

- Context: you are browsing through all your pictures to “like” those that you prefer.
- Steps: (1) “like” the first with a “thumbs up” gesture; (2) go to the next picture with a “flick left” motion; (3) “like” this picture; (4) after all, you did not like the previous picture, return to this picture with a “flick right” motion; (5) remove the like with a “thumbs down” gesture.

5. View a video.

- Context: you are looking at the home screen of the *Videos* app and decide to watch one of the videos.
- Steps: (1) hover over the video that you like; (2) “tap” to view it in full-screen; (3) “tap” to start it.

6. Change the volume of a video.

- Context: you are watching a video, but the volume is too high. You decide to decrease the volume to a more acceptable level.
- Steps: (1) point your index; (2) decrease the volume to half its initial value by moving your hand down while keeping this pose.

7. Go to a specific part of a video.

- Context: you are watching a video and you decide to go to a part of it that you enjoy.
- Steps: (1) point your index; (2) move in the video by moving your hand to the left (while keeping this pose) until you reach the middle of the video.

8. Return to the *app menu*.

- Context: you are watching a slightly boring video, and you want to go back to the *app menu*.
- Steps: (1) pause the video with a “tap”; (2) disable full-screen with a “flick up” motion; (3) close the app with a “flick up” motion.

At the start of the experiment, participants are installed in a setup similar to the one used in our elicitation study, *i.e.*, at a table, facing a large screen that displays the application. An LMC should be placed on the table, close enough for participants’ to reach it easily. Once comfortably installed, they are asked to perform each scenario in a randomized order. They should be correctly informed of the goal to reach, and the state of the application should correspond to the context of the scenario. After each scenario, regardless of whether they have reached the goal or not, they are asked to evaluate how easy the scenario was to perform on a scale from 1 (very easy) to 5 (very hard).

After they have completed every scenario, participants have to fill in a questionnaire, divided into four parts. Its first part contains a few questions that give us insight into their age, background, and prior experience with computers, smartphones, and 3D motion controllers (*e.g.*, the LMC):

- What is your age?
- What is your current occupation?
- What is your dominant hand?
- On a scale from 1 (never) to 5 (very often), how often do you use a computer?
- On a scale from 1 (never) to 5 (very often), how often do you use a smartphone/tablet?
- On a scale from 1 (never) to 5 (very often), how often do you use motion-sensing devices?

The second part asks them to evaluate the usability of the system. It contains the ten questions from John Brooke’s System Usability Scale (SUS) [13]. As it is a Likert scale, answers can range between 1 (strongly disagree) and 5 (strongly agree):

- I think that I would like to use this system frequently.
- I found the system unnecessarily complex.
- I thought the system was easy to use.
- I think that I would need the support of a technical person to be able to use this system.
- I found the various functions in this system were well integrated.

- I thought there was too much inconsistency in this system.
- I would imagine that most people would learn to use this system very quickly.
- I found the system very cumbersome to use.
- I felt very confident using the system.
- I needed to learn a lot of things before I could get going with this system.

The third part of the questionnaire consists of two open-ended questions:

- If you could not perform one of the scenarios. What do you think is the reason?
- Would you change any gestures? If you answered yes, why? What kind of gesture would you propose?

Finally, we invite participants to give any feedback related to the application and the tasks they had to perform.

6.2 At the Level of the Framework Itself

This section is divided into two parts: a discussion of the framework’s strengths and shortcomings based on the three selected software quality properties and an estimation of the development effort with the framework.

6.2.1 Does the Framework Meet its Requirements?

In Section 3.1, we defined the requirements that the framework should fulfill, in the light of three ISO/IEC 25010 [50] software quality properties: compatibility, maintainability, and portability. Now, we go through each one of these requirements to summarize the strengths and shortcomings of the framework. This discussion is based on the experience we gained in reviewing the related work, developing the framework, and applying it in the three use cases. Although mainly qualitative, this discussion also attempts to characterize quantitatively the extent to which each factor or sub-factor has been satisfied.

1. Compatibility (100%)

- *Co-existence* (100%): because it relies on the Leap Motion API to connect to the LMC, the framework behaves like any other LMC-compatible application. As such, it does not affect other applications and is not affected by them either.
- *Interoperability* (100%): the framework can support any skeleton-based gesture set, provided that there is an adaptation layer that can transform the gesture set into the standardized format used by the framework (see Sections 3.2.2 and 3.2.3).

2. Maintainability (80%)

- *Modularity* (60%): the framework is divided into a series of interchangeable modules described in Section 3.2.3. However, because of its fixed pipeline (see 3.2.2) the current architecture is quite restrictive and it may be interesting to move towards a more flexible “block-based” architecture. In such an architecture, components would consist of separate blocks with well-defined inputs and outputs. These components could be arbitrarily combined to form a gesture-recognition pipeline.
- *Reusability* (100%): we confirmed the reusability of the framework by using it in two applications of different scales, the DICOM viewer and the LUI project (*resp.*, Section 3.3 and Chapter 5).

- *Modifiability* (75%): we showed that adding new modules is easy by developing a series of modules for each hot spot of the framework (see Section 3.2.3). However, its architecture limits what developers could potentially achieve: it only works with skeleton data and the fixed pipeline may prevent developers from trying out more advanced recognition techniques, *e.g.*, using only one recognizer for both static and dynamic gestures.
- *Testability* (85%): we demonstrated how the framework can be used to compare gesture recognizers in Chapter 4 and, to a lesser extent, in Section 5.3. It currently only supports user-independent testing but supporting user-dependent testing should require only some small changes.

3. Portability (85%)

- *Adaptability* (70%): the configuration file allows developers to configure the framework to their needs quickly. However, there is still some room for improvement. For instance, it is not yet possible to dynamically change the gesture associated with an action, and configuring the framework for an application may take some time. To speed up this process, the framework could attempt to automatically propose an adequate configuration based on the type of gestures that it should recognize.
- *Installability* (85%): because it is written in JavaScript, the framework can be installed on most platforms. However, the installation process is too complex for less tech-savvy users. In the future, we should provide a quick and easy way to install it.
- *Replaceability* (100%): the modular nature of the framework allows developers to change any module in a matter of seconds, provided that the new module correctly implements all of the methods of the corresponding abstract class (see Section 3.2.3).

6.2.2 Qualitative Evaluation of the Framework

To quantitatively evaluate the development effort induced by the framework, an evaluation plan could consist of a between-subject design comparing two groups of developers: one group using the framework and one group relying on the programmatic approach. An ideal evaluation would consider multiple levels of experience (*e.g.*, the nine development expertise levels defined by Costabile *et al.* [31], ranging from “customizing components” to “Multiple language and paradigm programming”), multiple levels of project complexity (*e.g.*, ranging from easy such as the DICOM Viewer to complex such as the LUI project), multiple framework configurations (*e.g.*, different gesture sets, recognizers, configuration files). Participants could then be instructed to complete the LMC-based UI with or without the framework and we could then collect quantitative measures such as, but not limited to: lines of code (LOC), modeling time, programming time, perceived complexity, or total cost of ownership. Since conducting this ideal method would require a huge amount of resources (*e.g.*, professional developers are hard to find and expensive to pay), we prefer to consider a qualitative evaluation of the framework.

Therefore, this section proposes a method for evaluating whether our framework meets the needs of application developers. It consists of collecting and analyzing data from the development of gesture-enabled applications in two situations: (1) the developers use our framework; and (2) the developers rely purely on the Leap Motion API.

At the start of their project, the developer(s) of each application should answer a short questionnaire to assess their prior experience with the LMC and gesture recognition in general. It is composed of three questions whose answers can range between 1 (strongly disagree) and 5 (strongly agree):

- Me or my team already mastered the Leap Motion API before starting this project.
- Me or my team had a good knowledge of gesture recognition techniques before starting this project.
- Me or my team had a lot of experience in app development before starting this project.

At the end of the development process, the developers that used the framework should fill in a second questionnaire, inspired by John Brooke’s SUS [13]. Answers can range from 1 (strongly disagree) to 5 (strongly agree):

- I am confident that I will use the framework again if I develop another gesture-enabled application in the future.
- If I added a module to the framework (*e.g.*, a new recognizer), I found it difficult to write new modules.
- I found it easy to configure the framework to suit my needs.
- I think that it would be difficult to move to a different system for gesture recognition (*i.e.*, stop using the framework and use something else instead).
- I found that the framework met my expectations.
- I felt restricted by the framework.

Aside from filling in questionnaires, the developers of each application should time all the development phases to give us an idea of how much time can be saved by using the framework. Although it is near-impossible to provide an accurate estimation, we expect significant time-savings in three phases of software development: *design*, *implementation*, and *testing*.

Figure 6.1 compares the total effort needed for developing a gesture-based application when using our framework and when implementing gesture recognition from scratch. The *implementation* and *testing* phases should be considerably shorter as developers can rely entirely on the framework for gesture recognition. Although developers may take some time to learn how to use our framework, they do not have to discover the Leap Motion API and do not need to design a gesture recognition pipeline by themselves, which reduces the duration of the *design* phase. The extend of these time-savings will depend on how familiar developers are with the LMC and gesture recognition in general. However, they should still be significant, even for experienced developers.

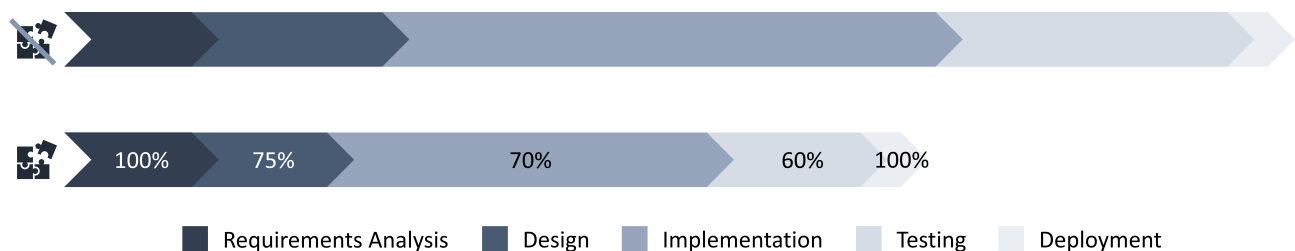


Figure 6.1: Rough qualitative estimation of the total effort needed for developing a gesture-based application with our framework (bottom) and without (top). The percentages in the bottom part give an estimation of the savings enabled by using the framework. The distribution of effort between the five development phases is based on data from [135].

Chapter 7

Final Conclusion

7.1 Overview of the Contributions

After completing this work, we are able to provide an overview of the various contributions brought throughout this manuscript.

In Chapter 1, we analyzed the context of the problem: how to effectively and efficiently develop gesture-based UIs for interactive applications using the LMC. We formulated working hypotheses and we selected three ISO 25010 software quality properties (*i.e.*, maintainability, portability, and compatibility) that were observed as unsatisfied in existing practices.

In Chapter 2, we performed a targeted literature review. We observed that the research targeting the LMC and gestural interaction in general was very prolific. However, most recognition techniques were specialized for a specific set of gestures and were not meant to be generalized to other contexts of use. On the other hand, we determined that template-based recognizers were the most suited to a generic gesture recognition framework.

Chapter 3 was dedicated to the development process of the framework. It first laid out a series of requirements and then described the design and implementation of the framework. We developed two recognizers for static gestures and six for dynamic gestures, including 3D versions of popular 2D recognizers and a novel GPSDa recognizer. We also proposed and discussed three methods for gesture segmentation. In the end, we illustrated how the framework could be used to add a gestural interface to a small application, the DICOM viewer.

In Chapter 4, we used the framework to compare the accuracy of seven recognizers on two existing datasets. We observed that $\$P^3+$ was significantly more accurate than the six other recognizers and that 16 seems to be the ideal number of training templates to maximize accuracy without impacting performance too much.

Chapter 5 described the complete process of adding a gestural interface to MIT's LUI project. We first performed an elicitation study to help us design an intuitive gesture set for the application. Then, we benchmarked a series of recognizers to maximize the recognition accuracy on this gesture set. Finally, we used this new insight to configure the framework and showed how we modified the LUI project to integrate gesture recognition. We added gestures for a total of 16 actions distributed over five modules of the LUI project, including a new PDFs application.

In Chapter 6, we proposed plans for evaluating both the utility of the framework and the user satisfaction for applications built using our framework. We also reviewed to what extent the framework met the requirements defined in Section 3.1. We found that, while it managed to meet most of our expectations, there is still a lot of room for improvement.

7.2 Future Work

The ramifications of this work are multiple. Future work could be envisioned at different levels of granularity:

- At the level of the framework software architecture: instead of relying on a pipeline architecture, the gesture recognition pipeline could be made even more modular by moving towards a “block-based” architecture, thus providing an easy way to install the framework for less tech-savvy users, or allowing end-users to submit their own gestures while the framework is executing at run-time (as opposed to at design-time).
- At the level of the framework modules:
 1. For gesture recognition by template matching: while the current software architecture is flexible enough to accommodate any new recognizer, a precise procedure should be followed for this purpose. Although this procedure is straightforward, it could become automated by offering the possibility to add, delete, modify, and configure any recognizer at run-time as opposed to design-time. In this way, a designer or any other non-expert person could submit a new recognizer to the framework without requiring any extensive programming.
 2. For gesture recognition by other machine learning methods than by template matching: while we pointed out that template matching offers the means to satisfy the quality properties, the framework could be extended with new module encapsulating machine learning techniques, in particular for benchmarking. In these conditions, these techniques should be modeled, trained, and calibrated enough to be running.
 3. For gesture segmentation: while it is essential to the proper working of gesture-enabled UIs, we barely scrapped the subject in this thesis because automated gesture segmentation is an open research problem, that is already partially addressed in some works [62]. It would be interesting to investigate methods for distinguishing intended gestures from parasitic movements in continuous streams of data, such as in [111], where Taranta *et al.* train their recognizer with automatically generated examples of parasitic gestures, a particular form of synthetic gestures [72].
- At the level of configurations: while the configuration file provides an effective way to configure the framework for a particular purpose, such as recognition, testing, or benchmarking, advanced facilities could be developed to further boost these processes by direct manipulation, by pattern matching based on existing configurations, and by learning adequate configurations from an existing base of configurations. Future work could investigate other recognition techniques. For instance, combining multiple recognizers to achieve better accuracy on a wide range of gestures, or developing more accurate recognizers which, together, would provide more accuracy.
- At the level of the LMC: the framework currently supports abstraction for one LMC, but nothing prevents it from reusing the same abstraction for exploiting many LMCs simultaneously. In this case, we are touching the field of multimodal interaction where fusion and fission of data should be parameterized in order to achieve the right configuration. For example, a two-hand interaction with one LMC for each hand represents an interesting case study. Multiple users could also be sensed by multiple LMC, thus posing the problem of user authentication and hand (right/left) identification. Computer vision techniques exist for this purpose.

Finally, while this framework only considered gestures collected using the LMC, one could focus on adding support for other types of sensors, such as smart rings and gloves, Intel RealSense cameras, or the Microsoft Kinect. But these devices require other abstractions of their raw data into higher-level data or information before handling them in a similar framework.

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Glossary

ANN Artificial Neural Network.

API Application Programming Interface.

AR Augmented Reality.

CNN Convolutional Neural Network.

CNN Conditional Random Fields.

DTW Dynamic Time Warping.

FPS Frames Per Second.

FSM Finite-State Machine.

GES Gesture Elicitation Study.

HMM Hidden Markov Model.

k-NN k-Nearest Neighbor.

LOC Lines Of Code.

LUI Large User Interface.

MIT Massachusetts Institute of Technology.

RNN Recurrent Neural Network.

SDK Software Development Kit.

SVM Support Vector Machine.

TLR Target Literature Review.

UCLouvain Université Catholique de Louvain.

UI User Interface.

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Appendix A

Work Distribution

Part of the work presented in this thesis was performed in collaboration with [Bastien Nothomb](#) [112]. Table A.1 details how the work was distributed between him and the author of this thesis (Arthur Sluÿters).

Framework Architecture	
V1 (June 2020)	
Gesture recognition pipeline	Bastien Nothomb & Arthur Sluÿters
Gesture set representation (gestures)	Bastien Nothomb
Unified format for storing datasets	Bastien Nothomb
Configuration file	Arthur Sluÿters
App-interface	Arthur Sluÿters
V2 (August 2020)	
Support for static gesture sets	Arthur Sluÿters
Dataset manipulation (configuration file)	Arthur Sluÿters
Code refactoring	Arthur Sluÿters
Modules	
Sensors	
Leap-sensor	Bastien Nothomb & Arthur Sluÿters
Datasets	
LUI-dynamic	Bastien Nothomb & Arthur Sluÿters
LUI-static	Arthur Sluÿters
Classifiers	
\$P^3+\$	Arthur Sluÿters
GPSDa	Arthur Sluÿters
Analyzers	
Basic-analyzer	Arthur Sluÿters
Segmenters	
Left-hand segmenter	Arthur Sluÿters
Zoning segmenter	Bastien Nothomb
Window segmenter	Arthur Sluÿters
Recognizers	
3 cent	Arthur Sluÿters
\$P^3\$	Arthur Sluÿters
\$P^3+\$	Arthur Sluÿters
\$P^3+X\$	Arthur Sluÿters
\$Q^3\$	Arthur Sluÿters
Jackknife	Arthur Sluÿters
Benchmarking Tool	
V1 (June 2020)	
Benchmarking pipeline	Bastien Nothomb
Configuration file	Bastien Nothomb
V2 (August 2020)	
Output results in JSON format	Arthur Sluÿters
Support for static gesture recognizers	Arthur Sluÿters
Code refactoring	Arthur Sluÿters
Applications	
DICOM viewer	Bastien Nothomb
LUI project (gestural interface)	Arthur Sluÿters

Table A.1: Distribution of the work between Bastien Nothomb and the author of this thesis (Arthur Sluÿters).

Appendix B

Preliminary Gesture Elicitation Studies

B.1 General Information About the Experiments

Two preliminary gesture elicitation studies [126,131,132] following the classical methodology [42,132] to collect users' preferences for mid-air gesture input. This section will provide general information about these experiments, such as how they were designed and what measures were employed.

B.1.1 Participants

Participants were selected to get a representative sample of potential users of large UIs.

B.1.2 Apparatus

We did not have a Kinect or Leap Motion device at our disposal for the experiment. However, due to the “non-wearable” nature of such motion-sensing devices, having such a device was not strictly required to complete the experiment (as opposed to wearable input devices, which can be needed by the participants to perform specific gestures on their surfaces). Thus, participants were asked to execute gestures in mid-air in front of a screen, as if it was able to distinguish any of their hand gestures.

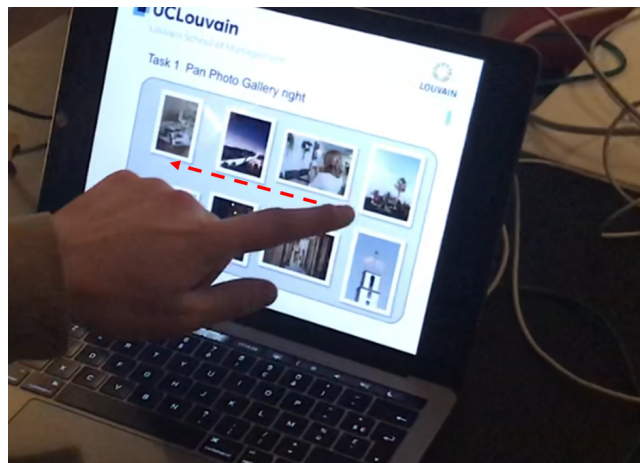


Figure B.1: Snapshot from the photo-browsing gesture elicitation study showing a participant performing a mid-air gesture.

B.1.3 Task

Participants were installed at a desk facing a screen, which presented them with *referents*, *i.e.*, common interactions with a photo or a video gallery, for which they proposed suitable gestures to execute those referents, *i.e.*, gestures that fit referents well while being easy to produce and remember. There were no constraints on the participants' choices of gestures, with the exception that a given gesture could not be assigned to more than one referent. The order of the referents was randomized per participant. Participants' fine motor skills and creativity levels were evaluated before the experiment, and a short questionnaire was administered after the experiment to give us an insight into the system user satisfaction.

B.1.4 Measures

We employed the same measures as Gheran *et al.* [42] to evaluate and understand users' preferences and cognitive and motor performance for gestures detected by a Kinect device:

1. We computed agreement rates (AR) for each REFERENT using the formula of Vatavu and Wobbrock [124] (p. 1327), as follows:

$$AR(r) = \frac{\sum_{i < j} \delta_{i,j}}{n \cdot (n - 1) / 2} \quad (\text{B.1})$$

where n is the number of participants from which gestures are elicited, and $\delta_{i,j}$ evaluates to 1 if the i -th and j -th participants are in agreement over referent r and to 0 otherwise.

2. Participants' creativity was evaluated before the elicitation procedure using a generic creativity test. The test is available online¹ and reports a score between 0 and 100 (higher scores denote more creativity) computed from answers to a set of 40 questions. We specifically chose this test due to its ease of application and large diversity of factors evaluated: *abstraction* (of concepts from ideas), *connection* (between things without an apparent link), *perspective* (shift in terms of space, time, and other people), *curiosity* (to change and improve things accepted as the norm), *boldness* (to push boundaries beyond accepted conventions), *paradox* (the ability to accept and work with contradictory concepts), *complexity* (the ability to operate with a large quantity of information), and *persistence* (to derive stronger solutions even when good ones have already been generated).
3. We measured participants' fine motor skills with a standard motor test of the NEPSY test batteries (a developmental NEuroPSYchological assessment) [57]. The test consists of touching each fingertip with the thumb of the same hand eight times in a row. Higher motor skills are reflected in less time to perform this task.
4. THINKING-TIME measures the time, in seconds, needed by participants to propose a gesture for a given referent.
5. GOODNESS-OF-FIT represents participants' subjective assessment, as a rating between 1 and 10, of their confidence about how well the proposed gestures fit the referents.

B.1.5 Taxonomy

To better understand the mid-air gesture proposals, we considered the following dimensions of analysis, strongly inspired by the taxonomy of Ring Gestures of Gheran *et al.* [42].

¹<http://www.testmycreativity.com/>

1. *Scale* characterizes the amplitude of a gesture, with three categories: (a) large, (b) medium, and (c) small. These categories correspond respectively to arm, wrist, and fingers' range of movements.
2. *Laterality* characterizes how the two hands are employed to produce mid-air gesture, with four categories: (a) *dominant unimanual*, (b) *nondominant unimanual*, (c) *symmetric bimanual*, and (d) *asymmetric bimanual*. We adopted this dimension from Piumsomboon *et al.* [91], who used it to characterize users' mid-air gestures for AR applications.
3. *Nature* describes the meaning of a gesture, with four categories: (a) *symbolic*, (b) *metaphorical*, (c) *physical* and (d) *abstract*. Symbolic gestures depict popular symbols, such as the "thumbs up" gesture, that is often associated with liking something. Metaphorical gestures are gestures that mimic the use of a physical object, such as pushing a button on an imaginary remote control. Physical gestures manipulate the object or content directly, *e.g.*, rotating, or scaling it. Abstract gestures' mapping is arbitrary, there is no connection with symbols or physical objects. These categories are adopted from Ruiz *et al.* [99].
4. *Form* characterizes the relative importance of hand poses versus hand motion in the articulation of a mid-air gesture, with four categories: (a) *stroke*, (b) *static*, (c) *static with motion*, and (d) *dynamic*. The stroke category contains only gestures that consist of a single uninterrupted and fast movement. For static gestures, only the configuration of the hand (*i.e.*, the hand pose) is meaningful. Static with motion gestures consist of a succession of postures (*e.g.*, pinch two fingers to zoom out in a picture). Finally, in dynamic gestures, both the evolution of the hand configuration and the motion are important. This category was inspired by the taxonomy of Vatavu and Pentiu [123].

B.2 Photo-Browsing

B.2.1 Experiment

This section will add more details about the experiment that were omitted at the beginning of this chapter.

Participants

Thirty (30) participants (16 female), aged between 18 and 77 years old ($M = 34.5$, $SD = 17.5$ years), volunteered for the study. Participant occupations included teachers, students, office clerks, computer scientists, retirees. 93% (28/30) of the participants were right-handed. All but one of the participants regularly used a smartphone or a tablet device and, thus, were accustomed to touch and gesture input.

Design

The study was within-subjects with one independent variable: the REFERENT. It is a nominal variable with 31 conditions, representing common tasks to execute in a collection-of-pictures type of environment, such as a photo gallery, with a Kinect device: (1) pan the photo gallery right, (2) left, (3) up and (4) down, (5) go to the next and (6) previous page of the photo gallery, (7) zoom in and (8) out in a photo, (9) maximize a photo from normal view to full screen and (10) unmaximize it, (11) open and (12) close photo information, (13) set the layout to carousel, (14) start and (15) stop a slideshow, (16) take a selfie, (17) insert a new photo, (18) duplicate

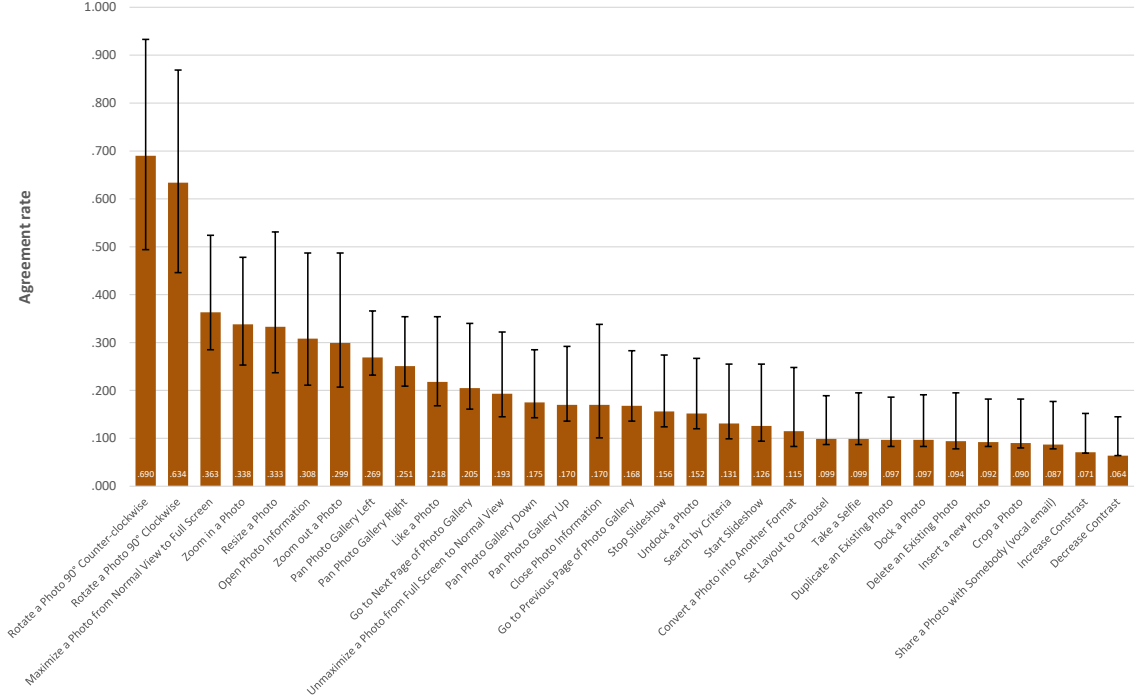


Figure B.2: Agreement rates for the gesture proposals (photo-browsing). Notes: referents are ordered on the horizontal axis in descending order of their agreement rates; error bars show 95% CIs computed with the AGATe tool [124].

and (19) delete an existing photo, (20) crop and (21) resize a photo, (22) rotate a photo 90° clockwise and (23) 90° counter-clockwise, (24) increase and (25) decrease the contrast of a photo, (26) dock and (27) undock a photo, (28) like a photo, (29) search photos within the gallery by criteria, (30) share a photo with somebody, (31) convert a photo into another format.

The choice of referents represents a collection of basic (e.g., pan the photo gallery right/left/up/down) and more complex tasks (e.g., search photos within the gallery by criteria) likely to be useful for interactions with a gallery of pictures.

B.2.2 Results

We collected a total number of 930 gesture proposals from 30 (participants) $\times$ 31 (referents) conditions, which we clustered into groups of similar gesture types according to the following criteria: We did not distinguish gestures according to their scale (*i.e.*, whether the amplitude of the gesture is large or small), direction, or handedness (*i.e.*, whether the gesture was drawn with the dominant or non-dominant hand). However, we considered gestures executed with different hand poses as different, meaning, *e.g.*, a “swipe” with the index finger pointed is considered different from the same “swipe” with the hand open.

We identified 21 distinct gestures. Next, we analyze the consensus between participants’ gesture proposals and assign gesture types to meaningful categories.

Consensus Between Proposed Gestures

Figure B.2 shows the agreement rates obtained for each REFERENT. Overall, agreement rates are average, between .064 and .690 ($M=.205$, $SD=.147$). These results fit within the reported agreement rates in the literature of gesture elicitation; see Vatavu and Wobbrock [124] (p. 1332) that summarize agreement rates of 18 studies. According to the recommendations of Vatavu

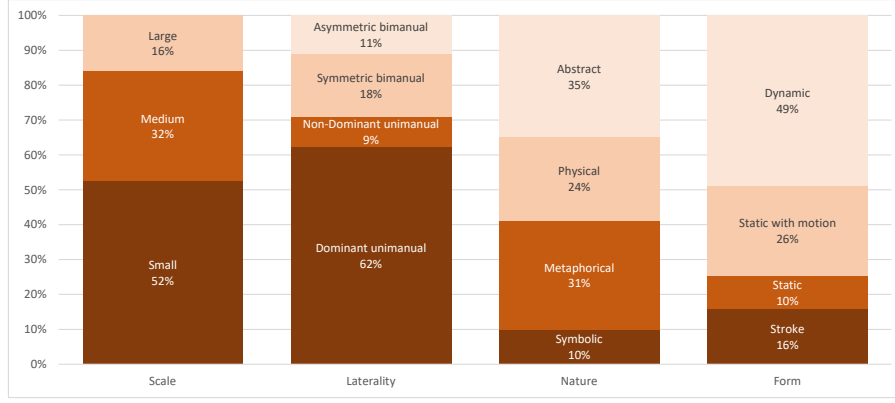


Figure B.3: Observed percentages of gestures for each category of our taxonomy (photo-browsing).

and Wobbrock [124] to interpret the magnitudes of agreement rates, most of our results fall inside the medium consensus (.100 – .300) category. These results were confirmed by Kendall’s coefficient of concordance:² $W = .150$ ($\chi^2(30) = 134.576$, $p < .0001$). As Kendall’s coefficient is related to the average of Spearman correlation coefficients between pairs of rankings [51] (p. 276), we can interpret the magnitude of its effect as small (*i.e.*, close to .100) according to Cohen’s suggested limits for interpreting effect sizes.

Taxonomy of Mid-Air Gestures

Figure B.3 illustrates the observed percentages of gestures falling in each category according to the taxonomy presented at the beginning of this chapter.

Gestures’ Goodness of Fit

Participants rated their gesture proposals with numbers from 1 (poor fit) to 10 (excellent fit) to denote their confidence in the goodness of fit of their proposals. GOODNESS-OF-FIT correlated significantly with the AGREEMENT-RATE (Pearson’s $r_{(N=31)} = .530$, $R^2 = .281$, $p = .002$): referents that reached high agreement rates were assigned gestures that were rated a good fit. Figure B.4 shows this relationship between the goodness of fit and agreement rates.

Thinking Time

The average thinking time was quite high ($M = 8.58$ s, $SD = 10.63$ s). Figure B.5 shows the relationship between thinking times and agreement rates per REFERENT. THINKING-TIME correlated significantly with AGREEMENT-RATE (Pearson’s $r_{(N=31)} = -.409$, $R^2 = .167$, $p = .022$): the agreement rate decreased for longer thinking times. Thinking time seemed to be longer for more complex tasks (*e.g.*, search by criteria or convert a photo into another format), and shorter for simpler tasks (*e.g.*, pan the photo gallery left/right or rotate a photo 90° clockwise). We noted that a majority of the simpler task already had a well-known gesture assigned to them for touchscreen devices. As most of our participants actively used a smartphone or a tablet, this may explain the lower thinking time and higher agreement rate.

²Kendall’s W is a normalization of the Friedman statistic used to assess the agreement between multiple raters with a number ranging between 0 (no agreement at all) and 1 (perfect agreement).

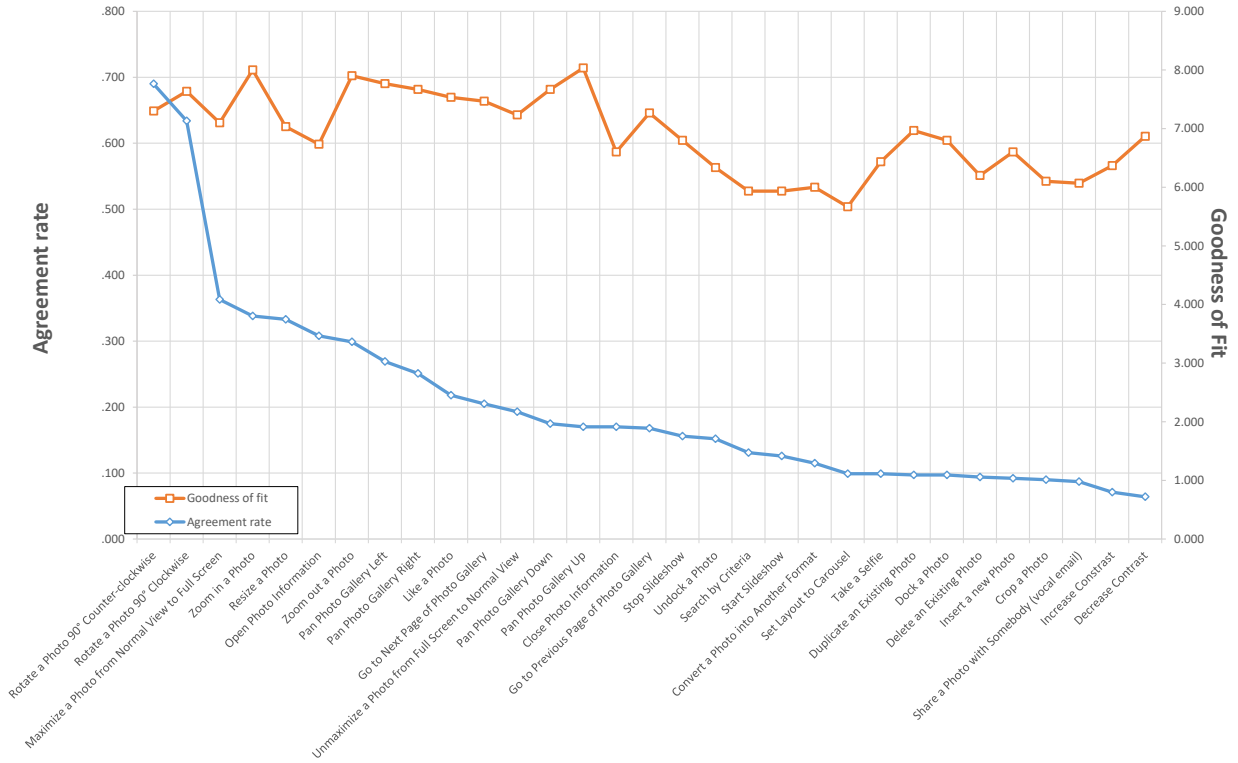


Figure B.4: Relationship between AGREEMENT-RATE and GOODNESS-OF-FIT for each referent (photo-browsing).

B.3 Video-Browsing

B.3.1 Experiment

This section will add more details about the experiment that were omitted at the beginning of this chapter.

Participants

Twenty-two (22) participants (8 female), aged between 15 and 54 years old ($M = 28.9$, $SD = 12.6$ years), volunteered for the study. Participant occupations included students, economists, teachers, engineers, and midwives. All the participants regularly used computers, and 90.9% of the participants (20/22) regularly used either a smartphone or a tablet device.

Design

The study was within-subjects with one independent variable: the REFERENT. It is a nominal variable with 27 conditions, representing common tasks to execute in a collection-of-videos type of environment, such as a video gallery, with a Kinect device: (1) pan the video gallery right, (2) left, (3) up and (4) down, (5) go to the next and (6) previous page of the video gallery, (7) zoom in and (8) out in a video, (9) maximize a video from normal view to full screen and (10) unmaximize it, (11) start and (12) stop playing a video, (13) go at the beginning and (14) the end of a video, (15) open and (16) close video information, (17) set the layout to carousel, (18)

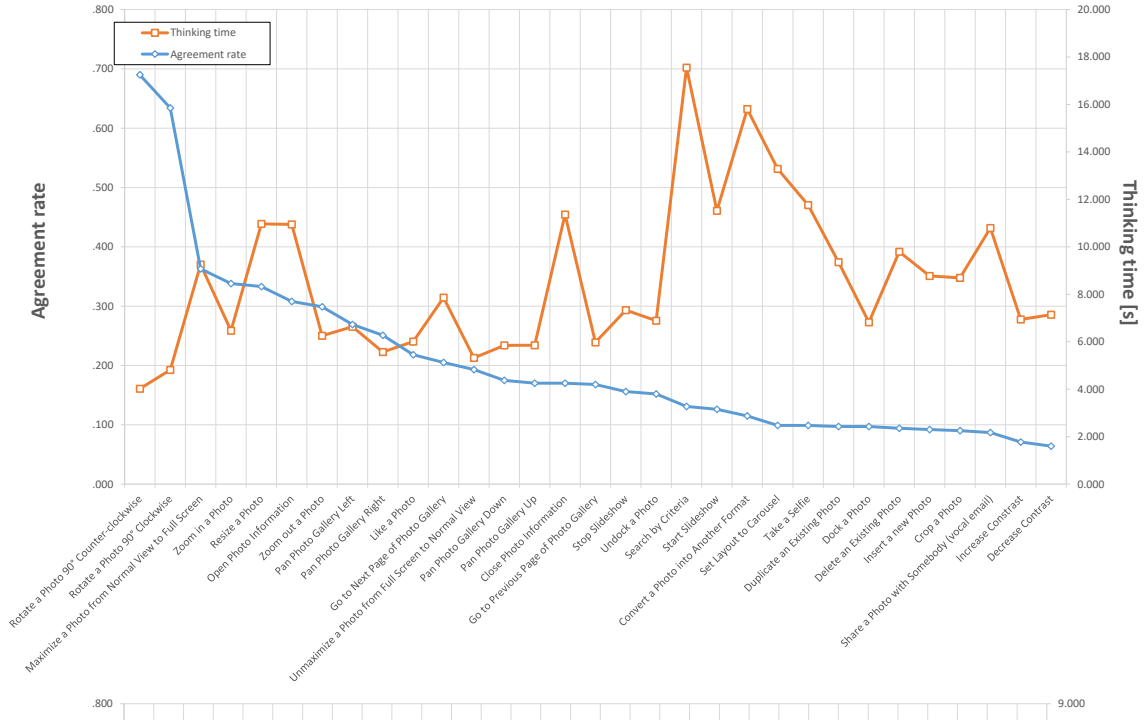


Figure B.5: Relationship between AGREEMENT-RATE and THINKING-TIME (photo-browsing).

insert a new video, (19) duplicate and (20) delete an existing video, (21) rotate a video 90° clockwise and (22) 90° counter-clockwise, (23) dock and (24) undock a video, (25) like a video, (26) search videos within the gallery by criteria, (27) share a video with somebody.

The choice of referents represents a collection of basic (*e.g.*, zoom in/out in a video) and more complex tasks (*e.g.*, share a video with someone) likely to be useful for interactions with a collection of videos.

B.3.2 Results

We collected a total number of 594 gesture proposals from 22 (participants) $\times$ 27 (referents) conditions, which we clustered into groups of similar gesture types according to the following criteria: We distinguished gestures according to their hand pose and the axis in which they were executed (*e.g.*, parallel to the body, or parallel to the normal vector to the body), but we did not distinguish them according to their scale, direction, or handedness. We identified 23 distinct gestures. Next, we analyze the consensus between participants' gesture proposals and assign gesture types to meaningful categories.

Consensus Between Proposed Gestures

Figure B.6 shows the agreement rates obtained for each REFERENT. Overall, agreement rates are average, between .052 and .593 ($M=.229$, $SD=.162$). These results fit within the reported agreement rates in the literature of gesture elicitation; see Vatavu and Wobbrock [124] (p. 1332) that summarize agreement rates of 18 studies. According to the recommendations of Vatavu and Wobbrock [124] to interpret the magnitudes of agreement rates, most of our results fall inside the medium consensus (.100 – .300) category.

These results were confirmed by Kendall's coefficient of concordance:³ $W = .251$ ($\chi^2(26) =$

³Kendall's W is a normalization of the Friedman statistic used to assess the agreement between

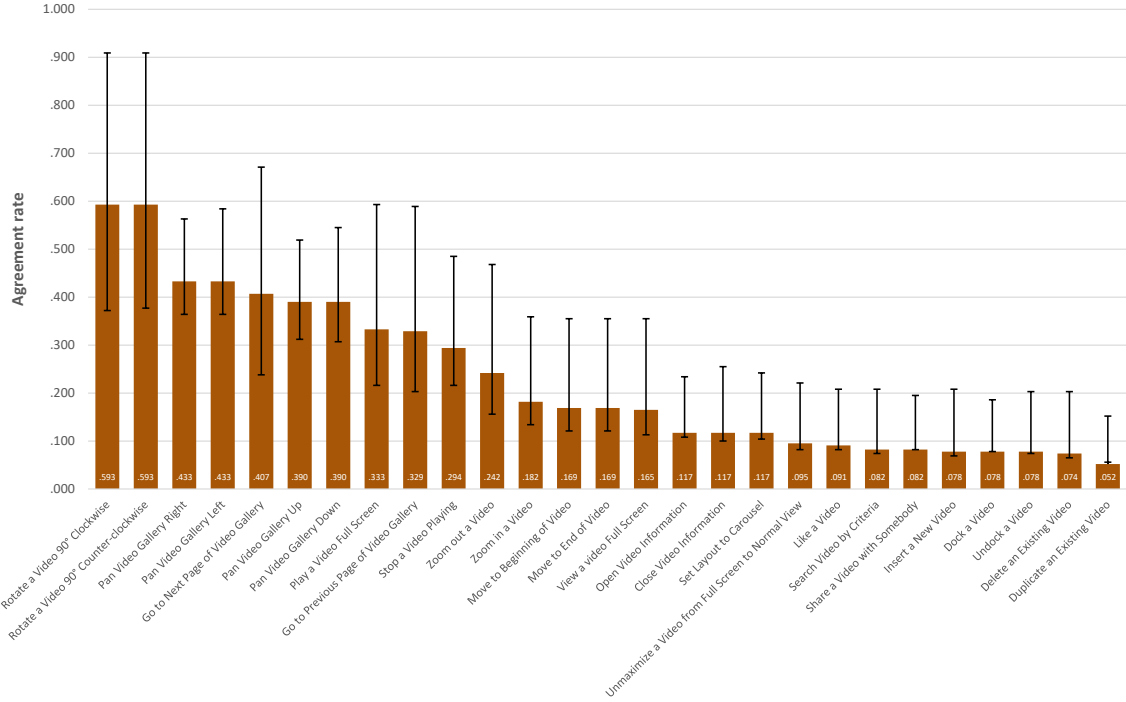


Figure B.6: Agreement rates for the gesture proposals (video-browsing). Notes: referents are ordered on the horizontal axis in descending order of their agreement rates; error bars show 95% CIs computed with the AGATe tool [124].

