COMPUTER-AIDED DESIGN & APPLICATIONS, 2016
VOL. 13, NO. 6, 799–807
http://dx.doi.org/10.1080/16864360.2016.1168223

Mixed reality to design lower limb prosthesis

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ABSTRACT
This paper presents a Mixed Reality environment, named Virtual Orthopedic LABoratory (VOLAB), which permits to emulate an orthopedic lab and design lower limb prosthesis, in particular, the socket component. The proposed solution is based on low cost devices (e.g., Microsoft Kinect) and open source libraries (e.g., OpenCL and VTK). In detail, the hardware architecture consists of three Microsoft Kinect v2, Oculus Rift for 3D environment visualization and Leap Motion device for hand/fingers tracking. The software development has been based on the modular structure of the prosthetic CAD system, named Socket Modelling Assistant (SMA) and modules have been developed to guarantee the communication among the devices and the performance. Finally, preliminary tests are illustrated as well as results reached so far and future development.

KEYWORDS
Prosthesis design; Mixed Reality; Augmented Interaction; Low Cost Hand-Tracking devices; Human body devices; Socket Modelling Assistant

1. Introduction

In the last years, different technological solutions have been developed to interact with virtual environments as done by humans being in the real world. In this context, many devices have been developed and are commercially available to emulate human senses (e.g., touch and sight) and offer a user experience very close to real one [3], [7], [17], [23]. For example, there are devices that permit to interact using hands and replicate the sense of touch, while others allow image acquisition of real places that can be merged with virtual environments. In fact, many researchers have understood the need of design systems more adequate than traditional CAD systems. This is particularly true for products that heavily depend on the morphology of human body and people's life style in order to satisfy the increasing needs of customers [24], [30].

In this context, our research group developed a system, named Socket Modelling Assistant (SMA), specifically targeted to the design of lower limb prosthesis for both below (transtibial) and above knee (transfemoral) amputation, with particular attention to the socket component highly customized according to the residual limb morphology. SMA allows the users to design the socket in a virtual environment emulating the several steps of the traditional manufacturing process. SMA aims at offering a solution that can be used by orthopedic technicians, who have experience in prosthesis design rather than skills about CAD systems.

In the traditional process, the technician uses continuously her/his hands to reach the optimal socket shape. After an initial evaluation of the patient's residual limb, s/he creates a negative cast manipulating by hands plaster patches directly on the residual limb. Then, the positive model is realized and modified, always by hands, adding and removing chalk in specific zones according to residuum measurements and patient's characteristics. In practice, the socket is manufactured following a hand-made procedure and the final shape heavily depends on the prosthetist's skills and experience according to residual limb morphology and conditions.

Even if prosthetic CAD systems are commercially available, they usually permit to interact with the 3D socket model using traditional interaction devices, such as keyboard and mouse [2], [25]. Therefore, we propose a mixed reality solution based on low cost devices to virtualize the environment of a traditional orthopedic laboratory and make more natural the interaction with SMA.

In this paper, first the background about IT devices for mixed reality [19], with a focus on low-cost devices, is introduced. Then, we briefly describe SMA and the use of augmented reality to emulate socket design. The hardware and software solutions are illustrated as well as the custom library developed to synchronize the selected devices and the software interface implemented to exploit the mixed reality for socket design using SMA modules. Finally, preliminary tests are described and discussed.

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2. Background

In recent years, many researchers have been involved in developing IT solutions to make more realistic the experiences with 3D virtual environment. To this end, a set of devices has been realized to emulate the most important human senses, such as touch and sight. Among them, we focused the attention on low cost devices, since they have reached an adequate level of performance (at least for application in the prosthetic field) and do not require huge investments for the orthopedic labs that have limited human and IT resources.

There are devices that allow the tracking of hands/fingers and gestures recognition, such as Leap Motion device (Fig. 1(a).), Duo3D (Fig. 1(b).) and Intel Gesture Camera (Fig. 1(c).) as well as other solutions able to track both whole human body and 3D objects, such as Microsoft Kinect v1 and v2 (Fig. 1(d). and Fig. 1(e).).

