Handover Document for Tangible Conversations

Tangible Conversations

Software and hardware development for exoskeleton hand.

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1 Introduction

In the following report we present the development of a software solution for the visuzalisation and the kinematic analysis of the exoskeleton hand shown in Fig. 1. The proposed design has been the result of the combined work of Tj A. Taiwo and Antonia Tzemanaki. A detailed description of the exoskeleton and its design can be found in the handover report of TJ A. Taiwo [1] and in the doctoral thesis of Antonia Tzemanaki [2], included with this document. In the following chapters we analyze the integration of the existing hardware with different software solutions for the visuzalisation of the exoskeletons kinematic behaviour. We also present the development of features and tools that fascilitated the manufacturing process of the exoskeleton.

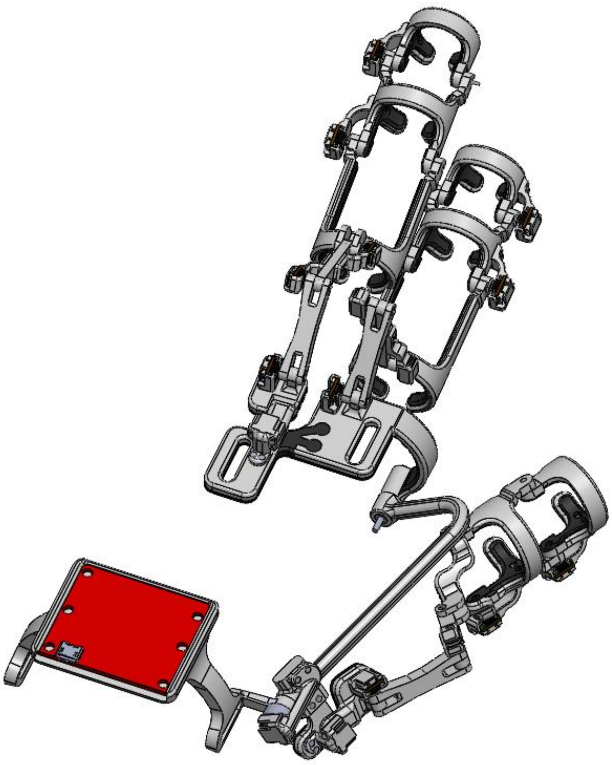


Figure 1: Exoskeleton assembly.

2 Hand Measurements

In [1] a detailed description of the exoskeleton's design and assembly is presented. One of the key features of the design is that it allows the parametric definition of its dimensions based on the user's hand measurements. This is made possible with the help of a set of equations that define the hand's geometry as a function of some characteristic lengths. As described in [1], these lengths are defined in the `"equation.txt"` file and they are automatically parsed by the software (Solidworks). To fascilitate the process of generating the `"equation.txt"` file a simple Python script was created. The

Measurement Name		Left Hand Value	Right Hand Value
thumbDistalDiameter			
thumbProximalDiameter			
indexDistalDiameter			
indexMiddleDiameter			
indexProximalDiameter			
middleDistalDiameter			
middleMiddleDiameter			
middleProximalDiameter			
indexDistalLength			
indexMiddleLength			
indexProximalLength			
middleDistalLength			
middleMiddleLength			
middleProximalLength			
thumbDistalLength			
thumbProximalLength			
thumbProximal2Wrist	Metecarpal bone length		
indexKnuckle2Wrist	Distance from the knuckle of the index		
knuckleThickness	Thickness of the palm measured at the knuckles		
wrist2BaseOfMiddle	Distance between the wrist and the base of the middle finger measured along the palm on the palmar side of the hand		
littleKunckle2Wrist	Distance from the knuckle of the little finger to the wrist joint		
palmarDorsalWidth	Width of the palm mesured across the knuckles		
wristWidth			
wristThickness			

Figure 2: Template format for storing the user's hand measurements.

script reads the user's hand measurements using the `"Exoskeleton Hand Measurements_AT.xlsx"` file and automatically produces the `"equation.txt"` file. The template used for storing the user's hand measurements is shown in Fig. 2. A detailed description of the measurements names shown in Fig. 2 and how to take them is given in [1].

To generate the equation file the user needs to create a new tab in the provided Excel file 'Exoskeleton Hand Measurements AT'. Then by executing the provided application `"hand_parameters.exe"` or the the associated Python script `"hand_parameters.py"`, the user can automatically generate the required equations file. The application has a command line interface, as shown in Fig. 3, where the user inserts the name of the tab as well as whether measurements are intented for the left or the right hand. To execute the files please first make a local copy of the `HandMeasurements` folder.

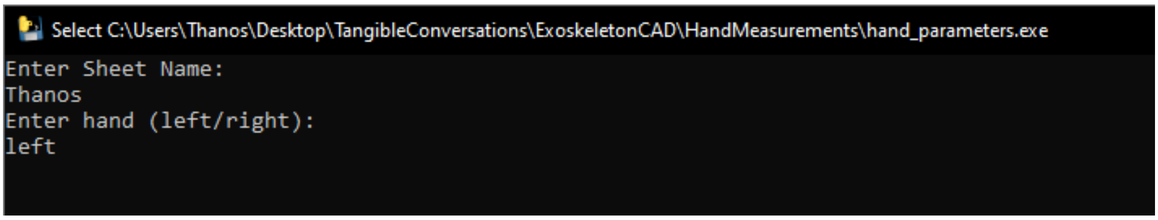
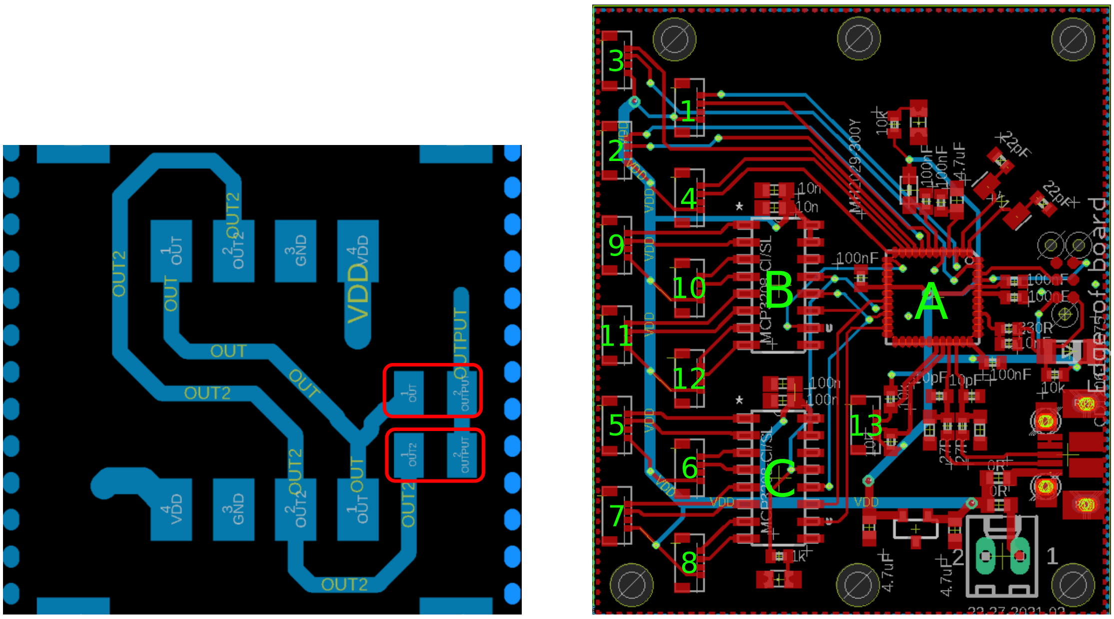


