Title:
Mixed Reality to Design Lower Limb Prosthesis

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Keywords:
Prosthesis design, Mixed Reality, Augmented Interaction, Low Cost, Hand-tracking devices, Human body devices, Socket Modelling Assistant

DOI: 10.14733/cadconfP.2015.136-139

Introduction:
Mixed reality has allowed the creation of virtual environments in which traditional workflows can be emulated in order to increase the quality of final product in terms of time and costs. In the last decade, many researchers have understood the need of systems more adequate than traditional CAD systems, especially for those products heavily depend on the morphology on human body and people's life style. In this research work, we present a system that permits to emulate an orthopedic lab to design lower limb prosthesis with particular attention to the socket component. To achieve our aim, low-cost devices have been used to recreate the virtual environment. A custom software library has been also developed to synchronize the devices exploited in the project and a software package, named Socket Modelling Assistant [2], has been used to emulate the traditional workflow of socket design.

Research Aim:
Today, many products are designed around the human body or part of it in order to satisfy the increasing needs of customers. In this paper we refer to lower limb prosthesis, both below (transtibial) and above knee (transfemoral), and in particular to the socket that is highly customized according to the residual limb morphology.

In the traditional process, the technician continuously uses her/his hands to reach the optimal socket shape. First, s/he makes an evaluation of the amputee and creates a negative cast manipulating by hands plaster patches directly on the patient's residual limb; then, s/he realizes the positive model and modifies it by adding and removing chalk in specific zones according to stump measurements and patient's characteristics (Fig. 1.).

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 [1], [5].

Therefore, our main goal has been to develop a mixed reality orthopedic laboratory that permits to replicate/emulate manual operations performed by the prosthetist and interact with the 3D model of the socket in a natural way.

The developed platform exploits low cost devices to directly design the socket around the residual limb of the patient. The kernel of the system is the software module, named Socket Modeling Assistant-SMA [3] that provides a set of virtual tools to emulate all phases of the socket development process.

The prosthetist is guided step-by-step by the system that applies in automatic or semi-automatic way the rules and the modeling procedures. In fact, it embeds a set of design rules and procedures

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(e.g., where and how to modify the socket shape) and makes available a set of interactive virtual tools to manipulate the socket shape according to traditional procedures.

Fig. 1: Main steps of traditional workflow to design socket.

Mixed Reality for Orthopedic lab:
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 performance. In addition open source software libraries has been considered for the software development. In the next sections, the hardware and software solutions are briefly described.

Hardware Architecture

Hardware architecture, shown in Fig. 2., has been conceived using the following devices:

- 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.
- Oculus Rift v2.0 to render scene. It is 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.
- 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 [4].
- Personal Computer that runs SMA and manages the synchronization of devices through the middleware.

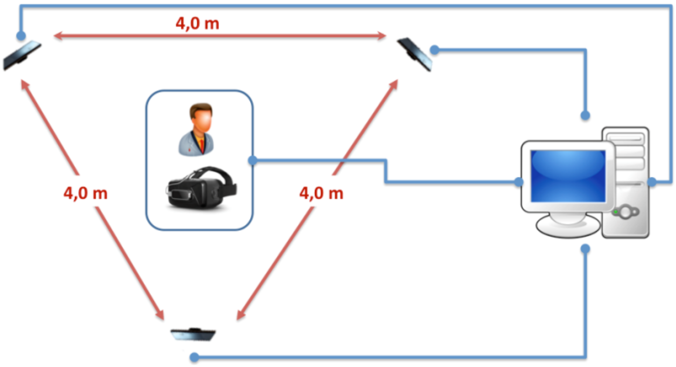

Fig. 2: Hardware architecture.

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Software Architecture

Software architecture has been developed in order to make more natural the use of virtual environment for final user and to manage mentioned devices. For each device, a Software Development Kit (SDK) is made available.

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 using Leap Motion SDK.
- Position and orientation of head using Oculus Rift SDK 2.0.

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

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.
- 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) 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.

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.

Fig. 3(a) and Fig. 3(b) show two different steps of preliminary tests carried out to verify the feasibility of proposed solution.

(a) (b)

Fig. 3: Two steps of preliminary tests: (a) synchronization of devices and (b) interaction with a trail socket (b).

Conclusions:

A set of preliminary tests has been made with engineering students in order to verify the potential of the mixed-reality platform and the new interface to interact with SMA using the Leap Motion device. Even though, the interaction with Leap Motion device permits to interact with SMA in a good way, the environment requires some improvements to make more real the virtual environment during socket

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design. 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 front-side of the Oculus Rift.
A final test has been planned with amputees and technicians of orthopedic lab in order to validate the system.

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Proceedings of CAD'15, London, UK, June 22-25, 2015, 136-139
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