The Leap Motion is a small device that is able to track hands/fingers with high precision through two infrared cameras. The detection space is small, but the quality of tracking is so high that permits to detect and distinguish each finger and its parts. Leap Motion has been tested in different research works in order to understand real potential applied to the design of natural user interface based on gesture [1], [12], [20], [31]. Furthermore, it makes available a Software Development Kit (SDK) to develop new application exploiting augmented interaction. The last version of SDK is already able to recognize a good set of basic gestures (e.g., grabbing, circle made by a single finger and pinch action) [16]. Duo3D is a small device composed by two infrared cameras, an accelerometer and a gyroscope. It is able to track hands/fingers with high precision, but the SDK is available only in pure ANSI C and doesn't offer an initial set of detectable gestures [8]. Intel Gesture Camera is a good hand-tracking device that is able to track simple gestures in front of PC screen [28], but doesn't permit to develop user interfaces for complex interaction. Microsoft Kinect v1 permits to track objects and human beings in large spaces and have been used for various applications [15], [18], [33], such as gait analysis and ergonomics studies [22]. Microsoft Kinect v2 has been totally redesigned in order to exploit high definition sensor and improve data acquisition [32]. Windows Kinect SDK offers a large set of features, such as face detection, human body tracking and 3D reconstruction [27], [34]. The Windows SDK does not permit to manage multiple Kinects on the same computer and to overcome this limit it is necessary to use open source SDKs, such as libfreenect2 (https://github.com/OpenKinect/ libfreenect2).

3D vision systems have been developed to recreate depth sense during the visualization of 3D environments. These systems can offer either partial or total immersive user experience. The first one is based on PC screen using LCD shutter glasses, such as NVIDIA 3D Vision System (Fig. 1(g).). This solution has been used into several research works, such as emulation of amblyopia treatments and measurements of stereo acuity of sight [9]–[11].

Totally immersive 3D systems are based on the use of wearable head-mounted displays, such as Google Cardboard and Oculus Rift. The Google Cardboard is a simple box with two lenses that, used in combination with a smartphone (Fig. 1(f).), constitutes a simple and powerful virtual reality viewer. The smartphone must be inserted in the box and the user looks inside in order to see the images displayed by the phone. Oculus Rift is a new solution to create a real user experience into virtual reality (Fig. 1(h)). Indeed, older head mounted display for virtual reality had problem of latency on rendered

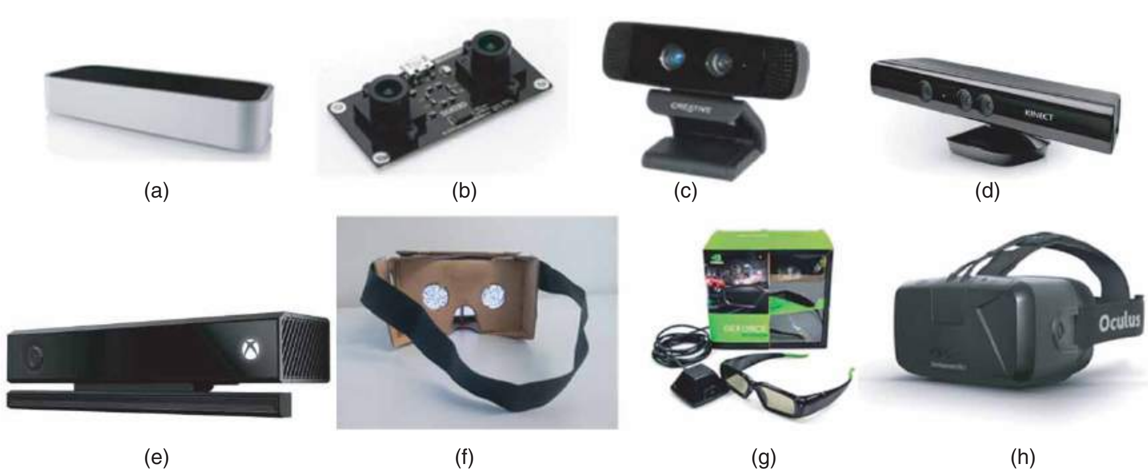


Figure 1. (a) Leap Motion, (b) Duo3D, (c) Intel Gesture Camera, (d) Microsoft Kinect v1, (e) Microsoft Kinect v2, (f) Google Cardboard, (g) NVidia 3D vision –system, (h) Oculus Rift.

images and thus, user could present some diseases, such as loss of balance and sickness. Oculus Rift technology solved this problem and the HD displays behind the two lenses offer a realistic experience into 3D environment in which the user can interact with it. This device has been used in research works related to different research field, such robotics and medicine [13], [14]. Oculus Rift makes also available a powerful SDK to develop new applications with several programming languages (e.g., C++ and C#).