Figure 3: Hand measurements application.

3 Electronics and Hardware

As discussed in [1] the exoskeleton uses magnetic rotary encodes to measure the hand's joint angles. In this project we use the `Melexis 90316` absolute rotary encoder. The sensors need to be calibrated with the help of specialist equipment in the BRL.



(a) Melexis custom PCB wiring.

(b) Custom PCB board and ports numbering convention.

Figure 4: Custom PCBs for the Melexis sensor and the exoskeleton's circuit board.

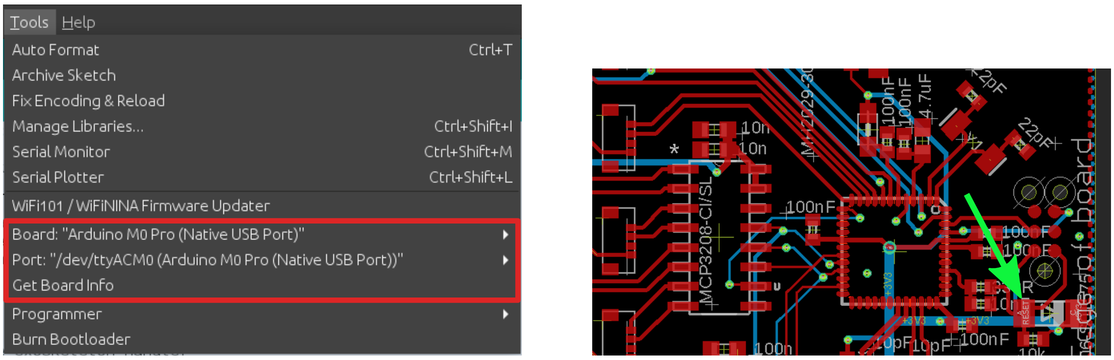
3.1 Melexis Custom PCB

The Melexis sensors are soldered onto a `custom PCB` made by Jason Welsby (BRL Technician). The files can be viewed and processed with the help of Autodesk Eagle. The custom PCB enables the daisy chaining of the Melexis sensors. Each PCB has the option to connect one of two "zero ohm resistors" which routes the signal coming from the sensor either to the OUT1 or OUT2 channel of the JST connector attached to the PCBs underside, see Fig. 4a. The JST connectors are wired so a cable can be plugged into either side of the board. For daisy chaining to work a PCB with the OUT1 signal needs to be connected to a PCB with the OUT2 signal, otherwise the sensors output will interfere will each other providing inaccurate data. To seperate the PCB's we color code them to green and red. Thus, a green sensor can only daisy chained to a red sensor. Sensors of the same color can not be connected together. To color code a sensor a microscope might be necessary. Please, ask Jason Welsby for more information.

3.2 Mainboard

The mainboard for the exoskeleton project was custom made by Jason Welsby and its design is shown in Fig. 4b. The board's PCB files can be found `here`.

The board uses the SAMD21G18A QFN microcontroller, denoted with A in Fig. 4b), and two MCP3208 analogue to digital converters (ADCs), B and C, Fig. 4b. Each port on the microcontroller (numbered 1-13 in Fig. 4b) allows receives two analog signals from the melexis sensors. These signals are the sent from the ports to the 8 built-in analog pins of the microcontroller or to the analog pins of the MCP3208. The mapping of the ports to the analog pins of the board or the ADCs is explained



(a) Arduino IDE setup. (b) Arduino reset pin.

Figure 5: Arduino Configuration.

in 3.4.

3.3 Arduino Connection

The SAMD21G18A QFN can be programmed through the Arduino IDE. For this the user needs to install the following external boards:

- Arduino SAM Boards (32-bits ARM Cortex-M3), tested with version 1.6.12.
- Arduino SAMD Boards (32-bits ARM Cortex-M0+), tested with version 1.8.12.
- Adafruit SAMD Boards, tested with version 1.7.5.
- avdweb.nl SAM15X15 SAMD Boards, tested with version 27.0.0-Core-v1.8.11.
- Industruino SAMD Boards (32-bits ARM Cortex-M0+), tested with version 1.0.1.

To upload a program to the board, please connect it to our computer using a USB micro cable. In the Arduino board, under tools select board `"32-bits ARM Cortex-M0+` → `Arduino M0 Pro (Native USB Port)"`. Please also select the appropriate USB port. This should look similar to the one shown in Fig. 5a.

Note: If the board does not appear to the list of available devices it should be resetted. Since there is no reset button to the board, this can be done manually done by grounding the reset pin shown in Fig. 5b.

3.4 Board Software

In this project, we developed the software for the microcontroller which is responsible for reading the analog values produced by the Melexis sensors and the printing them to the serial output for further processing. For the source code of the software please visit `here`, while for the its documentation please click `here`. The links also provide installation instructions.