143.446, $p < .0001$). As Kendall's coefficient is related to the average of Spearman correlation coefficients between pairs of rankings [51] (p. 276), we can interpret the magnitude of its effect as medium (*i.e.*, close to .300) according to Cohen's suggested limits for interpreting effect sizes.

Taxonomy of Mid-Air Gestures

Figure B.7 illustrates the observed percentages of gestures falling in each category according to the taxonomy presented at the beginning of this chapter.

Gestures' Goodness of Fit

Participants rated their gesture proposals with numbers from 1 (poor fit) to 10 (excellent fit) to denote their confidence in the goodness of fit of their proposals. GOODNESS-OF-FIT correlated significantly with the AGREEMENT-RATE (Pearson's $r_{(N=27)} = .723$, $R^2 = .522$, $p < .0001$): referents that reached high agreement rates were assigned gestures that were rated a good fit. Figure B.8 shows this relationship between the goodness of fit and agreement rates.

Thinking Time

The average thinking time was quite high ($M = 9.85$ s, $SD = 26.90$ s). Figure B.9 shows the relationship between thinking times and agreement rates per REFERENT. THINKING-TIME correlated significantly with AGREEMENT-RATE (Pearson's $r_{(N=27)} = -.545$, $R^2 = .297$, $p = .0033$): the agreement rate decreased for longer thinking times. Usually, simpler tasks (*e.g.*, rotate a video, or zoom in/out) were associated with shorter thinking time. Most of these simple tasks were already associated with well-known gestures (mostly from touchscreen devices).

multiple raters with a number ranging between 0 (no agreement at all) and 1 (perfect agreement).

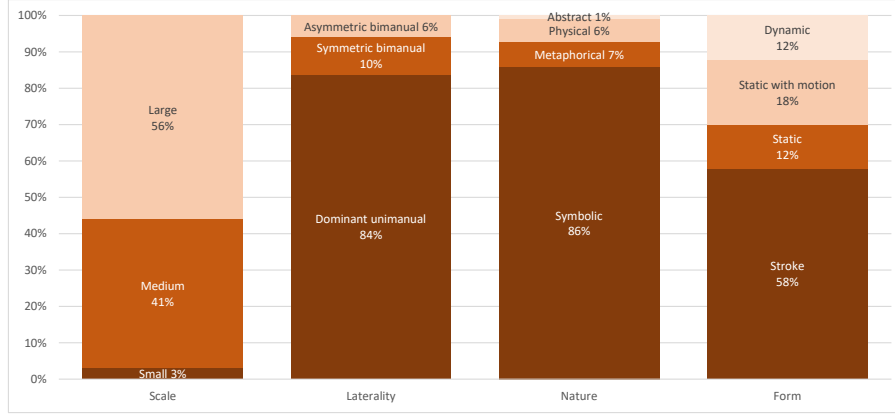


Figure B.7: Observed percentages of gestures for each category of our taxonomy (video-browsing).

B.4 What Can We Conclude From Both Experiments?

In this section, we analyze the (dis)similarities between the results of the photo-browsing and the video-browsing elicitation studies. We try to draw conclusions for future elicitation studies.

B.4.1 Agreement Rate, Thinking Time and Goodness of Fit

Both experiments showed that thinking time correlated significantly with the agreement rate: a higher thinking time seemed linked to a lower agreement rate. The same can be said for the goodness of fit: the agreement rate increased with the goodness of fit in both elicitation studies.

Influence of the Gesture Pairing Criteria

Both experiments showed quite high agreement rates. Gheran *et al.* [42] have shown that the gesture pairing criteria may influence the magnitude of the agreement rate. In both experiments, the criteria used to categorize gestures were quite relaxed (e.g., gestures executed in different directions were considered equivalent). This can explain their slightly higher agreement rates compared to other similar experiments [124].

Influence of the Methodology and Experiment Design

The visual indication given to the users for each referent may have impacted their choice of gesture. Especially when those visual indications were not extremely clear. Furthermore, having to choose a unique gesture for each referent may have negatively impacted the agreement rate, as participants sometimes had to propose a different gesture from the one that they would have preferred. The setup for the experiment may also have impacted the choice of gestures of the user. Indeed, in the photo-browsing experiment, participants were situated very close to the screen showing them the visual indications, to the point where some of them physically touched the screen while performing their gestures. This may have encouraged them to choose more “touch-oriented” gestures. It could be interesting to repeat the experiment in a more “open” setup, where participants are installed further away from the screen.

B.4.2 Taxonomy of Gestures

Despite the referents of the two experiments being very similar, we observed quite varying percentages of gestures falling into the categories of our taxonomy (see figures B.3 and B.7):

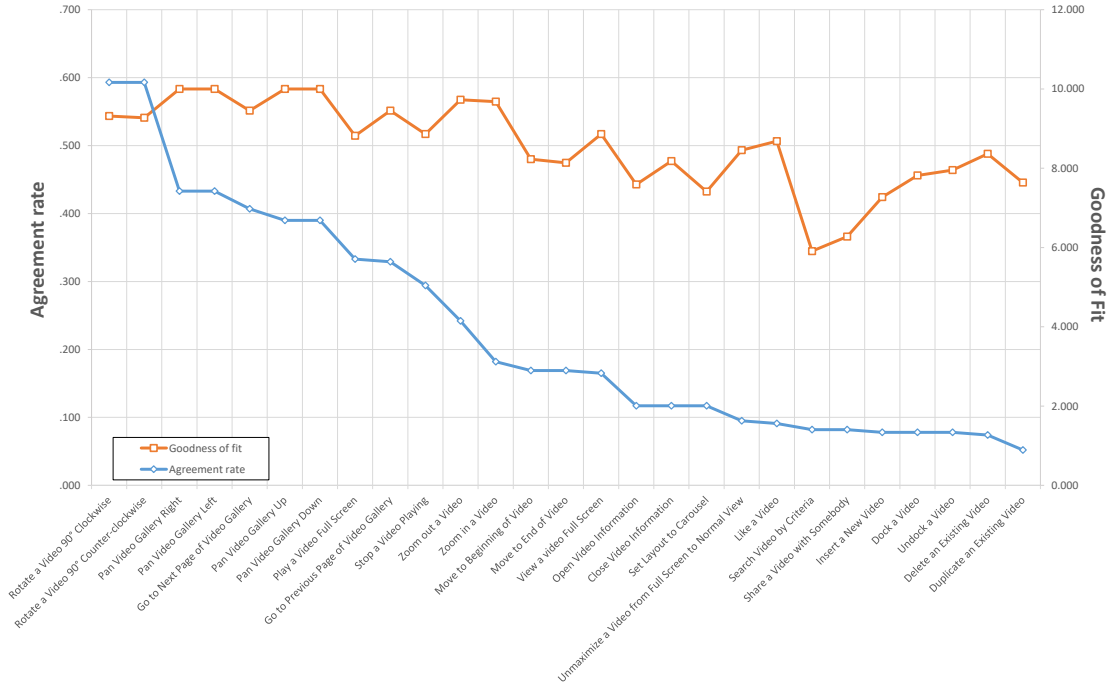


Figure B.8: Relationship between AGREEMENT-RATE and GOODNESS-OF-FIT for each referent (video-browsing).

- *Scale*: in the photo-browsing experiment, a majority of gestures fall into the *small* (52%) and *medium* (32%) categories, while respectively 56% and 41% of the gestures elicited in the video-browsing experiment fall in the *large* and *medium* categories. These conflicting results may be due to differences in the setup of the experiments. Participants of the photo-browsing experiment were situated close enough to the screen that they could touch it. This may have encouraged them to use more touchscreen-inspired gestures and to limit the amplitude of their movements.
- *Laterality*: the results of both elicitation studies seem quite similar, with a strong preference for *dominant unimanual* gestures, although the photo-browsing experiment showed a higher percentage of gestures falling into the other categories.
- *Nature*: the distribution of gestures into the various categories is vastly different between both experiments. In the video-browsing elicitation study, most gestures are *symbolic* (86%), while they are more evenly distributed into the 4 categories in the photo-browsing experiment, with a majority of them being either *abstract* (35%) or *metaphorical* (31%).
- *Form*: both elicitation studies show a similar number of gestures falling into the *static* and *static with motion* categories but they disagree on the *Dynamic* (12% vs 49% for resp. the video-browsing and the photo-browsing experiment) and *Stroke* categories (58% vs 16% for resp. the video-browsing and the photo-browsing experiment).

B.4.3 Guidelines for Future Elicitation Studies

In this section, we discuss the results of our experiment, we suggest elements to investigate in future elicitation studies and we derive some recommendations for mid-air gestures.

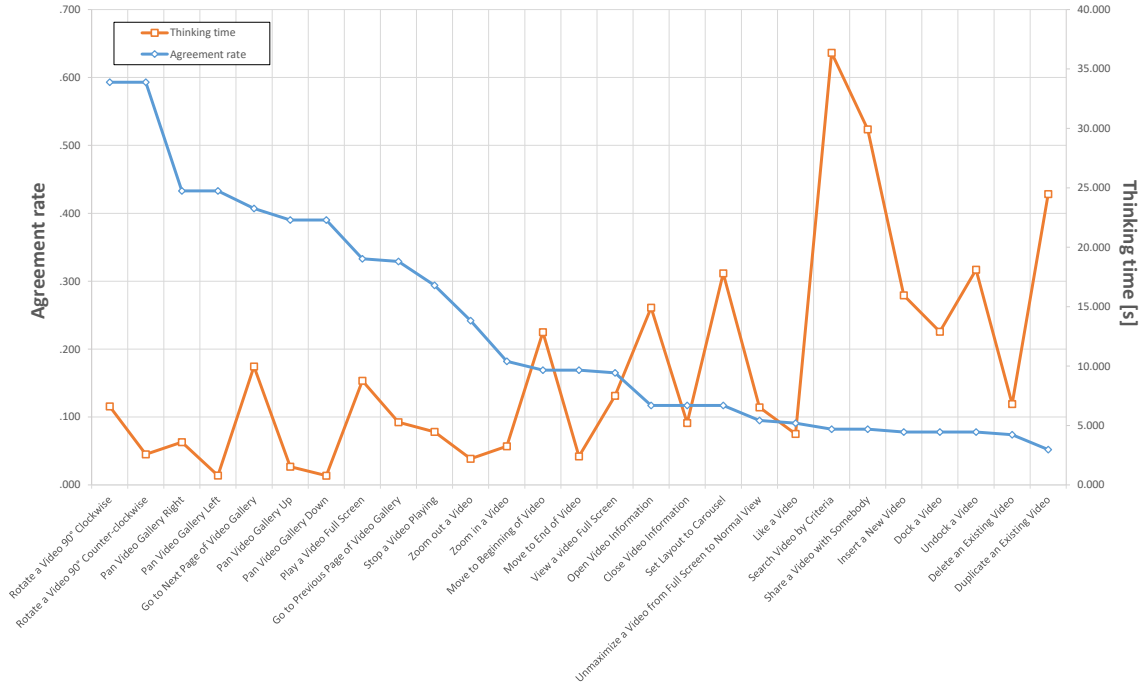


Figure B.9: Relationship between AGREEMENT-RATE and THINKING-TIME (video-browsing).

- *Motion seems to be preferred over static gestures.*
Only about a tenth of the proposed gestures were static, with the rest of the gestures being either dynamic, static with motion, or stroke. Participants especially avoided static gestures for referents representing “navigation” actions (*e.g.*, panning the photo gallery left or right). However, they were more frequently used for actions such as like a photo/video, set the layout to carousel, or take a selfie.
- *Users prefer gestures of the dominant hand.*
As discussed before, most of the proposed gestures involved only the dominant hand, with a minority of gestures involving two hands. However, there was no real consensus between both experiments on the size of those gestures.
- *Many proposed gestures are inherited from touchscreen devices.*
Participants mostly limited themselves to using “touch-inspired” gestures, such as swiping with a hand/finger or tapping with one finger. As opposed to the findings of Gheran *et al.* [42] when studying gestures for smart rings, very few of the proposed gestures involved more complex gestures, such as using a hand as an invisible “tv-remote”, that are not executable on touchscreen devices. Maybe wearing or physically holding an input device (*e.g.*, a smart ring) encourages participants to find more original gestures, by giving them a hint about the kind of gestures they could execute.
- *User interface plays an important role while defining intuitive gestures.*
The agreement rate for some referents (*e.g.*, search by criteria, share a video with someone) was very low. These referents mainly represented actions that are quite complex to execute on devices with touch or mouse-input. For instance, sharing a video with a contact usually implies selecting a video, the sharing medium, and finally the intended recipient. Without a proper hint of the layout of the interface, devising a gesture that could replace all these actions at once is difficult as it mostly depends on how the interface is setup. Future

experiments should concentrate more on designing an interface that would make such actions easy and natural to perform through mid-air gestures.

- *Consider context-sensitive gestures.*

The constraint that a unique gesture should be assigned to each referent was quite frustrating according to some participants. To reduce this frustration, we could assign a gesture to multiple referents if the context allows the system to correctly recognize the action prompted by the gesture (*e.g.*, a flick to the left in the photo gallery could have a different effect than the same gesture when viewing a photo in full screen). This would limit the number of gestures to be remembered, and thus make it easier for new users to learn how to navigate through the interface.

Referent	AR	Most frequent	Second most frequent
1. <i>Pan Photo Gallery Right</i>	.251	1 hand flick	Multiple fingers swipe
2. <i>Pan Photo Gallery Left</i>	.269	Multiple fingers swipe	1 finger swipe
3. <i>Pan Photo Gallery Up</i>	.170	1 finger swipe	Hand rotation
4. <i>Pan Photo Gallery Down</i>	.175	1 hand flick	1 finger swipe
5. <i>Go to Next Page of Photo Gallery</i>	.205	Multiple fingers swipe	1 hand flick
6. <i>Go to Previous Page of Photo Gallery</i>	.168	Multiple fingers swipe	1 hand flick
7. <i>Zoom in a Photo</i>	.338	Splay the hand	Bring hands further apart
8. <i>Zoom out a Photo</i>	.299	Clench the hand	Bring hands further apart
9. <i>Maximize a Photo from Normal View to Full Screen</i>	.363	Bring hands further apart	Splay the hand
10. <i>Unmaximize a Photo from Full Screen to Normal View</i>	.193	Clench the hand	Bring hands closer
11. <i>Open Photo Information</i>	.308	1 finger tap	Splay the hand
12. <i>Close Photo Information</i>	.170	1 finger tap	1 finger swipe
13. <i>Set Layout to Carousel</i>	.099	Hand rotation	1 finger tap
14. <i>Start Slideshow</i>	.126	1 finger tap	Hand pose
15. <i>Stop Slideshow</i>	.156	1 finger tap	Move flat hand forward/backward
16. <i>Take a Selfie</i>	.099	Hand pose	1 finger tap
17. <i>Insert a new Photo</i>	.092	Hand pose	1 finger tap
18. <i>Duplicate an Existing Photo</i>	.097	1 finger swipe	1 finger tap
19. <i>Delete an Existing Photo</i>	.094	1 finger swipe	Hand pose
20. <i>Crop a Photo</i>	.090	Draw	Bring hands further apart
21. <i>Resize a Photo</i>	.333	Bring hands further apart	Splay the hand
22. <i>Rotate a Photo 90° Clockwise</i>	.634	Hand rotation	N/A
23. <i>Rotate a Photo 90° Counterclockwise</i>	.690	Hand rotation	N/A
24. <i>Increase Contrast</i>	.071	1 finger swipe	Open arms (with flat hands)
25. <i>Decrease Contrast</i>	.064	1 finger swipe	Multiple fingers swipe
26. <i>Dock a Photo</i>	.097	1 finger swipe	1 hand flick
27. <i>Undock a Photo</i>	.152	1 finger swipe	Take and throw
28. <i>Like a Photo</i>	.218	1 finger tap	Hand pose
29. <i>Search by Criteria</i>	.131	Hand pose	Draw
30. <i>Share a Photo with Somebody (vocal email)</i>	.087	Hand pose	1 finger swipe
31. <i>Convert a Photo into Another Format</i>	.115	Bring hands further apart	1 finger tap

Referents with agreement rates above average are highlighted in blue.

Table B.1: First and second most frequent gesture proposals for each referent (photo-browsing).

Referent	AR	Most frequent	Second most frequent
1. <i>Pan Video Gallery Right</i>	.433	1 hand drag	1 finger drag
2. <i>Pan Video Gallery Left</i>	.433	1 hand drag	1 finger drag
3. <i>Pan Video Gallery Up</i>	.390	1 hand drag	1 finger drag
4. <i>Pan Video Gallery Down</i>	.390	1 hand drag	1 finger drag
5. <i>Go to Next Page of Video Gallery</i>	.407	1 hand drag	1 finger drag
6. <i>Go to Previous Page of Video Gallery</i>	.329	1 hand drag	1 finger drag
7. <i>Zoom in a Video</i>	.182	1 hand drag	Close one hand
8. <i>Zoom out a Video</i>	.242	1 hand drag	Close one hand
9. <i>Set a Video in Full Screen</i>	.165	1 finger tap	Drag 1 finger from each hand
10. <i>Unmaximize a Video from Full Screen to Normal View</i>	.095	Drag 1 finger from each hand	2 hands drag
11. <i>Play a Video</i>	.333	1 finger tap	1 finger drag
12. <i>Stop Playing a Video</i>	.294	Push/pull 1 hand	1 finger tap
13. <i>Move to the Beginning of Video</i>	.169	1 hand drag	1 finger tap
14. <i>Move to the End of a Video</i>	.169	1 hand drag	1 finger tap
15. <i>Open Video Information</i>	.117	1 finger tap	Push/pull 1 hand
16. <i>Close Video Information</i>	.117	1 hand drag	1 finger drag
17. <i>Set Layout to Carousel</i>	.117	1 hand drag	Tap and drag 1 finger
18. <i>Insert a New Video</i>	.078	Push/pull and drag 1 hand	Push/pull 1 hand
19. <i>Duplicate a Video</i>	.052	2 hands drag	Tap and drag 1 finger from each hand
20. <i>Delete a Video</i>	.074	1 hand drag	1 finger drag
21. <i>Rotate a Video 90° Clockwise</i>	.593	1 hand drag	Push/pull 1 hand
22. <i>Rotate a Video 90° Counter-clockwise</i>	.593	1 hand drag	Push/pull 1 hand
23. <i>Dock a Video</i>	.078	Push/pull and drag 1 hand	Tap and drag 1 finger
24. <i>Undock a Video</i>	.078	Push/pull and drag 1 hand	Close, push/pull and drag 1 hand
25. <i>Like a Video</i>	.091	1 finger drag	Push/pull 1 hand
26. <i>Search for a Video by Criteria</i>	.082	1 finger drag	1 hand drag
27. <i>Share a Video with Somebody</i>	.082	1 hand drag	Close, push/pull and drag 1 hand

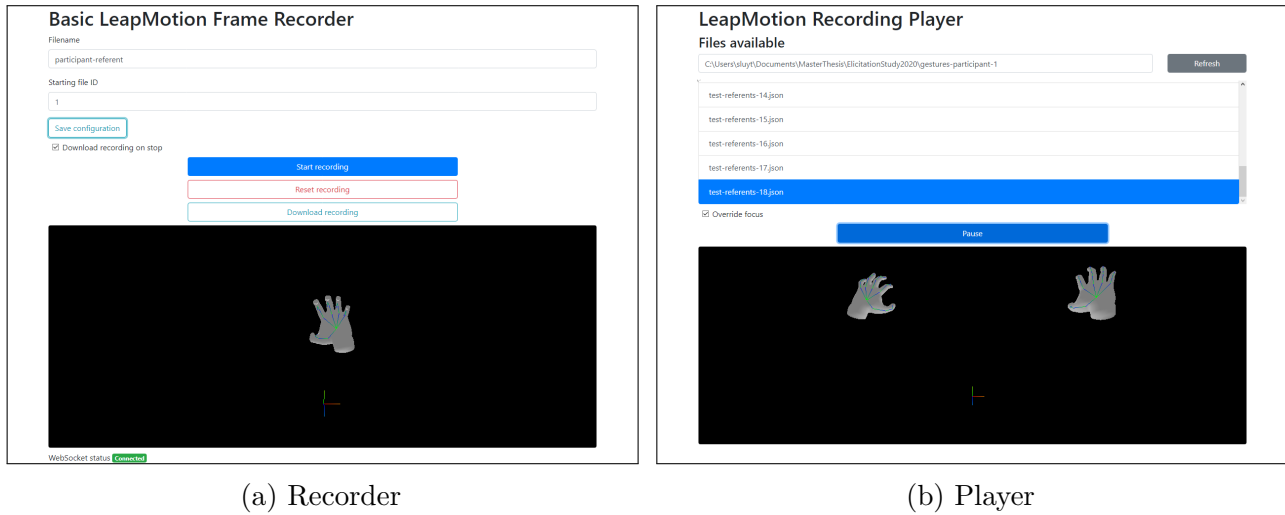
Referents with agreement rates above average are highlighted in blue.

Table B.2: First and second most frequent gesture proposals for each referent (video-browsing).

Appendix C

Recording and Playback Tool

For the purposes of our new elicitation study, it was important to have a simple and reliable tool to both record and playback the mid-air gestures proposed by each participant. As no software with the required set of features existed, a new one was designed and is now openly available on GitHub¹.



(a) Recorder

(b) Player

Figure C.1: Screenshots of the player and recorder tools.

The recording tool (Figure C.1a) retrieves tracking data by connecting to the LMC's WebSocket Server². It offers the following functionalities:

- Select a base name that stays the same for all the recordings and a starting index, which is incremented for each new recording.
- Start/stop/reset/download recording.
- Automatically download the recording after stopping it. This functionality proved very useful to streamline the process of recording gestures during the elicitation study.
- Visualize the data, *e.g.*, to check whether the LMC correctly picked up participants' gestures.

The playback tool (Figure C.1b) emulates an LMC. It consists of a WebSocket server that

¹<https://github.com/sluyters/LeapGesturePlayback>

²https://developer-archive.leapmotion.com/documentation/javascript/supplements/Leap_JSON.html

keeps track of the state of clients and sends them recorded frames. It offers the following functionalities:

- Select a recording from anywhere on the computer.
- Play/pause recording.
- Focus override: send the frames to each known client, regardless of whether they are focused or not. If this option is not enabled, frames are only sent to focused clients (*i.e.*, those that the user is actively using).
- Visualize the recording, *e.g.*, to analyze participants' gesture propositions after the completion of the elicitation study.

Appendix D

New Elicitation Study

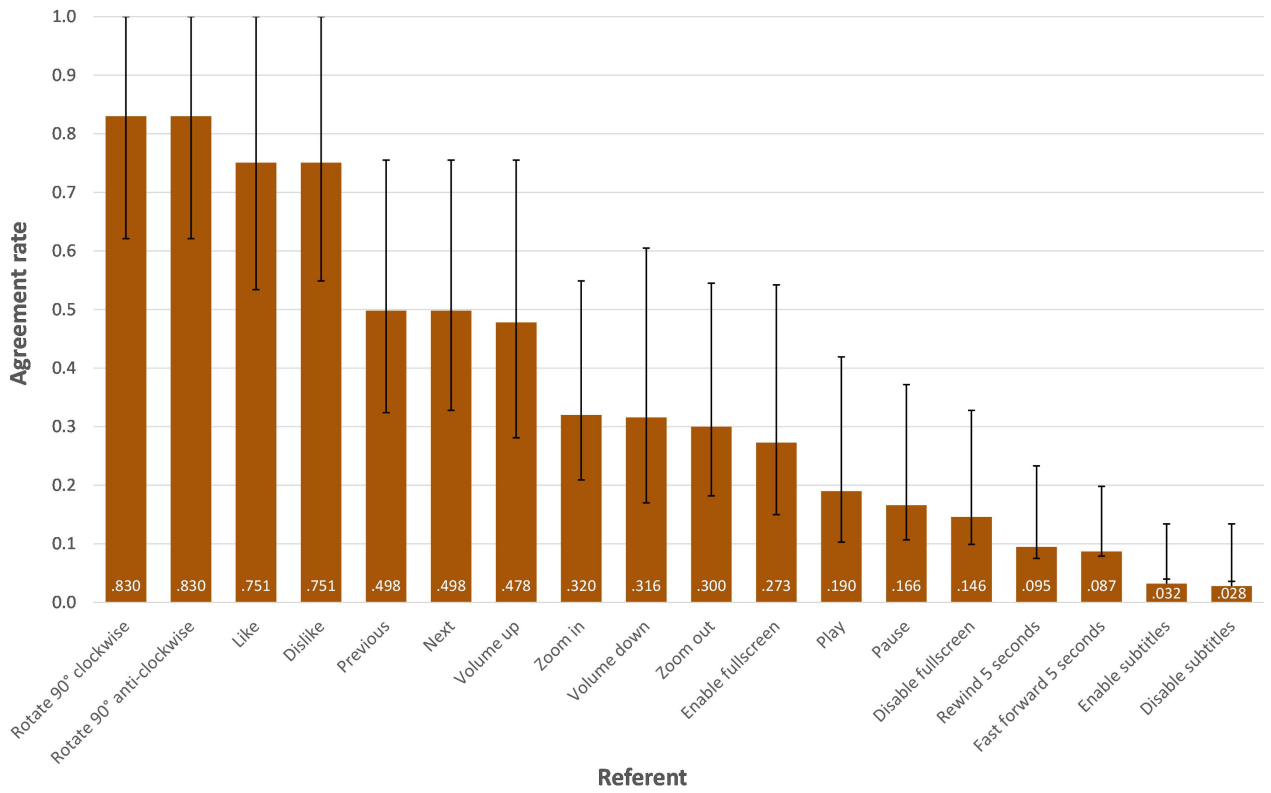


Figure D.1: Agreement rates for the gesture proposals. Notes: referents are ordered on the horizontal axis in descending order of their agreement rates; error bars show 95% CIs computed with the AGATe tool [124].

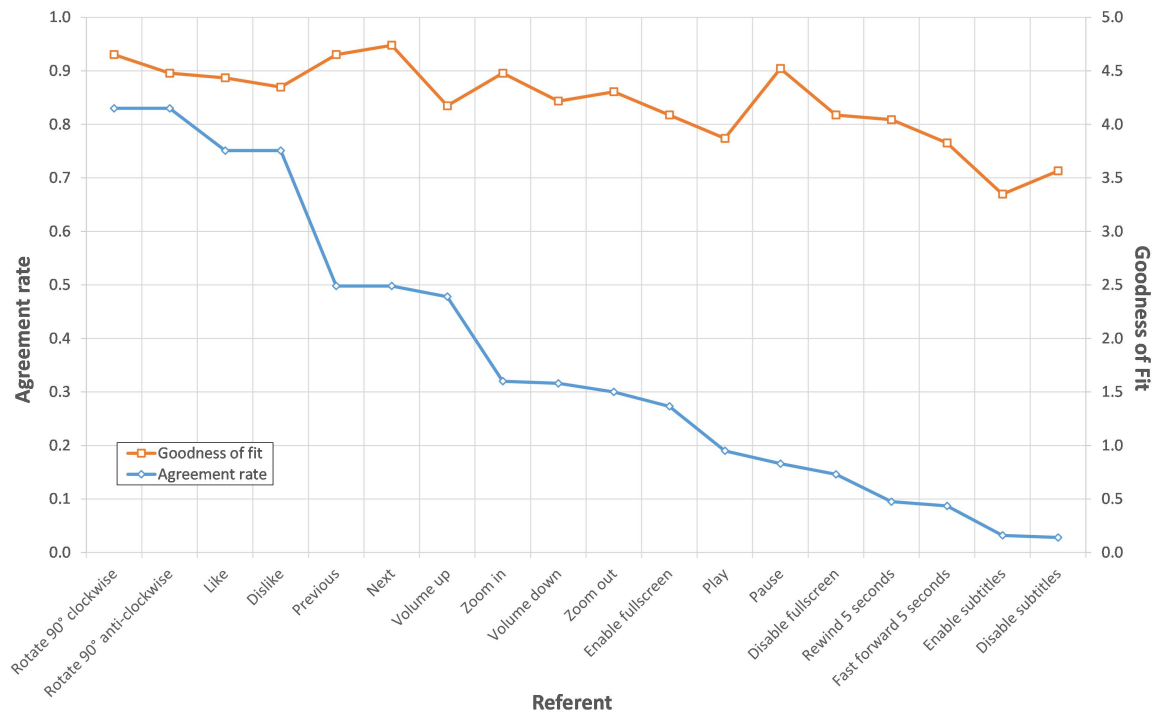


Figure D.2: Relationship between AGREEMENT-RATE and GOODNESS-OF-FIT.

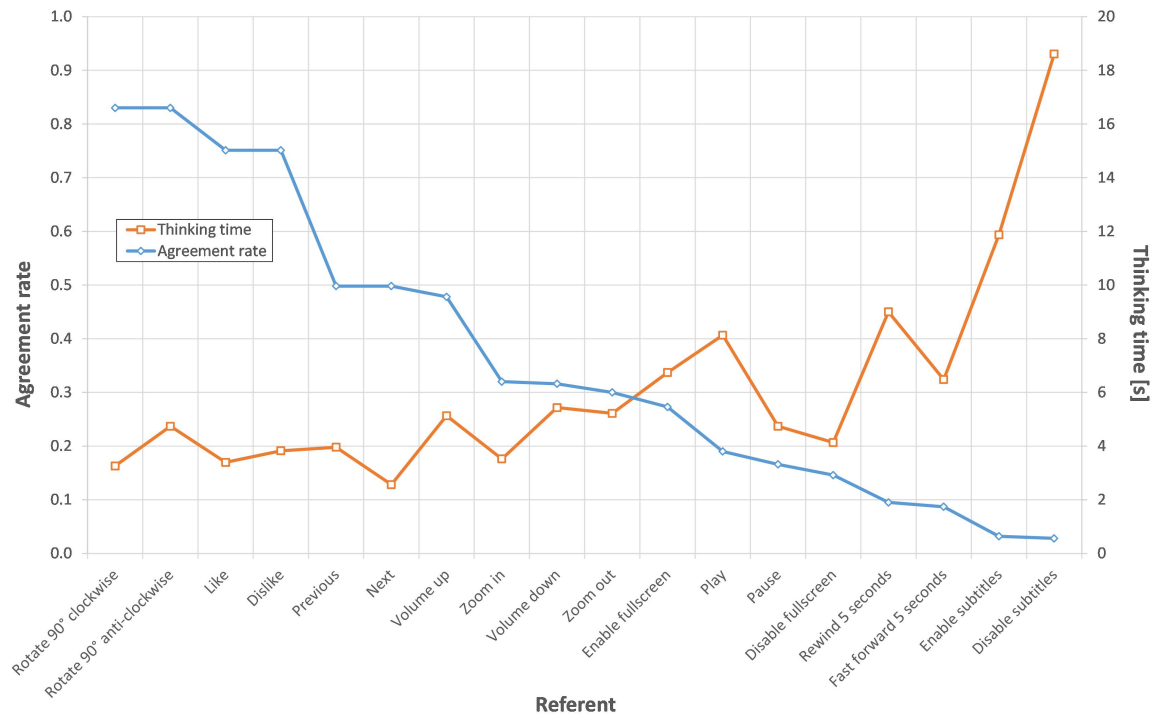


Figure D.3: Relationship between AGREEMENT-RATE and THINKING-TIME.

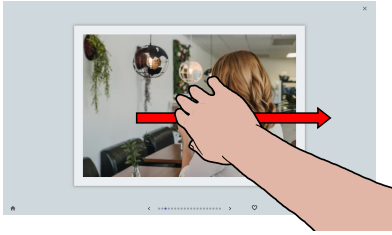
Appendix E

LUI Gesture Set

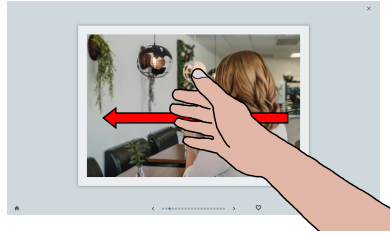
Action	Gesture	Justifications and Notes
<i>Previous</i>	Flick right	We kept the most popular gestures, but changed the <i>swipe</i> motion into the similar but faster <i>flick</i> motion.
<i>Next</i>	Flick left	
<i>Enable fullscreen</i>	Tap	We defined a new gesture, because in the LUI project, enabling fullscreen requires users to first select the item that they want to magnify. However, neither of the two most popular elicited gestures (<i>bring hands further apart</i> and <i>pinch out</i>) were appropriate for this task.
<i>Disable fullscreen</i>	Flick up	As neither of the two most popular elicited gestures were ideal for our context of use, we selected a different one. Indeed, the most popular gesture involved two hands, which may have proven harder to recognize and would have required users to have two free hands. The second most popular gesture, <i>pinch in</i> , would have clashed with the <i>zoom in</i> action.
<i>Zoom in</i>	Pinch out	We kept the most popular gestures from the elicitation study.
<i>Zoom out</i>	Pinch in	
<i>Volume up</i>	Swipe up*	
<i>Volume down</i>	Swipe down*	
<i>Rotate clockwise</i>	Rotate a knob clockwise	
<i>Rotate anti-clockwise</i>	Rotate a knob anti-clockwise	
<i>Play</i>	Tap	
<i>Pause</i>	Tap	
<i>Like</i>	Thumbs up	
<i>Dislike</i>	Thumbs down	
<i>Fast-forward</i>	Swipe left*	We selected the second most popular elicited gesture in order to stay coherent with the <i>rewind</i> action. Furthermore, the most popular gesture (<i>flick right twice</i>) would have been problematic to recognize, as it can clash with both <i>flick left</i> and <i>flick right</i> .
<i>Rewind</i>	Swipe right*	We kept the most popular elicited gesture.

* The *swipe up*, *swipe down*, *swipe left* and *swipe right* gestures must be performed while pointing the index finger in order to differentiate more easily between them and the *flick up*, *flick left* and *flick right* gestures (see Figure E.1 for graphical representations of these gestures).

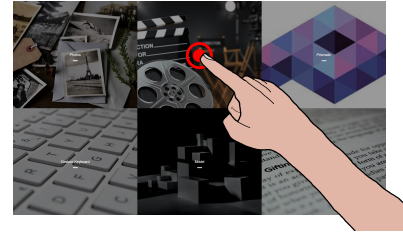
Table E.1: Assigned gestures for each referent.



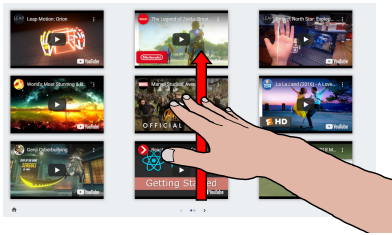
(a) Previous



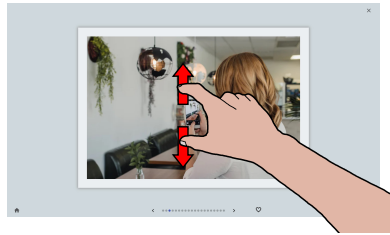
(b) Next



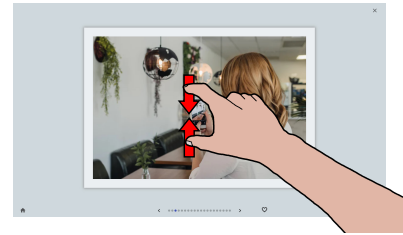
(c) Enable fullscreen



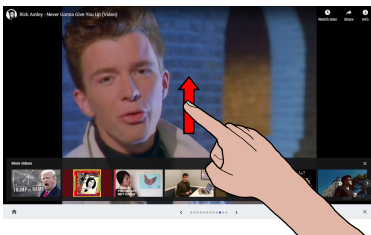
(d) Disable fullscreen



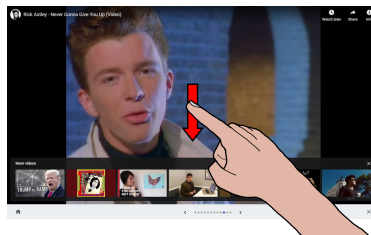
(e) Zoom in



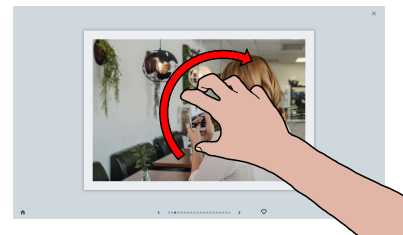
(f) Zoom out



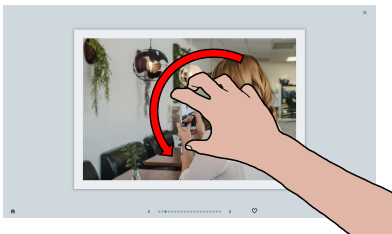
(g) Volume up



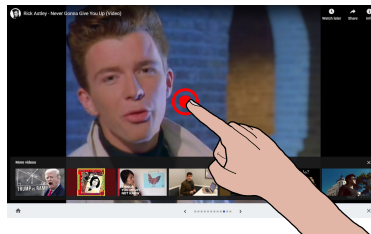
(h) Volume down



(i) Rotate clockwise



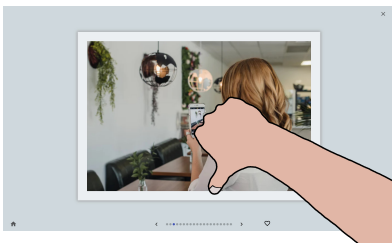
(j) Rotate anti-clockwise



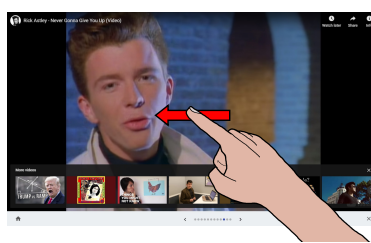
(k) Play/pause



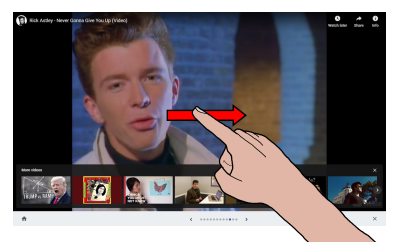
(l) Like



(m) Dislike



(n) Fast-forward



(o) Rewind

Figure E.1: Illustrations of each action and its assigned gesture.

Appendix F

Code of the Software

This appendix contains most of the code of the framework and the LUI application.