In the following sections, we depict which devices have been chosen to achieve our aim through a description of both hardware and software architectures.

3. Mixed reality and orthopedic lab

In this section, we present the use of mixed reality applied to the SMA prosthetic CAD system.

3.1. Socket Modelling Assistant

Socket Modelling Assistant is a knowledge based CAD system developed in house [4] whose main components are shown in Fig. 2.

The design of the socket, the custom-made part of the prosthesis, starts from the digital model of patient's residuum and her/his data (e.g., anthropometric measurements and life-style).

The reconstruction of the residuum model is done automatically from MRI images [5]. It is based on NURBS models, which are managed using a developed in house software library, named SimplyNURBS [6]. A preliminary 3D shape of the socket is generated starting from the 3D model of the residuum; then, the socket shape is customized according to the morphology of the residuum. The user can modify the socket model by means of ad hoc virtual modeling tools that can be applied interactively or automatically. The prosthetist completes the model shaping the trim line of the upper edge and the system automatically creates the socket thickness taking into account the patient's weight. Finally, a module has been developed to analyze the interaction between the socket and the residuum exploiting commercial FEA software Abaqus.

The socket model can be exported in different formats (e.g., STL and IGES) and used to perform the gait analysis with virtual bio-mechanicals human models or to create the real socket by a 3D printer. For further details see [4].