Due to the daisy chaining of the sensors, each port of the board receives two analog signals; one corresponding to the red sensor and one corresponding to the green sensor. Furthermore, each port can be directly connected to the microcontroller's built-in analog ports or it can be connected

Ports Mapping		
Port ID	*Green Sensor Read Function*	*Red Sensor Read Function*
X_1	analogRead(A0)	analogRead(A1)
X_2	analogRead(A2)	analogRead(A3)
X_3	analogRead(A4)	analogRead(A5)
X_4	analogRead(A6)	analogRead(A7)
X_5	readADC(0, 4)	readADC(1, 4)
X_6	readADC(2, 4)	readADC(3, 4)
X_7	readADC(4, 4)	readADC(5, 4)
X_8	readADC(6, 4) (Not Working)	readADC(7, 4)
X_9	readADC(0, 2)	readADC(1, 2)
X_{10}	readADC(2, 2)	readADC(3, 2)
X_{11}	readADC(4, 2)	readADC(5, 2)
X_{12}	readADC(6, 2)	readADC(7, 2)

Table 1: Ports mapping.

to one of the MCP3208 ADCs. The type of connection (direct on indirect) defines the way that the analog data is read by the software. For direct connections, we can use the built-in Arduino `analogRead` while for indirect connection we use the custom method `readADC`. For more information, please see the `AnalogPort` class. Table 1 summarizes the type of connection that each port allows (defined by the utilized function) as well as the wiring of each port (e.g. port X_2 is connected to the built-in analog ports A_2 and A_3 of the microcontroller). The connectivity of the ports with the microcontroller and the ADCs was derived based on the `custom PCB schematic`. As you can see in table 1 we only consider the first 12 ports, as the 13th is intended for different application.

The sensors of the exoskeleton following numbering convention shown in Fig. 6. This numbering allows the mapping between the sensors and the board ports IDs of Fig. 4b. The total number of sensors is 18, while according to our model(see) the degrees of freedom of the exoskeleton is 13. This is due to the requirement of 2 extra sensors per finger for the measurement of the Metacarpophalangeal (MCP) angle, see 4.3.3 in [2]. Furthermore, one degree of freedom (the yaw of the index finger) is ommited for simplicity.

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Following this convention, our software gives the user the ability to connect different sensors on different ports. This is achieved with the help of the initialization routine of the Sensor class. For more information please visit `here`.

4 Visualisation Software

To allow the visualization of the exoskleleton we developed two applications. The first, that will be referred to as `Skeletal Animation`, offers a photorealistic deformation of virtual hands, using the principles of skeletal animation. The second, that will be referred to as `Kinematic Animation`, implements a kinematically accurate representation of the exoskeletons deformations adapted to its dimensions. Both applications, receive the data from the exoskeleton in real-time and render the animation. A screen capture of both applications is illustrated in Fig. 7. Furthermore, our applications can capture real-time video stream and perform face landmarking with the help of Google's machine learning library `MediaPipe`. The data are then sent in real-time to the animation environment and they get rendered. A screen capture of the face landmarking application, that will

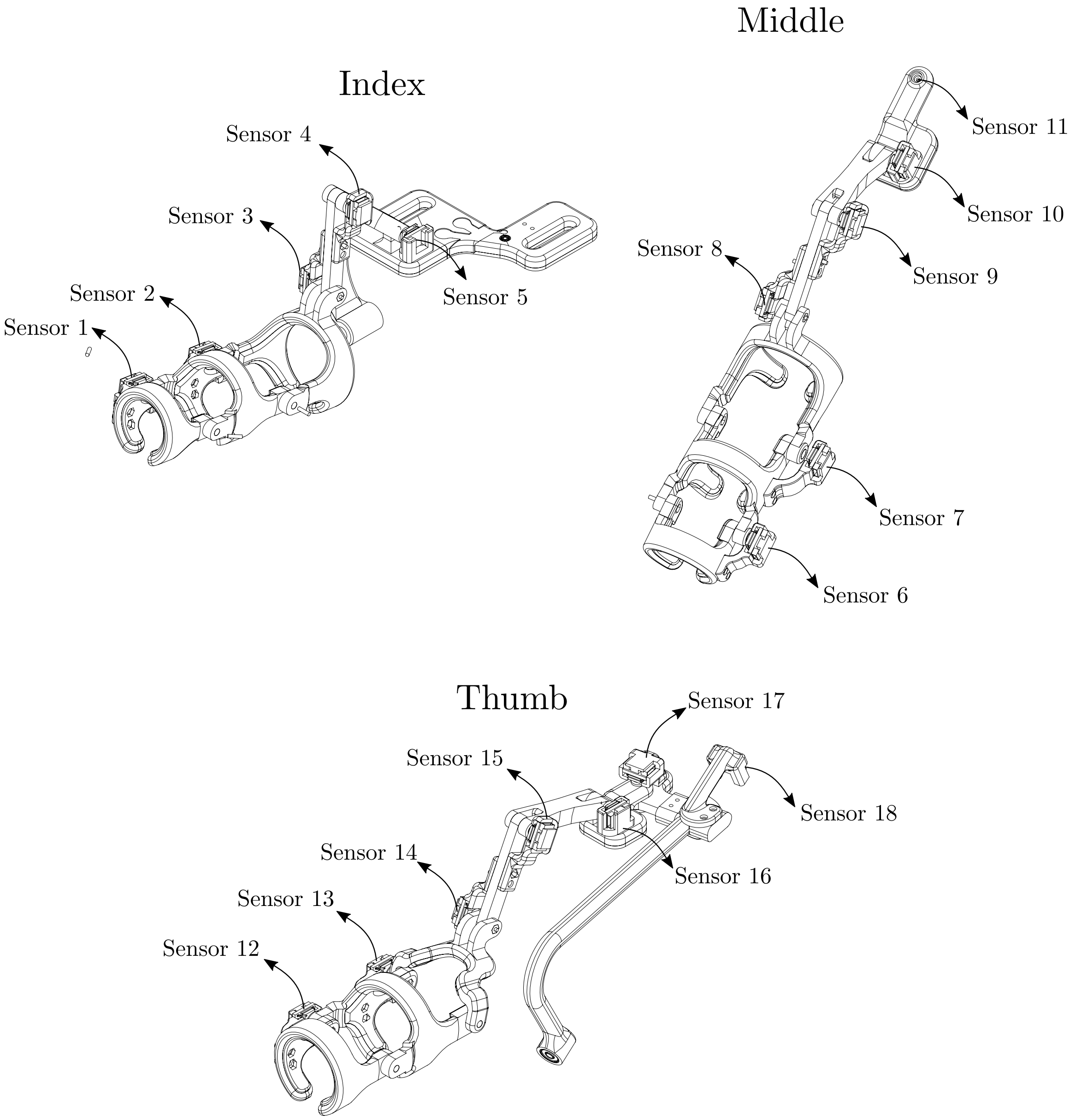
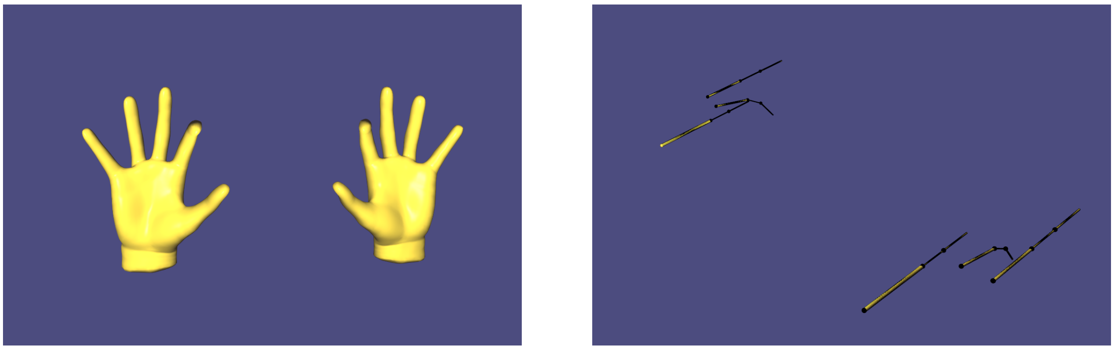


Figure 6: Custom PCB board and ports numbering convention.



