



SimplyNURBS: A Software Library to Model NURBS for Medical Applications

Giorgio Colombo¹, Giancarlo Facoetti², Caterina Rizzi² and Andrea Vitali²

¹Politecnico di Milano, giorgio.colombo@polimi.it

²Università degli studi di Bergamo, caterina.rizzi@unibg.it, faco1976@gmail.com, andrea.vitali1@unibg.it

ABSTRACT

Custom-fit products, such as artificial prostheses, often require the development of hoc modeling tools and procedures. In such a context, this paper describes an open source library, named SimplyNURBS, developed for NURBS modeling in medical and health-care domains. This new suite makes available a development kit that integrates the key features of existing open source libraries and new ones to fulfill the requirements of the considered domain. First, the paper introduces the library requirements with particular attention to the prosthetic field as well as pros and cons of current NURBS modeling libraries (both commercial and open sources). Then, the software architecture of SimplyNURBS and the basic libraries (e.g., OPENCASCADE and NURBS++) used for its implementation are illustrated enhancing differences and improvements. Finally, a socket modeling tool, named Virtual Socket Laboratory (VSL) developed using SimplyNURBS is described as well as results of tests carried out to evaluate the new system performances.

Keywords: NURBS, open source libraries, prosthetic socket

1. INTRODUCTION

Nowadays, several 3D CAD systems can be found on the market. They are commonly used and widespread in several industrial contexts; however, there are still some fields where their diffusion is limited or there is a lack of appropriate modeling systems. For example, artificial prostheses (e.g., dental, maxillofacial) often require ad hoc surface-based modeling tools that permit to define the product shape around the human body morphology. This paper refers to prosthetic socket for both transfemoral (amputation above knee) and transtibial (amputation below knee) prostheses, and to the development of new modeling tools that embed the expert's knowledge, guide the user along the modeling steps and make available automated numerical simulations. In fact, the socket is the most important component to guarantee the prosthesis comfort and fit. It has to be modeled according to the residual limb morphology and a surface-based representation is needed.

Furthermore, in the last decade many researchers have developed devices that permit user to interact with 3D objects using hands as well as mouse and keyboard. The birth of augmented interaction could simplify the use of 3D CAD systems emulating the traditional development processes. That is the case

of socket design, which is based on the emulation of manual operations through the interaction with 3D surfaces representing residuum and socket shape.

To implement such type of tools, there are many software libraries (both open source and commercial), which provide the basic features to manage NURBS surfaces [17]. Usually, the definition of these models requires skills about the mathematical representation and the implementation of the software modules is closely related to the mathematical parameters. Therefore, the use of such libraries cannot be easy for software developers without deep knowledge about NURBS representation.

In this paper we consider open source libraries for the development of a modeling system specifically conceived to design prosthetic socket. This choice is due to the fact that free software suites are the best suited for development in academia since they can be easily extended, adapted and shared among different research groups. However, even if these libraries are broadly used and include many basic operations on NURBS models, they still have some criticalities. For example, we have experienced the use of NURBS++ library to develop the first release of the above-mentioned socket modeling system, named Socket Modeling Assistant-SMA [8]. Even if this library makes

available features for NURBS creation and management, it has some lacks with regards to its usability and socket geometry representation.

In such a context, the underlying idea has been to develop: (i) an open source NURBS suite, named SimplyNURBS, able to meet the requirements of the considered applicative domain and (ii) a virtual socket laboratory, named VSL. SimplyNURBS integrates key features of some open sources libraries and new ones to satisfy the needs of the socket design platform. Even if, SimplyNURBS has been conceived for the prosthetic domain, it can be used to develop NURBS-based modeling tools for a range of applicative domains.

The paper first presents an overview of the scientific background and main requirements of the prosthetic domain. Then, SimplyNURBS is introduced describing its architecture and main features. Finally, the new socket design platform based upon the SimplyNURBS is presented. Final remarks conclude the paper.

2. SCIENTIFIC BACKGROUND

At present, on the market one can find some prosthetic CAD systems (e.g., [2], [10], [19], [25]). They permit to model the positive cast onto which the socket will be thermoformed but most of them propose a traditional interaction paradigm and cannot be easily extended to make available new features, such as new interaction devices or numerical simulations. This last issue is becoming more and more important and in line with the current trend to adopt a fully computer-based approach to design custom-fit products for different applicative domains, such as medical applications [1],[6],[24] and clothing [9], [13], [26]. In this context, our main goal is to develop a virtual laboratory where the prosthetist can model the socket shape around the geometry of the residual limb and manipulate/interact with the 3D socket model in a natural way as s/he usually performs using hands and sense of touch. The platform has also to include a module to automatically reconstruct the residuum geometry from MRI images and to be integrated with a FEA (Finite Element Analysis) tool to simulate and study the socket-residuum interaction.

As mentioned above, the first version, named SMA, was developed using the free NURBS++ library and its testing permitted to identify problems and requirements. Fig. 1. shows two examples of criticalities related to the creation of a close surface along u and v directions and to the fitting of the socket surface. Fitting accuracy could be improved by increasing the number of points but this can cause computing performance drop during the interaction with NURBS models.