F.1 Framework

F.1.1 Frozen Spots

WebSocket Server

index.js

```
1  const WebSocket = require('ws');
2  const http = require('http');
3  const config = require('./config');
4  const FrameProcessor = require('./framework/frame-processor').FrameProcessor;
5
6  // Load the modules
7  const Sensor = config.sensor.module;
8
9  // Main function
10 function run() {
11     // Initialize the sensor interface, dataset, recognizer and segmenter
12     var sensor = new Sensor(config.sensor.options);
13     var frameProcessor = new FrameProcessor(config);
14     // Start the websocket server
15     var wsServer = getWebSocketServer(config.server.ip, config.server.port);
16     wsServer.on('connection', async function connection(ws) {
17         console.log('Connected!')
18         // Handle messages from the client
19         ws.on('message', function(message) {
20             if (config.general.debug) {
21                 console.log(message)
22             }
23             var msg = JSON.parse(message);
24             if (msg.type === 'operation') {
25                 for (const operation of msg.data) {
26                     if (operation.type === 'addPose') {
27                         frameProcessor.enablePose(operation.name);
```

```

28         } else if (operation.type === 'addGesture') {
29             frameProcessor.enableGesture(operation.name);
30         } else if (operation.type === 'removePose') {
31             frameProcessor.disablePose(operation.name);
32         } else if (operation.type === 'removeGesture') {
33             frameProcessor.disableGesture(operation.name);
34         }
35     }
36 }
37 });
38 // Process sensor frames
39 sensor.loop((frame, appData) => {
40     let message = getMessage('data');
41     if (appData && config.general.sendContinuousData) {
42         // If there is continuous data to send to the application
43         message.data.push({
44             'type': 'frame',
45             'data': appData
46         })
47     }
48     // Gesture recognition
49     var ret = frameProcessor.processFrame(frame);
50     if (ret) {
51         // If there is gesture data to send to the application
52         message.data.push(ret);
53         if (config.general.debug) {
54             console.log(JSON.stringify(message));
55         }
56     }
57     if (message.data.length > 0) {
58         ws.send(JSON.stringify(message));
59     }
60 });
61 // Stop processing frames after disconnection
62 ws.on('close', function() {
63     console.log("Disconnected!")
64     sensor.stop();
65     frameProcessor.resetContext();
66 });
67 // Connection error
68 ws.on('error', function(error) {
69     console.log(JSON.stringify(error));
70 });
71 });
72 }
73
74 function getMessage(type) {
75     return {
76         'type': type,
77         'data' : []
78     };

```

```

79 }
80
81 function getWebSocketServer(ip, port) {
82     // Create HTTP server
83     var server = http.createServer();
84     server.listen(port, ip, function () {
85         console.log("WebSocket server listening on port " + port);
86     });
87     // Create WebSocket server
88     var wsServer = new WebSocket.Server({ server });
89     return wsServer;
90 }
91
92 if (require.main === module) {
93     run();
94 }

```

Frame Processor

frame-processor.js

```

1  const GestureSet = require('./gestures/gesture-set').GestureSet;
2  const GestureClass = require('./gestures/gesture-class').GestureClass;
3  const RingBuffer = require('ringbufferjs');
4
5  class FrameProcessor {
6      constructor(config) {
7          // Initialize analyzer, segmenter, datasets, recognizer and classifier
8          this.analyzer = new config.analyzer.module(config.analyzer.options);
9          this.segmenter = new config.segmenter.module(config.segmenter.options);
10         this.gestureDataset = initDataset(config.datasets.gesture);
11         this.poseDataset = initDataset(config.datasets.pose);
12         if (config.general.gesture.loadOnRequest) {
13             this.recognizer = new
14                 ↪ config.recognizer.module(config.recognizer.options);
15         } else {
16             this.recognizer = new
17                 ↪ config.recognizer.module(config.recognizer.options,
18                 ↪ this.gestureDataset);
19         }
20         if (config.general.pose.loadOnRequest) {
21             this.classifier = new
22                 ↪ config.classifier.module(config.classifier.options);
23         } else {
24             this.classifier = new
25                 ↪ config.classifier.module(config.classifier.options,
26                 ↪ this.poseDataset);
27         }
28         // Keep track of enabled poses and gestures
29         this.enabledPoses = [];

```

```

24     this.enabledGestures = [];
25     // Initialize pose buffer
26     this.poseBuffer = new RingBuffer(config.classifier.options.bufferLength);
27     this.poseCounter = {};
28     // Save config
29     this.config = config;
30 }
31
32 resetContext() {
33     if (this.config.general.gesture.loadOnRequest) {
34         this.recognizer = new
35             ↪ this.config.recognizer.module(this.config.recognizer.options);
36     }
37     if (this.config.general.pose.loadOnRequest) {
38         this.classifier = new
39             ↪ this.config.classifier.module(this.config.classifier.options);
40     }
41     this.enabledPoses = [];
42     this.enabledGestures = [];
43 }
44
45 enablePose(name) {
46     if (!this.enabledPoses.includes(name)) {
47         // The pose is not already enabled
48         if (this.config.general.pose.loadOnRequest) {
49             let gestureClass = this.poseDataset.getGestureClasses().get(name);
50             if (gestureClass) {
51                 for (const template of gestureClass.getSamples()) {
52                     this.classifier.addPose(name, template);
53                 }
54             } else {
55                 console.error(`No pose class in the dataset with name
56                     ↪ '${name}'`);
57             }
58         }
59         this.enabledPoses.push(name);
60     }
61 }
62
63 enableGesture(name) {
64     if (!this.enabledGestures.includes(name)) {
65         // The gesture is not already enabled
66         if (this.config.general.gesture.loadOnRequest) {
67             let gestureClass =
68                 ↪ this.gestureDataset.getGestureClasses().get(name);
69             if (gestureClass) {
70                 for (const template of gestureClass.getSamples()) {
71                     this.recognizer.addGesture(name, template);
72                 }
73             } else {
74                 console.error(`No gesture class in the dataset with name
75                     ↪ '${name}'`);

```

```

71     }
72 }
73     this.enabledGestures.push(name);
74 }
75 }
76
77 disablePose(name) {
78     var index = this.enabledPoses.indexOf(name);
79     if (index > -1) {
80         // The pose was enabled, disable it
81         this.enabledPoses.splice(index, 1);
82         if (this.config.general.pose.loadOnRequest) {
83             this.classifier.removePose(name);
84         }
85     }
86 }
87
88 disableGesture(name) {
89     var index = this.enabledGestures.indexOf(name);
90     if (index > -1) {
91         // The gesture was enabled, disable it
92         this.enabledGestures.splice(index, 1);
93         if (this.config.general.gesture.loadOnRequest) {
94             this.recognizer.removeGesture(name);
95         }
96     }
97 }
98
99 processFrame(frame) {
100     // Get pose and data from the pose buffer
101     let oldPoseInfo = "";
102     let oldPoseRatio = 0;
103     if (this.poseBuffer.isFull()) {
104         oldPoseInfo = this.poseBuffer.deq();
105         if (oldPoseInfo.pose) {
106             oldPoseRatio = (this.poseCounter[oldPoseInfo.pose]--) /
107                 ↪ this.config.classifier.options.bufferLength;
108         }
109     }
110     let staticPose = "";
111     try {
112         staticPose = this.classifier.classify(frame).name;
113     } catch(error) {
114         console.error(`Classifier error: ${error}`);
115     }
116     let newPoseInfo = { pose: "", data: "" };
117     if (staticPose && (!this.config.general.pose.sendIfRequested ||
118         ↪ this.enabledPoses.includes(staticPose))) {
119         newPoseInfo = { pose: staticPose, data: this.analyzer.analyze(frame) };
120         if (!this.poseCounter.hasOwnProperty(staticPose)) {
121             this.poseCounter[staticPose] = 1;
122         }
123     }
124 }

```



```

120         } else {
121             this.poseCounter[staticPose]++;
122         }
123     }
124     this.poseBuffer.enq(newPoseInfo);
125     if (oldPoseInfo.pose) {
126         if (oldPoseRatio > this.config.classifier.options.poseRatioThreshold) {
127             // Static pose detected
128             this.segmenter.notifyRecognition();
129             return { 'type': 'static', 'name': oldPoseInfo.pose, 'data':
130                 ↪ oldPoseInfo.data };
131         }
132     } else {
133         // Reset analyzer
134         this.analyzer.reset();
135         // Try to segment and recognize dynamic gesture
136         let segment = this.segmenter.segment(frame);
137         if (segment) {
138             let name = "";
139             try {
140                 name = this.recognizer.recognize(segment).name;
141             } catch (error) {
142                 console.error(`Recognizer error: ${error}`);
143             }
144             if (name && (!this.config.general.gesture.sendIfRequested ||
145                 ↪ this.enabledGestures.includes(name))) {
146                 this.segmenter.notifyRecognition();
147                 return { 'type': 'dynamic', 'name': name, 'data': {} };
148             }
149         }
150     }
151     // Nothing detected
152     return null;
153 }
154
155 function initDataset(config) {
156     // Load the dataset
157     let dataset = config.loader.loadDataset(config.name, config.directory);
158     // Select/aggregate/rename classes of the dataset if required
159     if (config.aggregateClasses.length !== 0) {
160         let newDataset = new GestureSet(dataset.name);
161         config.aggregateClasses.forEach((aggregate, index) => {
162             // Aggregate gesture class
163             let newClass = new GestureClass(aggregate.name, index);
164             let templates = [];
165             // Fuse the classes into a new aggregate class
166             for (const className of aggregate.classes) {
167                 let oldClass = dataset.getGestureClasses().get(className);
168                 templates = templates.concat(templates, oldClass.getSamples());
169             }
170         });
171     }
172 }

```

```

169         // Select a number of templates from the dataset if required
170         if (config.useCustomTemplatesPerClass) {
171             templates = getRandomSubarray(templates, config.templatesPerClass);
172         }
173         // Add the templates to the new gesture class
174         for (template of templates) {
175             newClass.addSample(template);
176         }
177         // Add the aggregate class to the new dataset
178         newDataset.addGestureClass(newClass);
179     });
180     return newDataset
181 } else {
182     // Select a number of templates from the dataset if required
183     if (config.useCustomTemplatesPerClass) {
184         let newDataset = new GestureSet(dataset.name);
185         dataset.getGestureClasses().forEach(gestureClass => {
186             let newClass = new GestureClass(gestureClass.name,
187                 ↳ gestureClass.index);
188             let templates = gestureClass.getSamples();
189             templates = getRandomSubarray(templates, config.templatesPerClass);
190             // Add the templates to the new gesture class
191             for (template of templates) {
192                 newClass.addSample(template);
193             }
194             newDataset.addGestureClass(newClass);
195         });
196         return newDataset;
197     }
198     return dataset;
199 }
200
201 //https://stackoverflow.com/questions/11935175/sampling-a-random-subset-from-an-array
202 function getRandomSubarray(arr, size) {
203     if (size > arr.length) {
204         console.log("Not enough templates!")
205         return arr;
206     }
207     var shuffled = arr.slice(0), i = arr.length, min = i - size, temp, index;
208     while (i-- > min) {
209         index = Math.floor((i + 1) * Math.random());
210         temp = shuffled[index];
211         shuffled[index] = shuffled[i];
212         shuffled[i] = temp;
213     }
214     return shuffled.slice(min);
215 }
216
217 module.exports = {
218     FrameProcessor

```

Application Interface

app-interface.js

```

1  import { w3cwebsocket as W3CWebSocket } from "websocket";
2  import ReconnectingWebSocket from 'reconnecting-websocket';
3
4  class GestureHandler {
5      constructor(addr = "ws://127.0.0.1:6442") {
6          // Save callbacks for gestures, poses, and frames
7          this.dynamicGestureHandlers = {};
8          this.staticGestureHandler = {};
9          this.forEachHandler = (gesture) => {};
10         this.frameHandler = (frame) => {};
11         // True if the interface is connected to the server
12         this.isConnected = false;
13         // The websocket client
14         this.client = null;
15         this.connect(addr, 10000, 3000);
16     }
17
18     /**
19      * Perform an action related to a gesture.
20      * @callback frameCallback
21      * @param {Object} frame - The data from the sensor.
22      */
23
24     /**
25      * Execute the callback each time a frame is received from the sensor.
26      * @param {frameCallback} callback - The callback that handles the frame
27      */
28     onFrame(callback) {
29         this.frameHandler = callback;
30     }
31
32     /**
33      * Perform an action for each gesture.
34      * @callback gesturesCallback
35      * @param {string} gesture - The name of the detected gesture.
36      */
37
38     /**
39      * Execute the callback each time any gesture is detected.
40      * @param {gesturesCallback} callback - The callback that handles the
41      ↪ gestures.
42      */
43     onEachGesture(callback) {
44         this.forEachHandler = callback;

```

```

44     }
45
46     /**
47      * Perform an action related to a gesture.
48      * @callback gestureCallback
49      */
50
51     /**
52      * Execute the callback each time the gesture is detected.
53      * @param {string} gesture - The name of the gesture which should trigger the
54     ↪ callback.
55      * @param {gestureCallback} callback - The callback that handles the gesture.
56      */
57     onGesture(gesture, callback) {
58         if (this.isConnected) {
59             this.client.send(JSON.stringify(getOperationMessage('addGesture',
60             ↪ gesture)));
61         }
62         this.dynamicGestureHandlers[gesture] = callback;
63     }
64
65     /**
66      * Execute the callback each time the pose is detected.
67      * @param {string} pose - The name of the pose which should trigger the
68     ↪ callback.
69      * @param {poseCallback} callback - The callback that handles the pose.
70      */
71     onPose(pose, callback) {
72         if (this.isConnected) {
73             this.client.send(JSON.stringify(getOperationMessage('addPose', pose)));
74         }
75         this.staticGestureHandler[pose] = callback;
76     }
77
78     /**
79      * Remove the callback associated to the gesture.
80      * @param {string} gesture - The name of the gesture for which the callback
81     ↪ should be removed.
82      */
83     removeGestureHandler(gesture) {
84         if (this.dynamicGestureHandlers.hasOwnProperty(gesture)) {
85             delete this.dynamicGestureHandlers[gesture];
86             if (this.isConnected) {
87                 ↪ this.client.send(JSON.stringify(getOperationMessage('removeGesture',
88                 ↪ gesture)));
89             }
90         }
91     }
92
93     /**

```

```

89     * Remove the callback associated to the pose.
90     * @param {string} pose - The name of the pose for which the callback should be
    ↪ removed.
91     */
92     removePoseHandler(pose) {
93         if (this.staticGestureHandler.hasOwnProperty(pose)) {
94             delete this.staticGestureHandler[pose];
95             if (this.isConnected) {
96                 this.client.send(JSON.stringify(getOperationMessage('removePose',
    ↪ pose)));
97             }
98         }
99     }
100
101     /**
102     * Connect to the gesture recognizer
103     */
104     connect(addr, timeout, interval) {
105         this.client = new ReconnectingWebSocket(addr, [], {
106             constructor: W3CWebSocket,
107             connectionTimeout: timeout, // in milliseconds
108             reconnectInterval: interval
109         });
110         this.client.onopen = function() {
111             console.log("WebSocket Client Connected");
112             this.isConnected = true;
113             // Init the message
114             let message = {
115                 'type': 'operation',
116                 'data': []
117             };
118             // Add addGestures operations to the message
119             for (const gesture of Object.keys(this.dynamicGestureHandlers)) {
120                 message.data.push({
121                     'type': 'addGesture',
122                     'name': gesture
123                 });
124             }
125             // Add addPose operations to the message
126             for (const pose of Object.keys(this.staticGestureHandler)) {
127                 message.data.push({
128                     'type': 'addPose',
129                     'name': pose
130                 });
131             }
132             // Send the message to the server
133             this.client.send(JSON.stringify(message));
134         }.bind(this);
135         // Handle messages from the server
136         this.client.onmessage = function(event) {
137             let msg = JSON.parse(event.data);

```

```

138         if (msg.type === 'data') {
139             for (const dataMsg of msg.data) {
140                 if (dataMsg.type === 'frame') {
141                     this.frameHandler(dataMsg.data);
142                 } else if (dataMsg.type === 'static') {
143                     if (this.staticGestureHandler.hasOwnProperty(dataMsg.name))
144                         ↪ {
145                             this.staticGestureHandler[dataMsg.name](dataMsg.data);
146                         }
147                 } else if (dataMsg.type === 'dynamic') {
148                     if
149                         ↪ (this.dynamicGestureHandlers.hasOwnProperty(dataMsg.name))
150                         ↪ {
151                             ↪ this.dynamicGestureHandlers[dataMsg.name](dataMsg.data);
152                             this.forEachHandler(dataMsg.name);
153                         }
154                 }
155             }
156         }
157         }.bind(this);
158     }
159
160     /**
161      * Disconnect from the gesture recognizer.
162      */
163     disconnect() {
164         this.client.close();
165     }
166 }
167
168 function getOperationMessage(type, name) {
169     return {
170         'type': 'operation',
171         'data': [
172             {
173                 'type': type,
174                 'name': name
175             }
176         ]
177     }
178 }
179
180 export default GestureHandler

```

Gestures

gesture-set.js

```

1  class GestureSet {
2      constructor(name) {
3          this.name = name;
4          this.gestures = new Map();
5          this.G = 0;
6      }
7
8      addGestureClass(gestureClass) {
9          this.gestures.set(gestureClass.name, gestureClass);
10         this.G += 1;
11     }
12
13     getGestureClasses() {
14         return this.gestures;
15     }
16
17     getMinTemplate() {
18         let TperG = Infinity;
19         for (var gestureClass of this.gestures.values()) {
20             TperG = Math.min(TperG, gestureClass.TperG);
21         }
22         return TperG;
23     }
24 }
25
26 module.exports = {
27     GestureSet
28 };

```

gesture-class.js

```

1  class GestureClass {
2      constructor(name, index) {
3          this.name = name;
4          this.samples = [];
5          this.index = index;
6          this.TperG = 0;
7      }
8
9      addSample(sample) {
10         this.samples.push(sample);
11         this.TperG += 1;
12     }
13
14     getSamples() {
15         return this.samples;
16     }
17 }
18
19 module.exports = {
20     GestureClass

```

```
21 };
```

sample.js

```
1 class Sample {
2   constructor(user, id, infosupp) {
3     this.user = user;
4     this.id = id;
5     this.infosupp = infosupp;
6   }
7 }
8
9 module.exports = {
10   Sample
11 };
```

pose-data.js

```
1 const Sample = require('./sample').Sample;
2
3 class PoseData extends Sample {
4   constructor(user, id, frame, infosupp) {
5     super(user, id, infosupp);
6     this.frame = frame;
7   }
8 }
9
10 module.exports = {
11   PoseData
12 };
```

stroke-data.js

```
1 const Sample = require('./sample').Sample;
2
3 class StrokeData extends Sample {
4   constructor(user, id, infosupp) {
5     super(user, id, infosupp);
6     this.paths = {};
7   }
8   addPath(label, path){
9     this.paths[label] = path;
10  }
11 }
12
13 class Stroke {
14   constructor(id) {
15     this.id = id;
16     this.points = [];
17   }
18   addPoint(stroke){
```



```

19     this.points.push(stroke);
20 }
21 }
22
23 class Path {
24     constructor(label) {
25         this.label = label;
26         this.strokes = [];
27     }
28     addStroke(stroke){
29         this.strokes.push(stroke);
30     }
31 }
32
33 module.exports = {
34     StrokeData,
35     Stroke,
36     Path
37 };

```

point.js

```

1  class Point2D {
2      constructor(x, y, t) {
3          this.x = x;
4          this.y = y;
5          this.t = t;
6      }
7  }
8
9  class Point3D {
10     constructor(x, y, z, t) {
11         this.x = x;
12         this.y = y;
13         this.z = z;
14         this.t = t;
15     }
16 }
17
18 module.exports = {
19     Point2D,
20     Point3D
21 };

```

Frames

frame.js

```

1  class Frame {
2      constructor(timestamp) {

```

```

3      this.timestamp = timestamp;
4      this.hasLeftHand = false;
5      this.hasRightHand = false;
6      this.articulations = [];
7  }
8
9  addArticulation(articulation) {
10     this.articulations.push(articulation);
11 }
12
13 getArticulation(name) {
14     for (const articulation of this.articulations) {
15         if (articulation.label === name) {
16             return articulation;
17         }
18     }
19     return null;
20 }
21 }
22
23 class Articulation {
24     constructor(label, point) {
25         this.label = label;
26         this.point = point;
27     }
28 }
29
30 module.exports = {
31     Frame,
32     Articulation
33 }

```

Benchmarking Tool

benchmark.js

```

1  const path = require('path');
2  const fs = require('fs');
3  const config = require('./benchmarkConfig');
4  const GestureSet = require('./framework/gestures/gesture-set').GestureSet;
5  const GestureClass = require('./framework/gestures/gesture-class').GestureClass;
6
7  // Important values
8  const MINT = config.minT; // Maximum Training Templates
9  const MAXT = config.maxT; // Maximum Training Templates
10 const computeNextT = config.nextT; // Function that computes the next number of
   → training templates
11 const R = config.r; // Repetitions
12 const N = config.recognizers.nSamplingPoints; // Points/Shapes
13

```

```

14 function run() {
15     // // Test classifiers
16     if (config.classifiers.modules.length > 0) {
17         let results = [];
18         for(let i=0; i < config.datasets.pose.length; i++){
19             let datasetConfig = config.datasets.pose[i];
20             let datasetPath = path.join(config.datasets.path, "pose");
21             let dataset = loadDataset(datasetPath, datasetConfig);
22             let datasetResults = {
23                 r: config.r,
24                 dataset: dataset.name,
25                 gestures: Array.from(dataset.getGestureClasses().keys()),
26                 data: []
27             };
28             for(let j=0; j < config.classifiers.modules.length; j++){
29                 let classifier = config.classifiers.modules[j];
30                 let res = test(dataset, classifier.module, classifier.options,
31                     ↵ "classifiers");
32                 console.log(classifier.module.name);
33                 datasetResults.data.push({
34                     name: classifier.module.name,
35                     options: classifier.options,
36                     data: res
37                 });
38             }
39             results.push(datasetResults);
40         }
41         fs.writeFileSync('results-poses.json', JSON.stringify(results, null, 2));
42     }
43     // Test recognizers
44     if (config.recognizers.modules.length > 0) {
45         let results = [];
46         for(let i=0; i < config.datasets.gesture.length; i++){
47             let datasetConfig = config.datasets.gesture[i];
48             let datasetPath = path.join(config.datasets.path, "gesture");
49             let dataset = loadDataset(datasetPath, datasetConfig);
50             let datasetResults = {
51                 r: config.r,
52                 dataset: dataset.name,
53                 gestures: Array.from(dataset.getGestureClasses().keys()),
54                 data: []
55             };
56             for(let j=0; j < config.recognizers.modules.length; j++){
57                 let recognizer = config.recognizers.modules[j];
58                 let res = test(dataset, recognizer.module, recognizer.options,
59                     ↵ "recognizer");
60                 console.log(recognizer.module.name);
61                 datasetResults.data.push({
62                     name: recognizer.module.name,
63                     options: recognizer.options,

```

```

63         data: res
64     });
65 }
66     results.push(datasetResults);
67 }
68     fs.writeFileSync('results-gestures.json', JSON.stringify(results, null,
69         ↪ 2));
70 }
71
72 /**
73  * User-independent testing
74  */
75 function startUserIndependentTesting(dataset, recognizerOrClassifierType, config,
76     ↪ type = "recognizer") {
77     let results = [];
78     // Perform the test for each size of training set
79     for(let trainingSetSize = MINT; trainingSetSize <=
80         ↪ Math.min(dataset.getMinTemplate(), MAXT); trainingSetSize =
81         ↪ computeNextT(trainingSetSize)) {
82         let res = {
83             n: trainingSetSize,
84             accuracy: 0.0,
85             time: 0.0,
86             confusionMatrix: []
87         };
88         res.confusionMatrix = new Array(dataset.G).fill(0).map(() => new
89             ↪ Array(dataset.G).fill(0));
90         // Repeat the test R times
91         for(let r = 0 ; r < R ; r++) {
92             // Initialize the recognizer and select the candidates
93             let recognizerOrClassifier = new recognizerOrClassifierType(config);
94             let candidates = selectCandidates(dataset);
95             // For each gesture class, mark the templates that cannot be reused
96             let markedTemplates = [];
97             candidates.forEach(candidate =>{
98                 markedTemplates.push([candidate]);
99             });
100             // Train the recognizer / classifier
101             for(let t = 0 ; t < trainingSetSize ; t++) { // Add trainingSetSize
102                 ↪ strokeData per gestureClass
103                 // Add one sample for each gesture class
104                 let index = 0;
105                 dataset.getGestureClasses().forEach((gestureClass) => {
106                     // Select a valid training template
107                     let training = -1;
108                     //while (training == -1 ||
109                     ↪ markedTemplates[index].includes(training) ||
110                     ↪ gestureClass.getSamples()[training].user ==
111                     ↪ gestureClass.getSamples()[markedTemplates[index][0]].user)
112                     ↪ {

```

```

104         while (training == -1 ||
105             ↪ markedTemplates[index].includes(training)) {
106             training = getRandomNumber(0,
107             ↪ gestureClass.getSamples().length);
108         }
109         // Mark the training template
110         markedTemplates[index].push(training);
111         // Train the recognizer / classifier
112         if (type === "recognizer") {
113             recognizerOrClassifier.addGesture(gestureClass.name,
114             ↪ gestureClass.getSamples()[training]);
115         } else {
116             recognizerOrClassifier.addPose(gestureClass.name,
117             ↪ gestureClass.getSamples()[training]);
118         }
119         index++;
120     });
121 }
122 // Test the recognizer / classifier
123 let index = 0;
124 dataset.getGestureClasses().forEach((gestureClass) => {
125     // Retrieve the testing sample
126     let toBeTested = gestureClass.getSamples()[candidates[index]];
127     // Attempt recognition
128     if (type === "recognizer") {
129         var result = recognizerOrClassifier.recognize(toBeTested);
130     } else {
131         var result = recognizerOrClassifier.classify(toBeTested.frame);
132     }
133     // Update the confusion matrix
134     if (dataset.getGestureClasses().has(result.name)) {
135         let resultIndex =
136         ↪ dataset.getGestureClasses().get(result.name).index;
137         res.confusionMatrix[gestureClass.index][resultIndex] += 1;
138     }
139     // Update execution time and accuracy
140     res.accuracy += (result.name===gestureClass.name) ? 1 : 0;
141     res.time += result.time;
142     index++;
143 });
144 }
145 res.accuracy = res.accuracy / (R * dataset.G);
146 res.time = res.time / (R * dataset.G);
147 results.push(res);
148 }
149 return results;
150 };
151
152 /**
153  * Return a random list of candidate gestures, 1 candidate per gesture class.
154  */

```

```

150 function selectCandidates(dataset) {
151     let candidates = [];
152     dataset.getGestureClasses().forEach((value) => {
153         candidates.push(getRandomNumber(0, value.getSamples().length));
154     });
155     return candidates;
156 };
157
158 /**
159  * Return a random number between min and max.
160  */
161 function getRandomNumber(min, max) {
162     min = Math.ceil(min);
163     max = Math.floor(max);
164     return Math.floor(Math.random()*(max - min))+min;
165 };
166
167 /**
168  * Load a gesture dataset
169  */
170 function loadDataset(datasetPath, datasetConfig) {
171     // Load the dataset
172     let dataset = datasetConfig.loader.loadDataset(datasetConfig.name,
173         ↪ datasetPath);
174     // Select/aggregate/rename classes of the dataset if required
175     if (datasetConfig.aggregateClasses.length != 0) {
176         let newDataset = new GestureSet(dataset.name);
177         datasetConfig.aggregateClasses.forEach((aggregate, index) => {
178             // Aggregate gesture class
179             let newClass = new GestureClass(aggregate.name, index);
180             let templates = [];
181             // Fuse the classes into a new aggregate class
182             for (const className of aggregate.classes) {
183                 let oldClass = dataset.getGestureClasses().get(className);
184                 templates = templates.concat(templates, oldClass.getSamples());
185             }
186             // Add the templates to the new gesture class
187             for (template of templates) {
188                 newClass.addSample(template);
189             }
190             // Add the aggregate class to the new dataset
191             newDataset.addGestureClass(newClass);
192         });
193         return newDataset
194     } else {
195         return dataset;
196     }
197 }
198
199 /**
200  * Test a specific recognizer/classifier with a specific dataset

```

```

200  */
201  function test(dataset, recognizerOrClassifierType, config, type = "recognizer"){
202      let result = startUserIndependentTesting(dataset, recognizerOrClassifierType,
203          ↪ config, type);
204      return result;
205  };
206
207  if (require.main === module) {
208      run();
209  }

```

F.1.2 Hot Spots

Sensors

abstract-sensor.js

```

1  class AbstractSensor {
2      constructor(name) {
3          this.name = name;
4      }
5
6      /**
7       * Process one frame from the sensor.
8       * @callback frameCallback
9       * @param {Object} frame - The frame to process.
10      */
11
12      /**
13       * Process frames from the sensor. Executes the callback for each frame.
14       * @param {frameCallback} callback - The callback that handles the frame from
15       ↪ the sensor.
16       * @param {Object} options - A set of options for the sensor.
17      */
18      loop(callback, options) {
19          throw new Error('You have to implement this function');
20      }
21
22      /**
23       * Stop processing frames from the sensor.
24      */
25      stop() {
26          throw new Error('You have to implement this function');
27      }
28  }
29
30  module.exports = {
31      AbstractSensor
32  }

```

Datasets

unified-loader.js

```
1  const path = require('path');
2  const fs = require('fs-extra');
3
4  const GestureSet = require('../gestures/gesture-set').GestureSet;
5  const GestureClass = require('../gestures/gesture-class').GestureClass;
6  const StrokeData = require('../gestures/stroke-data').StrokeData;
7
8
9  function loadDataset(name, directory) {
10     let gestureSet = new GestureSet(name);
11     let dirPath = path.join(directory, name);
12     let gestureIndex = 0;
13
14     fs.readdirSync(dirPath).forEach((gesture) => {
15         let gestureDirPath = path.join(dirPath, gesture);
16         let gestureClass = new GestureClass(gesture, gestureIndex);
17         gestureSet.addGestureClass(gestureClass);
18         fs.readdirSync(gestureDirPath).forEach((user) => {
19             let userDirPath = path.join(gestureDirPath, user);
20             fs.readdirSync(userDirPath).forEach((file) => {
21                 let rawGesturePath = path.join(userDirPath, file);
22                 let strokeData = JSON.parse(fs.readFileSync(rawGesturePath));
23
24                 let filenameParsed = file.split(".")[0].split("-");
25                 let gestureName = filenameParsed[0];
26                 let infosupp;
27                 if(filenameParsed.length > 2){
28                     infosupp = filenameParsed[1];
29                 }
30                 let id = parseInt(filenameParsed[filenameParsed.length-1]);
31
32                 let gestureData = new StrokeData(parseInt(user), id, infosupp);
33
34                 strokeData.paths.forEach(path =>{
35                     gestureData.addPath(path.label, path);
36                 });
37                 gestureClass.addSample(gestureData);
38             });
39         });
40         gestureIndex+=1;
41     });
42
43     return gestureSet;
44 }
45
46 function writeDataset(dataset, directory) {
47     if (fs.existsSync(directory)) {
48         fs.removeSync(directory);
```



```

49 }
50 fs.mkdirSync(directory);
51
52 dataset.getGestureClasses().forEach(gestureClass =>{
53     fs.mkdirSync(path.join(directory, gestureClass.name));
54     gestureClass.samples.forEach(sample =>{
55         let userDirPath = path.join(directory, gestureClass.name,
56             ↪ sample.user.toString().padStart(2, "0"));
57         if(!fs.existsSync(userDirPath)){
58             fs.mkdirSync(userDirPath);
59         }
60         let newFilename = gestureClass.name + "-";
61         if(sample.infosupp)
62             newFilename = newFilename + sample.infosupp + "-";
63         newFilename = newFilename + sample.id.toString().padStart(2, "0") +
64             ↪ ".json";
65         newFilename = path.join(userDirPath, newFilename);
66         let toWrite = {};
67         toWrite.name = gestureClass.name;
68         toWrite.subject = sample.user;
69
70         toWrite.paths = [];
71         for(let path in sample.paths){
72             toWrite.paths.push({
73                 "label": sample.paths[path].label,
74                 "strokes": sample.paths[path].strokes
75             });
76         }
77
78         fs.writeFileSync(newFilename, JSON.stringify(toWrite, null, 2),
79             ↪ function (err) {
80                 if (err) throw err;
81                 //console.log('Saved!');
82             });
83     })
84 })
85
86 module.exports = {
87     loadDataset,
88     writeDataset
89 };

```

Classifiers

abstract-classifier.js

```

1 class AbstractClassifier {
2     constructor(options, dataset) {
3         // Empty

```

```

4      }
5
6      /**
7       * Add a pose to the training set of this classifier.
8       * @param {Object} name - The name of the pose to add.
9       * @param {Object} frame - The frame containing the pose to add.
10      */
11     addPose(name, frame) {
12         throw new Error('You have to implement this function');
13     }
14
15     /**
16     * Remove a pose from the training set of this classifier.
17     * @param {Object} name - The name of the pose to remove.
18     */
19     removePose(name) {
20         throw new Error('You have to implement this function');
21     }
22
23     /**
24     * Return the name of the pose that corresponds to the frame.
25     * @param {Object} frame - A frame from the sensor.
26     * @returns a JavaScript object with at least 2 properties: name (the name of
    ↪ the pose) and time (the execution time).
27     */
28     classify(frame) {
29         throw new Error('You have to implement this function');
30     }
31 }
32
33 module.exports = {
34     AbstractClassifier
35 }

```

Analyzers

abstract-analyzer.js

```

1  class AbstractAnalyzer {
2      constructor(options) {
3          // Empty
4      }
5
6      /**
7       * Extract and return information from a frame.
8       * @param {Object} frame - A frame from the sensor.
9       * @returns a JavaScript object with the information extracted from the frame.
10     */
11     analyze(frame) {
12         throw new Error('You have to implement this function');

```

```

13     }
14
15     /**
16      * Reset the internal state of the analyzer.
17      */
18     reset() {
19         throw new Error('You have to implement this function');
20     }
21 }
22
23 module.exports = {
24     AbstractAnalyzer
25 }

```

Segmenters

abstract-segmenter.js

```

1  class AbstractSegmenter {
2      constructor(options) {
3          // Empty
4      }
5
6      /**
7       * Process a frame and return a StrokeData object if the frame marks the end of
8       ↪ a gesture.
9       * @param {Object} frame - A frame from the sensor.
10      * @returns null if the frame and the current set of frames do not correspond
11      ↪ to a gesture, a StrokeData object otherwise.
12      */
13      segment(frame) {
14          throw new Error('You have to implement this function');
15      }
16
17      /**
18       * Indicate to the segmenter that a gesture has been recognized.
19       */
20      notifyRecognition() {
21          throw new Error('You have to implement this function');
22      }
23 }
24
25 module.exports = {
26     AbstractSegmenter
27 };

```

Recognizers

abstract-recognizer.js

```

1  class AbstractRecognizer {
2      constructor(options, dataset) {
3          // Empty
4      }
5
6      /**
7       * Add a gesture to the training set of this recognizer.
8       * @param {Object} name - The name of the gesture to add.
9       * @param {Object} sample - The gesture to add.
10      */
11     addGesture(name, sample) {
12         throw new Error('You have to implement this function');
13     }
14
15     /**
16      * Remove a gesture from the training set of this recognizer.
17      * @param {Object} name - The name of the gesture to remove.
18      */
19     removeGesture(name) {
20         throw new Error('You have to implement this function');
21     }
22
23     /**
24      * Check whether the sample corresponds to a known gesture.
25      * @param {Object} sample - A gesture sample from the sensor.
26      * @returns a JavaScript object with at least 2 properties: name (the name of
27      ↪ the gesture) and time (the execution time).
28      */
29     recognize(sample) {
30         throw new Error('You have to implement this function');
31     }
32 }
33
34 module.exports = {
35     AbstractRecognizer
36 };

```

F.1.3 Configuration Files

Framework Configuration

config.js

```

1  // MODULES -----
2  // Sensor Interfaces
3  const LeapSensor = require('./implementation/sensors/leap-sensor/sensor').Sensor;
4
5  // Pose Analyzers
6  const NoAnalyzer =
7  ↪ require('./implementation/analyzers/placeholder-analyzer/analyzer').Analyzer;

```

```

7  const BasicAnalyzer =
  ↳ require('./implementation/analyzers/basic-analyzer/analyzer').Analyzer;
8
9  // Gesture Segmenters
10 const WindowSegmenter =
  ↳ require('./implementation/segmenters/window-segmenter').Segmenter;
11 const ZoningSegmenter =
  ↳ require('./implementation/segmenters/zoning-segmenter').Segmenter;
12 const LeftHandSegmenter =
  ↳ require('./implementation/segmenters/lefthand-segmenter').Segmenter;
13 const FrameSegmenter =
  ↳ require('./implementation/segmenters/frame-segmenter').Segmenter;
14
15 // Gesture Recognizers
16 const NoRecognizer =
  ↳ require('./implementation/recognizers/placeholder-recognizer/recognizer').Recognizer;
17 //3D
18 const HybridP3DollarPlusXRecognizer =
  ↳ require('./implementation/recognizers/hybridp3dollarplusx-recognizer/recognizer').Recognizer;
19 const JackknifeRecognizer =
  ↳ require('./implementation/recognizers/jackknife-recognizer/recognizer').Recognizer;
20 const P3DollarPlusXRecognizer =
  ↳ require('./implementation/recognizers/p3dollarplusx-recognizer/recognizer').Recognizer;
21 const UVPRRecognizer =
  ↳ require('./implementation/recognizers/uvplusflexiblecloud-recognizer/recognizer').Recognizer;
22 const ThreeCentRecognizer =
  ↳ require('./implementation/recognizers/threecent-recognizer/recognizer').Recognizer;
23 const P3DollarPlusRecognizer =
  ↳ require('./implementation/recognizers/p3dollarplus-recognizer/recognizer').Recognizer;
24 //2D
25 const PDollarPlusRecognizer =
  ↳ require('./implementation/recognizers/pdollarplus-recognizer/recognizer').Recognizer;
26
27 // Pose Classifiers
28 const NoClassifier =
  ↳ require('./implementation/classifiers/placeholder-classifier/classifier').Classifier;
29 const GPSDClassifier =
  ↳ require('./implementation/classifiers/gpsd-classifier/classifier').Classifier;
30 const GPSDaClassifier =
  ↳ require('./implementation/classifiers/gpsda-classifier/classifier').Classifier;
31 const GPSDaDissimilarityClassifier =
  ↳ require('./implementation/classifiers/gpsdadissimilarity-classifier/classifier').Classifier;
32 const P3DollarPlusClassifier =
  ↳ require('./implementation/classifiers/p3dollarplus-classifier/classifier').Classifier;
33
34 // Gesture Dataset Loaders
35 const UnifiedDatasetLoader = require('./framework/datasets/unified-loader');
36 const GuinevereDatasetLoader =
  ↳ require('./implementation/datasets/gesture/guinevere-loader');
37 const LeapMotionDatasetLoader =
  ↳ require('./implementation/datasets/gesture/leap-gesture-loader');

```

```

38 const SmartphoneDatasetLoader =
    ↪ require('./implementation/datasets/gesture/smartphone-loader');
39 const HandGestureDatasetLoader =
    ↪ require('./implementation/datasets/gesture/hand-gesture-csv-loader');
40 const UWaveDatasetLoader =
    ↪ require('./implementation/datasets/gesture/uwave-loader');
41
42 // Pose Dataset Loaders
43 const MMHGRDatasetLoader = require('./implementation/datasets/pose/mmhgr-loader');
44 const LeapPoseDatasetLoader =
    ↪ require('./implementation/datasets/pose/leap-pose-loader');
45
46 // Articulations
47 const fingerMcps = {
48     left: ["leftThumbMcpPosition", "leftIndexMcpPosition", "leftMiddleMcpPosition",
    ↪ "leftRingMcpPosition", "leftPinkyMcpPosition"],
49     right: ["rightThumbMcpPosition", "rightIndexMcpPosition",
    ↪ "rightMiddleMcpPosition", "rightRingMcpPosition", "rightPinkyMcpPosition"]
50 }
51 const fingerPips = {
52     left: ["leftThumbPipPosition", "leftIndexPipPosition", "leftMiddlePipPosition",
    ↪ "leftRingPipPosition", "leftPinkyPipPosition"],
53     right: ["rightThumbPipPosition", "rightIndexPipPosition",
    ↪ "rightMiddlePipPosition", "rightRingPipPosition", "rightPinkyPipPosition"]
54 }
55 const fingerTips = {
56     left: ["leftThumbTipPosition", "leftIndexTipPosition", "leftMiddleTipPosition",
    ↪ "leftRingTipPosition", "leftPinkyTipPosition"],
57     right: ["rightThumbTipPosition", "rightIndexTipPosition",
    ↪ "rightMiddleTipPosition", "rightRingTipPosition", "rightPinkyTipPosition"]
58 }
59 const palms = {
60     left: ["leftPalmPosition"],
61     right: ["rightPalmPosition"]
62 }
63 const articulationsBothHandsSimple = [].concat(palms.right, palms.left,
    ↪ fingerTips.right, fingerTips.left);
64 const articulationsRightHandSimple = [].concat(palms.right, fingerTips.right);
65 const articulationsRightHandDetailed = [].concat(palms.right, fingerMcps.right,
    ↪ fingerPips.right, fingerTips.right);
66
67 // CONFIG INIT -----
68 var config = {};
69 config.general = {};
70 config.general.pose = {};
71 config.general.gesture = {};
72 config.server = {};
73 config.datasets = {};
74
75 // CONFIGURATION -----
76 // General Configuration

```

```

77 config.general.debug = false;           // Show debug logs
78 config.general.sendContinuousData = true; // Send data from each frame to
    ↪ the client
79 config.general.gesture = {
80     sendIfRequested: true,               // Send recognized gestures
    ↪ only if they are requested by the client
81     loadOnRequest: false                 // Load gestures based on
    ↪ requests from the client
82 }
83 config.general.pose = {
84     sendIfRequested: true,               // Send recognized gestures
    ↪ only if they are requested by the client
85     loadOnRequest: false                 // Load gestures based on
    ↪ requests from the client
86 }
87
88 // Server
89 config.server.ip = '127.0.0.1';          // IP of the server (for app interface)
90 config.server.port = 6442;              // Port of the server (for app interface)
91
92 // Sensor Interface
93 config.sensor = {
94     module: LeapSensor,
95     options: {
96         framerate: 60                    // Sensor framerate [images/seconds]
97     }
98 }
99
100 // Pose Analyzer
101 config.analyzer = {
102     module: BasicAnalyzer,
103     options: {}
104 }
105
106 // Gesture Segmenter
107 config.segmenter = {
108     module: WindowSegmenter,
109     options: {
110         motionThreshold: 90,              // Minimum hand motion to
    ↪ consider that the segment may be a gesture
111         minSegmentLength: 10,             // Minimum length of a segment
    ↪ (if applicable) [#frames]
112         maxSegmentLength: 60,            // Maximum length of a segment
    ↪ (if applicable) [#frames]
113         windowHeight: 20,                // Width of the window (if
    ↪ applicable) [#frames]
114         intervalLength: 3,                // Length of the interval
    ↪ between 2 consecutive segments (if applicable) [#frames]
115         pauseLength: 60,                  // Length of the pause after a
    ↪ gesture has been detected (if applicable) [#frames]
116         xBound: 120,                      // 1/2 width of the zone (if
    ↪ applicable) [mm]

```

```

117         zBound: 60                                     // 1/2 depth of the zone (if
            ↪ applicable) [mm]
118     }
119 }
120
121 // Gesture Dataset
122 config.datasets.gesture = {
123     directory: __dirname + "/datasets/gesture",
124     loader: LeapMotionDatasetLoader,
125     name: "guinevere",
126     useCustomTemplatesPerClass: true,
127     templatesPerClass: 16,
128     aggregateClasses: [
129         { name: "rhand_uswipe", classes: ["swipe_up"] },
130         { name: "rhand_dswipe", classes: ["swipe_down"] },
131         { name: "rhand_lswipe", classes: ["swipe_left"] },
132         { name: "rhand_rswipe", classes: ["swipe_right"] },
133         { name: "rindex_airtap", classes: ["tap"] },
134         //{ name: "rhand_crotate", classes: ["turn_clockwise"] },
135         //{ name: "rhand_acrotate", classes: ["turn_counter_clockwise"] },
136         //{ name: "rhand_close", classes: ["pinch_in"] },
137         //{ name: "rhand_open", classes: ["pinch_out"] },
138         //{ name: "thumbs_up", classes: ["thumbs_up"] },
139         //{ name: "thumbs_down", classes: ["thumbs_down"] }
140     ]
141 }
142
143 // Pose Dataset
144 config.datasets.pose = {
145     directory: __dirname + "/datasets/pose",
146     loader: LeapPoseDatasetLoader,
147     name: "guinevre-pose",
148     useCustomTemplatesPerClass: true,
149     templatesPerClass: 100,
150     aggregateClasses: []
151 }
152
153 // Gesture Recognizer
154 config.recognizer = {
155     module: JackknifeRecognizer,
156     options: {
157         palmThreshold: 50,
158         fingerThreshold: 15,
159         samplingPoints: 16,                                     // Number of sampling points
            ↪ [#points]
160         articulations: palms.right,
161         //pathName: "rightPalmPosition"
162     }
163 }
164
165 // Pose Classifier

```



```

166 config.classifier = {
167     module: GPSDaClassifier,
168     options: {
169         bufferLength: 15,
170         poseRatioThreshold: 0.8,
171         alpha: 0.8,
172         articulations: articulationsRightHandDetailed
173     }
174 }
175
176 module.exports = config;

```

Benchmark Configuration

benchmarkConfig.js

```

1  // MODULES
   ↳ -----
2  const path = require('path');
3
4  // Gesture datasets loaders
5  const UnifiedDatasetLoader = require('./framework/datasets/unified-loader');
6  const GuinevereDatasetLoader =
   ↳ require('./implementation/datasets/gesture/guinevere-loader');
7  const LeapMotionDatasetLoader =
   ↳ require('./implementation/datasets/gesture/leap-gesture-loader');
8  const SmartphoneDatasetLoader =
   ↳ require('./implementation/datasets/gesture/smartphone-loader');
9  const HandGestureDatasetLoader =
   ↳ require('./implementation/datasets/gesture/hand-gesture-csv-loader');
10 const UWaveDatasetLoader =
   ↳ require('./implementation/datasets/gesture/uwave-loader');
11
12 // Pose datasets loaders
13 const MMHGRDatasetLoader = require('./implementation/datasets/pose/mmhgr-loader');
14 const LeapPoseDatasetLoader =
   ↳ require('./implementation/datasets/pose/leap-pose-loader');
15
16 // Gesture recognizers
17 //3D
18 const HybridP3DollarPlusXRecognizer = require('./implementation/
   ↳ recognizers/hybridp3dollarplusx-recognizer/recognizer').Recognizer;
19 const JackknifeRecognizer = require('./implementation/
   ↳ recognizers/jackknife-recognizer/recognizer').Recognizer;
20 const P3DollarPlusXRecognizer = require('./implementation/
   ↳ recognizers/p3dollarplusx-recognizer/recognizer').Recognizer;
21 const UVPRRecognizer = require('./implementation/
   ↳ recognizers/uvplusflexiblecloud-recognizer/recognizer').Recognizer;
22 const ThreeCentRecognizer = require('./implementation/
   ↳ recognizers/threecent-recognizer/recognizer').Recognizer;