(a) Skeletal animation. (b) Kinematics animation.

Figure 7: The two visualisation applications.

be reffered to as `Skeletal Animation Face`, is illustrated in Fig. 8.

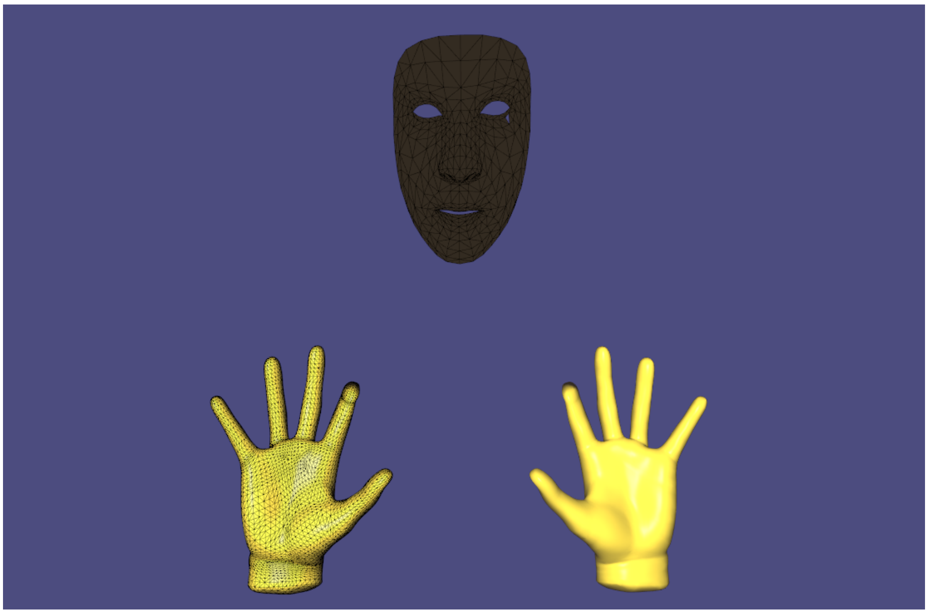


Figure 8: Hands and face rendering.

4.1 Core Libraries

Our software depends on two key liraries; the `LibIGL` lirary and the `MediaPipe` library.

4.1.1 LibIGL

LibIGL is an open source C++ library for geometry processing research and development. LibIGL builds on top of OpenGL and its API gives a high level control of geoemrtry rendering without the

$$V = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 1 \\ 2 & 1 & 0 \end{pmatrix} \qquad F = \begin{pmatrix} 0 & 1 & 2 \\ 1 & 3 & 2 \end{pmatrix}$$

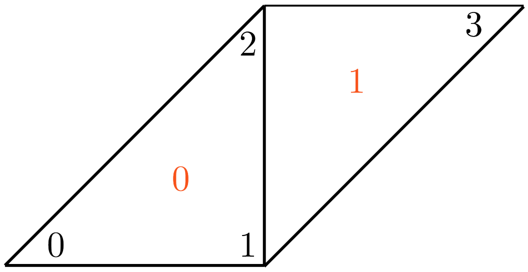


Figure 9: LibIGL representation of a simple mesh made of 2 triangles and 4 vertices.

need for low level manipulation of graphics primitives, such as fragment and geometry shaders. The library uses `Eigen` to encode vectos and mutrices. A triangular mesh is encoded as pair of matrices:

```
Eigen::MatrixXd V;
Eigen::MatrixXd F;
```

where V is a $n \times 3$ matrix which stores the coordinates of the vertices, with n the number of vertices in the geometry. Each row stores the coordinates of a vertiex, with its x, y and z coordinates in teh first, second and third column, respectively. The matrix F stores the triangle connectivity: each line of F denotes a trinagle whose 3 vertices are represented as indices pointing to rows of V. Fig. 9 shows a representation of a simple mesh using the storage mechanism of LibIGL. Note that the order of the vertex indices in F determines the orientation of the triangles and it should thus be consistent for the entire surface. For more information about the library please visit `LibIGL`.

4.1.2 MediaPipe

MediaPipe Face Mesh is a face geometry solution that estimates 468 3D face landmarks in real-time, as shown in 10. It employs machine learning (ML) to infer the 3D surface geometry, requiring only a single camera input without the need for a dedicated depth sensor. Utilizing lightweight model architectures together with GPU acceleration throughout the pipeline, the solution delivers real-time performance critical for live experiences. The library is combined with our rendering application to allow real-time rendering of a face mesh, using just a webcam. To run the library we use the Python API combined with OpenCV for image acquisition. The user can find the Python script `here`, while for more information on MediaPipe please visit `here`.

4.2 Dependencies and Installation

4.2.1 LibIGL Dependencies

Our software has some core dependencies that need to be installed before use. As we discussed before, the core dependency of LibIGL are the Eigen C++ linear algebra library. Our software also uses the GLFW library creating windows, contexts and surfaces, receiving input and events and the dear ImGui for the graphical user interface. Installation of LibIGL and its dependicies is done with the help of the `CMake` build system. LibIGL can be installed as a header-only library or as a static library. Installing as a static library leads to significantly less compilation time. In this regard, our software builds the static version of the library. However, as discussed `here` in the case of static compilation special care must be taken by the developers of each function and class in the