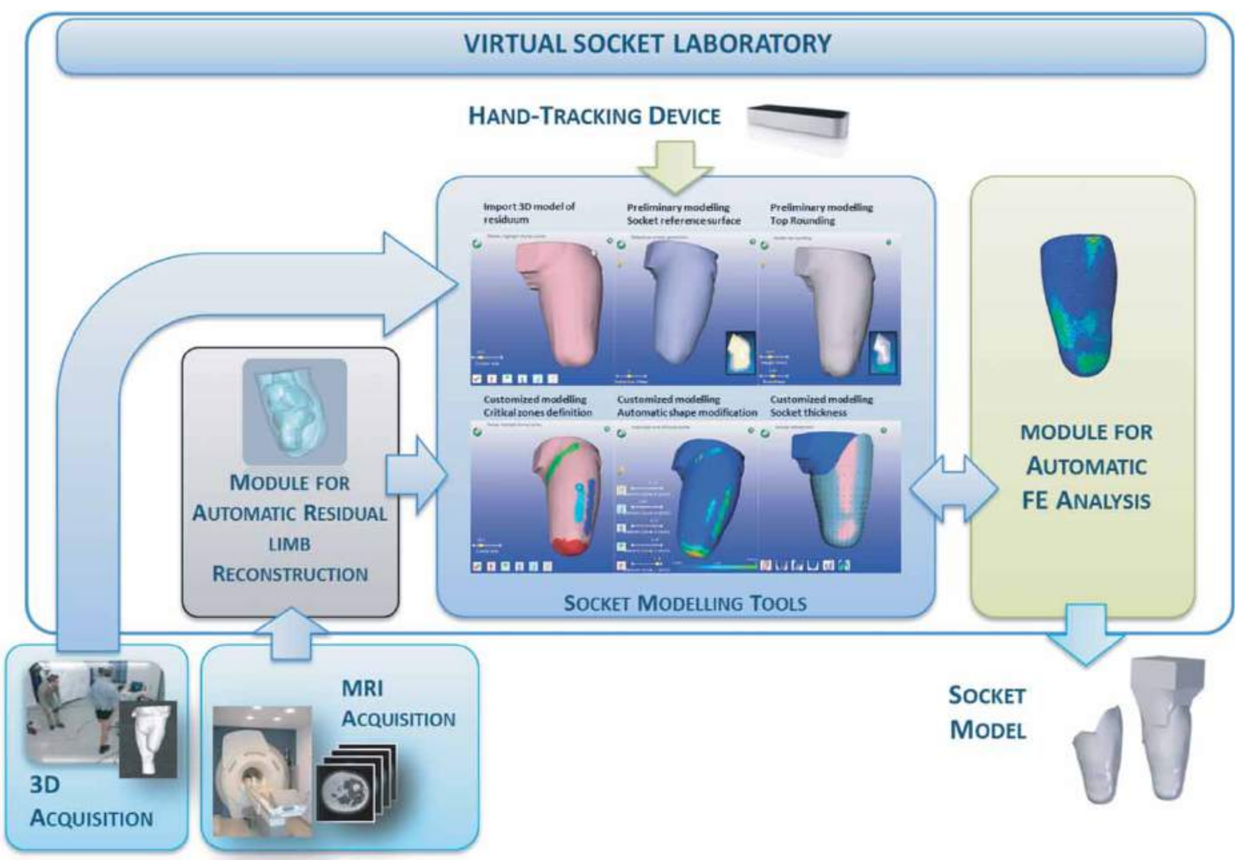


Figure 2. SMA architecture.

SMA has been implemented using open-source SDKs based on C++ language, such as Qt [21], VTK [29] and OpenCascade [26]. Qt permitted us to create the user interface through a very simple graphic editor. The Visualization Tool Kit allows modeling techniques, such as implicit modeling, mesh reduction and Delaunay triangulation as well. VTK exploits OpenGL and parallel computing in automatic way and thus, the developer can realize his/her applications with high performance computing. OpenCascade has been mainly used for its exporting modules, which permit to save socket model in either STL or IGES format. Furthermore, SimplyNURBS has been used to manage NURBS surface.

The modularity of the SMA software architecture allowed us to add new modules to realize the mixed reality environment for the orthopedic lab.

3.2. Mixed reality for prosthesis design

In order to create the virtual orthopedic lab, we need to interact with virtual models (i.e. the residuum and socket models) as the prosthetists typically does during the traditional process.

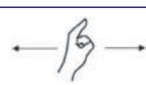
The proposed solution is based on low-cost devices as follows:

- Oculus Rift to render the scene (i.e., the orthopedic lab) with depth perception.
- Microsoft Kinects v2.0 to acquire high definition images rendered through the HD display of Oculus Rift. The multiple images are used to recreate real environment into a 3D scene. Both orthopedic technician and patient are tracked using Kinects. In fact, the real world has to be visible to the user and the interested part (i.e., patient's residuum) has to be detected into the scene.
- Leap Motion device to track hand/finger and allow the prosthetist to interact by hands with the socket and residual limb models.

As mentioned, SMA offers a set of virtual tools to emulate the most important tasks executed by orthopedic technicians. Therefore, thanks to its modularity, the virtual modeling tools can be used to manipulate socket shape tracking hands/fingers through the Leap Motion device.

Regarding the last issue, we have defined a set of gestures according to different actions that are executed to design the socket with SMA, such as marking of critical zones. Accordingly a Natural User Interface (NUI) based on the use of Leap Motion device has been implemented to interact with the 3D models of the residual limb and the socket using hands/fingers. The gestures are listed in Tab. 1. and are subdivided into two main groups: basic interactions with 3D environment (e.g., moving from one modeling tool to another one) and modeling operations

Table 1. Set of defined gestures.

Action	Gestures	Notes
	Basic Interaction	
Moving from one modeling tool to another		It changes the active virtual tool during virtual socket design.
Moving selection cursor		It permits to select objects in the virtual world.
	Modeling Operations	
Selecting a single point of 3D model	 	Traditionally the technician sketchs the trim-line along upper part of negative model of the socket. Virtual trim-line definition is based on the use of a line defined along upper part of virtual residuum. The technicians can modify the curve of virtual trim-line by pinching its points and thus, the pinched points can be moved to the correct position along the residuum.
Marking parts of the 3D model	 	Technician usually marks critical zones using a pencil. The corresponding SMA modeling tool permits to perform the same action using a pencil held in the hand.

(e.g., marking critical zones and trim-line definition of the upper edge).