```

```

23 const P3DollarRecognizer = require('./implementation/
    ↳ recognizers/p3dollar-recognizer/recognizer').Recognizer;
24 const P3DollarPlusRecognizer = require('./implementation/
    ↳ recognizers/p3dollarplus-recognizer/recognizer').Recognizer;
25 const Q3DollarRecognizer = require('./implementation/
    ↳ recognizers/q3dollar-recognizer/recognizer').Recognizer;
26 //2D
27 const PDollarPlusRecognizer = require('./implementation/
    ↳ recognizers/pdollarplus-recognizer/recognizer').Recognizer;
28
29 // Pose classifiers
30 const GPSDClassifier = require('./implementation/
    ↳ classifiers/gpsd-classifier/classifier').Classifier;
31 const GPSDaClassifier = require('./implementation/
    ↳ classifiers/gpsda-classifier/classifier').Classifier;
32 const GPSDaDisimilarityClassifier = require('./implementation/
    ↳ classifiers/gpsdadisimilarity-classifier/classifier').Classifier;
33 const P3DollarPlusClassifier = require('./implementation/
    ↳ classifiers/p3dollarplus-classifier/classifier').Classifier;
34
35 // Articulations
36 const fingerMcps = {
37   left: ["leftThumbMcpPosition", "leftIndexMcpPosition", "leftMiddleMcpPosition",
    ↳ "leftRingMcpPosition", "leftPinkyMcpPosition"],
38   right: ["rightThumbMcpPosition", "rightIndexMcpPosition",
    ↳ "rightMiddleMcpPosition", "rightRingMcpPosition", "rightPinkyMcpPosition"]
39 }
40 const fingerPips = {
41   left: ["leftThumbPipPosition", "leftIndexPipPosition", "leftMiddlePipPosition",
    ↳ "leftRingPipPosition", "leftPinkyPipPosition"],
42   right: ["rightThumbPipPosition", "rightIndexPipPosition",
    ↳ "rightMiddlePipPosition", "rightRingPipPosition", "rightPinkyPipPosition"]
43 }
44 const fingerTips = {
45   left: ["leftThumbTipPosition", "leftIndexTipPosition", "leftMiddleTipPosition",
    ↳ "leftRingTipPosition", "leftPinkyTipPosition"],
46   right: ["rightThumbTipPosition", "rightIndexTipPosition",
    ↳ "rightMiddleTipPosition", "rightRingTipPosition", "rightPinkyTipPosition"]
47 }
48 const palms = {
49   left: ["leftPalmPosition"],
50   right: ["rightPalmPosition"]
51 }
52 const articulationsBothHandsSimple = [].concat(palms.right, palms.left,
    ↳ fingerTips.right, fingerTips.left);
53 const articulationsRightHandSimple = [].concat(palms.right, fingerTips.right);
54 const articulationsRightHandDetailed = [].concat(palms.right, fingerMcps.right,
    ↳ fingerPips.right, fingerTips.right);
55
56
57 // CONFIG INIT
    ↳ -----

```

```

58 var config = {};
59 config.datasets = {};
60 config.recognizers = {};
61 config.classifiers = {};
62
63 // CONFIGURATION
64 ↪ -----
65 // General configuration
66 config.minT = 1; // Minimum Training Templates
67 config.maxT = 8; // Maximum Training Templates (included)
68 config.nextT = x => x * 2; // Function used to increment the number of training
69 ↪ templates
70 config.r = 100; // Repetitions
71
72 // Recognizers
73 N_SAMPLING_POINTS = 16;
74 config.recognizers.nSamplingPoints = N_SAMPLING_POINTS;
75 config.recognizers.modules = [
76   {
77     module: UVPR recognizer,
78     options: {
79       samplingPoints: N_SAMPLING_POINTS,
80       articulations: articulationsRightHandSimple
81     }
82   },
83   {
84     module: UVPR recognizer,
85     options: {
86       samplingPoints: N_SAMPLING_POINTS,
87       articulations: ["rightPalmPosition"]
88     }
89   },
90   {
91     module: JackknifeRecognizer,
92     options: {
93       samplingPoints: N_SAMPLING_POINTS,
94       articulations: articulationsRightHandSimple
95     }
96   },
97   {
98     module: JackknifeRecognizer,
99     options: {
100       samplingPoints: N_SAMPLING_POINTS,
101       articulations: ["rightPalmPosition"]
102     }
103   },
104   {
105     module: ThreeCentRecognizer,
106     options: {
107       samplingPoints: N_SAMPLING_POINTS,
108       pathName: "rightPalmPosition"
109     }
110   }
111 ]

```

```

107     }
108 },
109 {
110     module: P3DollarRecognizer,
111     options: {
112         samplingPoints: N_SAMPLING_POINTS,
113         articulations: articulationsRightHandSimple
114     }
115 },
116 {
117     module: P3DollarRecognizer,
118     options: {
119         samplingPoints: N_SAMPLING_POINTS,
120         articulations: ["rightPalmPosition"]
121     }
122 },
123 {
124     module: P3DollarPlusRecognizer,
125     options: {
126         samplingPoints: N_SAMPLING_POINTS,
127         articulations: articulationsRightHandSimple
128     }
129 },
130 {
131     module: P3DollarPlusRecognizer,
132     options: {
133         samplingPoints: N_SAMPLING_POINTS,
134         articulations: ["rightPalmPosition"]
135     }
136 },
137 {
138     module: Q3DollarRecognizer,
139     options: {
140         samplingPoints: N_SAMPLING_POINTS,
141         articulations: articulationsRightHandSimple
142     }
143 },
144 {
145     module: Q3DollarRecognizer,
146     options: {
147         samplingPoints: N_SAMPLING_POINTS,
148         articulations: ["rightPalmPosition"]
149     }
150 },
151 {
152     module: P3DollarPlusXRecognizer,
153     options: {
154         samplingPoints: N_SAMPLING_POINTS,
155         articulations: articulationsRightHandSimple
156     }
157 },

```

```

158 {
159     module: P3DollarPlusXRecognizer,
160     options: {
161         samplingPoints: N_SAMPLING_POINTS,
162         articulations: ["rightPalmPosition"]
163     }
164 },
165 {
166     module: HybridP3DollarPlusXRecognizer,
167     options: {
168         samplingPoints: N_SAMPLING_POINTS,
169         palmThreshold: 50,
170         fingerThreshold: 0
171     }
172 },
173
174 {
175     module: HybridP3DollarPlusXRecognizer,
176     options: {
177         samplingPoints: N_SAMPLING_POINTS,
178         palmThreshold: 50,
179         fingerThreshold: 5
180     }
181 },
182 {
183     module: HybridP3DollarPlusXRecognizer,
184     options: {
185         samplingPoints: N_SAMPLING_POINTS,
186         palmThreshold: 1000,
187         fingerThreshold: 0
188     }
189 },
190 {
191     module: PDollarPlusRecognizer,
192     options: {
193         samplingPoints: N_SAMPLING_POINTS,
194         pathName: "rightPalmPosition"
195     }
196 }
197 ];
198
199 // Classifiers
200 config.classifiers.modules = [
201     {
202         module: GPSDaClassifier,
203         options: {
204             alpha: 0.60,
205             articulations: articulationsRightHandSimple
206         }
207     },
208     {

```

```

209     module: GPSDaClassifier,
210     options: {
211         alpha: 0.60,
212         articulations: articulationsRightHandDetailed
213     }
214 },
215 {
216     module: GPSDaClassifier,
217     options: {
218         alpha: 0.70,
219         articulations: articulationsRightHandSimple
220     }
221 },
222 {
223     module: GPSDaClassifier,
224     options: {
225         alpha: 0.70,
226         articulations: articulationsRightHandDetailed
227     }
228 },
229 {
230     module: GPSDaClassifier,
231     options: {
232         alpha: 0.80,
233         articulations: articulationsRightHandSimple
234     }
235 },
236 {
237     module: GPSDaClassifier,
238     options: {
239         alpha: 0.80,
240         articulations: articulationsRightHandDetailed
241     }
242 },
243 {
244     module: GPSDaClassifier,
245     options: {
246         alpha: 0.90,
247         articulations: articulationsRightHandSimple
248     }
249 },
250 {
251     module: GPSDaClassifier,
252     options: {
253         alpha: 0.90,
254         articulations: articulationsRightHandDetailed
255     }
256 },
257 {
258     module: GPSDaClassifier,
259     options: {

```

```

260         alpha: 1.00,
261         articulations: articulationsRightHandSimple
262     },
263 },
264 {
265     module: GPSDaClassifier,
266     options: {
267         alpha: 1.00,
268         articulations: articulationsRightHandDetailed
269     }
270 },
271 {
272     module: GPSDaClassifier,
273     options: {
274         alpha: 1.10,
275         articulations: articulationsRightHandSimple
276     }
277 },
278 {
279     module: GPSDaClassifier,
280     options: {
281         alpha: 1.10,
282         articulations: articulationsRightHandDetailed
283     }
284 },
285 {
286     module: GPSDaDissimilarityClassifier,
287     options: {
288         alpha: 0.7,
289         articulations: articulationsRightHandSimple
290     }
291 },
292 {
293     module: GPSDaDissimilarityClassifier,
294     options: {
295         alpha: 0.7,
296         articulations: articulationsRightHandDetailed
297     }
298 },
299 {
300     module: P3DollarPlusClassifier,
301     options: {
302         articulations: articulationsRightHandSimple
303     }
304 },
305 {
306     module: P3DollarPlusClassifier,
307     options: {
308         articulations: articulationsRightHandDetailed
309     }
310 }

```

```

311 ];
312
313 // Datasets path
314 config.datasets.path = path.join(__dirname, "datasets");
315
316 // Gesture datasets
317 config.datasets.gesture = [
318     {
319         name: "guinevere_unified",
320         loader: UnifiedDatasetLoader,
321         aggregateClasses: [
322             { name: "swipe up", classes: ["swipe_up"] },
323             { name: "swipe down", classes: ["swipe_down"] },
324             { name: "swipe left", classes: ["swipe_left"] },
325             { name: "swipe right", classes: ["swipe_right"] },
326             { name: "tap", classes: ["tap"] },
327             { name: "rotate clockwise", classes: ["turn_clockwise"] },
328             { name: "rotate anti-clockwise", classes: ["turn_counter_clockwise"] },
329             { name: "pinch in", classes: ["pinch_in"] },
330             { name: "pinch out", classes: ["pinch_out"] },
331             { name: "thumbs up", classes: ["thumbs_up"] },
332             { name: "thumbs down", classes: ["thumbs_down"] }
333         ]
334     },
335     {
336         name: "guinevere_unified",
337         loader: UnifiedDatasetLoader,
338         aggregateClasses: [
339             { name: "swipe up", classes: ["swipe_up"] },
340             { name: "swipe left", classes: ["swipe_left"] },
341             { name: "swipe right", classes: ["swipe_right"] },
342             { name: "tap", classes: ["tap"] }
343         ]
344     }
345     // {
346     //     name: "leapmotion",
347     //     loader: LeapMotionDatasetLoader,
348     //     aggregateClasses: []
349     // }
350     // {
351     //     name: "uWaveGestureLibrary",
352     //     loader: UWaveDatasetLoader,
353     //     aggregateClasses: []
354     // }
355     // {
356     //     name: "smartphone",
357     //     loader: SmartphoneDatasetLoader,
358     //     aggregateClasses: []
359     // }
360 ];
361

```



```

362 // Pose datasets
363 config.datasets.pose = [
364     {
365         loader: LeapPoseDatasetLoader,
366         name: "guinevre-pose",
367         aggregateClasses: [
368             { name: "flat", classes: ["flat"] },
369             { name: "point", classes: ["point-index"] },
370             { name: "pinch", classes: ["pinch"] },
371             { name: "grab", classes: ["grab"] },
372             { name: "thumb", classes: ["thumb"] }
373         ]
374     }
375     // {
376     //     loader: MMHGRDatasetLoader,
377     //     name: "multi_mod_hand_gest_recog"
378     //     aggregateClasses: []
379     // }
380 ];
381
382 module.exports = config;

```

F.2 Sensors

F.2.1 Leap Motion Controller

sensor.js

```
1  const AbstractSensor =
    ↳ require('../../framework/sensors/abstract-sensor').AbstractSensor
2  const Point = require('../../framework/gestures/point').Point3D;
3  const { Frame, Articulation } = require('../../framework/frames/frame');
4  const Leap = require('leapjs');
5
6  const fingerNames = ["Thumb", "Index", "Middle", "Ring", "Pinky"];
7  const fingerArticulations = ["Mcp", "Pip", "Tip"];
8
9  class Sensor extends AbstractSensor {
10     constructor(options) {
11         super("Leap-Interface");
12         this.framerate = options.framerate;
13         this.controller = new Leap.Controller({
14             frameEventName: 'deviceFrame',
15             loopWhileDisconnected: false
16         })
17         this.sensorLoop = null;
18     }
19
20     loop(callback) {
21         this.controller.connect()
22         this.callback = callback;
23         let hadRightHand = false;
24         let processLeapFrame = function () {
25             let frame = this.controller.frame();
26             let parsedFrame = new Frame(frame.timestamp);
27             let fingers = [];
28             // Palm positions
29             for (const hand of frame.hands) {
30                 let palmName;
31                 if (hand.type === 'right') {
32                     palmName = "rightPalmPosition";
33                     hadRightHand = true;
34                     parsedFrame.hasRightHand = true;
35                 }
36                 else {
37                     palmName = "leftPalmPosition";
38                     parsedFrame.hasLeftHand = true;
39                 }
40                 let palmPosition = hand.palmPosition;
41                 parsedFrame.articulations.push({ label: palmName, point: new
                    ↳ Point(palmPosition[0], palmPosition[1], palmPosition[2],
                    ↳ frame.timestamp) });
42                 hand.fingers.forEach((finger) => {
```

```

43     if (hand.type === 'right') {
44         // Get data usable by the application
45         let position = finger.stabilizedTipPosition;
46         let normalized =
47             ↪ frame.interactionBox.normalizePoint(position);
48         fingers.push({
49             'type': finger.type,
50             'normalizedPosition': normalized,
51             'touchDistance': finger.touchDistance,
52             'tipVelocity': finger.tipVelocity
53         });
54     }
55     for (const fingerArticulation of fingerArticulations) {
56         // Get label (e.g., rightIndexPipPosition)
57         let label = `${hand.type}${fingerNames[finger.type]}
58             ↪ ${fingerArticulation}Position`;
59         let position = new Point(
60             ↪ ...finger[`${fingerArticulation.toLowerCase()}Position`]);
61         let articulation = new Articulation(label, position);
62         parsedFrame.addArticulation(articulation);
63     }
64 });
65 }
66 // Add points if articulation not visible
67 if (!parsedFrame.hasRightHand) {
68     let label = `rightPalmPosition`;
69     let articulation = new Articulation(label, new Point(0.0, 0.0, 0.0,
70         ↪ frame.timestamp));
71     parsedFrame.addArticulation(articulation);
72     for (const fingerName of fingerNames) {
73         for (const fingerArticulation of fingerArticulations) {
74             let label =
75                 ↪ `right${fingerName}${fingerArticulation}Position`;
76             let articulation = new Articulation(label, new Point(0.0,
77                 ↪ 0.0, 0.0, frame.timestamp));
78             parsedFrame.addArticulation(articulation);
79         }
80     }
81 }
82 if (!parsedFrame.hasLeftHand) {
83     let label = `leftPalmPosition`;
84     let articulation = new Articulation(label, new Point(0.0, 0.0, 0.0,
85         ↪ frame.timestamp));
86     parsedFrame.addArticulation(articulation);
87     for (const fingerName of fingerNames) {
88         for (const fingerArticulation of fingerArticulations) {
89             let label =
90                 ↪ `left${fingerName}${fingerArticulation}Position`;
91             let articulation = new Articulation(label, new Point(0.0,
92                 ↪ 0.0, 0.0, frame.timestamp));
93             parsedFrame.addArticulation(articulation);
94         }
95     }
96 }

```

```

85         }
86     }
87 }
88 let appData = { 'fingers': fingers };
89 // Callback only if a hand is visible
90 if (parsedFrame.hasRightHand || parsedFrame.hasLeftHand) {
91     callback(parsedFrame, appData);
92 } else if (fingers.length == 0 && hadRightHand) {
93     callback(parsedFrame, appData);
94     hadRightHand = false;
95 }
96 }.bind(this);
97
98 this.sensorLoop = setInterval(processLeapFrame, 1000/this.framerate);
99 }
100
101 stop() {
102     if (this.sensorLoop !== null) {
103         clearInterval(this.sensorLoop);
104         this.controller.disconnect();
105         this.sensorLoop = null;
106     }
107 }
108 }
109
110 module.exports = {
111     Sensor
112 }

```

F.3 Datasets

F.3.1 Static Gestures

Custom Leap Motion Pose Dataset

leap-pose-loader.js

```
1  const path = require('path');
2  const fs = require('fs');
3
4  const GestureSet = require('../../../framework/gestures/gesture-set').GestureSet;
5  const GestureClass =
6    ↪ require('../../../framework/gestures/gesture-class').GestureClass;
7  const PoseData = require('../../../framework/gestures/pose-data').PoseData;
8  const { Frame, Articulation } = require('../../../framework/frames/frame');
9  const Point = require('../../../framework/gestures/point').Point3D;
10
11 const fingerNames = ["Thumb", "Index", "Middle", "Ring", "Pinky"];
12 const fingerArticulations = ["Mcp", "Pip", "Tip"];
13
14 function loadDataset(name, directory) {
15   let gestureSet = new GestureSet(name);
16   let dirPath = path.join(directory, name);
17   let gestureIndex = 0;
18   fs.readdirSync(dirPath).forEach((gesture) => {
19     let gestureDirPath = path.join(dirPath, gesture);
20     let gestureClass = new GestureClass(gesture, gestureIndex);
21     gestureSet.addGestureClass(gestureClass);
22     fs.readdirSync(gestureDirPath).forEach((user) => {
23       let userDirPath = path.join(gestureDirPath, user);
24       fs.readdirSync(userDirPath).forEach((file) => {
25         let rawGesturePath = path.join(userDirPath, file);
26         let parsedFile = JSON.parse(fs.readFileSync(rawGesturePath));
27         let id = 0;
28         for (const frame of parsedFile.data) {
29           let parsedFrame = parseFrame(frame);
30           let poseData = new PoseData(parseInt(user), id, parsedFrame,
31             ↪ undefined);
32           gestureClass.addSample(poseData);
33           id++;
34         }
35       });
36     });
37     gestureIndex += 1;
38   });
39   return gestureSet;
40 }
41
42 function parseFrame(frame) {
43   let parsedFrame = new Frame(frame.id);
```

```

42     let rightHandId = -1;
43     // Add palms
44     for (const hand of frame.hands) {
45         // Save id of right hand
46         if (hand.type === "right") {
47             rightHandId = hand.id;
48         }
49         let label = `${hand.type}PalmPosition`;
50         let position = new Point(...hand.palmPosition);
51         let articulation = new Articulation(label, position);
52         parsedFrame.addArticulation(articulation);
53     }
54     // Add fingers
55     for (const pointable of frame.pointables) {
56         if (!pointable.tool) {
57             for (const fingerArticulation of fingerArticulations) {
58                 // Get label (e.g., rightIndexPipPosition)
59                 let side = pointable.handId == rightHandId ? "right" : "left";
60                 let label =
61                     ↪ `${side}${fingerNames[pointable.type]}${fingerArticulation}
62                     ↪ Position`;
63                 let position = new
64                     ↪ Point(...pointable[`${fingerArticulation.toLowerCase()}
65                     ↪ Position`]);
66                 let articulation = new Articulation(label, position);
67                 parsedFrame.addArticulation(articulation);
68             }
69         }
70     }
71     return parsedFrame;
72 }

module.exports = {
  loadDataset
}

```

MultiModHandGestRecog Dataset

mmhgr-loader.js

```

1  const path = require('path');
2  const fs = require('fs');
3  const xml2js = require('xml2js');
4
5  const { Frame, Articulation } = require('../../../framework/frames/frame');
6  const GestureClass =
7  ↪ require('../../../framework/gestures/gesture-class').GestureClass;
8  const GestureSet = require('../../../framework/gestures/gesture-set').GestureSet;
9  const PoseData = require('../../../framework/gestures/pose-data').PoseData;
10 const Point = require('../../../framework/gestures/point').Point3D;

```

```

10
11 const fingers = ["Thumb", "Index", "Middle", "Ring", "Pinky"];
12 //const classNames = ["C", "down", "fist_moved", "five", "four", "hang", "heavy",
    ↪ "index", "L", "ok", "palm", "palm_m", "palm_u", "three", "two", "up"];
13 const classNames = ["C", "down"];
14
15 function loadDataset(name, directory) {
16     let datasetPath = path.join(directory, name);
17     console.log("Loading dataset (this might take some time)...");
18     let dataset = parseGestureSet(datasetPath, "MultiModHandGestRecog");
19     console.log("Data set loaded!");
20     return dataset;
21 }
22
23 // Helper functions
24 function parseFrame(path) {
25     let xml = fs.readFileSync(path);
26     let parsedFrame;
27     // Parse the xml file
28     var parser = new xml2js.Parser({explicitArray: false, mergeAttrs: true});
29     parser.parseString(xml, (err, res) => {
30         // Extract the frame
31         let frame = res.opencv_storage.Frame;
32         // Initialize the parsed frame
33         parsedFrame = new Frame(frame.ID);
34         for (const hand of ["Left", "Right"]) {
35             if (frame.Images.LeftImage.Hands.hasOwnProperty(hand)) {
36                 // Set hasXHand property
37                 if (hand === "Right") {
38                     parsedFrame.hasRightHand = true;
39                 } else {
40                     parsedFrame.hasLeftHand = true;
41                 }
42                 // Extract the position of the palm [x, y, z]
43                 let palmPosition =
44                     ↪ frame.Images.LeftImage.Hands[hand].Center.data.split(/\s+/g).
45                     ↪ slice(1).map(str => parseFloat(str));
46                 parsedFrame.addArticulation(new
47                     ↪ Articulation(getArticulationLabel(hand === "Right", "Palm"),
48                     ↪ new Point(...palmPosition)));
49                 // Extract the position of each finger
50                 let frameFingers = frame.Images.LeftImage.Hands[hand].Fingers;
51                 for (const finger of fingers) {
52                     // [x, y, z]
53                     let fingerPosition =
54                         ↪ frameFingers[finger].TipPosition.data.split(/\s+/g).
55                         ↪ slice(1).map(str => parseFloat(str));
56                     parsedFrame.addArticulation(new
57                         ↪ Articulation(getArticulationLabel(hand === "Right", finger
58                         ↪ + "Tip"), new Point(...fingerPosition)));
59                 }
60             }
61         }
62     });
63 }

```

```

52     }
53   }
54 })
55   return parsedFrame;
56 }
57
58 function parseGestureSet(datasetPath, name) {
59   let gestureSet = new GestureSet(name);
60   let classIndex = 0;
61   for (const className of classNames) {
62     console.log(className)
63     let gestureClass = new GestureClass(className, classIndex);
64     classIndex += 1;
65     fs.readdirSync(datasetPath).forEach((userDir) => {
66       for (const type of ["train_pose", "test_pose"]) {
67         let classPath = path.join(datasetPath, userDir, type, className);
68         let id = 0;
69         fs.readdirSync(classPath).forEach((frame) => {
70           let framePath = path.join(classPath, frame);
71           let parsedFrame = parseFrame(framePath);
72           let userId = parseInt(userDir.split("_"));
73           let poseData = new PoseData(userId, id, parsedFrame,
74             ↳ undefined);
75           gestureClass.addSample(poseData);
76           id++;
77         });
78       });
79       gestureSet.addGestureClass(gestureClass);
80     }
81     return gestureSet;
82   }
83
84   function getArticulationLabel(isRight, name) {
85     return `${isRight ? "right" : "left"}${name}Position`;
86   }
87
88   module.exports = {
89     loadDataset
90   }

```

F.3.2 Dynamic Gestures

Custom Leap Motion Gesture Dataset

leap-gesture-loader.js

```

1  const fs = require('fs');
2  const path = require('path');
3

```



```

4  const GestureSet = require('../../../../framework/gestures/gesture-set').GestureSet;
5  const GestureClass =
    ↪ require('../../../../framework/gestures/gesture-class').GestureClass;
6  const StrokeData = require('../../../../framework/gestures/stroke-data').StrokeData;
7  const Stroke = require('../../../../framework/gestures/stroke-data').Stroke;
8  const Path = require('../../../../framework/gestures/stroke-data').Path;
9  const Point = require('../../../../framework/gestures/point').Point3D;
10
11  const fingerNames = ["Thumb", "Index", "Middle", "Ring", "Pinky"];
12  const fingerArticulations = ["Mcp", "Pip", "Tip"];
13
14  const device = {
15      'osBrowserInfo': 'Leap Motion Controller', 'resolutionHeight': null,
16      'resolutionWidth': null, 'windowHeight': null, 'windowWidth': null,
17      'pixelRatio': null, 'mouse': false, 'pen': false, 'finger': false,
18      'acceleration': false, 'webcam': true
19  };
20
21  function loadDataset(name, directory) {
22      let gestureSet = new GestureSet(name);
23      let dirPath = path.join(directory, name);
24      let gestureIndex = 0;
25      fs.readdirSync(dirPath).forEach((user_dir) => {
26          let gestureSampleDirPath = path.join(dirPath, user_dir);
27          fs.readdirSync(gestureSampleDirPath).forEach((sample) => {
28              let rawGesturePath = path.join(gestureSampleDirPath, sample);
29              let rawGestureData = JSON.parse(fs.readFileSync(rawGesturePath));
30              let filename = sample.split(".")[0].split("-");
31              let gestureName = filename[0].split("#")[0];
32              let infosupp = undefined;
33              if (filename[0].split("#").length > 1) {
34                  infosupp = filename[0].split("#")[1];
35              }
36              let id = filename[1];
37              let gestureData = new StrokeData(parseInt(user_dir), id, infosupp);
38              if (gestureSet.getGestureClasses().has(gestureName)) {
39                  gestureSet.getGestureClasses().get(gestureName).addSample(
40                      ↪ gestureData);
41              } else {
42                  let gestureClass = new GestureClass(gestureName, gestureIndex);
43                  gestureIndex += 1;
44                  gestureClass.addSample(gestureData);
45                  gestureSet.addGestureClass(gestureClass);
46              }
47              // Init stroke paths
48              for (const side of ["left", "right"]) {
49                  let label = `${side}PalmPosition`;
50                  let strokePath = new Path(label);
51                  gestureData.addPath(label, strokePath);
52                  let stroke = new Stroke(0);
53                  strokePath.addStroke(stroke);

```

```

53     for (const fingerName of fingerNames) {
54         for (const fingerArticulation of fingerArticulations) {
55             let label =
56                 ↳ `_${side}_${fingerName}_${fingerArticulation}Position`;
57             let strokePath = new Path(label);
58             gestureData.addPath(label, strokePath);
59             let stroke = new Stroke(0);
60             strokePath.addStroke(stroke);
61         }
62     }
63     for (let i = 0; i < rawGestureData['data'].length; i++) {
64         let frame = rawGestureData['data'][i];
65         let points = {};
66         for (const side of ["left", "right"]) {
67             points[`_${side}PalmPosition`] = null;
68             for (const fingerName of fingerNames) {
69                 for (const fingerArticulation of fingerArticulations) {
70                     let label =
71                         ↳ `_${side}_${fingerName}_${fingerArticulation}Position`;
72                     points[label] = null;
73                 }
74             }
75             let rightHandId = -1;
76             let leftHandId = -1;
77             for (const hand of frame['hands']) {
78                 let palmName;
79                 if (hand['type'] === 'right') {
80                     rightHandId = hand['id'];
81                     palmName = "rightPalmPosition";
82                 }
83                 else {
84                     leftHandId = hand['id'];
85                     palmName = "leftPalmPosition";
86                 }
87                 let palmPosition = hand['palmPosition'];
88                 points[palmName] = new Point(palmPosition[0], palmPosition[1],
89                     ↳ palmPosition[2], frame['timestamp']);
90             }
91             for (const pointable of frame.pointables) {
92                 if (!pointable.tool) {
93                     for (const fingerArticulation of fingerArticulations) {
94                         // Get label (e.g., rightIndexTipPosition)
95                         let side = pointable.handId == rightHandId ? "right" :
96                             ↳ "left";
97                         let label = `_${side}_${fingerNames[pointable.type]}_${
98                             ↳ fingerArticulation}Position`;
99                         let position = pointable[
100                             ↳ `_${fingerArticulation.toLowerCase()}Position`;
101                         points[label] = new Point(position[0], position[1],
102                             ↳ position[2], frame.timestamp);

```

```

98         }
99     }
100 }
101 // Add points to paths (with default point w/ coordinates (x=0,
102   ↪ y=0, z=0))
103 Object.keys(points).forEach((articulation) => {
104     let stroke = gestureData.paths[articulation].strokes[0];
105     if (points[articulation] === null) {
106         // Default coordinates
107         stroke.addPoint(new Point(0, 0, 0, frame['timestamp']));
108     } else {
109         // Coordinates from frame
110         stroke.addPoint(points[articulation]);
111     }
112 });
113 });
114 });
115 return gestureSet;
116 }
117
118 module.exports = {
119     loadDataset
120 };

```

uWave Dataset

uwave-loader.js

```

1  const path = require('path');
2  const fs = require('fs');
3
4  const GestureSet = require('../framework/gestures/gesture-set').GestureSet;
5  const GestureClass =
6    ↪ require('../framework/gestures/gesture-class').GestureClass;
7  const StrokeData = require('../framework/gestures/stroke-data').StrokeData;
8  const Stroke = require('../framework/gestures/stroke-data').Stroke;
9  const Path = require('../framework/gestures/stroke-data').Path;
10 const Point = require('../framework/gestures/point').Point3D;
11
12 function loadDataset(name, directory) {
13     let gestureSet = new GestureSet(name);
14     let dirPath = path.join(directory, name);
15
16     let gestureClasses = {};
17
18     // Browse main directory
19     fs.readdirSync(dirPath).forEach((dir) => {
20         let gestureClassDirPath = path.join(dirPath, dir);

```

```

21 // Subdirectories
22 fs.readdirSync(gestureClassDirPath).forEach((file) => {
23     let rawGesturePath = path.join(gestureClassDirPath, file);
24     let lines = fs.readFileSync(rawGesturePath, 'utf-8').split(/\r?\n/);
25     let gestureData = new StrokeData();
26     let strokePath = new Path("main");
27     let stroke = new Stroke(0);
28     strokePath.addStroke(stroke);
29
30     let gestureId = file.slice(23, 24);
31
32     let index = 0;
33     for (const line of lines) {
34         let data = line.split(' ');
35         if(data.length == 3) {
36             let x = parseFloat(data[0]);
37             let y = parseFloat(data[1]);
38             let z = parseFloat(data[2]);
39             let t = index++;
40             stroke.addPoint(new Point(x, y, z, t));
41         }
42     }
43
44     if (index < 10) {
45         // Ignore, probably bad data
46         console.log(`Too few datapoints (${index}) - ${rawGesturePath}`);
47     } else {
48         gestureData.addPath("main", strokePath);
49         if (!gestureClasses.hasOwnProperty(gestureId)) {
50             gestureClasses[gestureId] = new GestureClass(`Gesture
51                 ↪ ${gestureId}`);
52             gestureClasses[gestureId].addSample(gestureData);
53         }
54     });
55 })
56
57 Object.keys(gestureClasses).forEach((key) => {
58     gestureSet.addGestureClass(gestureClasses[key]);
59 });
60
61 return gestureSet;
62 }
63
64 module.exports = {
65     loadDataset
66 };

```

F.4 Classifiers

F.4.1 GPSDa

gpsda-static-recognizer.js

```
1  class Recognizer {
2      static name = "GPSDAlphaRecognizer";
3
4      constructor(numPoints, alpha = 1) {
5          this.alpha = alpha;
6          this.numPoints = numPoints;
7          this.templates = [];
8      }
9
10     recognize(points) {
11         if (points.length !== this.numPoints) {
12             return { success: false, name: 'No match', time: 0.0 };
13         }
14         var t0 = Date.now();
15         var candidate = new CPS("", points, this.alpha);
16         var bestTemplate = null;
17         var bestDistance = +Infinity;
18         for (const template of this.templates) {
19             var distance = computeGPSD(candidate.cps, template.cps);
20             if (distance < bestDistance) {
21                 bestTemplate = template;
22                 bestDistance = distance;
23             }
24         }
25         var t1 = Date.now();
26         return (bestTemplate === null) ? { success: false, name: 'No match', time:
27             ↪ t1-t0 } : { success: true, name: bestTemplate.name, time: t1-t0 };
28     }
29
30     addGesture(name, points) {
31         if (points.length !== this.numPoints) {
32             return false;
33         }
34         this.templates.push(new CPS(name, points, this.alpha));
35         return true;
36     }
37
38     removeGesture(name) {
39         this.templates = this.templates.filter(cps => cps.name !== name);
40     }
41
42     /**
43     * Complete point shape descriptor
44     */
```

```

45 class CPS {
46     constructor(name, points, alpha) {
47         this.name = name;
48         this.cps = computeCPS(points, alpha);
49     }
50 }
51
52 class Point {
53     constructor(x, y, z) {
54         this.x = x;
55         this.y = y;
56         this.z = z;
57     }
58 }
59
60 /**
61  * Compute the Global Point Shape Distance (distance between the 2 complete point
62  * → shapes)
63  */
64 function computeGPSD(cps1, cps2) {
65     var distance = 0.0;
66     for (var i = 0; i < cps1.length; i++) {
67         distance += Math.abs(cps2[i] - cps1[i]);
68     }
69     return distance;
70 }
71
72 /**
73  * Compute the Complete Point Shape descriptor of a set of points
74  */
75 function computeCPS(points, alpha) {
76     let barycentre = getBarycentre(points);
77     let avgDistance = getAvgAlphaDistance(barycentre, points, alpha);
78     let cps = [];
79     for (var i = 0; i < points.length - 1; i++) {
80         for (var j = i + 1; j < points.length; j++) {
81             let alphaDistance = Math.pow(getDistance(points[i], points[j]), alpha);
82             cps.push(alphaDistance / avgDistance);
83         }
84     }
85     cps.sort();
86     return cps;
87 }
88
89 /**
90  * Compute the barycentre of a set of points
91  */
92 function getBarycentre(points) {
93     var x = 0.0, y = 0.0, z = 0.0;
94     for (const point of points) {
95         x += point.x;

```

```

95     y += point.y;
96     z += point.z;
97 }
98 x /= points.length;
99 y /= points.length;
100 z /= points.length;
101 return new Point(x, y, z);
102 }
103
104 /**
105  * Compute the average distance between a set of points and a reference point
106  */
107 function getAvgAlphaDistance(refPoint, points, alpha) {
108     var d = 0.0;
109     for (const point of points) {
110         d += Math.pow(getDistance(point, refPoint), alpha);
111     }
112     return d / points.length;
113 }
114
115 /**
116  * Compute the euclidean distance between two points
117  */
118 function getDistance(p1, p2) {
119     var dx = p2.x - p1.x;
120     var dy = p2.y - p1.y;
121     var dz = p2.z - p1.z;
122     return Math.sqrt(dx * dx + dy * dy + dz * dz);
123 }
124
125 module.exports = {
126     Recognizer,
127     Point
128 };

```

classifier.js

```

1  const AbstractClassifier =
    ↪ require('../framework/classifiers/abstract-classifier').AbstractClassifier;
2  const GPSDaRecognizer = require('./gpsda/gpsda-static-recognizer').Recognizer;
3  const Point = require('./gpsda/gpsda-static-recognizer').Point;
4
5  class Classifier extends AbstractClassifier {
6
7      static name = "GPSDaClassifier";
8
9      constructor(options, dataset) {
10         super(options);
11         this.articulations = options.articulations;
12         this.alpha = options.alpha;
13         this.staticRecognizer = new GPSDaRecognizer(options.articulations.length,
            ↪ options.alpha);

```

```

14      // Load gestures from the dataset
15      if (dataset !== undefined) {
16          dataset.getGestureClasses().forEach((gesture) => {
17              gesture.getSamples().forEach(sample => {
18                  this.addPose(gesture.name, sample);
19              });
20          });
21      }
22  }
23
24  addPose(name, sample) {
25      let frame = sample.frame;
26      let points = []
27      for (const articulation of this.articulations) {
28          points.push(frame.getArticulation(articulation).point);
29      }
30      this.staticRecognizer.addGesture(name, points);
31  }
32
33  removePose(name) {
34      this.staticRecognizer.removeGesture(name);
35  }
36
37  classify(frame) {
38      let points = []
39      for (const articulation of this.articulations) {
40          points.push(frame.getArticulation(articulation).point);
41      }
42      let { success, name, time } = this.staticRecognizer.recognize(points);
43      return success ? { 'name': name, 'time': time } : { 'name': "", 'time':
44          ↪ time };
45  }
46
47  toString() {
48      return `${Classifier.name} [ alpha = ${this.alpha.toFixed(2)} ]`;
49  }
50
51  module.exports = {
52      Classifier,
53      Point
54  }

```

F.4.2 $\$P^3+$

recognizer.js

```

1  //
2  // Point class
3  //

```



```

4  class Point {
5      constructor(x, y, z, id, angle = 0.0) {
6          this.x = x;
7          this.y = y;
8          this.z = z;
9              this.id = id;
10             this.angle = angle; // normalized turning angle, $P+
11     }
12 }
13
14 //
15 // PointCloud class: a point-cloud template
16 //
17 function PointCloud(name, points) // constructor
18 {
19     this.Name = name;
20     this.Points = Resample(points, NumPoints);
21     this.Points = Scale(this.Points);
22     this.Points = TranslateTo(this.Points, Origin);
23     this.Points = ComputeNormalizedTurningAngles(this.Points); // $P+
24 }
25
26 //
27 // PDollarPlusRecognizer constants
28 //
29 let NumPoints = 6;
30 const Origin = new Point(0, 0, 0, 0);
31
32 //
33 // PDollarPlusRecognizer class
34 //
35 class Recognizer {
36
37     static name = "P3DollarPlusRecognizer";
38
39     constructor(numArticulations = 6) {
40         NumPoints = numArticulations;
41         this.PointClouds = new Array();
42     }
43
44     //
45     // The $P+ Point-Cloud Recognizer API begins here -- 3 methods:
46     //   ↳ Recognize(), AddGesture(), DeleteUserGestures()
47     //
48     recognize(points) {
49         if(points.length != NumPoints) {
50             return { success: false, name: 'No match', time: 0.0 };
51         }
52         let t0 = Date.now();
53         var candidate = new PointCloud("", points);
54         var u = -1;

```

```

54     var b = +Infinity;
55     for (var i = 0; i < this.PointClouds.length; i++) // for each
56         ↪ point-cloud template
57     {
58         var d = Math.min(
59             CloudDistance(candidate.Points,
60                 ↪ this.PointClouds[i].Points, b),
61             CloudDistance(this.PointClouds[i].Points,
62                 ↪ candidate.Points, b)
63         ); // $P+
64         if (d < b) {
65             b = d; // best (least) distance
66             u = i; // point-cloud index
67         }
68     }
69     let t1 = Date.now();
70     return (u == -1) ? { success: false, name: 'No match', time: t1-t0
71         ↪ } : { success: true, name: this.PointClouds[u].Name, time:
72         ↪ t1-t0 };
73 }
74
75 addGesture(name, points) {
76     this.PointClouds[this.PointClouds.length] = new PointCloud(name,
77         ↪ points);
78     var num = 0;
79     for (var i = 0; i < this.PointClouds.length; i++) {
80         if (this.PointClouds[i].Name == name)
81             num++;
82     }
83     return num;
84 }
85
86 removeGesture(name) {
87     this.PointClouds = this.PointClouds.filter(pointCloud =>
88         ↪ pointCloud.Name !== name);
89 }
90 }
91
92 //
93 // Private helper functions from here on down
94 //
95 function CloudDistance(pts1, pts2, minSoFar) // revised for $P+
96 {
97     var matched = new Array(pts1.length); // pts1.length == pts2.length
98     for (var k = 0; k < pts1.length; k++)
99         matched[k] = false;
100     var sum = 0;
101     for (var i = 0; i < pts1.length; i++)
102     {
103         var index = -1;
104         var min = +Infinity;

```

```

98         for (var j = 0; j < pts1.length; j++)
99         {
100             var d = DistanceWithAngle(pts1[i], pts2[j]);
101             if (d < min) {
102                 min = d;
103                 index = j;
104             }
105         }
106         matched[index] = true;
107         sum += min;
108         if (sum >= minSoFar) return sum; // early abandoning
109     }
110     for (var j = 0; j < matched.length; j++)
111     {
112         if (!matched[j]) {
113             var min = +Infinity;
114             for (var i = 0; i < pts1.length; i++) {
115                 var d = DistanceWithAngle(pts1[i], pts2[j]);
116                 if (d < min)
117                     min = d;
118             }
119             sum += min;
120             if (sum >= minSoFar) return sum; // early abandoning
121         }
122     }
123     return sum;
124 }
125
126 function Resample(points, n)
127 {
128     var I = PathLength(points) / (n - 1); // interval length
129     var D = 0.0;
130     var newpoints = new Array(points[0]);
131     for (var i = 1; i < points.length; i++)
132     {
133         if (points[i].id == points[i-1].id)
134         {
135             var d = Distance(points[i-1], points[i]);
136             if ((D + d) >= I)
137             {
138                 var qx = points[i-1].x + ((I - D) / d) *
139                     ↪ (points[i].x - points[i-1].x);
140                 var qy = points[i-1].y + ((I - D) / d) *
141                     ↪ (points[i].y - points[i-1].y);
142                 var qz = points[i-1].z + ((I - D) / d) *
143                     ↪ (points[i].z - points[i-1].z);
144                 var q = new Point(qx, qy, qz, points[i].id);
145                 newpoints[newpoints.length] = q; // append new
146                     ↪ point 'q'
147                 points.splice(i, 0, q); // insert 'q' at position i
148                     ↪ in points s.t. 'q' will be the next i