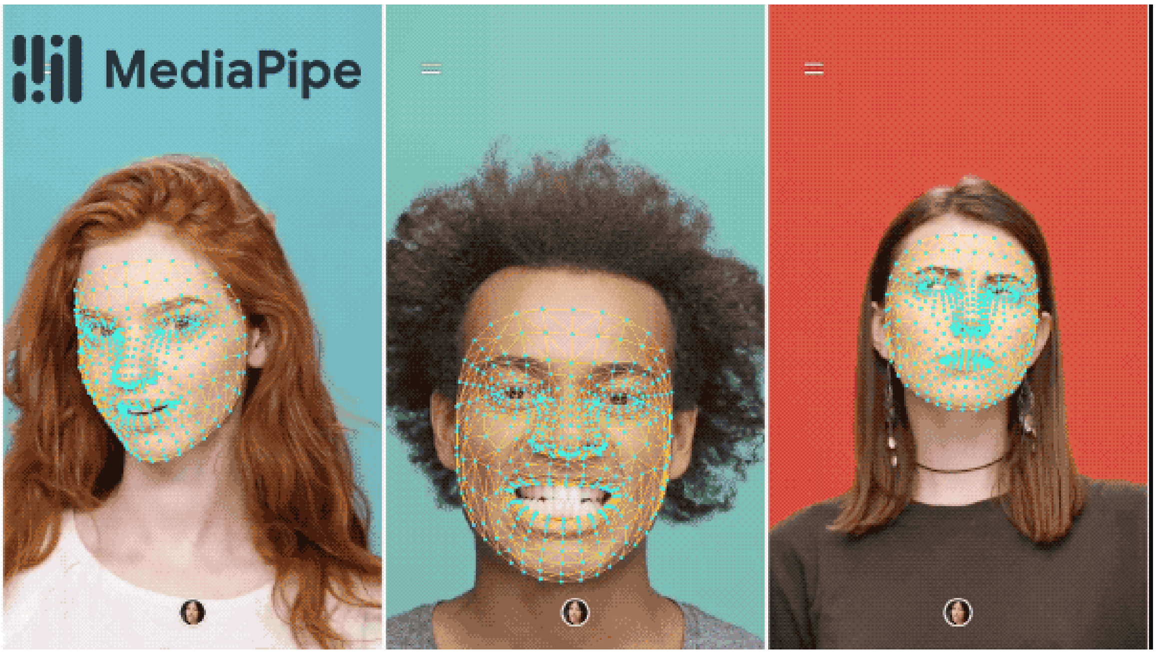


Figure 10: MediaPipe mesh.

LibIGL library that uses C++ templates. Analyical instructions for avoiding compilation errors for templated functions are presented `here`. In the case that the user prefers a header-only installation of LibIGL and of our software this is provided here. In the case the user wants to further develop our software, a full list of LibIGL dependencies is given `here`.

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4.2.2 MediaPipe Dependencies

For our application the MediaPipe library is combined with `OpenCV` for real-time image acquisition and the `numpy` module for linear algebra operations. For the installation of the library see 4.2.4.

4.2.3 Other Dependencies

As discussed before, our software allows the user to combine MediaPipe and LibIGL and render face-landmarking data in real time. Since the LibIGL is a C++ application and MediaPipe is a Python application an inter-process communication between the two is recquired. For this, we use C++ and Python sockets, to establish a TCP communication between the two applications. The data is transmitted between the two applications with the help of the `JSON` data-interchange format. To allow the generation and parsing of JSON files we use `JSON module` on the Python side and the header-only `nlohmann-json` library on the C++ side. Further dependencies can be found in the provided `.installlation.sh` script.

4.2.4 Installation

As discussed before, the software has multiple dependencies. To fascilitate the installation process we have created a shell script document that automatically installs all the required dependencies.

The current version of the software runs only in Linux, but extension to Windows platforms is also possible. The installation process for all the three provided applications (Skeletal Animation", Kinematic Animation and Skeletal Animation Face) is the same. The steps for installing the appropriate software are the following:

- Clone the appropriate github repository to your local directory.

  ```
  $git clone https://github.com/amartsop/Project.git
  ```

  where "Project" can be one of the following:

  - SkeletalAnimationMultiThread,
  - KinematicsAnimationMultiThread,
  - SkeletalAnimationMultiThreadFace.

- Install the appropriate dependencies. This can be done manually or with the help of the inculded installation bash script `.installlation.sh`. If the user wants to install dependencies manually, the full list of them is included in the provided `.installlation.sh` file. To execute the installation file:

  1. Login as root and navigate to the directory where the installation file is located.
  2. Run

     ```
     $source ./.installation.sh
     ```

     Warning: This will install quite a few libraries and packages in your computer. Please make sure that you are aware of the packages that are installed and with the location in which they are installed. Both settings can be changed by editing the ".installations.sh" file.

- Build the provided software. To do this:

  1. Navigate to the home location of the directory you have cloned.
  2. Generate a build directory and navigate to it by executing:

     ```
     $mkdir build && cd build
     ```

  3. Execute the CMake file by running:

     ```
     $cmake ..
     ```

  4. Build the executable by running:

     ```
     $make -j4
     ```

     Note: Using the command "-j4" we ask the compiler to use 4 threads for build the executable. The user can use as many as they prefer. The first time that you build the executable, LibIGL fetches its files from github and builds them as a static library. Since LigIGL is a quite heavy library this will take a while. However, all the following build commands will not build the LibIGL again but only the files that the user has added. If you want to update your build directory we recommend deleting the "CMakeCache.txt" file in it instead of deleting the whole build directory (as this will mean that the user will have To build LibIGL from scratch).

4.2.5 Other Considerations

The applications that we developed need to process data simulataneously from multiple source. More specifically, our applications need to read in real-time serial-data from two sources (for the two hands), acquire image data from the camera, process everything and render them on the screen. Furthermore, the frequency of these different processes varies significantly among them. For example the seria data acquisition process is significantly faster than the rendering process. In this regard, handling all these operations using a single recursive loop is not fisibile, not only because of the variability of frequencies but also because such an approach would create significant lag between the data acquisition and rendering. To tackle this problem, we recognize that the acquisition of the data for the different processes can be performed concurently (the processes are decoupled). In this regard, our software splits the different tasks in seperate threads. Each thread is respsonsible for capturing incoming data recusrsively and when all the thread are finished the final results is rendered on the screen. Threading in our applications is performed with the help of the C++ standard library and more specifically the async function. Except for multithreading, we have also used forking for process creation `here`. For more on forking please visit `here`.

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4.3 Kinematic model

In this section we discuss some of aspects of the proposed kinematic hand/exoskleton model. This model allows the mapping the exoskeleton movement to the movenemt of a virtual hands. In our model only three fingers are studied; namely the thumb, the index and the middle finger. In Fig. 11 we represent the kinematic model that we use as the basis for modeling the exoskeleton's movement (left hand). The joint angles measured from the exoskeletons are directly mapped to this model. For example, the angle measured from sensor 1 in Fig. 6 corresponds to the angle θ_{i_4} of Fig. 11. It should be noted that the angles $\theta_{w_1}, \theta_{w_2}$ and θ_{w_3} are not used by can be easily incorporated into the current model. It is important to note that this kinematic model is decoupled from the animation used. As we will discuss below, the avatars that will be introduced to represent the virtual hands can have their own frame conventions. However, all avatars must report to the basis frame convention shown in Fig. 11 as this is the one corresponding to the actual motion of the physical exoskeleton. The mapping between the avatar frames and the basis frame convention is discussed in the following paragraphs.