Moreover, a set of icons and simple messages are shown on the lower right corner of the SMA User Interface so that the user can understand which hand gesture has been detected.

4. Volab implementation

The prosthetic mixed reality, named **V**irtual **O**rthopedic **LAB**oratory (VOLAB), has been based on the modular structure of SMA and new modules have been developed to guarantee the communication among the devices and the real time performance. In addition open source software libraries have been considered for the software development. In the next sections, the hardware and software solutions are described.

4.1. Hardware architecture

Fig. 3 shows the hardware architecture of VOLAB, which consists of:

- *Three Kinect v2* connected to a desktop computer. They are positioned to create an equilateral triangle with side length of 4.0 meters. The use of multiple Kinects v2 guarantees an adequate human body detection and tracking of residuum as well as a good 3D reconstruction by acquired infrareds images. The RGB camera of each Kinect is able to capture the scene video with high definition (1920 x 1080 pixels), which is visualized through the use of Oculus Rift. Kinect v2 has a frame rate of 30 fps, which is good enough for our goal.
- *Oculus Rift v2.0* connected to a personal computer both through the HDMI and USB port. HDMI port is used to send HD RGB images to HD displays and the connection to USB port permits to switch on the device. Even if Oculus Rift permits to reach a refresh rate of 75 fps, we have to use 30 fps as maximum refresh rate according to frame rate of Kinect v2.
- *Leap Motion* device placed on the front side of Oculus Rift connected to a USB port of the computer. Hands/fingers of the technicians are detected to interact with virtual interface that SMA makes available. The depth cameras of Leap Motion device are able to reach a refresh rate of 100 fps, but as mentioned we exploited 30 fps for hand tracking. This feature is very important to ensure a good synchronization between what the user sees and what the user does during socket design.
- *Personal Computer* that runs VOLAB and manages the synchronization of devices through the middleware. The PC must have at least three USB 3.0 ports for the three Kinect v2 as well as two USB 2.0 ports for Leap motion device and Oculus Rift v2.0. Furthermore, an NVidia graphic card has been mounted on the PC in order to permit excellent rendering of VOLAB. According to these technical features and our low-cost approach, we are using an HP Pavilion 500–333nl personal computer.

Optionally, a Microsoft Kinect v1 or v2 can be used to scan the 3D model of the residual limb.

Two main features are required:

- Device synchronization. In fact, the system needs synchronizing different signals emitted by the devices (e.g., frames and orientation of objects) that have to be read by SMA to perform modeling operations and manipulate socket shape.
- Devices Connections. All devices are connected to a unique personal computer through different USB ports as before mentioned. If, we consider an additional Kinect v1 to scan the residual limb, another USB 2.0 is required.

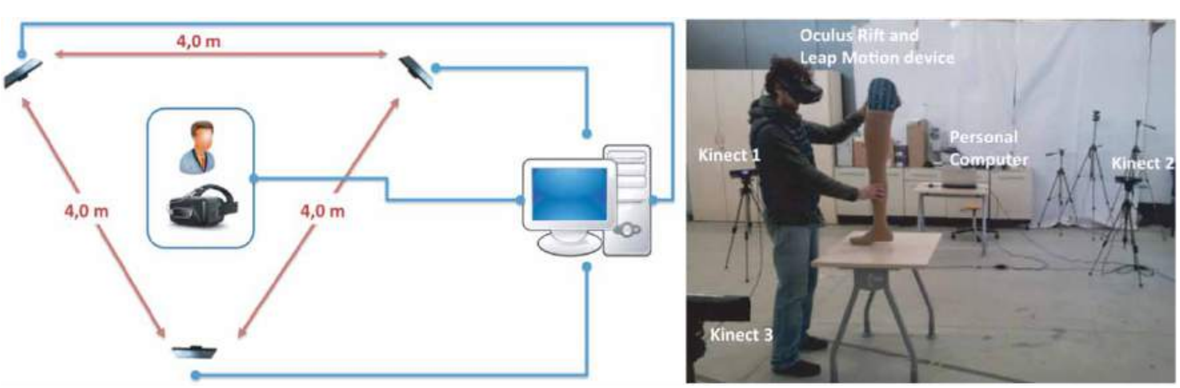


Figure 3. VOLAB Hardware architecture.