```

```

144         D = 0.0;
145     }
146     else D += d;
147 }
148 }
149 if (newpoints.length == n - 1) // sometimes we fall a rounding-error short
    ↪ of adding the last point, so add it if so
150     newpoints[newpoints.length] = new Point(points[points.length -
    ↪ 1].x, points[points.length - 1].y, points[points.length - 1].z,
    ↪ points[points.length - 1].id);
151 return newpoints;
152 }
153
154 function Scale(points)
155 {
156     var minX = +Infinity, maxX = -Infinity, minY = +Infinity, maxY = -Infinity,
    ↪ minZ = +Infinity, maxZ = -Infinity;
157     for (var i = 0; i < points.length; i++) {
158         minX = Math.min(minX, points[i].x);
159         minY = Math.min(minY, points[i].y);
160         minZ = Math.min(minZ, points[i].z);
161         maxX = Math.max(maxX, points[i].x);
162         maxY = Math.max(maxY, points[i].y);
163         maxZ = Math.max(maxZ, points[i].z);
164     }
165     var size = Math.max(maxX - minX, maxY - minY, maxZ - minZ);
166     var newpoints = new Array();
167     for (var i = 0; i < points.length; i++) {
168         var qx = (points[i].x - minX) / size;
169         var qy = (points[i].y - minY) / size;
170         var qz = (points[i].z - minZ) / size;
171         newpoints[newpoints.length] = new Point(qx, qy, qz, points[i].id);
172     }
173     return newpoints;
174 }
175
176 function TranslateTo(points, pt) // translates points' centroid
177 {
178     var c = Centroid(points);
179     var newpoints = new Array();
180     for (var i = 0; i < points.length; i++) {
181         var qx = points[i].x + pt.x - c.x;
182         var qy = points[i].y + pt.y - c.y;
183         var qz = points[i].z + pt.z - c.z;
184         newpoints[newpoints.length] = new Point(qx, qy, qz, points[i].id);
185     }
186     return newpoints;
187 }
188
189 function ComputeNormalizedTurningAngles(points) // $P+
190 {

```

```

191     var newpoints = new Array();
192     newpoints[0] = new Point(points[0].x, points[0].y, points[0].z,
193         ↪ points[0].id); // first point
194     for (var i = 1; i < points.length - 1; i++)
195     {
196         var dx = (points[i+1].x - points[i].x) * (points[i].x -
197             ↪ points[i-1].x);
198         var dy = (points[i+1].y - points[i].y) * (points[i].y -
199             ↪ points[i-1].y);
200         var dz = (points[i+1].z - points[i].z) * (points[i].z -
201             ↪ points[i-1].z);
202         var dn = Distance(points[i+1], points[i]) * Distance(points[i],
203             ↪ points[i-1]);
204         var cosangle = Math.max(-1.0, Math.min(1.0, (dx + dy + dz) / dn));
205         ↪ // ensure [-1,+1]
206         var angle = Math.acos(cosangle) / Math.PI; // normalized angle
207         newpoints[newpoints.length] = new Point(points[i].x, points[i].y,
208             ↪ points[i].z, points[i].id, angle);
209     }
210     newpoints[newpoints.length] = new Point( // last point
211         points[points.length - 1].x,
212         points[points.length - 1].y,
213         points[points.length - 1].z,
214         points[points.length - 1].id);
215     return newpoints;
216 }
217
218 function Centroid(points)
219 {
220     var x = 0.0, y = 0.0, z = 0.0;
221     for (var i = 0; i < points.length; i++) {
222         x += points[i].x;
223         y += points[i].y;
224         z += points[i].z;
225     }
226     x /= points.length;
227     y /= points.length;
228     z /= points.length;
229     return new Point(x, y, z, 0);
230 }
231
232 function PathLength(points) // length traversed by a point path
233 {
234     var d = 0.0;
235     for (var i = 1; i < points.length; i++) {
236         if (points[i].id == points[i-1].id)
237             d += Distance(points[i-1], points[i]);
238     }
239     return d;
240 }
241

```

```

235 function DistanceWithAngle(p1, p2) // $P+
236 {
237     var dx = p2.x - p1.x;
238     var dy = p2.y - p1.y;
239     var dz = p2.z - p1.z;
240     var da = p2.angle - p1.angle;
241     return Math.sqrt(dx * dx + dy * dy + dz * dz + da * da);
242 }
243
244 function Distance(p1, p2) // Euclidean distance between two points
245 {
246     var dx = p2.x - p1.x;
247     var dy = p2.y - p1.y;
248     var dz = p2.z - p1.z;
249     return Math.sqrt(dx * dx + dy * dy + dz * dz);
250 }
251
252 module.exports = {
253     Point,
254     Recognizer
255 };

```

classifier.js

```

1  const AbstractClassifier =
    ↪ require('../../framework/classifiers/abstract-classifier').AbstractClassifier;
2  const P3DollarPlusRecognizer = require('./p3dollarplus/recognizer').Recognizer;
3  const Point = require('./p3dollarplus/recognizer').Point;
4
5  class Classifier extends AbstractClassifier {
6
7      static name = "P3DollarPlusClassifier";
8
9      constructor(options, dataset) {
10         super(options);
11         this.articulations = options.articulations;
12         this.staticRecognizer = new
            ↪ P3DollarPlusRecognizer(this.articulations.length);
13         // Load gestures from the dataset
14         if (dataset !== undefined) {
15             dataset.getGestureClasses().forEach((gesture) => {
16                 gesture.getSamples().forEach(sample => {
17                     this.addPose(gesture.name, sample);
18                 });
19             });
20         }
21     }
22
23     addPose(name, sample) {
24         let frame = sample.frame;
25         let points = []

```

```

26     for (const articulation of this.articulations) {
27         points.push(frame.getArticulation(articulation).point);
28     }
29     this.staticRecognizer.addGesture(name, points);
30 }
31
32 removePose(name) {
33     this.staticRecognizer.removeGesture(name);
34 }
35
36 classify(frame) {
37     let points = []
38     for (const articulation of this.articulations) {
39         let point = frame.getArticulation(articulation).point;
40         points.push(new Point(point.x, point.y, point.z, 0));
41     }
42     try {
43         let { success, name, time } = this.staticRecognizer.recognize(points);
44         return success ? { 'name': name, 'time': time } : { 'name': "", 'time':
            ↳ time };
45     } catch(err) {
46         return { 'name': "", 'time': 0.0 };
47     }
48 }
49
50 toString() {
51     return `${Classifier.name}`;
52 }
53 }
54
55 module.exports = {
56     Classifier,
57     Point
58 }

```

F.5 Analyzers

F.5.1 Basic Analyzer

basic-analyzer.js

```
1  const Point = require('../../../../framework/gestures/point').Point3D;
2  const AbstractAnalyzer =
   ↪  require('../../../../framework/analyzers/abstract-analyzer').AbstractAnalyzer;
3
4  class Analyzer extends AbstractAnalyzer {
5
6      constructor(options) {
7          super(options);
8          this.previousFrame = null;
9      }
10
11     analyze(frame) {
12         if (this.previousFrame === null) {
13             // Initialize first frame
14             this.previousFrame = frame;
15         }
16         // Compute pinch, rotation, and translation wrt. first frame.
17         let pinch = computePinch(this.previousFrame, frame);
18         let rotation = computeRotation(this.previousFrame, frame);
19         let translation = computeTranslation(this.previousFrame, frame);
20         let thumbVector = computeThumbVector(frame);
21         // Save the current frame for next call
22         this.previousFrame = frame;
23         return { 'rotation': rotation, 'pinch': pinch, 'translation': translation,
   ↪      'thumbVector': thumbVector };
24     }
25
26     reset() {
27         this.previousFrame = null;
28     }
29 }
30
31 function computePinch(fromFrame, toFrame) {
32     let dFrom =
   ↪     getDistance(fromFrame.getArticulation("rightThumbTipPosition").point,
   ↪     fromFrame.getArticulation("rightIndexTipPosition").point);
33     let dTo = getDistance(toFrame.getArticulation("rightThumbTipPosition").point,
   ↪     toFrame.getArticulation("rightIndexTipPosition").point);
34     return (dTo / dFrom);
35 }
36
37 function computeRotation(fromFrame, toFrame) {
38     let vectorFrom =
   ↪     translateTo(fromFrame.getArticulation("rightIndexTipPosition").point,
   ↪     fromFrame.getArticulation("rightThumbTipPosition").point);
```



```

39     let vectorTo =
40       ↪ translateTo(toFrame.getArticulation("rightIndexTipPosition").point,
41       ↪ toFrame.getArticulation("rightThumbTipPosition").point);
42     let a = computeAngle(vectorTo, vectorFrom);
43     return a
44   }
45
46   function computeTranslation(fromFrame, toFrame) {
47     let pFrom = fromFrame.getArticulation("rightPalmPosition").point;
48     let pTo = toFrame.getArticulation("rightPalmPosition").point;
49     let dx = pTo.x - pFrom.x;
50     let dy = pTo.y - pFrom.y;
51     let dz = pTo.z - pFrom.z;
52     return [dx, dy, dz];
53   }
54
55   function computeThumbVector(frame) {
56     let tVector = translateTo(frame.getArticulation("rightThumbTipPosition").point,
57     ↪ frame.getArticulation("rightPalmPosition").point);
58     return [tVector.x, tVector.y, tVector.z];
59   }
60
61   function computeAngle(p1, p2) {
62     return Math.atan2(p1.x * p2.y - p1.y * p2.x, p1.x * p2.x + p1.y * p2.y);
63   }
64
65   function getDistance(p1, p2) {
66     var dx = p2.x - p1.x;
67     var dy = p2.y - p1.y;
68     var dz = p2.z - p1.z;
69     return Math.sqrt(dx * dx + dy * dy + dz * dz);
70   }
71
72   function translateTo(p1, p2) {
73     return new Point(p1.x - p2.x, p1.y - p2.y, p1.z - p2.z);
74   }
75
76   module.exports = {
77     Analyzer
78   }

```

F.6 Segmenters

F.6.1 Left-Hand Segmenter

lefthand-segmenter.js

```
1  const AbstractSegmenter =
   ↪  require('../../framework/segmenters/abstract-segmenter').AbstractSegmenter;
2  const StrokeData = require('../../framework/gestures/stroke-data').StrokeData;
3  const Stroke = require('../../framework/gestures/stroke-data').Stroke;
4  const Path = require('../../framework/gestures/stroke-data').Path;
5  const Point = require('../../framework/gestures/point').Point3D;
6
7  class Segmenter extends AbstractSegmenter {
8    constructor(options) {
9      super(options);
10     this.minFrames = options.minSegmentLength;
11     this.maxFrames = options.maxSegmentLength;
12     this.strokeData = null;
13     this.frameCount = 0;
14   }
15
16   segment(frame) {
17     if (frame.hasLeftHand) {
18       if (this.frameCount >= this.maxFrames) {
19         // Max number of frames reached
20         let oldStrokeData = this.strokeData;
21         this.strokeData = null;
22         this.frameCount = 0;
23         return oldStrokeData;
24       }
25       if (this.strokeData === null) {
26         // Initialize strokeData
27         this.strokeData = new StrokeData();
28         for (const articulation of frame.articulations) {
29           let path = new Path(articulation.label);
30           this.strokeData.addPath(articulation.label, path);
31           let stroke = new Stroke();
32           path.addStroke(stroke);
33           // Quick hack to remove left hand
34           if (articulation.label.includes("left")) {
35             stroke.addPoint(new Point(0, 0, 0, frame.timestamp));
36           } else {
37             stroke.addPoint(articulation.point);
38           }
39         }
40       } else {
41         for (const articulation of frame.articulations) {
42           let path = this.strokeData.paths[articulation.label];
43           let stroke = path.strokes[0];
44           // Quick hack to remove left hand
```

```

45         if (articulation.label.includes("left")) {
46             stroke.addPoint(new Point(0, 0, 0, frame.timestamp));
47         } else {
48             stroke.addPoint(articulation.point);
49         }
50     }
51 }
52 this.frameCount++;
53 } else if (this.frameCount > this.minFrames) {
54     // Left hand removed and enough frames
55     let oldStrokeData = this.strokeData;
56     this.strokeData = null;
57     this.frameCount = 0;
58     return oldStrokeData;
59 } else {
60     // Left hand removed and not enough frames
61     this.strokeData = null;
62     this.frameCount = 0;
63 }
64 return null;
65 }
66
67 notifyRecognition() {
68     // Do nothing
69 }
70 }
71
72 module.exports = {
73     Segmenter
74 };

```

F.6.2 Zoning Segmenter

zoning-segmenter.js

```

1  const AbstractSegmenter =
   ↪  require('../framework/segmenters/abstract-segmenter').AbstractSegmenter;
2  const StrokeData = require('../framework/gestures/stroke-data').StrokeData;
3  const Stroke = require('../framework/gestures/stroke-data').Stroke;
4  const Path = require('../framework/gestures/stroke-data').Path;
5
6  const xBound = 120;
7  const zBound = 60;
8
9  class Segmenter extends AbstractSegmenter {
10     constructor(options) {
11         super(options);
12         this.minFrames = options.minSegmentLength;
13         this.maxFrames = options.maxSegmentLength;
14         this.numberPauseFrames = options.pauseLength;

```

```

15     this.strokeData = null;
16     this.pauseCount = 0;
17 }
18
19 segment(frame) {
20     // Increment pause count
21     this.pauseCount = Math.max(this.pauseCount - 1, 0);
22     if (this.pauseCount != 0) {
23         return null;
24     }
25     if (isWithinBounds(frame)) {
26         // At least one hand is in the zone
27         if (this.frameCount >= this.maxFrames) {
28             // Max number of frames reached
29             let oldStrokeData = this.strokeData;
30             this.strokeData = null;
31             this.frameCount = 0;
32             return oldStrokeData;
33         }
34         if (this.strokeData === null) {
35             // Initialize strokeData
36             this.strokeData = new StrokeData();
37             for (const articulation of frame.articulations) {
38                 let path = new Path(articulation.label);
39                 this.strokeData.addPath(articulation.label, path);
40                 let stroke = new Stroke();
41                 path.addStroke(stroke);
42                 stroke.addPoint(articulation.point);
43             }
44         } else {
45             for (const articulation of frame.articulations) {
46                 let path = this.strokeData.paths[articulation.label];
47                 let stroke = path.strokes[0];
48                 stroke.addPoint(articulation.point);
49             }
50         }
51         this.frameCount++;
52     } else if (this.frameCount > this.minFrames) {
53         // Hands outside of the zone & enough frames
54         let oldStrokeData = this.strokeData;
55         this.strokeData = null;
56         this.frameCount = 0;
57         return oldStrokeData;
58     } else {
59         // Hands outside of the zone and not enough frames
60         this.strokeData = null;
61         this.frameCount = 0;
62     }
63     return null;
64 }
65

```

```

66     notifyRecognition() {
67         this.pauseCount = this.numberPauseFrames;
68     }
69 }
70
71 function isWithinBounds(frame) {
72     let withinBounds = false;
73     if (frame.hasLeftHand) {
74         let x = frame.getArticulation("leftPalmPosition").point.x;
75         let z = frame.getArticulation("leftPalmPosition").point.z;
76         withinBounds = x < xBound && x > -xBound && z < zBound && z > -zBound;
77     }
78     if (!withinBounds && frame.hasRightHand) {
79         let x = frame.getArticulation("rightPalmPosition").point.x;
80         let z = frame.getArticulation("rightPalmPosition").point.z;
81         withinBounds = x < xBound && x > -xBound && z < zBound && z > -zBound;
82     }
83     return withinBounds;
84 }
85
86 module.exports = {
87     Segmenter
88 };

```

F.6.3 Window Segmenter

window-segmenter.js

```

1  const AbstractSegmenter =
    ↪ require('../framework/segmenters/abstract-segmenter').AbstractSegmenter;
2  const StrokeData = require('../framework/gestures/stroke-data').StrokeData;
3  const Stroke = require('../framework/gestures/stroke-data').Stroke;
4  const Path = require('../framework/gestures/stroke-data').Path;
5
6  class Segmenter extends AbstractSegmenter {
7
8      constructor(options) {
9          super(options);
10         this.windowWidth = options.windowWidth;
11         this.numberIntervalFrames = options.intervalLength;
12         this.numberPauseFrames = options.pauseLength;
13         this.motionThreshold = options.motionThreshold;
14         this.frameBuffer = null;
15         this.intervalCount = 0;
16         this.pauseCount = 0;
17         this.bufferLength = 0;
18     }
19
20     segment(frame) {
21         if (this.frameBuffer === null) {

```

```

22         // Initialize frameBuffer
23         this.frameBuffer = initBuffer(frame);
24     } else {
25         for (const articulation of frame.articulations) {
26             // Add the position of this articulation to the buffer
27             this.frameBuffer[articulation.label].push(articulation.point);
28             if (this.bufferLength >= this.windowWidth) {
29                 // Shift items in buffer
30                 this.frameBuffer[articulation.label].shift();
31             }
32         }
33     }
34     // Increment pause count
35     this.pauseCount = Math.max(this.pauseCount - 1, 0);
36     this.intervalCount = (this.intervalCount + 1) % this.numberIntervalFrames;
37     if (this.bufferLength < this.windowWidth) {
38         // Buffer not full
39         this.bufferLength++;
40     } else if (this.pauseCount == 0 && this.intervalCount == 0 &&
41         ↪ (frame.hasLeftHand || frame.hasRightHand)) {
42         // Buffer full & ready
43         if (isMotion(this.frameBuffer, this.motionThreshold,
44             ↪ ["rightPalmPosition", "rightThumbTipPosition",
45             ↪ "rightIndexTipPosition"])) {
46             // Create the StrokeData object from the frames in the buffer
47             let strokeData = new StrokeData();
48             for (const articulation of frame.articulations) {
49                 let path = new Path(articulation.label);
50                 strokeData.addPath(articulation.label, path);
51                 let stroke = new Stroke();
52                 path.addStroke(stroke);
53                 stroke.points = this.frameBuffer[articulation.label].slice();
54             }
55             return strokeData;
56         }
57     }
58     return null;
59 }
60
61
62
63 function initBuffer(frame) {
64     let buffer = {};
65     for (const articulation of frame.articulations) {
66         buffer[articulation.label] = [ articulation.point ];
67     }
68     return buffer;
69 }

```

```

70
71 function isMotion(frameBuffer, threshold, articulations) {
72     for (const articulation of articulations) {
73         // Compute motion related to first point
74         let refPoint = frameBuffer[articulation][0];
75         for (let i = frameBuffer[articulation].length - 1; i > 0; i--) {
76             let motion = distance(refPoint, frameBuffer[articulation][i]);
77             if (motion >= threshold) {
78                 return true;
79             }
80         }
81     }
82     return false;
83 }
84
85 function distance(p1, p2) {
86     var dx = p2.x - p1.x;
87     var dy = p2.y - p1.y;
88     var dz = p2.z - p1.z;
89     return Math.sqrt(dx * dx + dy * dy + dz * dz);
90 }
91
92 module.exports = {
93     Segmenter
94 };

```

F.7 Recognizers

F.7.1 3 cent

recognizer.js

```
1  const AbstractRecognizer =  
    ↪ require('../../framework/recognizers/abstract-recognizer').AbstractRecognizer;  
2  const math = require('mathjs');  
3  const Spline = require('cubic-spline');  
4  
5  
6  class Point {  
7      constructor(x, y, z) {  
8          this.x = x;  
9          this.y = y;  
10         this.z = z;  
11     }  
12 }  
13  
14  
15 let NumPoints = 8;  
16 let pathName;  
17  
18 class Recognizer extends AbstractRecognizer {  
19  
20     static name = "ThreeCentRecognizer";  
21  
22     constructor(options, dataset) {  
23         super();  
24         NumPoints = options.samplingPoints;  
25         pathName = options.pathName;  
26         this.templates = {};  
27         this.threshold = Infinity;  
28         if (dataset !== undefined){  
29             dataset.getGestureClasses().forEach((gesture) => {  
30                 gesture.getSamples().forEach(sample => {  
31                     this.addGesture(gesture.name,  
32                         ↪ sample);  
33                 })  
34             });  
35         }  
36     }  
37  
38     addGesture(name, sample) {  
39         let points = convert(sample);  
40         points = normalizeP(points, NumPoints);  
41         if (!this.templates.hasOwnProperty(name)) {  
42             this.templates[name] = [];  
43         }
```



```

44     this.templates[name].push(points);
45     let distances = new Array();
46     // For each class of gesture
47     Object.keys(this.templates).forEach((name) => {
48         // Compute the distance between each pair of gesture in the class, add
49         ↪ it to distances
50         for (let i = 0; i < this.templates[name].length; i++) {
51             for (let k = i+1; k < this.templates[name].length; k++) {
52                 distances.push(gestureDistance(this.templates[name][i],
53                 ↪ this.templates[name][k]));
54             }
55         }
56     });
57
58     if (distances.length > 0) {
59         // Remove outliers and sort distances
60         //distances = rmOutliers(distances);
61         distances = distances.sort(function(a, b){return a - b});
62         // Histogram heuristic to compute decision distance threshold
63         var hist = histogram(distances, 30);
64         var max = Math.max(...hist["values"]);
65         var indexMax = hist["values"].indexOf(max);
66         var binWidth = hist["binWidth"];
67         var distancesHist = (((indexMax) * binWidth) + ((indexMax + 1) *
68         ↪ binWidth)) / 2;
69         this.threshold = distancesHist;
70     }
71
72     }
73
74     removeGesture(name) {
75         console.log("Cannot remove gesture!");
76     }
77
78     recognize(sample) {
79         let points = convert(sample);
80         let t0 = Date.now();
81         points = normalizeP(points, NumPoints);
82         let bestFitClass = "";
83         //let minDist = this.threshold;
84         let minDist = Infinity;
85         // Compare gesture w/ each template
86         Object.keys(this.templates).forEach((name) => {
87             for (let i = 0; i < this.templates[name].length; i++) {
88                 let tmpDist = gestureDistance(points, this.templates[name][i]);
89                 if (tmpDist < minDist) {
90                     minDist = tmpDist;
91                     bestFitClass = name;
92                 }
93             }
94         });
95         let t1 = Date.now();

```

```

92         return (bestFitClass === "") ? { name: "", time: t1-t0, 'Score':
          ↪ 0.0 } : { name: bestFitClass, time: t1-t0, 'Score': minDist };
93     }
94
95     toString() {
96         return `${Recognizer.name} [ samplingPoints = ${NumPoints}, pathName =
          ↪ ${pathName} ]`;
97     }
98 }
99
100 function convert(sample) {
101     return sample.paths[pathName].strokes[0].points;
102 }
103
104 function histogram(data, numBins) {
105     let binWidth = math.round((math.max(data) / numBins) + 0.0005, 3);
106     let currentItemId = 0;
107     var bins = new Array(numBins).fill(0);
108     for (let i = 0; i < numBins; i++) {
109         while (currentItemId < math.size(data)[0] && (data[currentItemId] < (i + 1)
          ↪ * binWidth || i == numBins - 1)) {
110             bins[i] += 1;
111             currentItemId += 1;
112         }
113     }
114     return { "values": bins, "binWidth": binWidth };
115 }
116
117 function gestureDistance(points1, points2) {
118     let dq = 0;
119     for (var i = 0; i < points1.length; i++) {
120         var dx = points1[i].x - points2[i].x;
121         var dy = points1[i].y - points2[i].y;
122         var dz = points1[i].z - points2[i].z;
123         dq += dx * dx + dy * dy + dz * dz;
124     }
125     return dq;
126 }
127
128 function normalizeP(points, n) {
129     let dist = [0];
130     for (let i = 1; i < points.length; i++) {
131         dx = points[i].x - points[i-1].x;
132         dy = points[i].y - points[i-1].y;
133         dz = points[i].z - points[i-1].z;
134         dist.push(Math.sqrt(dx * dx + dy * dy + dz * dz));
135     }
136     var s = cumsum(dist);
137     var len = s[s.length - 1];
138     // Resample
139     let h = (points.length-1) / (n - 1);

```

```

140   let xq = math.range(0, points.length - 1, h)._data;
141   xq.push(points.length - 1);
142   let x = [];
143   let xAxis = [];
144   let yAxis = [];
145   let zAxis = [];
146   for (let i = 0; i < points.length; i++) {
147     x.push(i);
148     xAxis.push(points[i].x);
149     yAxis.push(points[i].y);
150     zAxis.push(points[i].z);
151   }
152   let sX = spline(x, xAxis, xq);
153   let sY = spline(x, yAxis, xq);
154   let sZ = spline(x, zAxis, xq);
155   let avgX = sX.reduce((a,b) => a + b, 0) / sX.length;
156   let avgY = sY.reduce((a,b) => a + b, 0) / sY.length;
157   let avgZ = sZ.reduce((a,b) => a + b, 0) / sZ.length;
158   let newPoints = [];
159   for (let i = 0; i < xq.length; i++) {
160     // Center (wrt. centroid) and scale
161     newPoints.push(new Point((sX[i] - avgX) / len, (sY[i] - avgY) / len, (sZ[i]
162       ↪ - avgZ) / len));
163   }
164   return newPoints;
165 }
166
167 function cumsum(data) {
168   var acc = 0;
169   return math.map(data, function(x) {
170     acc += x;
171     return acc;
172   })
173 }
174
175 // cubic interpolation of x and y.
176 // xq: query points
177 function spline(x, y, xq) {
178   const spline = new Spline(x, y);
179   var s = new Array(xq.length);
180   for (let i = 0; i < xq.length; i++) {
181     s[i] = spline.at(xq[i]);
182   }
183   return s;
184 }
185
186 module.exports = {
187   Recognizer
188 };

```

F.7.2 \$P³

p3dollar.js

```
1  //
2  // Point class
3  //
4  function Point(x, y, z, id) // constructor
5  {
6      this.X = x;
7      this.Y = y;
8      this.Z = z;
9      this.ID = id; // stroke ID to which this point belongs (1,2,3,etc.)
10 }
11 //
12 // PointCloud class: a point-cloud template
13 //
14 function PointCloud(name, points) // constructor
15 {
16     this.Name = name;
17     this.Points = Resample(points, NumPoints);
18     this.Points = Scale(this.Points);
19     this.Points = TranslateTo(this.Points, Origin);
20 }
21 //
22 // Result class
23 //
24 function Result(name, score, ms) // constructor
25 {
26     this.Name = name;
27     this.Score = score;
28     this.Time = ms;
29 }
30 //
31 // P3DollarRecognizer constants
32 //
33 let NumPoints = 32;
34 const Origin = new Point(0, 0, 0, 0);
35 //
36 // P3DollarRecognizer class
37 //
38 function P3DollarRecognizer(numPoints) // constructor
39 {
40     this.PointClouds = new Array();
41     NumPoints = numPoints;
42     //
43     // The $P3 Point-Cloud Recognizer API begins here -- 4 methods:
44     //   ↳ Recognize(), AddGesture(), RemoveGesture(), DeleteUserGestures()
45     //
46     this.Recognize = function(points)
47     {
48         var t0 = Date.now();
```

```

48     var candidate = new PointCloud("", points);
49
50     var u = -1;
51     var b = +Infinity;
52     for (var i = 0; i < this.PointClouds.length; i++) // for each
53         ↪ point-cloud template
54     {
55         var d = GreedyCloudMatch(candidate.Points,
56             ↪ this.PointClouds[i]);
57         if (d < b) {
58             b = d; // best (least) distance
59             u = i; // point-cloud index
60         }
61     }
62     var t1 = Date.now();
63     return (u == -1) ? new Result("No match.", 0.0, t1-t0) : new
64         ↪ Result(this.PointClouds[u].Name, b > 1.0 ? 1.0 / b : 1.0,
65         ↪ t1-t0);
66 }
67 this.AddGesture = function(name, points)
68 {
69     this.PointClouds[this.PointClouds.length] = new PointCloud(name,
70         ↪ points);
71     var num = 0;
72     for (var i = 0; i < this.PointClouds.length; i++) {
73         if (this.PointClouds[i].Name == name)
74             num++;
75     }
76     return num;
77 }
78 this.RemoveGesture = function(name)
79 {
80     this.PointClouds = this.PointClouds.filter(pointCloud =>
81         ↪ pointCloud.Name !== name);
82 }
83 this.DeleteUserGestures = function()
84 {
85     this.PointClouds.length = NumPointClouds; // clears any beyond the
86     ↪ original set
87     return NumPointClouds;
88 }
89 }
90 //
91 // Private helper functions from here on down
92 //
93 function GreedyCloudMatch(points, P)
94 {
95     var e = 0.50;
96     var step = Math.floor(Math.pow(points.length, 1.0 - e));
97     var min = +Infinity;
98     for (var i = 0; i < points.length; i += step) {

```

```

92         var d1 = CloudDistance(points, P.Points, i);
93         var d2 = CloudDistance(P.Points, points, i);
94         min = Math.min(min, Math.min(d1, d2)); // min3
95     }
96     return min;
97 }
98 function CloudDistance(pts1, pts2, start)
99 {
100     var matched = new Array(pts1.length); // pts1.length == pts2.length
101     for (var k = 0; k < pts1.length; k++)
102         matched[k] = false;
103     var sum = 0;
104     var i = start;
105     do
106     {
107         var index = -1;
108         var min = +Infinity;
109         for (var j = 0; j < matched.length; j++)
110         {
111             if (!matched[j]) {
112                 var d = Distance(pts1[i], pts2[j]);
113                 if (d < min) {
114                     min = d;
115                     index = j;
116                 }
117             }
118         }
119         matched[index] = true;
120         var weight = 1 - ((i - start + pts1.length) % pts1.length) /
            ↪ pts1.length;
121         sum += weight * min;
122         i = (i + 1) % pts1.length;
123     } while (i != start);
124     return sum;
125 }
126 function Resample(points, n)
127 {
128     var I = PathLength(points) / (n - 1); // interval length
129     var D = 0.0;
130     var newpoints = new Array(points[0]);
131     for (var i = 1; i < points.length; i++)
132     {
133         if (points[i].ID == points[i-1].ID)
134         {
135             var d = Distance(points[i-1], points[i]);
136             if ((D + d) >= I)
137             {
138                 var qx = points[i-1].X + ((I - D) / d) *
                    ↪ (points[i].X - points[i-1].X);
139                 var qy = points[i-1].Y + ((I - D) / d) *
                    ↪ (points[i].Y - points[i-1].Y);

```

```

140         var qz = points[i-1].Z + ((I - D) / d) *
           ↪ (points[i].Z - points[i-1].Z);
141         var q = new Point(qx, qy, qz, points[i].ID);
142         newpoints[newpoints.length] = q; // append new
           ↪ point 'q'
143         points.splice(i, 0, q); // insert 'q' at position i
           ↪ in points s.t. 'q' will be the next i
144         D = 0.0;
145     }
146     else D += d;
147 }
148 }
149 if (newpoints.length == n - 1) // sometimes we fall a rounding-error short
   ↪ of adding the last point, so add it if so
150     newpoints[newpoints.length] = new Point(points[points.length -
       ↪ 1].X, points[points.length - 1].Y, points[points.length - 1].Z,
       ↪ points[points.length - 1].ID);
151     return newpoints;
152 }
153 function Scale(points)
154 {
155     var minX = +Infinity, maxX = -Infinity, minY = +Infinity, maxY = -Infinity,
       ↪ minZ = +Infinity, maxZ = -Infinity;
156     for (var i = 0; i < points.length; i++) {
157         minX = Math.min(minX, points[i].X);
158         minY = Math.min(minY, points[i].Y);
159         minZ = Math.min(minZ, points[i].Z);
160         maxX = Math.max(maxX, points[i].X);
161         maxY = Math.max(maxY, points[i].Y);
162         maxZ = Math.max(maxZ, points[i].Z);
163     }
164     var size = Math.max(maxX - minX, maxY - minY, maxZ - minZ);
165     var newpoints = new Array();
166     for (var i = 0; i < points.length; i++) {
167         var qx = (points[i].X - minX) / size;
168         var qy = (points[i].Y - minY) / size;
169         var qz = (points[i].Z - minZ) / size;
170         newpoints[newpoints.length] = new Point(qx, qy, qz, points[i].ID);
171     }
172     return newpoints;
173 }
174 function TranslateTo(points, pt) // translates points' centroid to pt
175 {
176     var c = Centroid(points);
177     var newpoints = new Array();
178     for (var i = 0; i < points.length; i++) {
179         var qx = points[i].X + pt.X - c.X;
180         var qy = points[i].Y + pt.Y - c.Y;
181         newpoints[newpoints.length] = new Point(qx, qy, points[i].ID);
182     }
183     return newpoints;

```

```

184 }
185 function Centroid(points)
186 {
187     var x = 0.0, y = 0.0, z = 0.0;
188     for (var i = 0; i < points.length; i++) {
189         x += points[i].X;
190         y += points[i].Y;
191         z += points[i].Z;
192     }
193     x /= points.length;
194     y /= points.length;
195     z /= points.length;
196     return new Point(x, y, z, 0);
197 }
198 function PathLength(points) // length traversed by a point path
199 {
200     var d = 0.0;
201     for (var i = 1; i < points.length; i++) {
202         if (points[i].ID == points[i-1].ID)
203             d += Distance(points[i-1], points[i]);
204     }
205     return d;
206 }
207 function Distance(p1, p2) // Euclidean distance between two points
208 {
209     var dx = p2.X - p1.X;
210     var dy = p2.Y - p1.Y;
211     var dz = p2.Z - p1.Z;
212     return Math.sqrt(dx * dx + dy * dy + dz * dz);
213 }
214
215 module.exports = {
216     P3DollarRecognizer,
217     Point
218 }

```

recognizer.js

```

1  const AbstractRecognizer =
   →  require('.././../framework/recognizers/abstract-recognizer').AbstractRecognizer;
2  const P3DollarRecognizer = require('./p3dollar/p3dollar').P3DollarRecognizer;
3  const Point = require('./p3dollar/p3dollar').Point;
4
5  class Recognizer extends AbstractRecognizer {
6
7      static name = "P3DollarRecognizer";
8
9      constructor(options, dataset) {
10         super();
11         this.samplingPoints = options.samplingPoints;
12         this.articulations = options.articulations;

```



```

13     this.recognizer = new P3DollarRecognizer(this.samplingPoints);
14     if (dataset !== undefined){
15         dataset.getGestureClasses().forEach((gesture) => {
16             gesture.getSamples().forEach(sample => {
17                 this.addGesture(gesture.name,
18                     ↪ sample);
19             }
20         });
21     }
22 }
23
24 addGesture(name, sample) {
25     let points = convert(sample, this.articulations);
26     this.recognizer.AddGesture(name, points);
27 }
28
29 removeGesture(name) {
30     this.recognizer.RemoveGesture(name);
31 }
32
33 recognize(sample) {
34     let points = convert(sample, this.articulations);
35     if(points.length === 0) {
36         return { name: "", time: 0, score: 0.0 };
37     }
38     let result = this.recognizer.Recognize(points);
39     return (result.Name === "No match.") ? { name: "", time:
40         ↪ result.Time, score: result.Score } : { name: result.Name, time:
41         ↪ result.Time, score: result.Score };
42 }
43
44 toString() {
45     return `${Recognizer.name} [ samplingPoints = ${this.samplingPoints},
46         ↪ articulations = ${this.articulations} ]`;
47 }
48
49 function convert(sample, articulations) {
50     let points = [];
51     articulations.forEach((articulation, articulationID) => {
52         sample.paths[articulation].strokes.forEach((stroke, strokeId) => {
53             stroke.points.forEach((point) => {
54                 // If multipoint, one stroke per articulation,
55                 ↪ otherwise, keep original strokes
56                 let index = articulations.length > 1 ?
57                     ↪ articulationID : strokeId;
58                 points.push(new Point(point.x, point.y, point.z,
59                     ↪ index));
60             });
61         });
62     });

```

```

57         });
58     });
59     return points;
60 }
61
62
63 module.exports = {
64     Recognizer
65 };

```

F.7.3 $\$P^3+$

p3dollarplus.js

```

1  //
2  // Point class
3  //
4  function Point(x, y, z, id, angle = 0.0)
5  {
6      this.X = x;
7      this.Y = y;
8      this.Z = z;
9      this.ID = id;
10     this.Angle = angle; // normalized turning angle, $P+
11 }
12 //
13 // PointCloud class: a point-cloud template
14 //
15 function PointCloud(name, points) // constructor
16 {
17     this.Name = name;
18     this.Points = Resample(points, NumPoints);
19     this.Points = Scale(this.Points);
20     this.Points = TranslateTo(this.Points, Origin);
21     this.Points = ComputeNormalizedTurningAngles(this.Points); // $P+
22 }
23 //
24 // Result class
25 //
26 function Result(name, score, ms) // constructor
27 {
28     this.Name = name;
29     this.Score = score;
30     this.Time = ms;
31 }
32 //
33 // PDollarPlusRecognizer constants
34 //
35 var NumPoints = 32;
36 const Origin = new Point(0,0,0,0);

```

```

37 //
38 // PDollarPlusRecognizer class
39 //
40 function P3DollarPlusRecognizer(numPoints) // constructor
41 {
42     this.PointClouds = new Array();
43     NumPoints = numPoints;
44     //
45     // The $P+ Point-Cloud Recognizer API begins here -- 4 methods:
46     //   ↳ Recognize(), AddGesture(), RemoveGesture(), DeleteUserGestures()
47     //
48     this.Recognize = function(points)
49     {
50         var t0 = Date.now();
51         var candidate = new PointCloud("", points);
52
53         var u = -1;
54         var b = +Infinity;
55         for (var i = 0; i < this.PointClouds.length; i++) // for each
56             ↳ point-cloud template
57         {
58             var d = Math.min(
59                 CloudDistance(candidate.Points,
60                     ↳ this.PointClouds[i].Points, b),
61                 CloudDistance(this.PointClouds[i].Points,
62                     ↳ candidate.Points, b)
63             ); // $P+
64             if (d < b) {
65                 b = d; // best (least) distance
66                 u = i; // point-cloud index
67             }
68         }
69         var t1 = Date.now();
70         return (u == -1) ? new Result("No match.", 0.0, t1-t0) : new
71             ↳ Result(this.PointClouds[u].Name, b > 1.0 ? 1.0 / b : 1.0,
72             ↳ t1-t0);
73     }
74     this.AddGesture = function(name, points)
75     {
76         this.PointClouds[this.PointClouds.length] = new PointCloud(name,
77             ↳ points);
78         var num = 0;
79         for (var i = 0; i < this.PointClouds.length; i++) {
80             if (this.PointClouds[i].Name == name)
81                 num++;
82         }
83         return num;
84     }
85     this.RemoveGesture = function(name)
86     {
87         this.PointClouds = this.PointClouds.filter(pointCloud =>
88             ↳ pointCloud.Name !== name);
89     }
90 }

```

```

81     }
82     this.DeleteUserGestures = function()
83     {
84         this.PointClouds.length = NumPointClouds; // clears any beyond the
85         ↪ original set
86         return NumPointClouds;
87     }
88 //
89 // Private helper functions from here on down
90 //
91 function CloudDistance(pts1, pts2, minSoFar) // revised for $P+
92 {
93     var matched = new Array(pts1.length); // pts1.length == pts2.length
94     for (var k = 0; k < pts1.length; k++)
95         matched[k] = false;
96     var sum = 0;
97     for (var i = 0; i < pts1.length; i++)
98     {
99         var index = -1;
100        var min = +Infinity;
101        for (var j = 0; j < pts1.length; j++)
102        {
103            var d = DistanceWithAngle(pts1[i], pts2[j]);
104            if (d < min) {
105                min = d;
106                index = j;
107            }
108        }
109        matched[index] = true;
110        sum += min;
111        if (sum >= minSoFar) return sum; // early abandoning
112    }
113    for (var j = 0; j < matched.length; j++)
114    {
115        if (!matched[j]) {
116            var min = +Infinity;
117            for (var i = 0; i < pts1.length; i++) {
118                var d = DistanceWithAngle(pts1[i], pts2[j]);
119                if (d < min)
120                    min = d;
121            }
122            sum += min;
123            if (sum >= minSoFar) return sum; // early abandoning
124        }
125    }
126    return sum;
127 }
128 function Resample(points, n)
129 {
130     var I = PathLength(points) / (n - 1); // interval length

```

```

131     var D = 0.0;
132     var newpoints = new Array(points[0]);
133     for (var i = 1; i < points.length; i++)
134     {
135         if (points[i].ID == points[i-1].ID)
136         {
137             var d = Distance(points[i-1], points[i]);
138             if ((D + d) >= I)
139             {
140                 var qx = points[i-1].X + ((I - D) / d) *
141                     ↪ (points[i].X - points[i-1].X);
142                 var qy = points[i-1].Y + ((I - D) / d) *
143                     ↪ (points[i].Y - points[i-1].Y);
144                 var qz = points[i-1].Z + ((I - D) / d) * (points[i].Z -
145                     ↪ points[i-1].Z);
146                 var q = new Point(qx, qy, qz, points[i].ID);
147                 newpoints[newpoints.length] = q; // append new
148                     ↪ point 'q'
149                 points.splice(i, 0, q); // insert 'q' at position i
150                     ↪ in points s.t. 'q' will be the next i
151                 D = 0.0;
152             }
153             else D += d;
154         }
155     }
156     if (newpoints.length == n - 1) // sometimes we fall a rounding-error short
157         ↪ of adding the last point, so add it if so
158         newpoints[newpoints.length] = new Point(points[points.length -
159             ↪ 1].X, points[points.length - 1].Y, points[points.length - 1].Z,
160             ↪ points[points.length - 1].ID);
161     return newpoints;
162 }
163
164 function Scale(points)
165 {
166     var minX = +Infinity, maxX = -Infinity, minY = +Infinity, maxY = -Infinity,
167         ↪ minZ = +Infinity, maxZ = -Infinity;
168     for (var i = 0; i < points.length; i++) {
169         minX = Math.min(minX, points[i].X);
170         minY = Math.min(minY, points[i].Y);
171         minZ = Math.min(minZ, points[i].Z);
172         maxX = Math.max(maxX, points[i].X);
173         maxY = Math.max(maxY, points[i].Y);
174         maxZ = Math.max(maxZ, points[i].Z);
175     }
176     var size = Math.max(maxX - minX, maxY - minY, maxZ - minZ);
177     var newpoints = new Array();
178     for (var i = 0; i < points.length; i++) {
179         var qx = (points[i].X - minX) / size;
180         var qy = (points[i].Y - minY) / size;
181         var qz = (points[i].Z - minZ) / size;
182         newpoints[newpoints.length] = new Point(qx, qy, qz, points[i].ID);

```

```

173     }
174     return newpoints;
175 }
176 function TranslateTo(points, pt) // translates points' centroid
177 {
178     var c = Centroid(points);
179     var newpoints = new Array();
180     for (var i = 0; i < points.length; i++) {
181         var qx = points[i].X + pt.X - c.X;
182         var qy = points[i].Y + pt.Y - c.Y;
183         var qz = points[i].Z + pt.Z - c.Z;
184         newpoints[newpoints.length] = new Point(qx, qy, qz, points[i].ID);
185     }
186     return newpoints;
187 }
188 function ComputeNormalizedTurningAngles(points) // $P+
189 {
190     var newpoints = new Array();
191     newpoints[0] = new Point(points[0].X, points[0].Y, points[0].Z,
192         ↪ points[0].ID); // first point
193     for (var i = 1; i < points.length - 1; i++)
194     {
195         var dx = (points[i+1].X - points[i].X) * (points[i].X -
196             ↪ points[i-1].X);
197         var dy = (points[i+1].Y - points[i].Y) * (points[i].Y - points[i-1].Y);
198         var dz = (points[i+1].Z - points[i].Z) * (points[i].Z - points[i-1].Z);
199         var dn = Distance(points[i+1], points[i]) * Distance(points[i],
200             ↪ points[i-1]);
201         var cosangle = Math.max(-1.0, Math.min(1.0, (dx + dy + dz) / dn));
202         ↪ // ensure [-1,+1]
203         var angle = Math.acos(cosangle) / Math.PI; // normalized angle
204         newpoints[newpoints.length] = new Point(points[i].X, points[i].Y,
205             ↪ points[i].Z, points[i].ID, angle);
206     }
207     newpoints[newpoints.length] = new Point( // last point
208         points[points.length - 1].X,
209         points[points.length - 1].Y,
210         points[points.length - 1].Z,
211         points[points.length - 1].ID);
212     return newpoints;
213 }
214 function Centroid(points)
215 {
216     var x = 0.0, y = 0.0, z = 0.0;
217     for (var i = 0; i < points.length; i++) {
218         x += points[i].X;
219         y += points[i].Y;
220         z += points[i].Z;
221     }
222     x /= points.length;
223     y /= points.length;