4.4 Kinematic Animation

This application allows for a kinematically accurate representation of the hands movement. Each finger is represented by a set of cylinders that represent the finger's phalanges and a set of spheres representing the finger's knuckles. The lengths of the phalanges and knuckes are determined based on the configuration file that correspond to the specific dimensions of the exoskeleton (see file `here`). To allow the accurate representation of the hand's forward kinematics, the user can edit the configuration file based on their exoskeleton measurements.

The virtual hand follows the frame convention shown in Fig. 12b. As shown in Fig.12 the frames of the kinematic animation differ from the original/basis frame convention. However, mapping the configuration of the original kinematic model to that of the virtual hand is straightforward. The process is analytically documented `here`. The source code of the project can be found `here` while the full documentation of the application is `here`.

In Fig. 7b we present the rendering result of the `Kinematic Animation Model`.

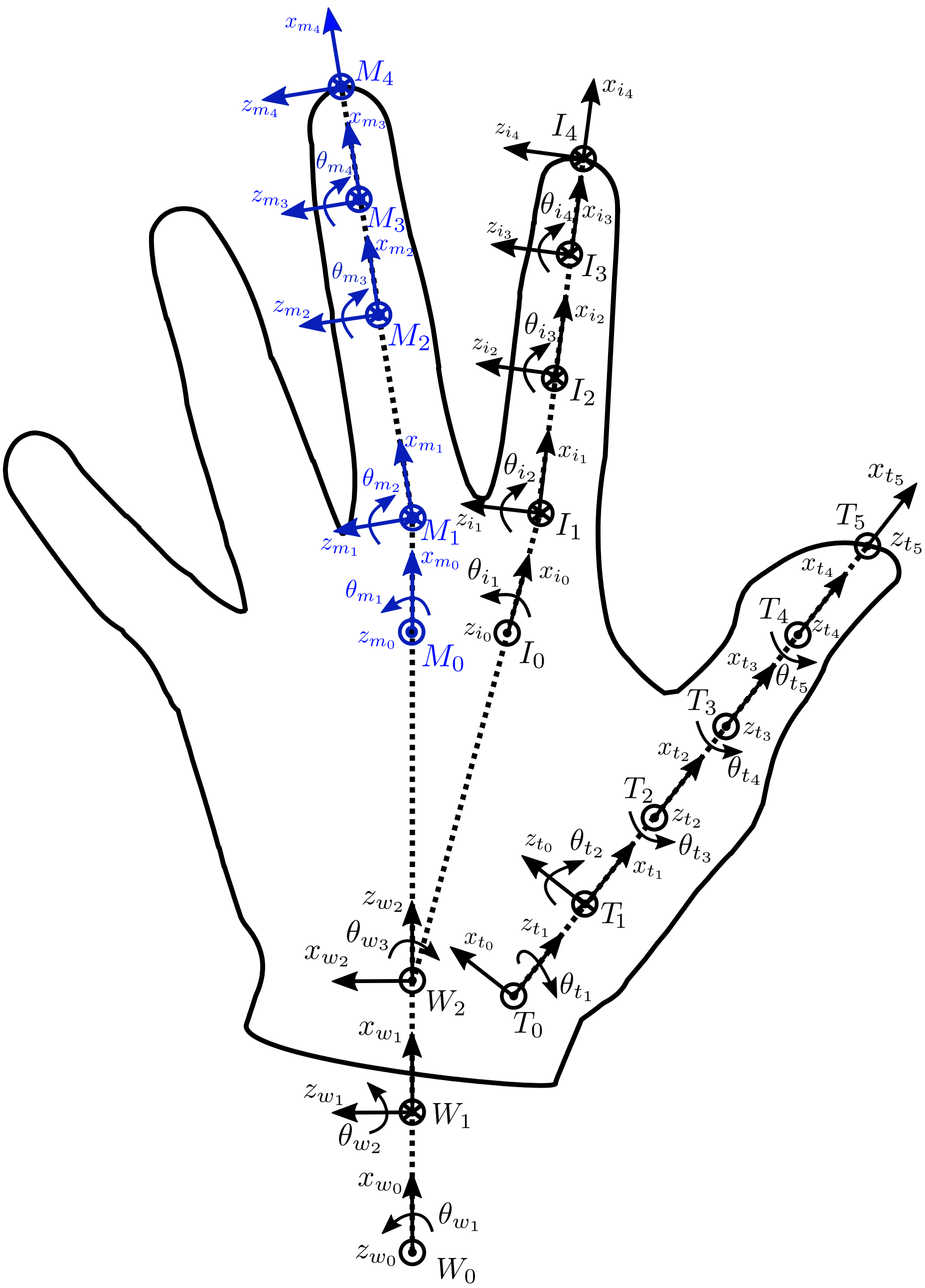
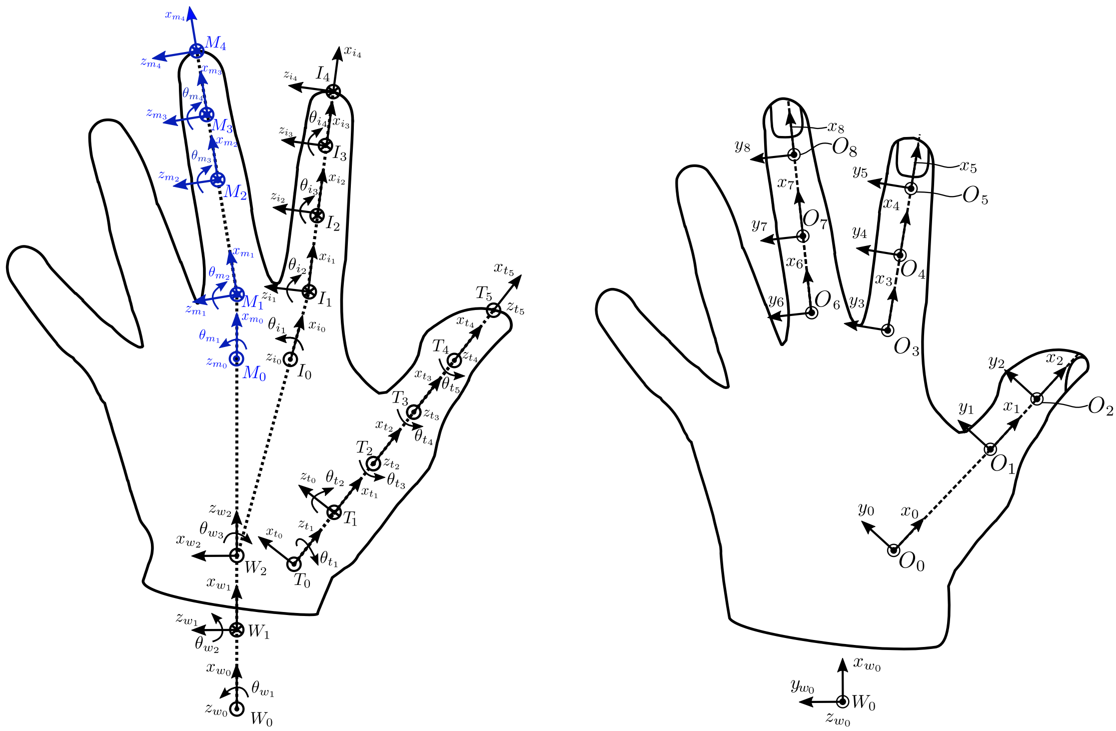