The real world is rendered on the viewer of Oculus Rift by exploiting the HD-RGB cameras of the three Microsoft Kinect v2 that detect human body parts and manipulate images used for creating the mixed reality environment. When the residuum is detected, the user can shape the socket model using virtual tools of SMA and interacting with hands/fingers or object held in the hand.

4.2. *Software architecture*

Fig. 4 shows the software architecture of the mixed reality environment.

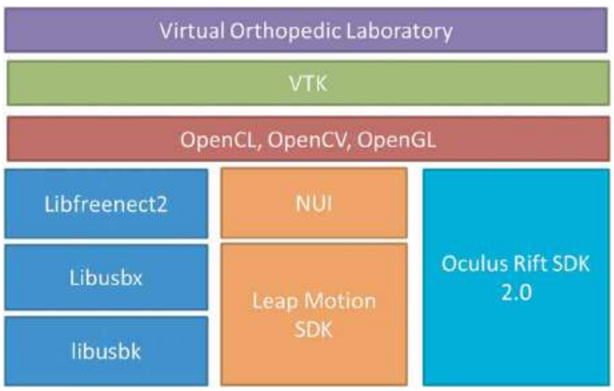


Figure 4. Software Architecture.

As mentioned in section 2, each device makes available a SDK (e.g., Leap Motion and Oculus Rift SDK).

Among the data made available by different SDKs, we considered:

- Depth maps and high definition images by Microsoft Kinect SDK;
- Position and orientation of hands/fingers by Leap Motion SDK;
- Position and orientation of head by Oculus Rift SDK 2.0.

The official Microsoft Kinect SDK v2 does not make available a driver to read multi Kinects by a single computer, so we adopted the open-source library named libfreenect2. Libfreenect2 is able to detect multiple Kinect v2 through libusbx as well as data acquisition of RGB camera, depth and infrared sensors. Libusbx uses libusbk, which is an USB driver substituting the original driver used for Kinect. Fig. 5 shows an example of patient's body reconstruction from multiple Kinects.

In addition, we used VTK for SMA modeling tools, OpenCL for parallel computing, OpenGL for scene rendering, and OpenCV for image processing.

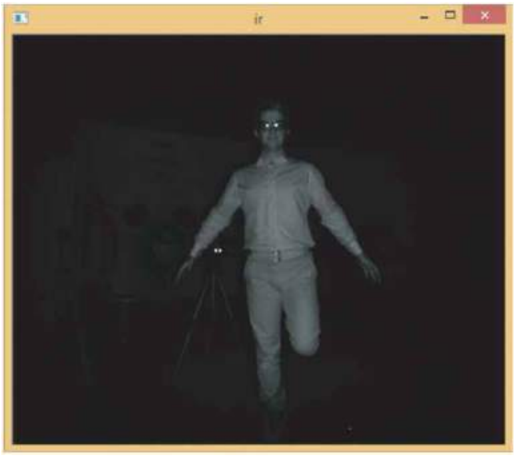


Figure 5. Infrared image from Microsoft Kinect v2.

New modules have been developed for:

- *Real Time performance.* The system needs high computing performance to have no delays between human interactions and rendering of virtual scene. As described in §4.1, VOLAB has to offer at least a frame rate of 30 fps with a full HD resolution (1920 × 1080).
- *Data synchronization.* The personal Computer executes VOLAB and manages synchronization of devices through the middleware. The personal computer makes available an NVidia Graphic Card, which is CUDA and OpenCL compatible. The graphic card has to make available a HDMI port for correct video rendering of Oculus Rift.

Finally, SMA modeling tools have been adapted for the prosthetic mixed reality. They have been implemented using VTK and each is composed of a set of widgets (e.g., sliders and buttons) (see Fig. 6.) to execute a particular modification and reach the final socket shape. Virtual widgets are automatically visualized in the user's field of view of the Oculus Rift when residuum is detected and thus, s/he can start to shape the socket using hands/fingers detected by the Leap Motion device. Each virtual object is rendered through the use of Oculus Rift SDK.