```

```

219     z /= points.length;
220     return new Point(x, y, z, 0);
221 }
222 function PathLength(points) // length traversed by a point path
223 {
224     var d = 0.0;
225     for (var i = 1; i < points.length; i++) {
226         if (points[i].ID == points[i-1].ID)
227             d += Distance(points[i-1], points[i]);
228     }
229     return d;
230 }
231 function DistanceWithAngle(p1, p2) // $P+
232 {
233     var dx = p2.X - p1.X;
234     var dy = p2.Y - p1.Y;
235     var dz = p2.Z - p1.Z;
236     var da = p2.Angle - p1.Angle;
237     return Math.sqrt(dx * dx + dy * dy + dz * dz + da * da);
238 }
239 function Distance(p1, p2) // Euclidean distance between two points
240 {
241     var dx = p2.X - p1.X;
242     var dy = p2.Y - p1.Y;
243     var dz = p2.Z - p1.Z;
244     return Math.sqrt(dx * dx + dy * dy + dz * dz);
245 }
246
247 module.exports = {
248     Point,
249     P3DollarPlusRecognizer
250 };

```

recognizer.js

```

1  const AbstractRecognizer =
    ↪ require('../framework/recognizers/abstract-recognizer').AbstractRecognizer;
2  const P3DollarPlusRecognizer =
    ↪ require('./p3dollarplus/p3dollarplus').P3DollarPlusRecognizer;
3  const Point = require('./p3dollarplus/p3dollarplus').Point;
4
5  class Recognizer extends AbstractRecognizer {
6
7      static name = "P3DollarPlusRecognizer";
8
9      constructor(options, dataset) {
10         super();
11         this.samplingPoints = options.samplingPoints;
12         this.articulations = options.articulations;
13         this.recognizer = new P3DollarPlusRecognizer(this.samplingPoints);
14         if (dataset !== undefined){

```

```

15         dataset.getGestureClasses().forEach((gesture) => {
16             gesture.getSamples().forEach(sample => {
17                 this.addGesture(gesture.name,
18                     ↪ sample);
19             }
20         });
21     });
22 }
23
24 addGesture(name, sample) {
25     let points = convert(sample, this.articulations);
26     this.recognizer.AddGesture(name, points);
27 }
28
29 removeGesture(name) {
30     this.recognizer.RemoveGesture(name);
31 }
32
33 recognize(sample) {
34     let points = convert(sample, this.articulations);
35     if(points.length === 0) {
36         return { name: "", time: 0, score: 0.0 };
37     }
38     let result = this.recognizer.Recognize(points);
39     return (result.Name === "No match.") ? { name: "", time:
40         ↪ result.Time, score: result.Score } : { name: result.Name, time:
41         ↪ result.Time, score: result.Score };
42 }
43
44 toString() {
45     return `${Recognizer.name} [ samplingPoints = ${this.samplingPoints},
46         ↪ articulations = ${this.articulations} ]`;
47 }
48
49 }
50
51 function convert(sample, articulations) {
52     let points = [];
53     articulations.forEach((articulation, articulationID) => {
54         sample.paths[articulation].strokes.forEach((stroke, strokeId) => {
55             stroke.points.forEach((point) => {
56                 // If multipoint, one stroke per articulation,
57                 ↪ otherwise, keep original strokes
58                 let index = articulations.length > 1 ?
59                     ↪ articulationID : strokeId;
60                 points.push(new Point(point.x, point.y, point.z,
61                     ↪ index));
62             });
63         });
64     });
65 }

```



```

59         return points;
60     }
61
62
63     module.exports = {
64         Recognizer
65     };

```

F.7.4 $\$P^3+X$

p3dollarplusx.js

```

1  //
2  // Point class
3  //
4  function Point(x, y, z, id, angle = 0.0)
5  {
6      this.X = x;
7      this.Y = y;
8      this.Z = z;
9      this.ID = id;
10     this.Angle = angle; // normalized turning angle, $P+
11 }
12 //
13 // PointCloud class: a point-cloud template
14 //
15 function PointCloud(name, points) // constructor
16 {
17     this.Name = name;
18     this.Points = Resample(points, NumPoints);
19     this.Points = Scale(this.Points);
20     this.Points = TranslateTo(this.Points, Origin);
21     this.Points = ComputeNormalizedTurningAngles(this.Points); // $P+
22 }
23 //
24 // Result class
25 //
26 function Result(name, score, ms) // constructor
27 {
28     this.Name = name;
29     this.Score = score;
30     this.Time = ms;
31 }
32 //
33 // P3DollarPlusXRecognizer constants
34 //
35 var NumPoints = 32;
36 const Origin = new Point(0,0,0,0);
37 //
38 // P3DollarPlusXRecognizer class

```

```

39 //
40 function P3DollarPlusXRecognizer(numPoints) // constructor
41 {
42     this.PointClouds = new Array();
43     this.Conflicts = {};
44     NumPoints = numPoints;
45     //
46     // The $P+ Point-Cloud Recognizer API begins here -- 4 methods:
47     ↪ Recognize(), AddGesture(), RemoveGesture(), DeleteUserGestures()
48     //
49     this.Recognize = function(points)
50     {
51         var t0 = Date.now();
52         var candidate = new PointCloud("", points);
53         var {u, b} = this.RecognizeHelper(candidate);
54         if (u !== -1 &&
55             ↪ this.Conflicts.hasOwnProperty(this.PointClouds[u].Name)) {
56             let dirDist1 = DirDist(candidate.Points,
57                 ↪ this.PointClouds[u].Points);
58             let dirDist2 = DirDist(candidate.Points,
59                 ↪ this.PointClouds[this.Conflicts[this.PointClouds[u].Name].Index].Points);
60             u = dirDist1 > dirDist2 ? u :
61                 ↪ this.Conflicts[this.PointClouds[u].Name].Index;
62         }
63         var t1 = Date.now();
64         return (u === -1) ? new Result("No match.", 0.0, t1-t0) : new
65             ↪ Result(this.PointClouds[u].Name, b > 1.0 ? 1.0 / b : 1.0,
66                 ↪ t1-t0);
67     }
68     this.AddGesture = function(name, points)
69     {
70         var template = new PointCloud(name, points);
71         if (this.PointClouds.length > 0) {
72             const {u, b} = this.RecognizeHelper(template);
73             if (u !== -1 && this.PointClouds[u].Name !== name && (1.0 /
74                 ↪ b) > 0.8) {
75                 this.Conflicts[name] = {'Name':
76                     ↪ this.PointClouds[u].Name, 'Index': u};
77                 this.Conflicts[this.PointClouds[u].Name] =
78                     ↪ {'Name': name, 'Index':
79                         ↪ this.PointClouds.length};
80             }
81         }
82         this.PointClouds[this.PointClouds.length] = template;
83         var num = 0;
84         for (var i = 0; i < this.PointClouds.length; i++) {
85             if (this.PointClouds[i].Name === name)
86                 num++;
87         }
88         return num;
89     }
90 }

```

```

79  this.RemoveGesture = function(name)
80  {
81      this.PointClouds = this.PointClouds.filter(pointCloud =>
82          ↪ pointCloud.Name !== name);
83      // Remove entry in Conflicts
84      if (this.Conflicts.hasOwnProperty(name)) {
85          let otherGestureName = this.Conflicts[name].Name;
86          delete this.Conflicts[name];
87          delete this.Conflicts[otherGestureName];
88      }
89      this.DeleteUserGestures = function()
90      {
91          this.PointClouds.length = NumPointClouds; // clears any beyond the
92          ↪ original set
93          return NumPointClouds;
94      }
95      this.RecognizeHelper = function(pointCloud)
96      {
97          var u = -1;
98          var b = +Infinity;
99          for (var i = 0; i < this.PointClouds.length; i++) // for each
100          ↪ point-cloud template
101          {
102              var d = Math.min(
103                  CloudDistance(pointCloud.Points,
104                  ↪ this.PointClouds[i].Points, b),
105                  CloudDistance(this.PointClouds[i].Points,
106                  ↪ pointCloud.Points, b)
107              ); // $P+
108              if (d < b) {
109                  b = d; // best (least) distance
110                  u = i; // point-cloud index
111              }
112          }
113          return {u, b};
114      }
115  }
116  //
117  // Private helper functions from here on down
118  //
119  function CloudDistance(pts1, pts2, minSoFar) // revised for $P+
120  {
121      var matched = new Array(pts1.length); // pts1.length == pts2.length
122      for (var k = 0; k < pts1.length; k++)
123          matched[k] = false;
124      var sum = 0;
125      for (var i = 0; i < pts1.length; i++)
126      {
127          var index = -1;
128          var min = +Infinity;

```

```

125         for (var j = 0; j < pts1.length; j++)
126         {
127             var d = DistanceWithAngle(pts1[i], pts2[j]);
128             if (d < min) {
129                 min = d;
130                 index = j;
131             }
132         }
133         matched[index] = true;
134     sum += min;
135     if (sum >= minSoFar) return sum; // early abandoning
136 }
137 for (var j = 0; j < matched.length; j++)
138 {
139     if (!matched[j]) {
140         var min = +Infinity;
141         for (var i = 0; i < pts1.length; i++) {
142             var d = DistanceWithAngle(pts1[i], pts2[j]);
143             if (d < min)
144                 min = d;
145         }
146         sum += min;
147         if (sum >= minSoFar) return sum; // early abandoning
148     }
149 }
150 return sum;
151 }
152 function Resample(points, n)
153 {
154     var I = PathLength(points) / (n - 1); // interval length
155     var D = 0.0;
156     var newpoints = new Array(points[0]);
157     for (var i = 1; i < points.length; i++)
158     {
159         if (points[i].ID == points[i-1].ID)
160         {
161             var d = Distance(points[i-1], points[i]);
162             if ((D + d) >= I)
163             {
164                 var qx = points[i-1].X + ((I - D) / d) *
165                     ↪ (points[i].X - points[i-1].X);
166                 var qy = points[i-1].Y + ((I - D) / d) *
167                     ↪ (points[i].Y - points[i-1].Y);
168                 var qz = points[i-1].Z + ((I - D) / d) * (points[i].Z -
169                     ↪ points[i-1].Z);
170                 var q = new Point(qx, qy, qz, points[i].ID);
171                 newpoints[newpoints.length] = q; // append new
172                     ↪ point 'q'
173                 points.splice(i, 0, q); // insert 'q' at position i
174                     ↪ in points s.t. 'q' will be the next i
175                 D = 0.0;

```

```

171         }
172         else D += d;
173     }
174 }
175 if (newpoints.length == n - 1) // sometimes we fall a rounding-error short
    ↪ of adding the last point, so add it if so
176     newpoints[newpoints.length] = new Point(points[points.length -
    ↪ 1].X, points[points.length - 1].Y, points[points.length - 1].Z,
    ↪ points[points.length - 1].ID);
177     return newpoints;
178 }
179 function Scale(points)
180 {
181     var minX = +Infinity, maxX = -Infinity, minY = +Infinity, maxY = -Infinity,
    ↪ minZ = +Infinity, maxZ = -Infinity;
182     for (var i = 0; i < points.length; i++) {
183         minX = Math.min(minX, points[i].X);
184         minY = Math.min(minY, points[i].Y);
185         minZ = Math.min(minZ, points[i].Z);
186         maxX = Math.max(maxX, points[i].X);
187         maxY = Math.max(maxY, points[i].Y);
188         maxZ = Math.max(maxZ, points[i].Z);
189     }
190     var size = Math.max(maxX - minX, maxY - minY, maxZ - minZ);
191     var newpoints = new Array();
192     for (var i = 0; i < points.length; i++) {
193         var qx = (points[i].X - minX) / size;
194         var qy = (points[i].Y - minY) / size;
195         var qz = (points[i].Z - minZ) / size;
196         newpoints[newpoints.length] = new Point(qx, qy, qz, points[i].ID);
197     }
198     return newpoints;
199 }
200 function TranslateTo(points, pt) // translates points' centroid
201 {
202     var c = Centroid(points);
203     var newpoints = new Array();
204     for (var i = 0; i < points.length; i++) {
205         var qx = points[i].X + pt.X - c.X;
206         var qy = points[i].Y + pt.Y - c.Y;
207         var qz = points[i].Z + pt.Z - c.Z;
208         newpoints[newpoints.length] = new Point(qx, qy, qz, points[i].ID);
209     }
210     return newpoints;
211 }
212 function ComputeNormalizedTurningAngles(points) // $P+
213 {
214     var newpoints = new Array();
215     newpoints[0] = new Point(points[0].X, points[0].Y, points[0].Z,
    ↪ points[0].ID); // first point
216     for (var i = 1; i < points.length - 1; i++)

```

```

217     {
218         var dx = (points[i+1].X - points[i].X) * (points[i].X -
                ↪ points[i-1].X);
219     var dy = (points[i+1].Y - points[i].Y) * (points[i].Y - points[i-1].Y);
220     var dz = (points[i+1].Z - points[i].Z) * (points[i].Z - points[i-1].Z);
221     var dn = Distance(points[i+1], points[i]) * Distance(points[i],
                ↪ points[i-1]);
222     var cosangle = Math.max(-1.0, Math.min(1.0, (dx + dy + dz) / dn));
                ↪ // ensure [-1,+1]
223     var angle = Math.acos(cosangle) / Math.PI; // normalized angle
224     newpoints[newpoints.length] = new Point(points[i].X, points[i].Y,
                ↪ points[i].Z, points[i].ID, angle);
225     }
226     newpoints[newpoints.length] = new Point( // last point
227         points[points.length - 1].X,
228         points[points.length - 1].Y,
229         points[points.length - 1].Z,
230         points[points.length - 1].ID);
231     return newpoints;
232 }
233 function Centroid(points)
234 {
235     var x = 0.0, y = 0.0, z = 0.0;
236     for (var i = 0; i < points.length; i++) {
237         x += points[i].X;
238         y += points[i].Y;
239         z += points[i].Z;
240     }
241     x /= points.length;
242     y /= points.length;
243     z /= points.length;
244     return new Point(x, y, z, 0);
245 }
246 function PathLength(points) // length traversed by a point path
247 {
248     var d = 0.0;
249     for (var i = 1; i < points.length; i++) {
250         if (points[i].ID == points[i-1].ID)
251             d += Distance(points[i-1], points[i]);
252     }
253     return d;
254 }
255 function DistanceWithAngle(p1, p2) // $P+
256 {
257     var dx = p2.X - p1.X;
258     var dy = p2.Y - p1.Y;
259     var dz = p2.Z - p1.Z;
260     var da = p2.Angle - p1.Angle;
261     return Math.sqrt(dx * dx + dy * dy + dz * dz + da * da);
262 }
263 function Distance(p1, p2) // Euclidean distance between two points

```

```

264 {
265     var dx = p2.X - p1.X;
266     var dy = p2.Y - p1.Y;
267     var dz = p2.Z - p1.Z;
268     return Math.sqrt(dx * dx + dy * dy + dz * dz);
269 }
270 function DirDist(points1, points2)
271 {
272     const padding = 2;
273     let dist = 0;
274     for (var i = padding; i < NumPoints - (1 + padding); i+=1) {
275         let v1x = points1[i+1].X - points1[i].X;
276         let v1y = points1[i+1].Y - points1[i].Y;
277         let v1z = points1[i+1].Z - points1[i].Z;
278         let v2x = points2[i+1].X - points2[i].X;
279         let v2y = points2[i+1].Y - points2[i].Y;
280         let v2z = points2[i+1].Z - points2[i].Z;
281         dist += v1x * v2x + v1y * v2y + v1z * v2z;
282     }
283     return dist;
284 }
285
286 module.exports = {
287     Point,
288     P3DollarPlusXRecognizer
289 };

```

recognizer.js

```

1  const AbstractRecognizer =
    ↳ require('.././../framework/recognizers/abstract-recognizer').AbstractRecognizer;
2  const P3DollarPlusXRecognizer =
    ↳ require('./p3dollarplusx/p3dollarplusx').P3DollarPlusXRecognizer;
3  const Point = require('./p3dollarplusx/p3dollarplusx').Point;
4
5  class Recognizer extends AbstractRecognizer {
6
7      static name = "P3DollarPlusXRecognizer";
8
9      constructor(options, dataset) {
10         super();
11         this.samplingPoints = options.samplingPoints;
12         this.articulations = options.articulations;
13         this.recognizer = new P3DollarPlusXRecognizer(this.samplingPoints);
14         if (dataset !== undefined){
15             dataset.getGestureClasses().forEach((gesture) => {
16                 gesture.getSamples().forEach(sample => {
17                     this.addGesture(gesture.name,
18                         ↳ sample);
19                 });

```

```

20         });
21     }
22 }
23
24 addGesture(name, sample) {
25     let points = convert(sample, this.articulations);
26     this.recognizer.AddGesture(name, points);
27 }
28
29 removeGesture(name) {
30     this.recognizer.RemoveGesture(name);
31 }
32
33 recognize(sample) {
34     let points = convert(sample, this.articulations);
35     if(points.length < 2) {
36         return { name: "", time: 0, score: 0.0 };
37     }
38     let result = this.recognizer.Recognize(points);
39     return (result.Name === "No match.") ? { name: "", time:
        ↳ result.Time, score: result.Score } : { name: result.Name, time:
        ↳ result.Time, score: result.Score };
40 }
41
42 toString() {
43     return `${Recognizer.name} [ samplingPoints = ${this.samplingPoints},
        ↳ articulations = ${this.articulations} ]`;
44 }
45
46 }
47
48 function convert(sample, articulations) {
49     let points = [];
50     articulations.forEach((articulation, articulationID) => {
51         sample.paths[articulation].strokes.forEach((stroke, strokeId) => {
52             stroke.points.forEach((point) => {
53                 // If multipoint, one stroke per articulation,
54                 ↳ otherwise, keep original strokes
55                 let index = articulations.length > 1 ?
56                 ↳ articulationID : strokeId;
57                 points.push(new Point(point.x, point.y, point.z,
58                 ↳ index));
59             });
60         });
61     });
62     return points;
63 }
64
65 module.exports = {
66     Recognizer
67 };

```


F.7.5 \$Q³

q3dollar.js

```
1  //
2  // Point class
3  //
4  function Point(x, y, z, id) // constructor
5  {
6      this.X = x;
7      this.Y = y;
8      this.Z = z;
9      this.ID = id; // stroke ID to which this point belongs (1,2,3,etc.)
10     this.IntX = 0; // for indexing into the LUT
11     this.IntY = 0; // for indexing into the LUT
12     this.IntZ = 0; // for indexing into the LUT
13 }
14 //
15 // PointCloud class
16 //
17 function PointCloud(name, points) // constructor
18 {
19     this.Name = name;
20     this.Points = Resample(points, NumPoints);
21     this.Points = Scale(this.Points);
22     this.Points = TranslateTo(this.Points, Origin);
23     this.Points = MakeIntCoords(this.Points); // fills in (IntX, IntY, IntZ)
24     ↪ values
25     this.LUT = ComputeLUT(this.Points);
26 }
27 //
28 // Result class
29 //
30 function Result(name, score, ms) // constructor
31 {
32     this.Name = name;
33     this.Score = score;
34     this.Time = ms;
35 }
36 //
37 // Q3DollarRecognizer constants
38 //
39 let NumPoints = 32;
40 const Origin = new Point(0, 0, 0, 0);
41 const MaxIntCoord = 1024; // (IntX, IntY, IntZ) range from [0, MaxIntCoord - 1]
42 const LUTSize = 16; // default size of the lookup table is 16 x 16 x 16
43 const LUTScaleFactor = MaxIntCoord / LUTSize; // used to scale from (IntX, IntY,
44     ↪ IntZ) to LUT
45 //
```

```

44 // Q3DollarRecognizer class
45 //
46 function Q3DollarRecognizer(numPoints) // constructor
47 {
48     this.PointClouds = new Array();
49     NumPoints = numPoints;
50     //
51     // The $Q3 Point-Cloud Recognizer API begins here -- 4 methods:
52     ↪ Recognize(), AddGesture(), RemoveGesture(), DeleteUserGestures()
53     //
54     this.Recognize = function(points)
55     {
56         var t0 = Date.now();
57         var candidate = new PointCloud("", points);
58
59         var u = -1;
60         var b = +Infinity;
61         for (var i = 0; i < this.PointClouds.length; i++) // for each
62             ↪ point-cloud template
63         {
64             var d = CloudMatch(candidate, this.PointClouds[i], b);
65             if (d < b) {
66                 b = d; // best (least) distance
67                 u = i; // point-cloud index
68             }
69         }
70         var t1 = Date.now();
71         return (u == -1) ? new Result("No match.", 0.0, t1-t0) : new
72             ↪ Result(this.PointClouds[u].Name, b > 1.0 ? 1.0 / b : 1.0,
73             ↪ t1-t0);
74     }
75     this.AddGesture = function(name, points)
76     {
77         this.PointClouds.push(new PointCloud(name, points));
78         var num = 0;
79         for (var i = 0; i < this.PointClouds.length; i++) {
80             if (this.PointClouds[i].Name == name)
81                 num++;
82         }
83         return num;
84     }
85     this.RemoveGesture = function(name)
86     {
87         this.PointClouds = this.PointClouds.filter(pointCloud =>
88             ↪ pointCloud.Name !== name);
89     }
90     this.DeleteUserGestures = function()
91     {
92         this.PointClouds.length = NumPointClouds; // clears any beyond the
93             ↪ original set
94         return NumPointClouds;
95     }
96 }

```

```

89     }
90 }
91 //
92 // Private helper functions from here on down
93 //
94 function CloudMatch(candidate, template, minSoFar)
95 {
96     var n = candidate.Points.length;
97     var step = Math.floor(Math.pow(n, 0.5));
98
99     var LB1 = ComputeLowerBound(candidate.Points, template.Points, step,
100     ↪ template.LUT);
101     let LB2 = ComputeLowerBound(template.Points, candidate.Points, step,
102     ↪ candidate.LUT);
103
104     for (var i = 0, j = 0; i < n; i += step, j++) {
105         if (LB1[j] < minSoFar)
106             minSoFar = Math.min(minSoFar,
107             ↪ CloudDistance(candidate.Points, template.Points, i,
108             ↪ minSoFar));
109         if (LB2[j] < minSoFar)
110             minSoFar = Math.min(minSoFar,
111             ↪ CloudDistance(template.Points, candidate.Points, i,
112             ↪ minSoFar));
113     }
114     return minSoFar;
115 }
116
117 function CloudDistance(pts1, pts2, start, minSoFar)
118 {
119     var n = pts1.length;
120     var unmatched = new Array(); // indices for pts2 that are not matched
121     for (var j = 0; j < n; j++)
122         unmatched[j] = j;
123     var i = start; // start matching with point 'start' from pts1
124     var weight = n; // weights decrease from n to 1
125     var sum = 0.0; // sum distance between the two clouds
126     do
127     {
128         var u = -1;
129         var b = +Infinity;
130         for (var j = 0; j < unmatched.length; j++)
131         {
132             d = SqrEuclideanDistance(pts1[i], pts2[unmatched[j]]);
133             if (d < b) {
134                 b = d;
135                 u = j;
136             }
137         }
138         unmatched.splice(u, 1); // remove item at index 'u'
139         sum += weight * b;
140         if (sum >= minSoFar)

```

```

134         return sum; // early abandoning
135         weight--;
136         i = (i + 1) % n;
137     } while (i != start);
138     return sum;
139 }
140 function ComputeLowerBound(pts1, pts2, step, LUT)
141 {
142     var n = pts1.length;
143     var LB = new Array(Math.floor(n / step) + 1);
144     var SAT = new Array(n);
145     LB[0] = 0.0;
146     for (var i = 0; i < n; i++)
147     {
148         var x = Math.round(pts1[i].IntX / LUTScaleFactor);
149         var y = Math.round(pts1[i].IntY / LUTScaleFactor);
150         var z = Math.round(pts1[i].IntZ / LUTScaleFactor);
151         var index = LUT[x][y][z];
152         var d = SqrEuclideanDistance(pts1[i], pts2[index]);
153         SAT[i] = (i == 0) ? d : SAT[i - 1] + d;
154         LB[0] += (n - i) * d;
155     }
156     for (var i = step, j = 1; i < n; i += step, j++)
157         LB[j] = LB[0] + i * SAT[n-1] - n * SAT[i-1];
158     return LB;
159 }
160 function Resample(points, n)
161 {
162     var I = PathLength(points) / (n - 1); // interval length
163     var D = 0.0;
164     var newpoints = new Array(points[0]);
165     for (var i = 1; i < points.length; i++)
166     {
167         if (points[i].ID == points[i-1].ID)
168         {
169             var d = EuclideanDistance(points[i-1], points[i]);
170             if ((D + d) >= I)
171             {
172                 var qx = points[i-1].X + ((I - D) / d) *
173                     ↪ (points[i].X - points[i-1].X);
174                 var qy = points[i-1].Y + ((I - D) / d) *
175                     ↪ (points[i].Y - points[i-1].Y);
176                 var qz = points[i-1].Z + ((I - D) / d) *
177                     ↪ (points[i].Z - points[i-1].Z);
178                 var q = new Point(qx, qy, qz, points[i].ID);
179                 newpoints[newpoints.length] = q; // append new
180                     ↪ point 'q'
181                 points.splice(i, 0, q); // insert 'q' at position i
182                     ↪ in points s.t. 'q' will be the next i
183                 D = 0.0;
184             }
185         }
186     }

```

```

180         else D += d;
181     }
182 }
183 if (newpoints.length == n - 1) // sometimes we fall a rounding-error short
    ↪ of adding the last point, so add it if so
184     newpoints[newpoints.length] = new Point(points[points.length -
    ↪ 1].X, points[points.length - 1].Y, points[points.length - 1].Z,
    ↪ points[points.length - 1].ID);
185     return newpoints;
186 }
187 function Scale(points)
188 {
189     var minX = +Infinity, maxX = -Infinity, minY = +Infinity, maxY = -Infinity,
    ↪ minZ = +Infinity, maxZ = -Infinity;
190     for (var i = 0; i < points.length; i++) {
191         minX = Math.min(minX, points[i].X);
192         minY = Math.min(minY, points[i].Y);
193         minZ = Math.min(minZ, points[i].Z);
194         maxX = Math.max(maxX, points[i].X);
195         maxY = Math.max(maxY, points[i].Y);
196         maxZ = Math.max(maxZ, points[i].Z);
197     }
198     var size = Math.max(maxX - minX, maxY - minY, maxZ - minZ);
199     var newpoints = new Array();
200     for (var i = 0; i < points.length; i++) {
201         var qx = (points[i].X - minX) / size;
202         var qy = (points[i].Y - minY) / size;
203         var qz = (points[i].Z - minZ) / size;
204         newpoints[newpoints.length] = new Point(qx, qy, qz, points[i].ID);
205     }
206     return newpoints;
207 }
208 function TranslateTo(points, pt) // translates points' centroid to pt
209 {
210     var c = Centroid(points);
211     var newpoints = new Array();
212     for (var i = 0; i < points.length; i++) {
213         var qx = points[i].X + pt.X - c.X;
214         var qy = points[i].Y + pt.Y - c.Y;
215         var qz = points[i].Z + pt.Z - c.Z;
216         newpoints[newpoints.length] = new Point(qx, qy, qz, points[i].ID);
217     }
218     return newpoints;
219 }
220 function Centroid(points)
221 {
222     var x = 0.0, y = 0.0, z = 0.0;
223     for (var i = 0; i < points.length; i++) {
224         x += points[i].X;
225         y += points[i].Y;
226         z += points[i].Z;

```

```

227     }
228     x /= points.length;
229     y /= points.length;
230     z /= points.length;
231     return new Point(x, y, z, 0);
232 }
233 function PathLength(points) // length traversed by a point path
234 {
235     var d = 0.0;
236     for (var i = 1; i < points.length; i++) {
237         if (points[i].ID == points[i-1].ID)
238             d += EuclideanDistance(points[i-1], points[i]);
239     }
240     return d;
241 }
242 function MakeIntCoords(points)
243 {
244     for (var i = 0; i < points.length; i++) {
245         points[i].IntX = Math.round((points[i].X + 1.0) / 2.0 *
246             ↪ (MaxIntCoord - 1));
247         points[i].IntY = Math.round((points[i].Y + 1.0) / 2.0 *
248             ↪ (MaxIntCoord - 1));
249         points[i].IntZ = Math.round((points[i].Z + 1.0) / 2.0 * (MaxIntCoord - 1));
250     }
251     return points;
252 }
253 function ComputeLUT(points)
254 {
255     var LUT = new Array();
256     for (var i = 0; i < LUTSize; i++) {
257         LUT[i] = new Array();
258         for (var j = 0; j < LUTSize; j++) {
259             LUT[i][j] = new Array();
260         }
261     }
262     for (var x = 0; x < LUTSize; x++)
263     {
264         for (var y = 0; y < LUTSize; y++)
265         {
266             for (var z = 0; z < LUTSize; z++)
267             {
268                 var u = -1;
269                 var b = +Infinity;
270                 for (var i = 0; i < points.length; i++)
271                 {
272                     var row = Math.round(points[i].IntX / LUTScaleFactor);
273                     var col = Math.round(points[i].IntY / LUTScaleFactor);
274                     var layer = Math.round(points[i].IntZ / LUTScaleFactor);
275                     var d = ((row - x) * (row - x)) + ((col - y) * (col - y)) +
276                         ↪ ((layer - z) * (layer - z));

```

```

275         if (d < b) {
276             b = d;
277             u = i;
278         }
279     }
280     LUT[x][y][z] = u;
281 }
282 }
283 }
284     return LUT;
285 }
286 function SqrEuclideanDistance(pt1, pt2)
287 {
288     var dx = pt2.X - pt1.X;
289     var dy = pt2.Y - pt1.Y;
290     var dz = pt2.Z - pt1.Z;
291     return (dx * dx + dy * dy + dz * dz);
292 }
293 function EuclideanDistance(pt1, pt2)
294 {
295     var s = SqrEuclideanDistance(pt1, pt2);
296     return Math.sqrt(s);
297 }
298
299 module.exports = {
300     Q3DollarRecognizer,
301     Point
302 }

```

recognizer.js

```

1  const AbstractRecognizer =
    ↪ require('../framework/recognizers/abstract-recognizer').AbstractRecognizer;
2  const Q3DollarRecognizer = require('./q3dollar/q3dollar').Q3DollarRecognizer;
3  const Point = require('./q3dollar/q3dollar').Point;
4
5  class Recognizer extends AbstractRecognizer {
6
7      static name = "Q3DollarRecognizer";
8
9      constructor(options, dataset) {
10         super();
11         this.samplingPoints = options.samplingPoints;
12         this.articulations = options.articulations;
13         this.recognizer = new Q3DollarRecognizer(this.samplingPoints);
14         if (dataset !== undefined){
15             dataset.getGestureClasses().forEach((gesture) => {
16                 gesture.getSamples().forEach(sample => {
17                     this.addGesture(gesture.name,
18                         ↪ sample);
19                 }

```

```

19         );
20     });
21 }
22 }
23
24 addGesture(name, sample) {
25     let points = convert(sample, this.articulations);
26     this.recognizer.AddGesture(name, points);
27 }
28
29 removeGesture(name) {
30     this.recognizer.RemoveGesture(name);
31 }
32
33 recognize(sample) {
34     let points = convert(sample, this.articulations);
35     if(points.length === 0) {
36         return { name: "", time: 0, score: 0.0 };
37     }
38     let result = this.recognizer.Recognize(points);
39     return (result.Name === "No match.") ? { name: "", time:
        ↳ result.Time, score: result.Score } : { name: result.Name, time:
        ↳ result.Time, score: result.Score };
40 }
41
42 toString() {
43     return `${Recognizer.name} [ samplingPoints = ${this.samplingPoints},
        ↳ articulations = ${this.articulations} ]`;
44 }
45
46 }
47
48 function convert(sample, articulations) {
49     let points = [];
50     articulations.forEach((articulation, articulationID) => {
51         sample.paths[articulation].strokes.forEach((stroke, strokeId) => {
52             stroke.points.forEach((point) => {
53                 // If multipoint, one stroke per articulation,
54                 ↳ otherwise, keep original strokes
55                 let index = articulations.length > 1 ?
56                 ↳ articulationID : strokeId;
57                 points.push(new Point(point.x, point.y, point.z,
58                 ↳ index));
59             });
60         });
61     });
62     return points;
63 }
64
65 module.exports = {

```



```

64 Recognizer
65 };

```

F.7.6 Jackknife

The official JavaScript source code of Jackknife is available on GitHub¹.

recognizer.js

```

1  const AbstractRecognizer =
    ↪ require('../framework/recognizers/abstract-recognizer').AbstractRecognizer;
2  const jackknife_blades = require('./jackknife/jackknife').jackknife_blades;
3  const Jackknife = require('./jackknife/jackknife_recognizer').Jackknife;
4  const Vector = require('./jackknife/vector').Vector;
5  const Sample = require('./jackknife/sample').Sample;
6
7  class Recognizer extends AbstractRecognizer {
8
9      static name = "JackknifeRecognizer";
10
11     constructor(options, dataset) {
12         super();
13         this.N = options.samplingPoints;
14         this.articulations = options.articulations;
15         let blades = new jackknife_blades();
16         blades.set_ip_defaults();
17         this.jackknifeRecognizer = new Jackknife(blades)
18             if (dataset !== undefined){
19                 dataset.getGestureClasses().forEach((gesture) => {
20                     gesture.getSamples().forEach(sample => {
21                         this.addGesture(gesture.name,
22                             ↪ sample, false);
23                     });
24                 });
25         this.jackknifeRecognizer.train(6, 2, 1.0);
26     }
27 }
28
29 addGesture(name, sample, train = false) {
30     let jackknifeSample = convert(sample, this.articulations, name);
31     if (jackknifeSample) {
32         this.jackknifeRecognizer.add_template(jackknifeSample);
33         if (train) {
34             this.jackknifeRecognizer.train(6, 2, 1.0);
35         }
36     }
37 }

```

¹<https://github.com/ISUE/Jackknife>

```

38
39 removeGesture(name) {
40     console.log("Cannot remove gesture!");
41 }
42
43 recognize(sample) {
44     let jackknifeSample = convert(sample, this.articulations);
45     if (!jackknifeSample) {
46         return { name: "", time: 0.0 };
47     }
48     let t0 = Date.now();
49     let ret = this.jackknifeRecognizer.classify(jackknifeSample);
50     let t1 = Date.now();
51     return (ret == -1) ? { name: "", time: t1-t0 } : { name: ret, time:
        ↪ t1-t0 };
52 }
53
54 toString() {
55     return `${Recognizer.name} [ samplingPoints = ${this.N} ]`;
56 }
57 }
58
59 function convert(sample, articulations, name) {
60     let jackknifeSample;
61     if (name) {
62         jackknifeSample = new Sample(0, name);
63     } else {
64         jackknifeSample = new Sample();
65     }
66     // check min distance START
67     let maxMovement = 0;
68     let threshold = 40;
69     let initPoints = {};
70     for (const articulation of articulations) {
71         initPoints[articulation] = sample.paths[articulation].strokes[0].points[0];
72     }
73     // check min distance END
74     let nFrames = sample.paths[articulations[0]].strokes[0].points.length;
75     let trajectory = [];
76     for (let i = 0; i < nFrames; i++) {
77         let vCoordinates = [];
78         for (const articulation of articulations) {
79             let point = sample.paths[articulation].strokes[0].points[i];
80             // check min distance START
81             let articulationMovement = distance(point, initPoints[articulation]);
82             maxMovement = Math.max(maxMovement, articulationMovement);
83             // check min distance END
84             vCoordinates.push(point.x);
85             vCoordinates.push(point.y);
86             vCoordinates.push(point.z);
87         }

```

```

88     trajectory.push(new Vector(vCoordinates));
89 }
90 jackknifeSample.add_trajectory(trajectory);
91 return maxMovement > threshold ? jackknifeSample : null;
92 }
93
94 function distance(p1, p2) // Euclidean distance between two points
95 {
96     var dx = p2.x - p1.x;
97     var dy = p2.y - p1.y;
98     var dz = p2.z - p1.z;
99     return Math.sqrt(dx * dx + dy * dy + dz * dz);
100 }
101
102 module.exports = {
103     Recognizer
104 };

```

F.8 Large User Interface

Please note that we only show the files that we have modified. The complete source code is available on my GitHub repository².