Figure 11: Kinematic model of left hand.



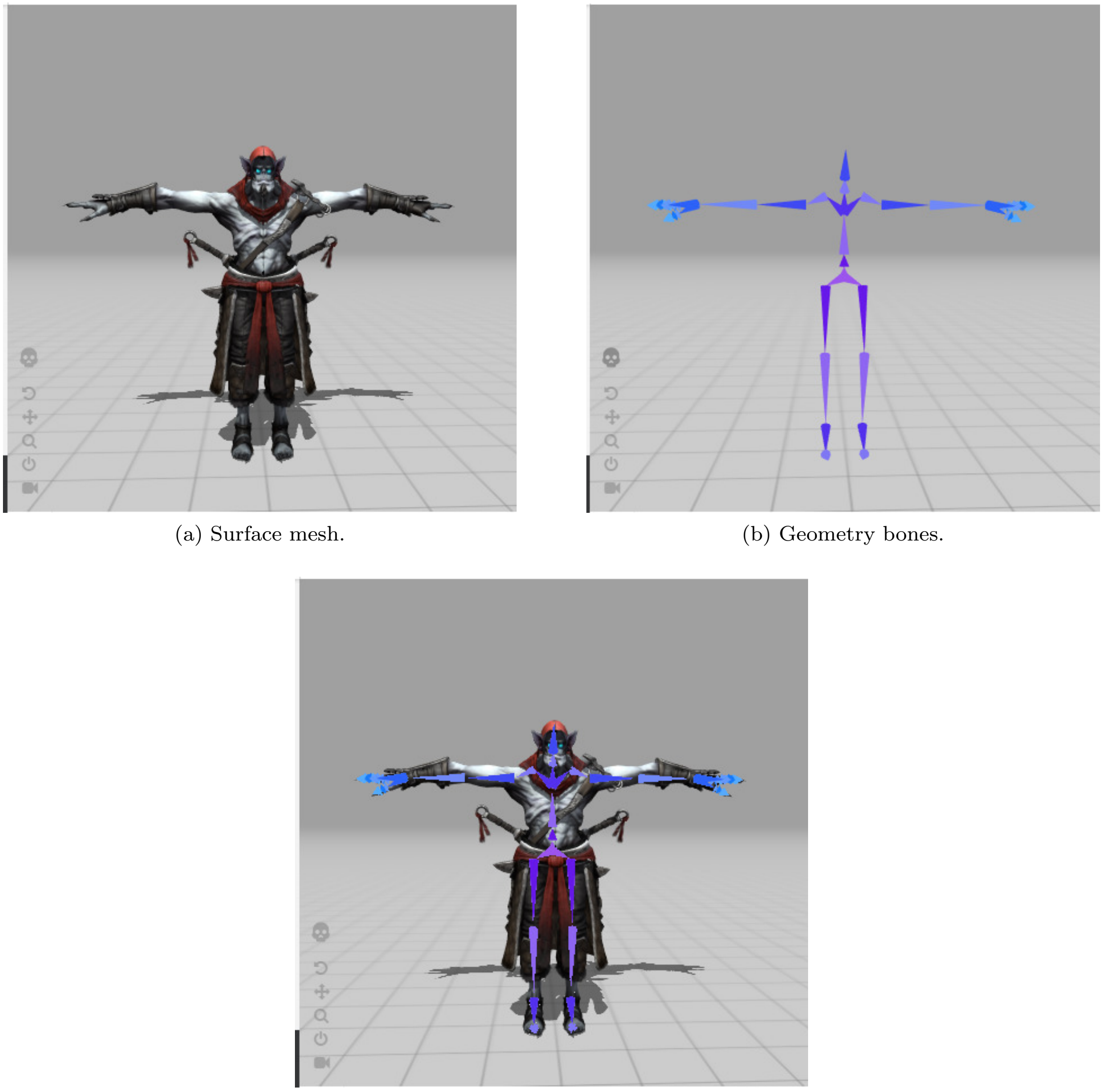
(a) Original kinematic model. (b) Animation kinematic model.

Figure 12: Orignal kinematic model and animation model.

4.5 Skeletal Animation

This application allows the rendering of photorealistic deformation of virtual hands, using the principles of skeletal animation. Using this techique the virtual hand is represented in two parts: the mesh which constitutes a realistic representation of the geometry and a hierarchical set of interconnected parts (called bones) that define the motion of the virtual avatar. Each bone has a three-dimensional transformation from the default bind pose (which includes its position, scale and orientation), and an optional parent bone. The bones therefore form a hierarchy. The full transform of a child node is the product of its parent transform and its own transform.

Each bone in the skeleton is associated with some portion of the character's visual representation (the mesh) in a process called skinning. In the most common case of a polygonal mesh character, the bone is associated with a group of vertices; for example, in a model of a human being, the bone for the thigh would be associated with the vertices making up the polygons in the model's thigh. Portions of the character's skin can normally be associated with multiple bones, each one having a scaling factors called vertex weights, or blend weights. The movement of skin near the joints of two bones, can therefore be influenced by both bones. By applying these ideas the user can apply direct transformations to the bones of the model and produce real-like deformations of the surrounding mesh, see Fig. 13. In Fig. 14 both the internal skeleton and the surrounding mesh of the hand is illustrated. Furthermore, the figure presents a color map that illustrates the effect of different bones on their surrounding mesh vertices. In our application, the weighting and mapping between boenes and mesh vertices with the help of the bounded biharmonic weight techique. For more information on



(a) Surface mesh.

(b) Geometry bones.