A software interface has been developed between VTK and Oculus Rift SDK to exploit rendering features of VTK. This interface has completely written in pure OpenGL because Oculus Rift renders the 3D scene using frame buffer objects (FBOs) and textures. At present, VTK doesn't make available a standard viewport that uses FBOs for 3D scene rendering. FBOs permits to directly route the rendering of a 3D environment on the two displays of Oculus Rift for stereovision. 3D scene is rendered through two textures, which are used as two

Figure 6. Interaction test using a trial socket.

images onto which an image-distortion is applied for creating the depth sense. Depth sense is possible because there are two lenses inside Oculus Rift, which magnify the screen so it fills the field of view of the user.

The NUI (Natural User Interface) uses the basic SDK of Leap Motion and it is part of an ad-hoc developed module that extends the C++ class of VTK to interact with the virtual tools of SMA. In particular, we implemented the events-handler made available by VTK. It uses a timer that starts when VOLAB application is initialized. The events handler generates a timer event each 5ms; if a gesture is detected when time event happened, the associated operations are executed.

Current VOLAB implementation permits to perform first trial tests, but some of mentioned modules need further developments. Data synchronization module has to improve the image processing during data acquisition when using multiple Kinects. To this end, a new software module is under development to exploit the Point Cloud Library (PCL, http://www.pointclouds.org/), which makes available many of required features. The interface between VTK and Oculus SDK has a basic structure and should be completed to totally take advantage of both SDKs. The other modules are stable but new features could be added to obtain the full software architecture useful for the development of new mixed reality environment.

5. Preliminary tests

At present, VOLAB is not fully integrated and we carried out two preliminary tests: one to verify if the proposed solution offers a virtual environment with real-time performance and another one to verify the augmented interaction with hands using SMA modeling tools.

In the first test, we considered two case studies related to the design of the socket for above knee and a below knee amputees where the two patients stand in the center of the tracking area in upright position (see Fig. 5.). It aimed to verify if the technical solution could adequately visualize the different parts of the residuum and permit the technicians to mark critical areas using hands. This permitted to validate the efficiency and adequacy of solution with regard real-time performances and residuum detection. The real-time performance was good but we are considering the use of another device instead of Kinect v2 to fully exploit the frame rate capability of both Oculus Rift (max 75 fps) and Leap motion device (max 100 fps). However, we identified a problem related to the quality of residuum detection. The above knee residuum is detected in real time with good precision, but below knee residuum had some problems. In fact, the knee area shape was not completely detected; in particular, there were some gaps in the patella zone of 3D residuum model. Therefore, further investigation is needed since this zone is a crucial one to define the optimal shape of the socket.

For the second test, we considered a trial socket and we applied the modeling tools on the detected socket model (Fig. 6.) using hands. In this test, three main basic operations were tested using hands: moving from one tool to another one, marking critical zones (Fig. 6.) and trim-line definition. Three testers have been involved. First we made a demo and then they were required to execute the mentioned operations using the same trial socket. Both gestures and modeling tasks have been performed by the testers and properly detected by the system, even if the last operation (i.e., trim-line definition) required more attempts to be correctly executed.

At this stage, the system permits to interact with the virtual environment as done during traditional process manufacturing and the results reached so far have been considered valuable. However, we need further development and improvements to make the whole system easy usable by prosthetists.

6. Conclusions

The paper presents a new solution to design lower limb prosthesis exploiting mixed reality technology. The proposed solution, VOLAB, is based on low cost devices that permit to create a virtual environment where the orthopedic technician can model virtual socket shape starting from the real model of the detected residual limb. Various open source libraries have been used to solve different problems we met during system implementation, such as device synchronization and real time performance. Preliminary tests and achieved results demonstrated some limits of this first version of VOLAB and we envisage further developments.

First, the quality of the 3D real world reconstruction, especially as far as concern the residual limb, should be improved using two HD-RGB cameras in the frontside of the Oculus Rift. Secondly, we will experiment the Duo3D device for augmented interaction instead of Leap Motion.

Even if VOLAB is partially integrated, preliminary tests have demonstrated effectiveness of the solution, which can be used for future developments of mixed-reality environments.

VOLAB has been initially targeted for application in the prosthetic domain but could be used for other applications, which require product designed around the human body. In fact, the authors have planned to use the system to develop application for 3D clothing design and simulations.

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