F.8.1 Welcome Screen

Intro.jsx

```
1  import React, { Component } from 'react';
2  import backdrop from './backdrop.png';
3  import './Intro.css';
4  import { css } from 'glamor';
5  import glamorous from 'glamorous'
6  import { withStyles } from '@material-ui/core/styles';
7  import Particles from 'react-particles-js';
8  import { Redirect } from 'react-router';
9  import Button from '@material-ui/core/Button';
10 import Home from '@material-ui/icons/Home';
11 import Leap from './leap.js';
12 import LeapMotion from 'leapjs';
13 // import Leap from './leap.js';
14 //firebase
15 import * as firebase from "firebase/app";
16 import "firebase/database";
17 const firebaseConfig = {
18   apiKey: "AIzaSyDjM37_DSv2RvPQzl5YiVzmgRHfpd4rJFU",
19   authDomain: "lui-medialab.firebaseio.com",
20   databaseURL: "https://lui-medialab.firebaseio.com",
21   projectId: "lui-medialab",
22   storageBucket: "lui-medialab.appspot.com",
23   messagingSenderId: "247289397118",
24   appId: "1:247289397118:web:eb2bcb0076d4bb4d"
25 };
26
27 if (!firebase.apps.length) {
28   firebase.initializeApp(firebaseConfig);
29 }
30 var database = firebase.database();
31 var currentRef = database.ref('voice');
32 //end
33
34 const particleOpt = require('./particles.json');
35
36 const fadeIn = css.keyframes({
37   '0%': { opacity: 0 },
38   '100%': { opacity: 1 }
39 })
40
```

²<https://github.com/sluyters/LUI>

```

41  const slideOut = css.keyframes({
42    '100%': { transform: 'translateX(-100%)' },
43  })
44
45  const fingers = ["#9bcfed", "#B2EBF2", "#80DEEA", "#4DD0E1", "#26C6DA"];
46
47
48  const styles = {
49
50    backDrop: {
51      width: '100%',
52      height: '100%',
53    },
54
55    canvas: {
56      position: 'absolute',
57      height: '100%',
58      width: '100%',
59      zIndex: 0,
60      pointerEvents: 'none',
61    },
62
63    // "::selection": {
64    //   background: "rgba(0,0,0,0)"
65    // },
66
67    button: {
68      position: 'fixed',
69      bottom: '10px',
70      left: '10px',
71      zIndex: 10,
72      color: "rgba(255,255,255,0.3)",
73      backgroundColor: "rgba(255,255,255,0.1)"
74    },
75  };
76
77  //Animations for entering/exiting the page:
78  const Wrapper = glamorous.div(props => ({
79    animation: props.isMounted ? `${fadeIn} 1s` : props.page === "app" ? '' :
80      ↳ `${fadeIn} 4s`,
81    position: 'absolute',
82    top: '0px',
83    left: '0px',
84    width: '100vw',
85    height: '100vh',
86    zIndex: 5
87  })))
88
89  class Intro extends Component {
90    constructor(props) {
91      super(props);

```

```

91
92     this.state = {
93         exit: false,
94     };
95 }
96
97 componentDidMount() {
98     //google home
99     currentRef.update({"current": "landing"});
100     var something = this;
101     currentRef.on('value', function(snapshot) {
102         console.log(snapshot.val());
103         var db = snapshot.val();
104         var name = db.goto;
105         if (db.update){
106             if (name === "home") {
107                 something.setState({ exit: true });
108                 currentRef.update({"update": false});
109             }
110         }
111     });
112 }
113
114 handleClick = () => {
115     console.log("clicked")
116 }
117 handleSwipeUp = () => {
118     let { clicked } = this.state;
119     if (clicked !== -1) {
120         this.setState({ clicked: -1 });
121         this.getPhotos();
122     } else {
123         this.setState({ exit: true });
124     }
125 }
126 handleExit = () => {
127     this.setState({
128         exit: true
129     })
130 }
131
132 render() {
133     const { classes } = this.props;
134     // Handling redirecting to home screen:
135     if (this.state.exit) {
136         console.log("EXITING")
137         return <Redirect to={{ pathname: "/Home", state: {page: "home"} }} />
138     }
139     if (this.props.page == "intro") {
140         return (
141             <Wrapper isMounted={this.props.isMounted} page={this.props.page}>

```

```

142     <div>
143
144         {/* <canvas className={classes.canvas} ref="canvas"></canvas> */}
145         <Leap
146             handleClick={this.handleClick}
147             handleSwipeUp={this.handleSwipeUp}
148             handleExit={this.handleExit}
149         />
150
151         <div className={classes.backDrop} >
152             {/* <input ref={input => this.inputElement = input} > */}
153
154             {/* Component that renders the interactive particles.js: */}
155             <Particles
156                 params={particleOpt}
157                 style={{ zIndex: 5, position: 'absolute' }}
158             />
159
160             {/* </input> */}
161         </div>
162
163         {/* Rendering the backdrop: */}
164         <div >
165             <img className={classes.backDrop} src={backDrop} style={{ zIndex: 1,
166                 ↪ position: 'absolute' }} />
167         </div>
168
169         {/* Home button: */}
170         <Button onClick={() => this.handleExit()} className={classes.button}>
171             <Home/>
172         </Button>
173
174     </Wrapper>
175 );
176 } else {
177     return null;
178 }
179 }
180
181 }
182
183 export default withStyles(styles)(Intro);

```

leap.js

```

1  import PropTypes from 'prop-types';
2  import React from 'react';
3  import ReactDOM from 'react-dom';
4  import { withStyles } from '@material-ui/core/styles';
5  import GestureHandler from '../gesture-interface/app-interface';

```

```

6  import { Fade } from '@material-ui/core';
7
8  const fingers = ["#9bcfed", "#B2EBF2", "#80DEEA", "#4DD0E1", "#26C6DA"];
9  const paused_fingers = ["#9bed9b", "#b1f0b1", "#80ea80", "#4ce14c", "#25da25"];
10
11  const styles = {
12    canvas: {
13      position: 'absolute',
14      height: '100%',
15      width: '100%',
16      zIndex: 100,
17      pointerEvents: 'none'
18    }
19  };
20
21  class Leap extends React.Component {
22    constructor(props) {
23      super(props)
24      this.state = {
25        frame: {},
26        hand: "",
27        indexFinger: "",
28      }
29    }
30
31    componentDidMount() {
32      this.gestureHandler = new GestureHandler();
33      this.gestureHandler.onEachGesture(function (gesture) {
34        console.log(gesture);
35        this.setState({ pause: 4 });
36      }).bind(this));
37      this.gestureHandler.onGesture("rhand_uswipe", function () {
38        this.props.handleExit();
39      }).bind(this));
40      this.gestureHandler.onGesture("rindex_airtap", function () {
41        this.props.handleClick();
42      }).bind(this));
43      this.gestureHandler.onFrame(function (frame) {
44        this.traceFingers(frame.fingers);
45      }).bind(this));
46      this.timer = setInterval(() => {
47        if (this.state.pause > 0) {
48          this.setState({ pause: this.state.pause - 1 });
49        }
50      }, 100);
51    }
52
53    componentWillUnmount() {
54      console.log("Intro leap is unmounted")
55      clearInterval(this.timer);
56      this.gestureHandler.disconnect();

```



```

57 }
58
59 traceFingers(pointables) {
60   try {
61     // TODO: make canvas and ctx global
62     const canvas = this.refs.canvas;
63     canvas.width = canvas.clientWidth;
64     canvas.height = canvas.clientHeight;
65     const ctx = canvas.getContext("2d");
66     ctx.clearRect(0, 0, canvas.width, canvas.height);
67     const { pause } = this.state;
68     pointables.forEach((pointable) => {
69       const color = pause > 0 ? paused_fingers[pointable.type] :
70         ↪ fingers[pointable.type];
71       const normalized = pointable.normalizedPosition;
72       const x = ctx.canvas.width * normalized[0];
73       const y = ctx.canvas.height * (1 - normalized[1]);
74       const radius = Math.min(20 / Math.abs(pointable.touchDistance),
75         ↪ 50);
76       this.drawCircle([x, y], radius, color, pointable.type === 1);
77
78       if (pointable.type === 1) {
79         this.setState({
80           indexFinger: { x, y, vel: pointable.tipVelocity[2] }
81         });
82       }
83     });
84   } catch (err) {
85     // console.log("ERR", err);
86   }
87 }
88
89 drawCircle(center, radius, color, fill) {
90   const canvas = this.refs.canvas;
91   const ctx = canvas.getContext("2d");
92   ctx.beginPath();
93   ctx.arc(center[0], center[1], radius, 0, 2 * Math.PI);
94   ctx.closePath();
95   ctx.lineWidth = 10;
96   if (fill) {
97     ctx.fillStyle = color;
98     ctx.fill();
99   } else {
100     ctx.strokeStyle = color;
101     ctx.stroke();
102   }
103 }
104
105 render() {
106   const { classes } = this.props;

```

```

106         return (
107             <canvas className={classes.canvas} ref="canvas"></canvas>
108         )
109     }
110 }
111
112 Leap.propTypes = {
113     handleUnlock: PropTypes.func
114 };
115
116 // TODO: better default values
117 Leap.defaultProps = {
118
119 };
120
121
122 export default withStyles(styles)(Leap);

```

F.8.2 App Menu

leap.js

```

1  import PropTypes from 'prop-types';
2  import React from 'react';
3  import ReactDOM from 'react-dom';
4  import { withStyles } from '@material-ui/core/styles';
5  import GestureHandler from '../gesture-interface/app-interface' // Added
6
7  const fingers = ["#9bcfed", "#B2EBF2", "#80DEEA", "#4DD0E1", "#26C6DA"];
8  const paused_fingers = ["#9bed9b", "#b1f0b1", "#80ea80", "#4ce14c", "#25da25"];
9
10 const styles = {
11     canvas: {
12         position: 'absolute',
13         height: '100%',
14         width: '100%',
15         zIndex: 10,
16         pointerEvents: 'none'
17     }
18 };
19
20
21 class Leap extends React.Component {
22     constructor(props) {
23         super(props)
24         this.state = {
25             hand: false,
26             indexFinger: "",
27             hovered: "",
28             clicked: "",

```

```

29     pause: 4
30   }
31 }
32
33 componentDidMount() {
34   this.gestureHandler = new GestureHandler();
35   this.gestureHandler.onEachGesture(function (gesture) {
36     console.log(gesture);
37     this.setState({ pause: 4 });
38   }.bind(this));
39   this.gestureHandler.onGesture("rhand_uswipe", function () {
40     this.props.handleSwipeUp();
41   }.bind(this));
42   this.gestureHandler.onGesture("rindex_airtap", function () {
43     var { hovered } = this.state;
44     this.setState({ clicked: hovered })
45     this.props.handleClick(hovered);
46   }.bind(this));
47   this.gestureHandler.onFrame(function (frame) {
48     if (frame.fingers.length != 0) {
49       this.setState({ hand: true });
50     } else {
51       this.setState({ hand: false });
52     }
53     this.traceFingers(frame.fingers);
54   }.bind(this));
55   this.timer = setInterval(() => {
56     if (this.state.pause > 0) {
57       this.setState({ pause: this.state.pause - 1 });
58     }
59     if (this.state.hand) {
60       var { hovered } = this.state;
61       // hovering
62       hovered = this.checkHover();
63       this.setState({ hovered });
64       this.props.handleHover(hovered);
65     }
66   }, 100);
67 }
68
69 componentWillUnmount() {
70   clearInterval(this.timer);
71   this.gestureHandler.disconnect();
72 }
73
74 traceFingers(pointables) {
75   try {
76     // TODO: make canvas and ctx global
77     const canvas = this.refs.canvas;
78     canvas.width = canvas.clientWidth;
79     canvas.height = canvas.clientHeight;

```

```

80     const ctx = canvas.getContext("2d");
81     ctx.clearRect(0, 0, canvas.width, canvas.height);
82
83     const { pause } = this.state;
84
85     pointables.forEach((pointable) => {
86         const color = pause > 0 ? paused_fingers[pointable.type] :
87             ↪ fingers[pointable.type];
88         const normalized = pointable.normalizedPosition;
89         const x = ctx.canvas.width * normalized[0];
90         const y = ctx.canvas.height * (1 - normalized[1]);
91         const radius = Math.min(20 / Math.abs(pointable.touchDistance),
92             ↪ 50);
93         this.drawCircle([x, y], radius, color, pointable.type === 1);
94
95         if (pointable.type === 1) {
96             this.setState({
97                 indexFinger: { x, y, vel: pointable.tipVelocity[2] }
98             })
99         }
100     });
101 } catch (err) {
102     // console.log("ERR", err);
103 }
104
105 drawCircle(center, radius, color, fill) {
106     const canvas = this.refs.canvas;
107     const ctx = canvas.getContext("2d");
108     ctx.beginPath();
109     ctx.arc(center[0], center[1], radius, 0, 2 * Math.PI);
110     ctx.closePath();
111     ctx.lineWidth = 10;
112     if (fill) {
113         ctx.fillStyle = color;
114         ctx.fill();
115     } else {
116         ctx.strokeStyle = color;
117         ctx.stroke();
118     }
119 }
120
121 checkHover() {
122     // calculate location of cards
123     const cards = this.props.cards;
124     const { x, y } = this.state.indexFinger;
125     for (let i = 0; i < cards.length; i++) {
126         if (cards[i]) {
127             const dims =
128                 ↪ ReactDOM.findDOMNode(cards[i]).getBoundingClientRect();
129             if (x > dims.left && x < dims.right &&

```

```

128         y > dims.top && y < dims.bottom) {
129             return ("card" + String(i + 1));
130         }
131     }
132 }
133 return ("");
134 }
135
136 render() {
137     const { classes } = this.props;
138     return (
139         <canvas className={classes.canvas} ref="canvas"></canvas>
140     )
141 }
142 }
143
144
145 Leap.propTypes = {
146     cards: PropTypes.array,
147     handleHover: PropTypes.func,
148     handleClick: PropTypes.func,
149     handleExit: PropTypes.func
150 };
151
152 // TODO: better default values
153 Leap.defaultProps = {
154
155 };
156
157 export default withStyles(styles)(Leap);

```

F.8.3 Videos App

VideosApp.jsx

```

1  import React, { Component } from 'react';
2  import { Grid } from '@material-ui/core';
3  import { withStyles } from '@material-ui/core/styles';
4  import classNames from 'classnames';
5  import YouTube from 'react-youtube';
6  import Leap from './leap.js'
7  import { Redirect } from 'react-router';
8  import glamorous from 'glamorous'
9  import { css } from 'glamor';
10 import SwipeableViews from 'react-swipeable-views';
11 import MobileStepper from '@material-ui/core/MobileStepper';
12 import Button from '@material-ui/core/Button';
13 import KeyboardArrowLeft from '@material-ui/icons/KeyboardArrowLeft';
14 import KeyboardArrowRight from '@material-ui/icons/KeyboardArrowRight';
15 import Home from '@material-ui/icons/Home';

```

```

16 //add firebase
17 import * as firebase from "firebase/app";
18 import "firebase/database";
19 import Clear from '@material-ui/icons/Clear';
20
21
22 const zoomIn = css.keyframes({
23   '0%': { transform: 'scale(0.5)' },
24   '100%': { transform: 'scale(1)' }
25 })
26 //firebase
27 const firebaseConfig = {
28   apiKey: "AIzaSyDjM37_DSv2RvPQzl5YiVzmgRHfpd4rJFU",
29   authDomain: "lui-medialab.firebaseio.com",
30   databaseURL: "https://lui-medialab.firebaseio.com",
31   projectId: "lui-medialab",
32   storageBucket: "lui-medialab.appspot.com",
33   messagingSenderId: "247289397118",
34   appId: "1:247289397118:web:eb2bcb0076d4bb4d"
35 };
36
37 if (!firebase.apps.length) {
38   firebase.initializeApp(firebaseConfig);
39 }
40 var database = firebase.database();
41 var currentRef = database.ref('voice');
42 //end
43
44 const styles = {
45
46   gallery: {
47     animation: `${zoomIn} 0.5s`,
48     maxHeight: '95vh',
49   },
50
51   carousel: {
52     // width: '90%',
53     maxHeight: '95vh',
54     padding: '0px',
55     margin: '0px',
56     overflow: 'hidden',
57     backgroundColor: 'rgba(0,0,0,0)',
58   },
59
60   row: {
61     height: '30%',
62     margin: '2%'
63   },
64
65   cell: {
66     display: 'inline-block',

```

```

67     width: '100%',
68     height: '100%',
69     verticalAlign: 'middle',
70     boxSizing: 'border-box',
71     margin: '0px',
72     position: 'relative',
73 },
74
75 container: {
76     position: 'absolute',
77     top: '0px',
78     left: '0px',
79     width: '100%',
80     height: '100%',
81     padding: '0px',
82     listStyle: 'none',
83     overflow: 'none',
84     zIndex: '1',
85     backgroundColor: '#ECEFF1',
86     overflow: 'hidden',
87 },
88
89 frameContainer: {
90     display: 'block',
91     width: '25vw',
92     height: '27vh',
93     verticalAlign: 'middle',
94     // boxSizing: 'border-box',
95     padding: '0px',
96     // margin: '1.5vw',
97     // transform: 'scale(1)',
98     // transition: '200ms',
99     // border: '2px solid #37474F',
100    boxShadow: '0px 0px 10px 2px #999',
101    overflow: 'hidden',
102    position: 'relative',
103    zIndex: 5
104    // pointerEvents: 'none'
105 },
106
107 zoomed: {
108     width: '100vw',
109     height: '93vh',
110     // top: '0px',
111     // left: '0px',
112     // position: 'fixed',
113     // zIndex: '100',
114 },
115
116 hovered: {
117     transform: 'scale(1.15)',

```

```

118     transition: '200ms ease-out',
119     position: 'relative',
120     zIndex: 5,
121 },
122
123 stepper: {
124     // display: 'auto',
125     marginLeft: 'auto',
126     marginRight: 'auto',
127     width: '8em',
128     backgroundColor: 'rgba(0,0,0,0)',
129     position: "absolute",
130     bottom: "1px",
131 },
132
133 dots: {
134     margin: 'auto',
135 },
136
137 button: {
138     position: 'fixed',
139     bottom: '10px',
140     left: '10px',
141     color: "rgba(50,50,50,0.8)",
142 },
143
144 xbutton: {
145     position: 'fixed',
146     bottom: '10px',
147     right: '10px',
148     color: "rgba(50,50,50,0.8)",
149 },
150
151 cover: {
152     display: 'block',
153     width: '25vw',
154     height: '27px',
155     // verticalAlign: 'middle',
156     // boxSizing: 'border-box',
157     padding: '0px',
158     // margin: '1.5vw',
159     // transform: 'scale(1)',
160     // transition: '200ms',
161     // border: '2px solid #37474F',
162     boxShadow: '0px 0px 10px 2px #999',
163     overflow: 'hidden',
164     zIndex: 50,
165     position: 'absolute',
166     pointerEvents: 'none'
167 },
168

```



```

169 // row: {
170 //   pointerEvents: "none"
171 // }
172
173 };
174
175 const videos = [
176   { id: 'rnlCGw-OR8g' },
177   { id: 'zw47_q9wbBE' },
178   { id: '7m6J8W6Ib4w' },
179   { id: 'l7uuTnk69Eo' },
180   { id: '6ZfuNTqbHE8' },
181   { id: '_8w9rOpV3gc' },
182   { id: 'c-SE2Qeqj1g' },
183   { id: '-AbaV3nrw6E' },
184   { id: 'FTPmnZVgDjQ' },
185   { id: 'dQw4w9WgXcQ' },
186   { id: 'Xnk4seEHmgw' },
187   { id: '5G1C3aBY62E' }
188 ]
189
190 const opts = {
191   height: '350',
192   width: '500',
193   playerVars: { // https://developers.google.com/youtube/player_parameters
194     autoplay: 0,
195     controls: 0
196   }
197 };
198
199 const fadeIn = css.keyframes({
200   '0%': { opacity: 0 },
201   '100%': { opacity: 1 }
202 })
203 const slideOut = css.keyframes({
204   '100%': { transform: 'translateY(-100%)' },
205 })
206 const Wrapper = glamorous.div(props => ({
207   animation: props.isMounted ? `${slideOut} 2.5s` : `${fadeIn} 1.5s`,
208   position: 'absolute',
209   top: '0px',
210   left: '0px',
211   width: '100vw',
212   height: '100vh',
213   zIndex: 5
214 })))
215
216
217 class VideosApp extends Component {
218   constructor(props) {
219     super(props);

```

```

220     this.state = {
221         videos: [],
222         target_dict: {},
223         playing: [],
224         zoomed: -1,
225         hovered: "",
226         index: 0,
227         exit: false,
228     }
229 }
230
231 componentDidMount() {
232     console.log("MOUNTED");
233     this.getVideos();
234     //google home
235     currentRef.update({"current": "videos"});
236     var something = this;
237     currentRef.on('value', function(snapshot) {
238         console.log(snapshot.val());
239         var db = snapshot.val();
240         var name = db.goto;
241         if (db.update){
242             if (name === "home") {
243                 something.setState({ exit: true });
244                 currentRef.update({"update": false});
245             }
246         }
247         if(db.back){
248             something.setState({ exit: true });
249             currentRef.update({"back": false});
250         }
251     });
252     //end
253 }
254
255
256 getVideos = () => {
257     const videos = [this.refs.video1, this.refs.video2, this.refs.video3,
258                     this.refs.video4, this.refs.video5, this.refs.video6,
259                     this.refs.video7, this.refs.video8, this.refs.video9,
260                     this.refs.video10, this.refs.video11, this.refs.video12];
261     this.setState({videos});
262 }
263
264 handleHover = (video) => {
265     this.setState({hovered: video})
266 }
267
268 handleSwipe = (dir) => {
269     var { zoomed, videos } = this.state;
270     // swipe between zoomed in videos

```

```

271     if (zoomed !== -1) {
272         if (dir === "right") {
273             zoomed = Math.max(0, zoomed - 1);
274         } else {
275             zoomed = Math.min(videos.length - 1, zoomed + 1);
276         }
277         console.log("SWIPE RIGHT (app) " + zoomed)
278         this.setState({ zoomed });
279     }
280     else {
281         if (dir === "left") {
282             this.setState({
283                 index: 1
284             })
285         } else {
286             this.setState({
287                 index: 0
288             })
289         }
290     }
291 }

292
293 handleNext = () => {           //for pointer
294     this.setState(state => ({
295         index: 1,
296     }));
297 };
298
299 handleBack = () => {
300     this.setState(state => ({
301         index: 0,
302     }));
303 };
304
305 handleExit = () => {
306     this.setState({
307         exit: true
308     })
309 }
310
311 handleClick = (video) => {
312     try{
313         var { playing, target_dict } = this.state;
314         var videoIndex = parseInt(video.slice(5));
315         var videoId = videos[videoIndex-1].id;
316         console.log("HANDLE CLICK", videoId)
317         if (!playing[videoIndex-1]) {
318             playing[videoIndex-1] = true;
319             console.log(target_dict[videoId])
320             target_dict[videoId].playVideo();
321             console.log("PLAY", videoIndex);

```

```

322     } else {
323       playing[videoIndex-1] = false;
324       target_dict[videoId].pauseVideo();
325       console.log("PAUSE", videoIndex);
326     }
327     this.setState({ playing });
328   } catch (err) { }
329 }
330
331 handleZoom = (video) => {
332   var { zoomed } = this.state;
333   console.log("ZOOMED", video);
334   zoomed = parseInt(video.slice(5)) - 1;
335   this.setState({ zoomed, hovered: "" });
336 }
337
338 handleIndex = (video, translation) => {
339   const threshold = 0.5;
340   var videoIndex = parseInt(video.slice(5));
341   var videoId = videos[videoIndex-1].id;
342   if (Math.abs(translation[0]) > threshold || Math.abs(translation[1]) >
343     ↪ threshold) {
344     if (Math.abs(translation[0]) > Math.abs(translation[1])) {
345       var seconds = this.state.target_dict[videoId].getCurrentTime() -
346         ↪ Math.round(translation[0]);
347       console.log("HANDLE FAST-FORWARD", videoId, seconds)
348       this.state.target_dict[videoId].seekTo(seconds, true);
349     } else {
350       var volume = Math.round(this.state.target_dict[videoId].getVolume() +
351         ↪ translation[1]);
352       console.log("HANDLE VOLUME", videoId, volume)
353       this.state.target_dict[videoId].setVolume(volume);
354     }
355   }
356 }
357
358 // adjust volume
359 handleKnob = (video, volume) => {
360   var videoIndex = parseInt(video.slice(5));
361   var videoId = videos[videoIndex-1].id;
362   console.log("HANDLE KNOB", videoId, volume)
363   this.state.target_dict[videoId].setVolume(volume);
364 }
365
366 handleSwipeUp = () => {
367   let { zoomed } = this.state;
368   if (zoomed !== -1) {
369     this.setState({ zoomed: -1 });
370     this.getVideos();
371   } else {
372     this.setState({ exit: true });
373   }
374 }

```

```

370     }
371   }
372
373   _onReady = (videoId, event) => {
374     // access to player in all event handlers via event.target
375     event.target.pauseVideo();
376     this.setState({playing:[...this.state.playing,false]});
377     var new_target_dict = this.state.target_dict;
378     new_target_dict[videoId] = event.target;
379     this.setState({target_dict: new_target_dict});
380   }
381
382   getVideoClass(video) {
383     const { classes } = this.props;
384     const { hovered } = this.state;
385     if (hovered === video)
386       return classNames(classes.frameContainer, classes.hovered);
387     return classes.frameContainer;
388   }
389
390   renderVideo(index) {
391     const { classes } = this.props;
392     const { hovered } = this.state;
393     const ref = "video" + String(index + 1);
394
395     return (
396
397       <Grid onMouseEnter={() => { this.setState({hovered: ref}) }}
398         onMouseLeave={() => { this.setState({hovered: ""}) }}
399         onClick={() => { this.handleClick(hovered) }}
400         item
401         className={classes.cell}
402         xs={12} sm={ 4 }>
403         <div className="cover">
404           <YouTube ref={ref} item
405             className={this.getVideoClass(ref)}
406             videoId={videos[index].id}
407             key={index}
408             opts={opts}
409             onReady={(event) => this._onReady(videos[index].id, event)}
410             onPause={this._onPause}
411           />
412         </div>
413       </Grid>);
414   }
415
416   renderVideos() {
417     const { classes } = this.props;
418
419     return (<div>
420       <SwipeableViews className={classes.gallery} index={this.state.index}
421         ↪ onTransitionEnd={this.getVideos}>

```

```

421     <div className={classes.carousel}>
422       <Grid container className={classes.row} spacing={0}
423         ↪ justify={"center"} >
424         {this.renderVideo(0)}
425         {this.renderVideo(1)}
426         {this.renderVideo(2)}
427       </Grid>
428       <Grid container className={classes.row} spacing={0}
429         ↪ justify={"center"}>
430         {this.renderVideo(3)}
431         {this.renderVideo(4)}
432         {this.renderVideo(5)}
433       </Grid>
434       <Grid container className={classes.row} spacing={0}
435         ↪ justify={"center"} >
436         {this.renderVideo(6)}
437         {this.renderVideo(7)}
438         {this.renderVideo(8)}
439       </Grid>
440     </div>
441     <div className={classes.carousel}>
442       <Grid container className={classes.row} spacing={0}
443         ↪ justify={"center"} >
444         {this.renderVideo(9)}
445         {this.renderVideo(10)}
446         {this.renderVideo(11)}
447       </Grid>
448     </div>
449   </SwipeableViews>
450   <MobileStepper
451     variant="dots"
452     steps={2}
453     position="bottom"
454     activeStep={this.state.index}
455     className={classes stepper}
456     classes={{ dots: classes.dots }}
457     nextButton={
458       <Button size="small" onClick={this.handleNext}
459         ↪ disabled={this.state.index === 1}>
460         <KeyboardArrowRight />
461         {/* {theme.direction === 'rtl' ? <KeyboardArrowLeft /> :
462           ↪ <KeyboardArrowRight />} */}
463       </Button>
464     }
465     backButton={
466       <Button size="small" onClick={this.handleBack}
467         ↪ disabled={this.state.index === 0}>
468         {/* {theme.direction === 'rtl' ? <KeyboardArrowRight /> :
469           ↪ <KeyboardArrowLeft />} */}
470         <KeyboardArrowLeft />
471       </Button>
472     }
473   </MobileStepper>
474 }

```

```

464     }
465     />
466   </div>
467 );
468 }
469
470 renderFullScreenVideo(index) {
471   const { classes } = this.props;
472
473   return (<div className={classes.carousel} justify={"center"}>
474     <Grid container spacing={0} justify={"center"} >
475       <Grid item
476         className={classes.cell}
477         xs={12} sm={ 12 }>
478         <YouTube item
479           className={classNames(classes.frameContainer, classes.zoomed)}
480           videoId={videos[index].id}
481           key={index}
482           opts={opts}
483           onReady={(event) => this._onReady(videos[index].id, event)}
484           onPause={this._onPause}
485         />
486       </Grid>
487     </Grid>
488   </div>);
489 }
490
491 renderFullScreen(index) {
492   const { classes } = this.props;
493
494   return (<div>
495     <SwipeableViews className={classes.gallery} index={index}
496       ↪ onTransitionEnd={this.getVideos}>
497       { this.renderFullScreenVideo(0) }
498       { this.renderFullScreenVideo(1) }
499       { this.renderFullScreenVideo(2) }
500       { this.renderFullScreenVideo(3) }
501       { this.renderFullScreenVideo(4) }
502       { this.renderFullScreenVideo(5) }
503       { this.renderFullScreenVideo(6) }
504       { this.renderFullScreenVideo(7) }
505       { this.renderFullScreenVideo(8) }
506       { this.renderFullScreenVideo(9) }
507       { this.renderFullScreenVideo(10) }
508       { this.renderFullScreenVideo(11) }
509     </SwipeableViews>
510     <div className = "stepper">
511       <MobileStepper
512         variant="dots"
513         steps={12}
514         position="bottom"

```

```

514     activeStep={index}
515     className={classes.stepper}
516     classes={{ dots: classes.dots }}
517     nextButton={
518       <Button size="small" onClick={()=>this.handleSwipe("left")}
519         ↪ disabled={index === 11}>
520         <KeyboardArrowRight />
521       </Button>
522     }
523     backButton={
524       <Button size="small" onClick={()=>this.handleSwipe("right")}
525         ↪ disabled={index === 0}>
526       <KeyboardArrowLeft />
527     </Button>
528   }
529   <Button onClick={() => this.handleSwipeUp()} className={classes.xbutton}>
530     <Clear/>
531   </Button>
532 </div>;
533 }
534
535 render() {
536   const { classes } = this.props;
537   const { zoomed } = this.state;
538
539   if (this.state.exit) {
540     return <Redirect to={{ pathname: "/Home", state: {page: "home"} }} />
541   }
542
543   return (
544     <Wrapper isMounted={this.props.isMounted} exit={this.state.exit}>
545       <div className={classes.container}>
546         <Leap
547           videos={this.state.videos}
548           handleHover={this.handleHover}
549           handleSwipe={this.handleSwipe}
550           handleSwipeUp={this.handleSwipeUp}
551           handleClick={this.handleClick}
552           handleZoom={this.handleZoom}
553           handleKnob={this.handleKnob}
554           handleIndex={this.handleIndex}
555         />
556
557         { zoomed !== -1 ? this.renderFullScreen(zoomed) : this.renderVideos()
558           ↪ }
559
560         <Button onClick={() => this.handleExit()}
561           ↪ className={classes.button}>
562           <Home/>

```



```

561         </Button>
562     </div>
563 </Wrapper>
564     );
565 }
566 }
567
568 VideosApp.defaultProps = {
569     hovered: false,
570     clicked: false,
571 };
572
573 export default withStyles(styles)(VideosApp);

```

leap.js

```

1  import PropTypes from 'prop-types';
2  import React from 'react';
3  import ReactDOM from 'react-dom';
4  import { withStyles } from '@material-ui/core/styles';
5  //import LeapMotion from 'leapjs';
6  import GestureHandler from '../gesture-interface/app-interface' // Added
7
8  const fingers = ["#9bcfed", "#B2EBF2", "#80DEEA", "#4DD0E1", "#26C6DA"];
9  const paused_fingers = ["#9bed9b", "#b1f0b1", "#80ea80", "#4ce14c", "#25da25"];
10
11  const videoSizeOffset = 100;
12
13  const styles = {
14      canvas: {
15          position: 'absolute',
16          height: '100%',
17          width: '100%',
18          zIndex: 100,
19          pointerEvents: 'none'
20      }
21  };
22
23  class Leap extends React.Component {
24      constructor(props) {
25          super(props)
26          this.state = {
27              indexFinger: "",
28              hovered: "",
29              zoomed: "",
30              pause: 4,
31          }
32      }
33
34      componentDidMount() {
35          let gestureHandler = new GestureHandler();

```

```

36     this.gestureHandler = gestureHandler;
37     gestureHandler.onEachGesture(function (gesture) {
38         console.log(gesture);
39         this.setState({ pause: 4 });
40     }.bind(this));
41     gestureHandler.onGesture("rhand_lswipe", function () {
42         this.props.handleSwipe("left");
43         let zoomed = this.state.zoomed;
44         if (zoomed) {
45             const index = parseInt(zoomed.slice(5));
46             const newIndex = Math.min(this.props.videos.length, index + 1)
47             zoomed = "video" + String(newIndex);
48             console.log("SWIPE LEFT (leap) " + zoomed)
49             this.setState({ zoomed });
50         }
51     }.bind(this));
52     gestureHandler.onGesture("rhand_rswipe", function () {
53         this.props.handleSwipe("right");
54         let zoomed = this.state.zoomed;
55         if (zoomed) {
56             const index = parseInt(zoomed.slice(5));
57             const newIndex = Math.max(1, index - 1)
58             zoomed = "video" + String(newIndex);
59             console.log("SWIPE RIGHT (leap) " + zoomed)
60             this.setState({ zoomed });
61         }
62     }.bind(this));
63     gestureHandler.onGesture("rhand_uswipe", function () {
64         let zoomed = this.state.zoomed;
65         if (zoomed) {
66             zoomed = "";
67             gestureHandler.removePoseHandler("point-index");
68             this.setState({ zoomed });
69         }
70         this.props.handleSwipeUp();
71     }.bind(this));
72     gestureHandler.onGesture("rindex_airtap", function () {
73         var { zoomed, hovered } = this.state;
74         if (hovered && !zoomed) { // zoom in
75             zoomed = hovered;
76             this.props.handleZoom(zoomed);
77             this.setState({ zoomed, hovered: "" });
78             // Add gesture handler for volume
79             gestureHandler.onPose("point-index", function (data) {
80                 let zoomed = this.state.zoomed;
81                 if (zoomed) {
82                     this.props.handleIndex(zoomed, data.translation);
83                 }
84             }.bind(this));
85         } else if (zoomed) { // play video
86             console.log("PLAY (leap) " + zoomed)

```

```

87         this.props.handleClick(zoomed);
88     }
89     }.bind(this));
90     this.gestureHandler.onFrame(function (frame) {
91         if (frame.fingers.length !== 0) {
92             this.setState({ hand: true });
93         } else {
94             this.setState({ hand: false });
95         }
96         this.traceFingers(frame.fingers);
97     }.bind(this));
98
99     this.timer = setInterval(() => {
100         if (this.state.pause > 0) {
101             this.setState({ pause: this.state.pause - 1 });
102         }
103         if (this.state.hand) {
104             var { zoomed, hovered } = this.state;
105             if (!zoomed) {
106                 hovered = this.checkHover();
107                 this.setState({ hovered });
108                 this.props.handleHover(hovered);
109             }
110         }
111     }, 100);
112 }
113
114 componentWillUnmount() {
115     clearInterval(this.timer);
116     this.gestureHandler.disconnect();
117 }
118
119 traceFingers(pointables) {
120     try {
121         // TODO: make canvas and ctx global
122         const canvas = this.refs.canvas;
123         canvas.width = canvas.clientWidth;
124         canvas.height = canvas.clientHeight;
125         const ctx = canvas.getContext("2d");
126         ctx.clearRect(0, 0, canvas.width, canvas.height);
127         const { pause } = this.state;
128         pointables.forEach((pointable) => {
129             const color = pause > 0 ? paused_fingers[pointable.type] :
130                 ↪ fingers[pointable.type];
131             const normalized = pointable.normalizedPosition;
132             const x = ctx.canvas.width * normalized[0];
133             const y = ctx.canvas.height * (1 - normalized[1]);
134             const radius = Math.min(20 / Math.abs(pointable.touchDistance),
135                 ↪ 50);
136             this.drawCircle([x, y], radius, color, pointable.type === 1);

```

```

136         if (pointable.type == 1) {
137             this.setState({
138                 indexFinger: { x, y, vel: pointable.tipVelocity[2] }
139             })
140         }
141     });
142 } catch (err) {
143     // console.log("ERR", err);
144 }
145 }
146
147 drawCircle(center, radius, color, fill) { //draws a circle
148     const canvas = this.refs.canvas;
149     const ctx = canvas.getContext("2d");
150     ctx.beginPath();
151     ctx.arc(center[0], center[1], radius, 0, 2 * Math.PI);
152     ctx.closePath();
153     ctx.lineWidth = 10;
154     if (fill) {
155         ctx.fillStyle = color;
156         ctx.fill();
157     } else {
158         ctx.strokeStyle = color;
159         ctx.stroke();
160     }
161 }
162
163 checkHover() {
164     const videos = this.props.videos;
165     const { x, y } = this.state.indexFinger;
166     // don't check for hovering while zoomed in
167     if (!this.state.zoomed) {
168         for (let i = 0; i < videos.length; i++) {
169             if (videos[i]){
170                 const videoNode = ReactDOM.findDOMNode(videos[i]);
171                 const dims = videoNode.getBoundingClientRect();
172                 if (x > dims.left && x < dims.right &&
173                     y > dims.top - videoSizeOffset && y < dims.bottom +
174                     ↪ videoSizeOffset) {
175                     return ("video" + String(i + 1));
176                 }
177             }
178         }
179         return ("");
180     }
181
182 render() {
183     const { classes } = this.props;
184     return (
185         <canvas className={classes.canvas} ref="canvas"></canvas>

```

```

186     )
187   }
188 }
189
190
191 Leap.propTypes = {
192   videos: PropTypes.array,
193   handleHover: PropTypes.func,
194   handleSwipe: PropTypes.func,
195   handleExit: PropTypes.func,
196   handleClick: PropTypes.func,
197   handleIndex: PropTypes.func
198 };
199
200 // TODO: better default values
201 Leap.defaultProps = {
202   videos: [],
203 };
204
205 export default withStyles(styles)(Leap);

```

F.8.4 Photos App

PhotosApp.jsx

```

1  import React, { Component } from 'react';
2  import { Redirect } from 'react-router';
3  import { withStyles } from '@material-ui/core/styles';
4  import glamorous from 'glamorous'
5  import classNames from 'classnames';
6  import Leap from './leap.js';
7  import { Grid } from '@material-ui/core';
8  import SwipeableViews from 'react-swipeable-views';
9  import MobileStepper from '@material-ui/core/MobileStepper';
10 import Button from '@material-ui/core/Button';
11 import KeyboardArrowLeft from '@material-ui/icons/KeyboardArrowLeft';
12 import KeyboardArrowRight from '@material-ui/icons/KeyboardArrowRight';
13 import Home from '@material-ui/icons/Home';
14 import Clear from '@material-ui/icons/Clear';
15 import FavoriteIcon from '@material-ui/icons/Favorite';
16 import FavoriteBorderIcon from '@material-ui/icons/FavoriteBorder';
17
18 import { css } from 'glamor';
19 import { Transition } from 'react-transition-group';
20 import Carousel from 'react-responsive-carousel';
21 //firebase
22 import * as firebase from "firebase/app";
23 import "firebase/database";
24
25 const zoomIn = css.keyframes({

```

```

26   '0%': { transform: 'scale(0.5)' },
27   '100%': { transform: 'scale(1)' }
28 })
29
30 //CSS:
31 const styles = {
32
33   gallery: {
34     animation: `${zoomIn} 1s`
35   },
36
37   container: {
38     display: 'flex',
39     flexDirection: 'column',
40     position: 'absolute',
41     top: '0px',
42     left: '0px',
43     width: '100%',
44     height: '100%',
45     padding: '0px',
46     listStyle: 'none',
47     overflow: 'hidden',
48     zIndex: '1',
49     backgroundColor: '#CFD8DC',
50   },
51
52   carousel: {
53     // width: '90%',
54     maxHeight: '95%',
55     padding: '0px',
56     margin: '0px',
57     overflow: 'hidden',
58   },
59
60   row: {
61     maxHeight: '50vh',
62   },
63
64   cell: {
65     display: 'inline-block',
66     maxWidth: '85%',
67     maxHeight: '85%',
68     verticalAlign: 'middle',
69     boxSizing: 'border-box',
70     margin: '0px',
71     padding: '3%',
72     position: 'relative',
73   },
74
75   image: {
76     display: 'block',

```

```

77     maxWidth: '90%',
78     maxHeight: '60%',
79     width: 'auto',
80     height: 'auto',
81     margin: 'auto',
82     padding: '3%',
83     border: 'none',
84     transform: 'scale(1)',
85     transition: 'all 0.4s',
86     boxShadow: '0px 0px 10px 2px #999',
87     backgroundColor: "#ECEFF1",
88     position: "relative",
89     zIndex: '1'
90 },
91
92 hovered: {
93     transform: 'scale(1.5)',
94     animationDuration: '0.1s',
95     zIndex: '15 !important',
96     cursor: 'pointer',
97 },
98
99 zoomed: {
100     maxHeight: '80vh'
101 },
102
103 dots: {
104     margin: 'auto',
105 },
106
107 maincontent: {
108     position: 'absolute',
109     bottom: '50px',
110     top: '50px',
111     left: 0,
112     right: 0,
113     overflow: 'hidden'
114 },
115
116 controlbar: {
117     boxSizing: 'border-box',
118     display: 'flex',
119     justifyContent: 'space-between',
120     alignItems: 'center',
121     margin: 0,
122     padding: '5px',
123     position: 'absolute',
124     bottom: 0,
125     left: 0,
126     right: 0,
127     height: '50px'

```

```

128 },
129
130 control: {
131   flex: '1 1 0'
132 },
133
134 stepper: {
135   // display: 'auto',
136   margin: 'auto',
137   width: 'fit-content',
138   maxWidth: '100%',
139   // marginLeft: 'auto',
140   // marginRight: 'auto',
141   //width: '8em',
142   backgroundColor: 'rgb(0,0,0,0)',
143   //position: "absolute",
144   //bottom: "1px",
145 },
146
147 button: {
148   //position: 'fixed',
149   // bottom: '10px',
150   // left: '10px',
151   color: "rgba(50,50,50,0.8)",
152 },
153
154 xbutton: {
155   position: 'fixed',
156   top: '10px',
157   right: '10px',
158   color: "rgba(50,50,50,0.8)",
159 }
160 };
161
162 const fadeIn = css.keyframes({
163   '0%': { opacity: 0 },
164   '100%': { opacity: 1 }
165 })
166 const slideOut = css.keyframes({
167   '100%': { transform: 'translateY(-100%)' },
168 })
169
170 //Animations entering/exiting this page:
171 const Wrapper = glamorous.div(props => ({
172   animation: props.isMounted ? `${slideOut} 2.5s` : `${fadeIn} 1.5s`,
173   position: 'absolute',
174   top: '0px',
175   left: '0px',
176   width: '100vw',
177   height: '100vh',
178   zIndex: 5

```



```

179   )))
180   const photos =
    ↪   ['https://images.unsplash.com/photo-1531752074002-abf991376d04?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
181         'https://images.unsplash.com/photo-1531700968341-bd114e5006ec?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
182         'https://images.unsplash.com/photo-1533247094082-709d7257cb7b?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
183         'https://images.unsplash.com/photo-1531686888376-83ee7d64f5eb?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
184         'https://images.unsplash.com/photo-1533213603451-060f6ec38bfa?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
185         'https://images.unsplash.com/photo-1531574595918-cb77c99fe5e2?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
186         'https://images.unsplash.com/photo-1533135347859-2d07f6e8199b?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
187         'https://images.unsplash.com/photo-1533071581733-1a1600ec8ac6?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
188         'https://images.unsplash.com/photo-1533213603451-060f6ec38bfa?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
189         'https://images.unsplash.com/photo-1531574595918-cb77c99fe5e2?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
190         'https://images.unsplash.com/photo-1533135347859-2d07f6e8199b?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
191         'https://images.unsplash.com/photo-1533071581733-1a1600ec8ac6?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
192         'https://images.unsplash.com/photo-1531752074002-abf991376d04?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
193         'https://images.unsplash.com/photo-1531700968341-bd114e5006ec?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
194         'https://images.unsplash.com/photo-1533247094082-709d7257cb7b?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
195         'https://images.unsplash.com/photo-1531686888376-83ee7d64f5eb?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
196         'https://images.unsplash.com/photo-1531686888376-83ee7d64f5eb?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
197         'https://images.unsplash.com/photo-1531686888376-83ee7d64f5eb?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
198         'https://images.unsplash.com/photo-1531686888376-83ee7d64f5eb?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80',
199         'https://images.unsplash.com/photo-1531686888376-83ee7d64f5eb?ixlib=rb-0.3.5&ixid=eyJhcHRlZDc9ImF1dG8ifQ==&w=1000&q=80']
200
201   //firebase
202   const firebaseConfig = {
203     apiKey: "AIzaSyDjM37_DSv2RvPQz15YiVzmGRHfpd4rJFU",
204     authDomain: "lui-medialab.firebaseio.com",
205     databaseURL: "https://lui-medialab.firebaseio.com",
206     projectId: "lui-medialab",
207     storageBucket: "lui-medialab.appspot.com",
208     messagingSenderId: "247289397118",
209     appId: "1:247289397118:web:eb2bc0076d4bb4d"

```

```

210 };
211
212 if (!firebase.apps.length) {
213   firebase.initializeApp(firebaseConfig);
214 }
215 var database = firebase.database();
216 var currentRef = database.ref('voice');
217 //end
218
219
220 class PhotosApp extends Component {
221   constructor(props) {
222     super(props);
223
224     let photoRefs = [];
225     for (let i = 0; i < photos.length; i++) {
226       photoRefs.push(React.createRef());
227     }
228
229     this.state = {
230       photoRefs: photoRefs,
231       numPreviewPages: Math.ceil(photoRefs.length / 8),
232       hovered: -1,
233       clicked: -1,
234       liked: {},
235       index: 0,
236       exit: false,
237       rotation: 0, // Added - rotate image
238       zoom: 1.0,
239       translation: { x: 0.0, y: 0.0 }
240     };
241
242     this.handleClick = this.handleClick.bind(this);
243   }
244
245   componentDidMount() {
246     //google home
247     currentRef.update({"current": "photos"});
248     var something = this;
249     currentRef.on('value', function(snapshot) {
250       var db = snapshot.val();
251       var name = db.goto;
252       if (db.update){
253         if (name === "home") {
254           something.setState({ exit: true });
255           currentRef.update({"update": false});
256         }
257       }
258       if(db.clicked){
259         currentRef.update({"clicked": false});
260       }

```

```

261     something.gestureDetected = true;
262     console.log(db.hovered);
263     something.handleClick(db.hovered);
264   }
265   if (db.back){
266     if (something.state.clicked !== -1){
267       something.handleSwipeUp();
268     }
269     else{
270       something.setState({ exit: true });
271     }
272   }
273   currentRef.update({"back":false});
274 }
275 });
276 }
277
278
279
280 rotate(){
281   let newRotation = this.state.rotation + 45;
282   if(newRotation >= 360){
283     newRotation -= 360;
284   }
285   this.setState({
286     rotation: newRotation,
287   })
288 }
289
290 handleHover = (photo) => {
291   this.setState({ hovered: photo })
292   currentRef.update({"hovered": photo});
293 }
294
295 handleClick = (photoId) => {
296   this.setState({ clicked: photoId, rotation: 0, zoom: 1.0, translation: { x:
    ↪ 0.0, y: 0.0 } })
297 }
298
299 handleExit = () => {
300   this.setState({
301     exit: true
302   })
303 }
304
305 handleRotate = (handRotation) => {
306   this.setState(prevState => ({ rotation: (prevState.rotation + 180 *
    ↪ handRotation / 3.14) })))
307 }
308
309 handlePinch = (pinch, handTranslation) => {

```

```

310 let { clicked, zoom, translation } = this.state;
311 if (clicked !== -1) {
312   zoom *= ((pinch - 1) * 1.2) + 1;
313   if (zoom < 0.4) {
314     zoom = 0.4;
315   } else if (zoom > 4) {
316     zoom = 4;
317   }
318   translation.x += handTranslation[0] * 5;
319   translation.y += handTranslation[1] * -5;
320   this.setState({ zoom, translation })
321 }
322 }
323
324 handleTranslate = (translation) => {
325   console.log("translate");
326   console.log(translation);
327 }
328
329 handleThumb = (isUp) => {
330   let { clicked, liked } = this.state;
331
332   if (!liked.hasOwnProperty(clicked) || liked[clicked] !== isUp) {
333     this.setState(prevState => ({
334       liked: {
335         ...prevState.liked,
336         [clicked]: isUp
337       }
338     }));
339   }
340 }
341
342 handleSwipe = (dir) => {
343   let { clicked, photoRefs, index, numPreviewPages } = this.state;
344   this.setState({ rotation: 0, zoom: 1.0, translation: { x: 0.0, y: 0.0 } })
345   ↪ // Added - rotation
346   if (dir === "left") {
347     console.log("swipe left");
348     if (clicked !== -1) {
349       this.setState({ clicked: Math.min(photoRefs.length - 1, clicked + 1) })
350     } else if (index < numPreviewPages - 1) {
351       this.setState({ index: index + 1 })
352     }
353   } else {
354     console.log("swipe right");
355     if (clicked !== -1) {
356       this.setState({ clicked: Math.max(0, clicked - 1) })
357     } else if (index > 0) {
358       this.setState({ index: index - 1 })
359     }
360   }
361 }