(c) Rigged character.

Figure 13: Steps of skeletal animation.

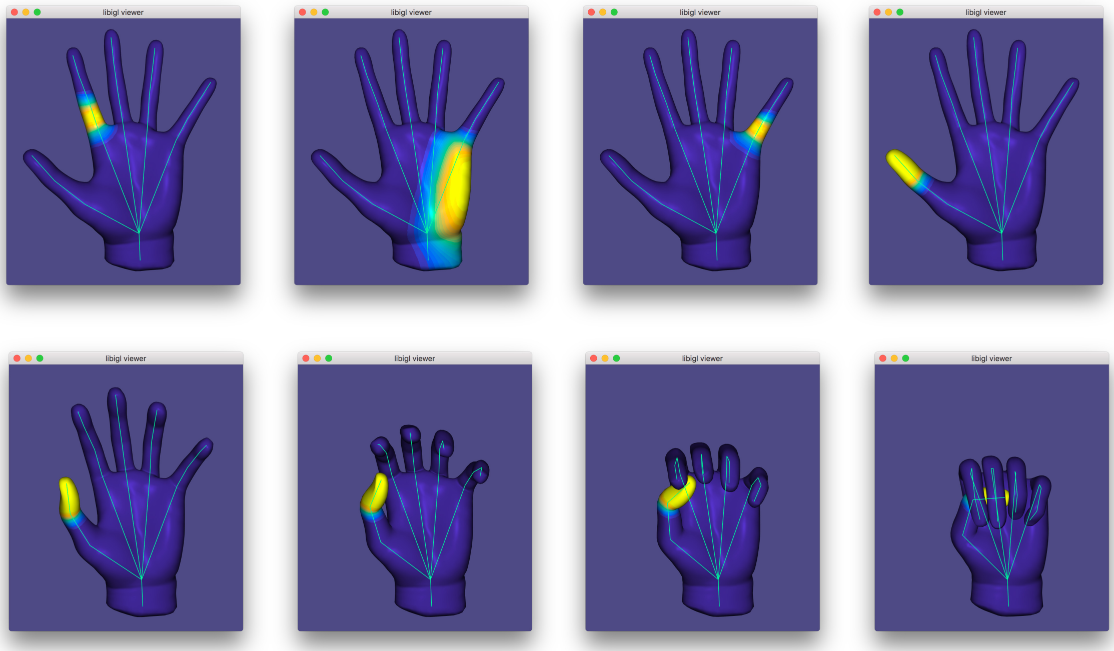
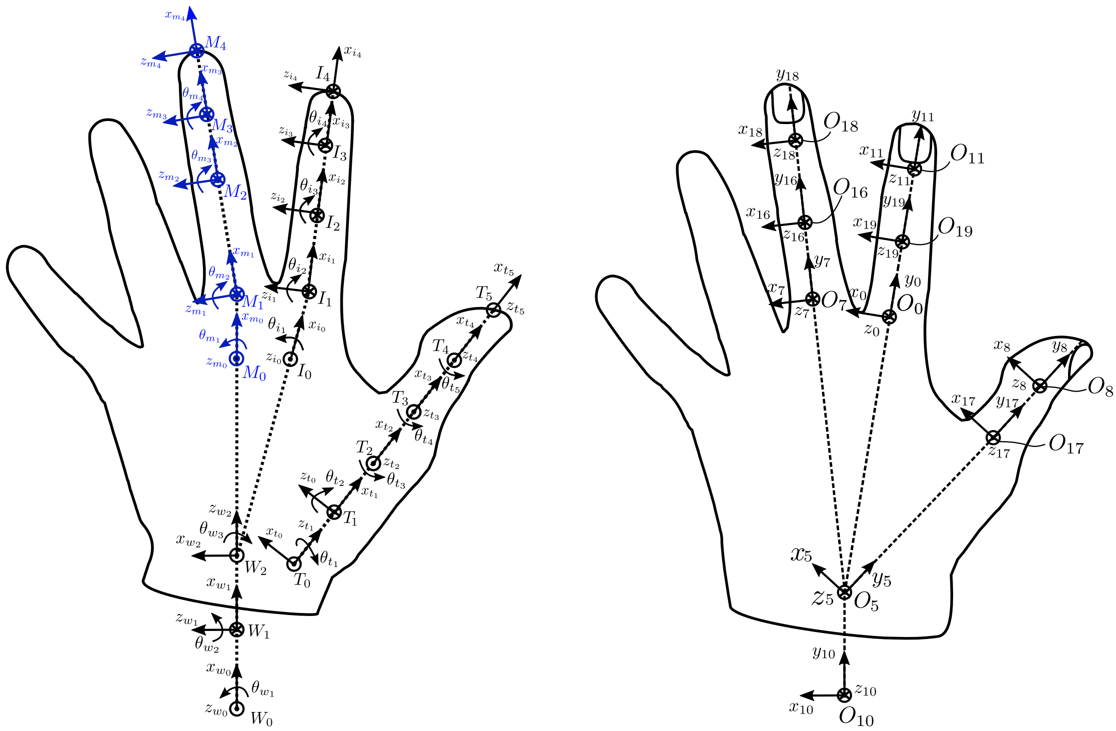


Figure 14: Hand rigging and bounded biharmonic weights visualisation.

the techique, please see the LibIGL's website and [3]. The virtual hand follows the frame convention shown in Fig. 15b. Again, as shown in Fig 15 the frames of the skeletal animation differ from the original/basis frame convention. However, mapping the configuration of the original kinematic model to that of the virtual hand is straightforward. The process is analytically documented `here`. The source code of the project can be found `here` while the full documentation of the application is `here`. In Fig. 7a we present the rendering result of the `Kinematic Animation Model`.

4.6 Face Landmarking

Our final application is the combination of the Skeletal Animation with face landmarking features. As discussed before, for this we have used the MediaPipe library, which uses machine learning algorithms for identifying 468 unique points that are scattered across the users face. The points are generated in real-time using a camera stream and they are to our rendering application (LibIGL) through means of interprocess communication. The connectivity relation of the generated vertices is known and it is stored as a csv file `here`. The source code of the project can be found `here` while the full documentation of the application is `here`.



(a) Original kinematic model. (b) Skeletal animation model.

Figure 15: Orignal kinematic model and skeletal animation model.

References

[1] Taiwo T. Exoskeleton handover. Nov; 2021.

[2] Tzemanaki A. Anthropomorphic surgical system for soft tissue robot-assisted surgery. Oct; 2016.

[3] Jacobson A, Baran I, Popović J, et al. Bounded biharmonic weights for real-time deformation. ACM Trans Graph. 2011 jul;30(4).