```

```

360 }
361
362 handleNext = () => {
363   let { index, numPreviewPages } = this.state;
364   if (index < numPreviewPages - 1) {
365     this.setState({ index: index + 1 });
366   }
367 };
368
369 handleBack = () => {
370   let { index } = this.state;
371   if (index > 0) {
372     this.setState({ index: index - 1 });
373   }
374 };
375
376 handleSwipeUp = () => {
377   let { clicked } = this.state;
378   if (clicked !== -1) {
379     this.setState({ clicked: -1 });
380   } else {
381     this.setState({ exit: true });
382   }
383 }
384
385 renderPhoto(index) { //renders a photo in the grid
386   const { classes } = this.props;
387   const { hovered, photoRefs } = this.state;
388   const ref = photoRefs[index];
389
390   return (<Grid item className={classes.cell} ref={ref} xs={12} sm={3}>
391     <img
392       onMouseEnter={() => { this.setState({hovered: index}) }}
393       onMouseLeave={() => { this.setState({hovered: -1}) }}
394       onClick={() => { this.handleClick(index) }}
395       className={hovered === index ? classNames(classes.image, classes.hovered) :
396         ↪ classes.image}
397       src={photos[index]} />
398     </Grid>);
399 }
400
401 renderFullScreenPhoto(index) { //renders the selected photo in full screen view
402   const { classes } = this.props;
403   const { rotation, zoom, translation } = this.state;
404   return (<div className={classes.carousel} justify={"center"}>
405     <Grid container spacing={0} justify={"center"} >
406       <Grid item className={classes.cell} xs={12} sm={12}>
407         <div style={{transform:
408           ↪ `translate(${translation.x}px,${translation.y}px)`}} >
409           <img
410             style={{transform: `rotate(${rotation}deg) scale(${zoom})`}}

```

```

409         onClick={() => { this.rotate() }}
410         className={classNames(classes.image, classes.zoomed)}
411         src={photos[index]} />
412     </div>
413 </Grid>
414 </Grid>
415 </div>);
416 }
417
418 renderFullScreen(index) { //renders the full screen gallery view for the photos
419     const { classes } = this.props;
420     const { photoRefs } = this.state;
421
422     let fullScreenPhotos = [];
423     for (let i = 0; i < photoRefs.length; i++) {
424         fullScreenPhotos.push(this.renderFullScreenPhoto(i));
425     }
426
427     return (<div>
428         <SwipeableViews className={classes.gallery} index={index} >
429             {fullScreenPhotos}
430         </SwipeableViews>
431         /* Exit button: */
432         <Button onClick={() => this.handleSwipeUp()} className={classes.xbutton}>
433             <Clear/>
434         </Button>
435     </div>);
436 }
437
438 renderPhotos() {
439     const { classes } = this.props;
440     const { index, photoRefs } = this.state;
441     let pages = [];
442     let rows = [];
443     let previews = [];
444     var i;
445     for (i = 0; i < photoRefs.length; i++) {
446         previews.push(this.renderPhoto(i));
447         if ((i + 1) % 4 == 0) {
448             rows.push(<Grid container className={classes.row} spacing={0}
449                 ↪ justify={"center"} >
450                 {previews}
451             </Grid>);
452             previews = [];
453         }
454         if ((i + 1) % 8 == 0) {
455             pages.push(<div className={classes.carousel} justify={"center"}>
456                 {rows}
457             </div>);
458             rows = [];
459         }
460     }

```

```

459 }
460 if ((photoRefs.length % 8) !== 0) {
461   if ((photoRefs.length % 4) !== 0) {
462     rows.push(<Grid container className={classes.row} spacing={0}
463       ↪ justify={"center"} >
464       {previews}
465     </Grid>);
466   }
467   pages.push(<div className={classes.carousel} justify={"center"}>
468     {rows}
469   </div>);
470 }
471
472 return (<div>
473   <div>
474     <SwipeableViews className={classes.gallery} index={index}>
475       {pages}
476     </SwipeableViews>
477   </div>
478 </div>);
479
480 renderStepper() {
481   const { classes } = this.props;
482   const { index, numPreviewPages } = this.state;
483
484   return (numPreviewPages <= 1) ? "" : (<div className = "stepper">
485     <MobileStepper
486       variant="dots"
487       steps={numPreviewPages}
488       position="bottom"
489       activeStep={index}
490       className={classes.stepper}
491       classes={{ dots: classes.dots }}
492       nextButton={
493         <Button size="small" onClick={this.handleNext} disabled={index >=
494           ↪ numPreviewPages - 1}>
495           <KeyboardArrowRight />
496         </Button>
497       }
498       backButton={
499         <Button size="small" onClick={this.handleBack} disabled={index <= 0}>
500           <KeyboardArrowLeft />
501         </Button>
502       }
503     </div>);
504 }
505
506 renderFullScreenStepper() {
507   const { classes } = this.props;

```

```

508     const { clicked, photoRefs } = this.state;
509
510     return (<div className = "stepper">
511         <MobileStepper
512             variant="dots"
513             steps={photoRefs.length}
514             position="bottom"
515             activeStep={clicked}
516             className={classes.stepper}
517             classes={{ dots: classes.dots }}
518             nextButton={
519                 <Button size="small" onClick={()=>this.handleSwipe("left")}
520                     ↪ disabled={clicked >= photoRefs.length - 1}>
521                     <KeyboardArrowRight />
522                 </Button>
523             }
524             backButton={
525                 <Button size="small" onClick={()=>this.handleSwipe("right")}
526                     ↪ disabled={clicked <= 0}>
527                     <KeyboardArrowLeft />
528                 </Button>
529             }
530         </div>);
531
532     renderFavorite() {
533         const { clicked, liked } = this.state;
534         return (<div>
535             { liked.hasOwnProperty(clicked) && liked[clicked] ? <FavoriteIcon/> :
536                 ↪ <FavoriteBorderIcon/> }
537         </div>);
538     }
539
540     render() {
541         const { classes } = this.props;
542         const { clicked } = this.state;
543
544         // Handling whether to go back to the Home page or display the Photos page
545         if (this.state.exit) {
546             console.log("EXITING")
547             return <Redirect to={{ pathname: "/Home", state: {page: "home"} }} />
548         }
549
550         return (
551             <Wrapper isMounted={this.props.isMounted} exit={this.state.exit}>
552                 <div className={classes.container} justify={"center"}>
553                     <Leap
554                         photos={this.state.photoRefs}
555                         handleHover={this.handleHover}

```



```

556         handleClick={this.handleClick}
557         handleSwipe={this.handleSwipe}
558         handleSwipeUp={this.handleSwipeUp}
559         handleRotate={this.handleRotate}
560         handlePinch={this.handlePinch}
561         handleTranslate={this.handleTranslate}
562         handleThumb={this.handleThumb}
563     />
564
565     /* Handling whether to render a full screen photo or not */
566     <div className={classes.maincontent}>
567         { clicked !== -1 ? this.renderFullScreen(clicked) :
568           ↪ this.renderPhotos() }
569     </div>
570
571     /* Control bar */
572     <div className={classes.controlbar}>
573         /* Home button: */
574         <div className={classes.control}>
575             <Button onClick={() => this.handleExit()}
576               ↪ className={classes.button}>
577                 <Home/>
578             </Button>
579         </div>
580         <div className={classes.control}>
581             { clicked !== -1 ? this.renderFullScreenStepper() :
582               ↪ this.renderStepper() }
583         </div>
584     </div>
585 </div>
586 </div>
587 </Wrapper>
588 );
589 }
590 }
591
592 export default withStyles(styles)(PhotosApp);

```

leap.js

```

1  import PropTypes from 'prop-types';
2  import React from 'react';
3  import ReactDOM from 'react-dom';
4  import { withStyles } from '@material-ui/core/styles';
5  import GestureHandler from '../gesture-interface/app-interface' // Added
6
7  const fingers = ["#9bcfedBB", "#B2EBF2CC", "#80DEEABB", "#4DD0E1BB", "#26C6DABB"];
8  const left_fingers = ["#d39bed", "#e1b1f1", "#ca80ea", "#b74ce1", "#a425da"];

```

```

9  const paused_fingers = ["#9bed9b", "#b1f0b1", "#80ea80", "#4ce14c", "#25da25"];
10
11  const styles = {
12    canvas: {
13      position: 'absolute',
14      height: '100%',
15      width: '100%',
16      zIndex: 10,
17      pointerEvents: 'none',
18    }
19  };
20
21  };
22
23  class Leap extends React.Component {
24    constructor(props) {
25      super(props)
26      this.state = {
27        indexFinger: "",
28        hovered: -1,
29        clicked: -1,
30        pause: 4,
31      }
32    }
33
34    componentDidMount() {
35      let gestureHandler = new GestureHandler();
36      this.gestureHandler = gestureHandler;
37      gestureHandler.onEachGesture(function (gesture) {
38        console.log(gesture);
39        this.setState({ pause: 4 });
40      }).bind(this));
41      gestureHandler.onGesture("rhand_lswipe", function () {
42        this.props.handleSwipe("left");
43      }).bind(this));
44      gestureHandler.onGesture("rhand_rswipe", function () {
45        this.props.handleSwipe("right");
46      }).bind(this));
47      gestureHandler.onGesture("rhand_uswipe", function () {
48        let clicked = this.state.clicked;
49        if (clicked !== -1) {
50          gestureHandler.removePoseHandler("grab");
51          gestureHandler.removePoseHandler("pinch");
52          gestureHandler.removePoseHandler("thumb");
53          clicked = -1;
54          this.setState({ clicked });
55        }
56        this.props.handleSwipeUp();
57      }).bind(this));
58      gestureHandler.onGesture("rindex_airtap", function () {
59        var { clicked, hovered } = this.state;
60        if (clicked == -1 && hovered !== -1) {

```

```

60         gestureHandler.onPose("grab", function (data) {
61             this.props.handleRotate(data.rotation);
62         }.bind(this));
63         gestureHandler.onPose("pinch", function (data) {
64             this.props.handlePinch(data.pinch, data.translation);
65         }.bind(this));
66         gestureHandler.onPose("thumb", function (data) {
67             let thumbUp = data.thumbVector[1] > 40;
68             let thumbDown = data.thumbVector[1] < -40;
69             if (thumbUp) {
70                 console.log("THUMB UP");
71                 this.props.handleThumb(true);
72             }
73             if (thumbDown) {
74                 console.log("THUMB DOWN");
75                 this.props.handleThumb(false);
76             }
77         }.bind(this));
78         clicked = hovered;
79         this.props.handleClick(clicked);
80         this.setState({ clicked: clicked, hovered: -1});
81     }
82     }.bind(this));
83     this.gestureHandler.onFrame(function (frame) {
84         if (frame.fingers.length !== 0) {
85             this.setState({ hand: true });
86         } else {
87             this.setState({ hand: false });
88         }
89         this.traceFingers(frame.fingers);
90     }.bind(this));
91
92     this.timer = setInterval(() => {
93         if (this.state.pause > 0) {
94             this.setState({ pause: this.state.pause - 1 });
95         }
96         if (this.state.hand) {
97             var { clicked, hovered } = this.state;
98             if (clicked == -1 && !this.state.amiclicked) {
99                 hovered = this.checkHover();
100                 this.setState({ hovered });
101                 this.props.handleHover(hovered);
102             }
103         }
104     }, 100);
105 }
106
107 componentWillUnmount() {
108     clearInterval(this.timer);
109     this.gestureHandler.disconnect();
110 }

```

```

111 traceFingers(pointables) {
112   try {
113     // TODO: make canvas and ctx global
114     const canvas = this.refs.canvas;
115     canvas.width = canvas.clientWidth;
116     canvas.height = canvas.clientHeight;
117     const ctx = canvas.getContext("2d");
118     ctx.clearRect(0, 0, canvas.width, canvas.height);
119
120
121     const { pause } = this.state;
122
123     pointables.forEach((pointable) => {
124       const color = pause > 0 ? paused_fingers[pointable.type] :
125         ↪ fingers[pointable.type];
126       const normalized = pointable.normalizedPosition;
127       const x = ctx.canvas.width * normalized[0];
128       const y = ctx.canvas.height * (1 - normalized[1]);
129       const radius = Math.min(20 / Math.abs(pointable.touchDistance),
130         ↪ 50);
131       this.drawCircle([x, y], radius, color, pointable.type === 1);
132
133       if (pointable.type == 1) {
134         this.setState({
135           indexFinger: { x, y, vel: pointable.tipVelocity[2] }
136         })
137       }
138     });
139   } catch (err) {
140     // console.log("ERR", err);
141   }
142 }
143
144 drawCircle(center, radius, color, fill) { //draws a circle
145   const canvas = this.refs.canvas;
146   const ctx = canvas.getContext("2d");
147   ctx.beginPath();
148   ctx.arc(center[0], center[1], radius, 0, 2 * Math.PI);
149   ctx.closePath();
150   ctx.lineWidth = 10;
151   if (fill) {
152     ctx.fillStyle = color;
153     ctx.fill();
154   } else {
155     ctx.strokeStyle = color;
156     ctx.stroke();
157   }
158 }
159
160 checkHover() { //returns which photo is hovered
161   const photos = this.props.photos;

```

```

160     const { x, y } = this.state.indexFinger;
161     for (let i = 0; i < photos.length; i++) {
162         if (photos[i] && photos[i].current) {
163             const dims = photos[i].current.getBoundingClientRect();
164             if (x > dims.left && x < dims.right &&
165                 y > dims.top && y < dims.bottom) {
166                 return i;
167             }
168         }
169     }
170     return -1;
171 }
172
173 render() {
174     const { classes } = this.props;
175     return (
176         <canvas className={classes.canvas} ref="canvas"></canvas>
177     )
178 }
179
180 }
181
182
183 Leap.propTypes = {
184     photos: PropTypes.array,
185     handleHover: PropTypes.func,
186     handleSwipe: PropTypes.func,
187     handleExit: PropTypes.func,
188     handleRotate: PropTypes.func,
189     handlePinch: PropTypes.func,
190     handleTranslate: PropTypes.func,
191     handleThumb: PropTypes.func
192 };
193
194 // TODO: better default values
195 Leap.defaultProps = {
196     photos: [],
197 };
198
199 export default withStyles(styles)(Leap);

```

F.8.5 PDFs App

index.js

```

1  import React, { Component } from 'react';
2  import { Redirect } from 'react-router';
3  import PropTypes from 'prop-types';
4  import { ButtonBase, Typography } from '@material-ui/core';
5  import { withStyles } from '@material-ui/core/styles';

```

```

6  import classNames from 'classnames';
7  import PDFsApp from './PDFsApp.jsx';
8  import { Link } from 'react-router-dom'
9
10
11  const styles = theme => ({
12    root: {
13      display: 'flex',
14      flexWrap: 'wrap',
15      width: '100%',
16      height: '100%'
17    },
18    image: {
19      position: 'relative',
20      height: '100%',
21      [theme.breakpoints.down('xs')]: {
22        width: '100% !important', // Overrides inline-style
23      },
24    },
25    hovered: {
26      zIndex: 5,
27      '& $imageBackdrop': {
28        opacity: 0.15,
29      },
30      '& $imageMarked': {
31        opacity: 0,
32      },
33      '& $imageTitle': {
34        border: '4px solid currentColor',
35      },
36    },
37    imageButton: {
38      position: 'absolute',
39      left: 0,
40      right: 0,
41      top: 0,
42      bottom: 0,
43      display: 'flex',
44      alignItems: 'center',
45      justifyContent: 'center',
46      color: theme.palette.common.white,
47    },
48    imageSrc: {
49      position: 'absolute',
50      left: 0,
51      right: 0,
52      top: 0,
53      bottom: 0,
54      backgroundSize: 'cover',
55      backgroundPosition: 'center 40%',
56    },

```

```

57   imageBackdrop: {
58     position: 'absolute',
59     left: 0,
60     right: 0,
61     top: 0,
62     bottom: 0,
63     backgroundColor: theme.palette.common.black,
64     opacity: 0.4,
65     transition: theme.transitions.create('opacity'),
66   },
67   imageTitle: {
68     position: 'relative',
69     padding: `${theme.spacing.unit * 2}px ${theme.spacing.unit * 4}px
    ↪   ${theme.spacing.unit * 6}px`,
70   },
71   imageMarked: {
72     height: 3,
73     width: 18,
74     backgroundColor: theme.palette.common.white,
75     position: 'absolute',
76     bottom: -2,
77     left: 'calc(50% - 9px)',
78     transition: theme.transitions.create('opacity'),
79   },
80 });
81
82 const image = {
83   url:
84     ↪ 'https://images.unsplash.com/photo-1523906891494-64b456bf3c9e?ixlib=rb-1.2.1&ixid=eyJ
85   title: 'PDFs',
86   width: '100%',
87 };
88
89 class PDFs extends Component {
90   constructor(props) {
91     super(props);
92   }
93
94   render() {
95     const { classes, hovered, clicked } = this.props;
96
97     if (clicked) {
98       return <Redirect to={{pathname: "/PDFs"}} />
99     } else {
100       // icon
101       return (
102         <ButtonBase
103           focusRipple
104           key={image.title}
105           className={hovered? classNames(classes.image, classes.hovered)
    ↪       : classes.image}

```

```

106         focusVisibleClassName={classes.focusVisible}
107         style={{
108             width: image.width,
109         }}
110         onClick = {this.props.onClick}
111     >
112         <span
113             className={classes.imageSrc}
114             style={{
115                 backgroundImage: `url(${image.url})`,
116             }}
117         />
118         <span className={classes.imageBackdrop} />
119         <span className={classes.imageButton}>
120             <Typography
121                 component="span"
122                 variant="subheading"
123                 color="inherit"
124                 className={classes.imageTitle}
125             >
126                 {image.title}
127                 <span className={classes.imageMarked} />
128             </Typography>
129         </span>
130     </ButtonBase>
131 );
132 }
133 }
134 }
135
136 PDFs.propTypes = {
137     hovered: PropTypes.bool,
138     clicked: PropTypes.bool,
139 };
140
141 export default withStyles(styles)(PDFs);

```

PDFsApp.jsx

```

1  import React, { Component } from 'react';
2  import { Redirect } from 'react-router';
3  import { withStyles } from '@material-ui/core/styles';
4  import glamorous from 'glamorous';
5  import classNames from 'classnames';
6  import Leap from './leap.js';
7  import { Grid } from '@material-ui/core';
8  import SwipeableViews from 'react-swipeable-views';
9  import MobileStepper from '@material-ui/core/MobileStepper';
10 import Button from '@material-ui/core/Button';
11 import Pagination from '@material-ui/lab/Pagination';
12 import KeyboardArrowLeft from '@material-ui/icons/KeyboardArrowLeft';

```



```

13 import KeyboardArrowRight from '@material-ui/icons/KeyboardArrowRight';
14 import Home from '@material-ui/icons/Home';
15 import Clear from '@material-ui/icons/Clear';
16
17 import { css } from 'glamor';
18 import { Transition } from 'react-transition-group';
19 import Carousel from 'react-responsive-carousel';
20 //firebase
21 import * as firebase from "firebase/app";
22 import "firebase/database";
23
24 import { Document, Page, pdfjs } from "react-pdf";
25 pdfjs.GlobalWorkerOptions.workerSrc =
  ↳ `//cdnjs.cloudflare.com/ajax/libs/pdf.js/${pdfjs.version}/pdf.worker.js`;
26
27 const zoomIn = css.keyframes({
28   '0%': { transform: 'scale(0.5)' },
29   '100%': { transform: 'scale(1)' }
30 })
31
32 //CSS:
33 const styles = {
34
35   gallery: {
36     animation: `${zoomIn} 1s`
37   },
38
39   container: {
40     display: 'flex',
41     flexDirection: 'column',
42     position: 'absolute',
43     top: '0px',
44     left: '0px',
45     width: '100%',
46     height: '100%',
47     padding: '0px',
48     listStyle: 'none',
49     overflow: 'hidden',
50     zIndex: '1',
51     backgroundColor: '#CFD8DC',
52   },
53
54   carousel: {
55     // width: '90%',
56     maxHeight: '95%',
57     padding: '0px',
58     margin: '0px',
59     overflow: 'hidden',
60   },
61
62   row: {

```

```

63     maxHeight: '50vh',
64 },
65
66 cell: {
67     display: 'inline-block',
68     maxWidth: '85%',
69     maxHeight: '85%',
70     verticalAlign: 'middle',
71     boxSizing: 'border-box',
72     margin: '0px',
73     padding: '3%',
74     position: 'relative',
75 },
76
77 thumbnail: {
78     display: 'block',
79     maxWidth: '90%',
80     maxHeight: '60%',
81     width: 'auto',
82     height: '300px',
83     margin: 'auto',
84     padding: '3%',
85     border: 'none',
86     transform: 'scale(1)',
87     transition: 'all 0.4s',
88     boxShadow: '0px 0px 10px 2px #999',
89     backgroundColor: "#ECEFF1",
90     position: "relative",
91     zIndex: '1'
92 },
93
94 hovered: {
95     transform: 'scale(1.5)',
96     animationDuration: '0.1s',
97     zIndex: '15 !important',
98     cursor: 'pointer',
99 },
100
101 dots: {
102     margin: 'auto',
103 },
104
105 maincontent: {
106     position: 'absolute',
107     bottom: '50px',
108     top: '50px',
109     left: 0,
110     right: 0,
111     overflow: 'hidden'
112 },
113

```

```

114 pdf: {
115     position: 'relative',
116     height: 'fit-content',
117     width: 'fit-content',
118     margin: 'auto'
119 },
120
121 controlbar: {
122     boxSizing: 'border-box',
123     display: 'flex',
124     justifyContent: 'space-between',
125     alignItems: 'center',
126     margin: 0,
127     padding: '5px',
128     position: 'absolute',
129     bottom: 0,
130     left: 0,
131     right: 0,
132     height: '50px'
133 },
134
135 control: {
136     flex: '1 1 0'
137 },
138
139 pagination: {
140     margin: 'auto',
141     width: 'fit-content',
142     maxWidth: '100%'
143 },
144
145 stepper: {
146     margin: 'auto',
147     width: 'fit-content',
148     maxWidth: '100%',
149     backgroundColor: 'rgb(0,0,0,0)'
150 },
151
152 button: {
153     position: 'relative',
154     height: '100%',
155     color: "rgba(50,50,50,0.8)"
156 },
157
158 xbutton: {
159     position: 'fixed',
160     top: '10px',
161     right: '10px',
162     color: "rgba(50,50,50,0.8)"
163 }
164 };

```

```

165
166 const fadeIn = css.keyframes({
167   '0%': { opacity: 0 },
168   '100%': { opacity: 1 }
169 })
170 const slideOut = css.keyframes({
171   '100%': { transform: 'translateY(-100%)' },
172 })
173
174 //Animations entering/exiting this page:
175 const Wrapper = glamorous.div(props => ({
176   animation: props.isMounted ? `${slideOut} 2.5s` : `${fadeIn} 1.5s`,
177   position: 'absolute',
178   top: '0px',
179   left: '0px',
180   width: '100vw',
181   height: '100vh',
182   zIndex: 5
183 })))
184 const pdfs = [require('./pdfs/test1.pdf'),
185               require('./pdfs/test2.pdf'),
186               require('./pdfs/test3.pdf'),
187               require('./pdfs/test1.pdf'),
188               require('./pdfs/test2.pdf'),
189               require('./pdfs/test3.pdf'),
190               require('./pdfs/test1.pdf'),
191               require('./pdfs/test2.pdf'),
192               require('./pdfs/test3.pdf')]
193
194 //firebase
195 const firebaseConfig = {
196   apiKey: "AIzaSyDjM37_DSv2RvPQzl5YiVzmgRHfpd4rJFU",
197   authDomain: "lui-medialab.firebaseio.com",
198   databaseURL: "https://lui-medialab.firebaseio.com",
199   projectId: "lui-medialab",
200   storageBucket: "lui-medialab.appspot.com",
201   messagingSenderId: "247289397118",
202   appId: "1:247289397118:web:eb2bcb0076d4bb4d"
203 };
204
205 if (!firebase.apps.length) {
206   firebase.initializeApp(firebaseConfig);
207 }
208 var database = firebase.database();
209 var currentRef = database.ref('voice');
210 //end
211 class PDFsApp extends Component {
212   constructor(props) {
213     super(props);
214
215     let refs = [];

```

```

216   for (let i = 0; i < pdfs.length; i++) {
217     refs.push(React.createRef());
218   }
219
220   this.state = {
221     refs: refs,
222     numPreviewPages: Math.ceil(refs.length / 8),
223     numPages: null,
224     currentPage: 1,
225     hovered: -1,
226     clicked: -1,
227     index: 0,
228     exit: false,
229     amiclicked:false,
230     rotation: 0, // Rotate pdf
231     zoom: 1.0
232   };
233
234   this.handleClick = this.handleClick.bind(this);
235 }
236
237 componentDidMount() {
238   //google home
239   currentRef.update({"current":"pdfs"});
240   var something = this;
241   currentRef.on('value', function(snapshot) {
242     var db = snapshot.val();
243     var name = db.goto;
244     if (db.update){
245       if (name === "home") {
246         something.setState({ exit: true });
247         currentRef.update({"update":false});
248       }
249     }
250   }
251   if(db.clicked){
252     currentRef.update({"clicked":false});
253     something.gestureDetected = true;
254     something.handleClick(db.hovered);
255   }
256   if (db.back){
257     if (something.state.amiclicked){
258       something.handleSwipeUp();
259     }
260     else{
261       something.setState({ exit: true });
262     }
263   }
264   currentRef.update({"back":false});
265 }
266 });

```

```

267 }
268
269 rotate(){
270   let newRotation = this.state.rotation + 90;
271   if(newRotation >= 360){
272     newRotation -= 360;
273   }
274   this.setState({
275     rotation: newRotation,
276   })
277 }
278
279 handleHover = (pdf) => {
280   this.setState({ hovered: pdf })
281   currentRef.update({ "hovered": pdf });
282 }
283
284 handleClick = (pdfId) => {
285   this.setState({ clicked: pdfId })
286   this.setState({ amiclicked: true })
287   this.setState({ currentPage: 1 })
288   this.setState({ rotation: 0 })
289 }
290
291 handleExit = () => {
292   this.setState({
293     exit: true
294   })
295 }
296
297 handleRotate = (handRotation) => {
298   this.setState(prevState => ({ rotation: (prevState.rotation + 180 *
299     ↪ handRotation / 3.14) })))
300 }
301
302 handlePinch = (pinch) => {
303   let { clicked, zoom } = this.state;
304   if (clicked !== -1) {
305     zoom *= ((pinch - 1) * 1.2) + 1;
306     if (zoom < 0.4) {
307       zoom = 0.4;
308     } else if (zoom > 4) {
309       zoom = 4;
310     }
311     this.setState({ zoom })
312   }
313 }
314
315 handleSwipe = (dir) => {
316   let { clicked, numPages, currentPage, index, numPreviewPages } = this.state;
317   if (dir === "left") {

```

```

317     console.log("swipe left");
318     if (clicked !== -1) {
319         this.setState({ currentPage: (currentPage < numPages) ? currentPage + 1 :
320             ↪ currentPage })
321     } else if (index < numPreviewPages - 1) {
322         this.setState({ index: index + 1 })
323     } else {
324         console.log("swipe right");
325         if (clicked !== -1) {
326             this.setState({ currentPage: (currentPage > 1) ? currentPage - 1 :
327                 ↪ currentPage })
328         } else if (index > 0) {
329             this.setState({ index: index - 1 })
330         }
331     }
332 }
333
334 handleNext = () => {
335     let { index, numPreviewPages } = this.state;
336     if (index < numPreviewPages - 1) {
337         this.setState({ index: index + 1 });
338     }
339 };
340
341 handleBack = () => {
342     let { index } = this.state;
343     if (index > 0) {
344         this.setState({ index: index - 1 });
345     }
346 };
347
348 handleSwipeUp = () => {
349     let { clicked } = this.state;
350     if (clicked !== -1) {
351         this.setState({ clicked: -1 });
352         this.setState({ amiclicked: false });
353     } else {
354         this.setState({ exit: true });
355     }
356 }
357
358 renderPDF(index) { //renders a pdf in the grid
359     const { classes } = this.props;
360     const { hovered, refs } = this.state;
361     const ref = refs[index]
362
363     return (<Grid item className={classes.cell} ref={ref} xs={12} sm={3}>
364         <div
365             onMouseEnter={() => { this.setState({hovered: index}) }}
366             onMouseLeave={() => { this.setState({hovered: -1}) }}

```

```

366         onClick={() => { this.handleClick(index) }}
367         className={hovered === index ? classNames(classes.thumbnail,
           ↳ classes.hovered) : classes.thumbnail} >
368             {pdfs[index]}
369         </div>
370     </Grid>;
371 }
372
373 onDocumentLoadSuccess = (document) => {
374     console.log("loaded")
375     const { numPages } = document;
376     this.setState({
377         numPages,
378         pageNumber: 1,
379     });
380 };
381
382 goToPage(page) {
383     const { numPages } = this.state;
384     if (page > 0 && page <= numPages) {
385         this.setState({ currentPage: page })
386     }
387 }
388
389 renderFullScreen(index) { //renders the full screen gallery view for the pdfs
390     const { classes } = this.props;
391     const { rotation, zoom, currentPage, numPages } = this.state;
392     let pdfRotation = Math.round(rotation / 90) * 90;
393     return (<div>
394         {/* PDF */}
395         <div className={classes.pdf} justify={"center"}>
396             <Document
397                 file={pdfs[index]}
398                 onLoadSuccess={this.onDocumentLoadSuccess}
399                 onLoadError={console.error}
400                 rotate={pdfRotation}
401             >
402                 <Page pageNumber={currentPage} scale={zoom}
403                     ↳ className={classes.pdfpage} />
404             </Document>
405         </div>
406         {/* Exit button: */}
407         <Button onClick={() => this.handleSwipeUp()} className={classes.xbutton}>
408             <Clear/>
409         </Button>
410     </div>);
411 }
412
413 renderPDFs() { //renders the full grid of pdfs
414     const { classes } = this.props;
415     const { index, refs } = this.state;

```



```

415 let pages = [];
416 let rows = [];
417 let previews = [];
418 var i;
419 for (i = 0; i < refs.length; i++) {
420   previews.push(this.renderPDF(i));
421   if ((i + 1) % 4 == 0) {
422     rows.push(<Grid container className={classes.row} spacing={0}
423       ↪ justify={"center"} >
424       {previews}
425     </Grid>);
426     previews = [];
427   }
428   if ((i + 1) % 8 == 0) {
429     pages.push(<div className={classes.carousel} justify={"center"}>
430       {rows}
431     </div>);
432     rows = [];
433   }
434   if ((refs.length % 8) != 0) {
435     if ((refs.length % 4) != 0) {
436       rows.push(<Grid container className={classes.row} spacing={0}
437         ↪ justify={"center"} >
438         {previews}
439       </Grid>);
440     }
441     pages.push(<div className={classes.carousel} justify={"center"}>
442       {rows}
443     </div>);
444   }
445   return (<div>
446     <div>
447       <SwipeableViews className={classes.gallery} index={index}>
448         {pages}
449       </SwipeableViews>
450     </div>
451   </div>);
452 }
453
454 renderStepper() {
455   const { classes } = this.props;
456   const { index, numPreviewPages } = this.state;
457
458   return (numPreviewPages <= 1) ? "" : (<div className = "stepper">
459     <MobileStepper
460       variant="dots"
461       steps={numPreviewPages}
462       position="bottom"
463       activeStep={index}

```

```

464     className={classes.stepper}
465     classes={{ dots: classes.dots }}
466     nextButton={
467       <Button size="small" onClick={this.handleNext} disabled={index >=
         ↪ numPreviewPages - 1}>
468         <KeyboardArrowRight />
469       </Button>
470     }
471     backButton={
472       <Button size="small" onClick={this.handleBack} disabled={index <= 0}>
473         <KeyboardArrowLeft />
474       </Button>
475     }
476   />
477 </div>);
478 }
479
480 renderPageSelection() {
481   const { classes } = this.props;
482   const { numPages, currentPage } = this.state;
483   return <div className = "pagination">
484     /* Page number at the bottom of the view: */
485     <Pagination className={classes.pagination} count={numPages}
         ↪ page={currentPage} onChange={(event, page) => this.goToPage(page)}
         ↪ shape="rounded" />
486   </div>
487 }
488
489 render() {
490   const { classes } = this.props;
491   const { clicked } = this.state;
492
493   // Handling whether to go back to the Home page or display the PDFs page
494   if (this.state.exit) {
495     console.log("EXITING")
496     return <Redirect to={{ pathname: "/Home", state: {page: "home"} }} />
497   }
498
499   return (
500     <Wrapper isMounted={this.props.isMounted} exit={this.state.exit}>
501       <div>
502         <div className={classes.container} justify={"center"}>
503           <Leap
504             pdfs={this.state.refs}
505             handleHover={this.handleHover}
506             handleClick={this.handleClick}
507             amiclicked = {this.state.amiclicked}
508             handleSwipe={this.handleSwipe}
509             handleSwipeUp={this.handleSwipeUp}
510             handleRotate={this.handleRotate}
511             handlePinch={this.handlePinch}

```

```

512     />
513
514     {/* Handling whether to render a full screen pdf or not */}
515     <div className={classes.maincontent}>
516         { clicked !== -1 ? this.renderFullScreen(clicked) : this.renderPDFs()
517           ↪ }
518     </div>
519
520     {/* Control bar */}
521     <div className={classes.controlbar}>
522         {/* Home button: */}
523         <div className={classes.control}>
524             <Button onClick={() => this.handleExit()}
525               ↪ className={classes.button}>
526                 <Home/>
527             </Button>
528         </div>
529         <div className={classes.control}>
530             { clicked !== -1 ? this.renderPageSelection() : this.renderStepper()
531               ↪ }
532         </div>
533     </div>
534 </div>
535 </Wrapper>
536 );
537 }
538 }
539
540 export default withStyles(styles)(PDFsApp);

```

leap.js

```

1  import PropTypes from 'prop-types';
2  import React from 'react';
3  import ReactDOM from 'react-dom';
4  import { withStyles } from '@material-ui/core/styles';
5  import Home from '@material-ui/icons/Home';
6  import GestureHandler from '../gesture-interface/app-interface';
7
8  const fingers = ["#9bcfedBB", "#B2EBF2CC", "#80DEEABB", "#4DD0E1BB", "#26C6DABB"];
9  const paused_fingers = ["#9bed9b", "#b1f0b1", "#80ea80", "#4ce14c", "#25da25"];
10
11  const styles = {
12      canvas: {
13          position: 'absolute',
14          height: '100%',
15          width: '100%',
16          zIndex: 10,

```

```

17     pointerEvents: 'none',
18   }
19 };
20
21 class Leap extends React.Component {
22   constructor(props) {
23     super(props)
24     this.state = {
25       hand: false,
26       indexFinger: "",
27       hovered: -1,
28       clicked: -1,
29       amiclicked: "",
30       pause: 4,
31       lhovered: "",
32       intervalId1: 0,
33       intervalId2: 0,
34       intervalId3: 0,
35       intervalId4: 0,
36     }
37   }
38   componentWillReceiveProps(nextProps) {
39     this.setState({ amiclicked: nextProps.amiclicked });
40   }
41
42   componentDidMount() {
43     let gestureHandler = new GestureHandler();
44     this.gestureHandler = gestureHandler;
45     gestureHandler.onEachGesture(function (gesture) {
46       console.log(gesture);
47       this.setState({ pause: 4 });
48     }.bind(this));
49
50     gestureHandler.onGesture("rhand_lswipe", function () {
51       this.props.handleSwipe("left");
52     }.bind(this));
53
54     gestureHandler.onGesture("rhand_rswipe", function () {
55       this.props.handleSwipe("right");
56     }.bind(this));
57
58     gestureHandler.onGesture("rhand_uswipe", function () {
59       let clicked = this.state.clicked;
60       if (clicked !== -1) {
61         gestureHandler.removePoseHandler("grab");
62         gestureHandler.removePoseHandler("pinch");
63         clicked = -1;
64         this.setState({ clicked });
65       }
66       this.props.handleSwipeUp();
67     }

```

```

68     }.bind(this));
69
70     gestureHandler.onGesture("rindex_airtap", function () {
71         var hovered = this.state.hovered;
72         if (hovered !== -1) {
73             gestureHandler.onPose("grab", function (data) {
74                 this.props.handleRotate(data.rotation);
75             }.bind(this));
76             gestureHandler.onPose("pinch", function (data) {
77                 this.props.handlePinch(data.pinch);
78             }.bind(this));
79             const clicked = hovered;
80             this.props.handleClick(clicked);
81             this.setState({ clicked: clicked, hovered: -1});
82         }
83     }.bind(this));
84
85     gestureHandler.onFrame(function (frame) {
86         if (frame.fingers.length !== 0) {
87             this.setState({ hand: true });
88         } else {
89             this.setState({ hand: false });
90         }
91         this.traceFingers(frame.fingers);
92     }.bind(this));
93
94     this.timer = setInterval(() => {
95         if (this.state.pause > 0) {
96             this.setState({ pause: this.state.pause - 1 });
97         }
98         if (this.state.hand) {
99             var { clicked, hovered } = this.state;
100             if (clicked === -1 && !this.state.amiclicked) {
101                 hovered = this.checkHover();
102                 this.setState({ hovered });
103                 this.props.handleHover(hovered);
104             }
105         }
106     }, 100);
107 }
108
109 componentWillMount() {
110     clearInterval(this.timer);
111     this.gestureHandler.disconnect();
112 }
113
114 traceFingers(pointables) {
115     try {
116         // TODO: make canvas and ctx global
117         const canvas = this.refs.canvas;

```

```

119     canvas.width = canvas.clientWidth;
120     canvas.height = canvas.clientHeight;
121     const ctx = canvas.getContext("2d");
122     ctx.clearRect(0, 0, canvas.width, canvas.height);
123
124     const { pause } = this.state;
125
126     pointables.forEach((pointable) => {
127         const color = pause > 0 ? paused_fingers[pointable.type] :
128             ↪ fingers[pointable.type];
129         const normalized = pointable.normalizedPosition;
130         const x = ctx.canvas.width * normalized[0];
131         const y = ctx.canvas.height * (1 - normalized[1]);
132         const radius = Math.min(20 / Math.abs(pointable.touchDistance),
133             ↪ 50);
134         this.drawCircle([x, y], radius, color, pointable.type === 1);
135
136         if (pointable.type === 1) {
137             this.setState({
138                 indexFinger: { x, y, vel: pointable.tipVelocity[2] }
139             })
140         }
141     });
142 } catch (err) {
143     // console.log("ERR", err);
144 }
145
146 darken() {
147     const canvas = this.refs.canvas;
148     const ctx = canvas.getContext("2d");
149     ctx.beginPath();
150     ctx.rect(20, 20, 150, 100);
151     ctx.fillStyle = "red";
152     ctx.fill();
153 }
154
155 getCoords(x, y, degrees, radius) {
156     /** Calculates the coordinates for the center of a button relative
157     * to the center of the radial menu.
158     *
159     * params: x,y are the center of the radial menu
160     * degrees is the angle of the button from the horizontal
161     * radius is the distance from the center of the radial menu to the center
162     ↪ of the button
163     *
164     * returns: coordinates of the center of the button
165     */
166     const newx = x + radius * Math.cos(degrees * Math.PI / 180)
167     const newy = y + radius * Math.sin(degrees * Math.PI / 180)
168     return [newx, newy]

```

```

167 }
168
169 clamp(val, min, max) {
170     return Math.min(Math.max(val, min), max);
171 }
172
173 rollToVolume(roll) {
174     return this.clamp(2 - roll, 0, 3) * 100 / 3;
175 }
176
177 drawLabel(center) { //label for button
178     const canvas = this.refs.canvas;
179     const ctx = canvas.getContext("2d");
180     ctx.font = "40px Helvetica";
181     // const coords = this.getCoords(x, y, )
182     ctx.fillText("Home", center[0] - 50, center[1] + 15);
183 }
184
185 drawArc(center, radius, color, percent) {
186     const canvas = this.refs.canvas;
187     const ctx = canvas.getContext("2d");
188     ctx.beginPath();
189     ctx.arc(center[0], center[1], radius, 0, percent * 2 * Math.PI, false);
190     ctx.lineWidth = 10;
191     ctx.strokeStyle = color;
192     ctx.stroke();
193 }
194
195 drawCircle(center, radius, color, fill) { //draws a circle
196     const canvas = this.refs.canvas;
197     const ctx = canvas.getContext("2d");
198     ctx.beginPath();
199     ctx.arc(center[0], center[1], radius, 0, 2 * Math.PI);
200     ctx.closePath();
201     ctx.lineWidth = 10;
202     if (fill) {
203         ctx.fillStyle = color;
204         ctx.fill();
205     } else {
206         ctx.strokeStyle = color;
207         ctx.stroke();
208     }
209 }
210
211 drawPointer(center, radius, color, fill) { //draw small circle that points to
    ↪ what is hovered
212     const canvas = this.refs.canvas;
213     const ctx = canvas.getContext("2d");
214     ctx.beginPath();
215     ctx.arc(center[0], center[1], radius, 0, 2 * Math.PI, false);
216     ctx.closePath();

```

```

217     ctx.lineWidth = 10;
218     if (fill) {
219         ctx.fillStyle = color;
220         ctx.fill();
221     } else {
222         ctx.strokeStyle = color;
223         ctx.stroke();
224     }
225 }
226
227 checkHover() { //returns which pdf is hovered
228     const pdfs = this.props.pdfs;
229     const { x, y } = this.state.indexFinger;
230     for (let i = 0; i < pdfs.length; i++) {
231         if (pdfs[i] && pdfs[i].current) {
232             const dims = pdfs[i].current.getBoundingClientRect();
233             if (x > dims.left && x < dims.right &&
234                 y > dims.top && y < dims.bottom) {
235                 return i;
236             }
237         }
238     }
239     return (-1);
240 }
241
242 render() {
243     const { classes } = this.props;
244     return (
245         <canvas className={classes.canvas} ref="canvas"></canvas>
246     )
247 }
248 }
249
250 Leap.propTypes = {
251     pdfs: PropTypes.array,
252     handleHover: PropTypes.func,
253     handleSwipe: PropTypes.func,
254     handleExit: PropTypes.func,
255     handleRotate: PropTypes.func,
256     handlePinch: PropTypes.func
257 };
258
259 // TODO: better default values
260 Leap.defaultProps = {
261     pdfs: [],
262 };
263
264 export default withStyles(styles)(Leap);

```


UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain

Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | www.uclouvain.be/epl