In addition, particular attention has been paid to the direct interaction with 3D virtual environments. There are many research works, which highlighted

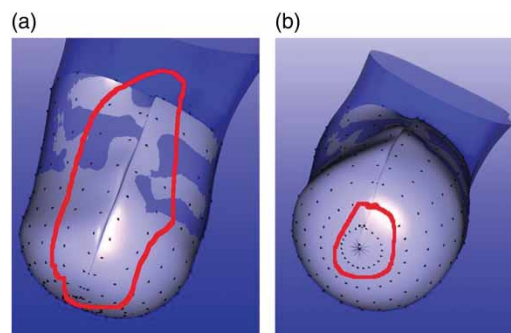


Fig. 1: Problems with NURBS surface generation.

new and innovative approaches based on augmented interaction, which can be considered as the new frontier of Human Computer Interface (HCI) [20]. In our case, it mainly concerns the emulation of tactile sense and thus, the capability to interact with the socket model using hands/fingers through low-cost haptic and hand-tracking devices, such as Leap Motion device and Microsoft Kinect [4], [12], [14], [18]. This interaction style is usually based on collision detection algorithms, which are able to detect the intersection among 3D geometric objects and, in our particular case, between the position of fingers and the 3D socket model.

According to our purposes, we need a library, which makes available the following features:

- Generation of NURBS surface from fitting of point clouds to reconstruct the residuum geometry.
- Generation of closed surface to define and manipulate the socket shape.
- Direct interaction and modification using curve or surface points.
- Data Exchange using different formats (e.g., IGES, step and STL) to transfer data to and from CAE tools (e.g., FEA and multi-body systems).
- Based on the Object Oriented Programming to simplify the comprehension of its modules.
- Simple to use, i.e. use of few user-friendly instructions, which do not require specific skills on NURBS representation.

To implement the new virtual socket laboratory, many modeling libraries are available to create NURBS models. Considering the commercial ones, the most interesting is SMS NLib™ (<http://www.smlib.com/nlib.html>). It offers a comprehensive suite of geometric modeling libraries, among which NLib™ the NURBS based library. NLib™ is written in C language and provides an extensive set of robust functions for generating and manipulating NURBS curves and surfaces [15]–[17]. It also embeds a set of modules to interface with other applicative software (e.g., CAD and CAE systems).

On the other hand, during last decades, several open source NURBS based libraries and 3D modeling tools have been developed (e.g., NURBS++, OpenCASCADE, Sintef, Nurbana and OpenNURBS). Among them, two libraries, NURBS++ [11], OpenCASCADE [21], and the 3D modeling environment AYAM [23] have been considered since they are broadly used, include many basic operations on NURBS models, and are sufficiently user-friendly.

NURBS++ it is a C++ library and, as already mentioned, it has been the first one we experimented to develop SMA. It hides the underlying mathematical representation and offers many functions to generate NURBS models from point dataset. However, its development stopped in 2002 and we experienced some troubles as shown in Fig. 1.

OpenCASCADE is a software development platform that includes C++ components for 3D surface and solid modeling, visualization, data exchange, and rapid application development. OpenCASCADE has a modular structure, which allows developing complete CAD/CAM/CAE application in an easy way. However, it permits to interact with NURBS models only through the control points. For our purpose, the most interesting feature is related to data exchange; in fact, NURBS models can be exported in different formats, such as IGES, STEP and STL, with few instructions.

The third one, AYAM, is not a library but a free 3D modeling environment that supports NURBS modeling. We focused the attention on its mathematical kernel completely developed in ANSI C. It permits to solve previous mentioned criticalities and has better performances than NURBS++ kernel.

Anyway, none of the mentioned open source tools is able to meet all requirements before mentioned. Therefore, we decided to develop an open source library, named SimplyNURBS, extracting from each of them the features that are meaningful for our applicative domain.

3. SIMPLYNURBS LIBRARY

SimplyNURBS has been developed upon AYAM, OpenCASCADE and NURBS++. Its architecture is structured in different modules according to considered features of mentioned libraries and the standards for high performance graphics (i.e., OpenGL).

3D Rendering is based on the software suite, named Visualization ToolKit (VTK) [22]. VTK is an open-source software system for 3D computer graphics, image processing and visualization. It is mainly used to develop 3D application in research domain, such as medical and physics fields.

This also permits to introduce how to use SimplyNURBS for other applications. In fact, the library has been mainly designed to meet the requirements of the prosthetics field, but it can be used for other applications in health care that require 3D surface models of anatomical districts and organs.

3.1. Layered Architecture

SimplyNURBS is based on a layered structure. Fig. 2 shows the architecture and main features are the following ones:

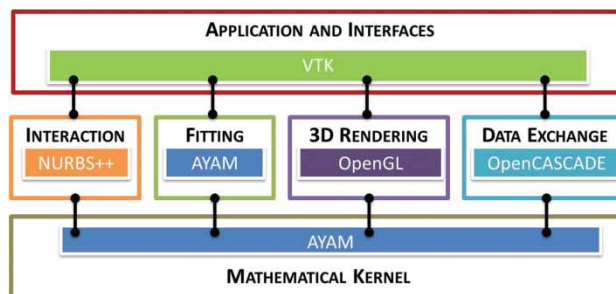


Fig. 2: Software architecture.

- **Mathematical Kernel.** This part is completely written in ANSI C, and it has been extracted from AYAM.
- **Interaction paradigm.** It permits to modify NURBS surface acting directly on the surface point and without the use of the control points. This feature is based on a part of code extracted from NURBS++ and specifically updated for our purpose. Furthermore, this module permits to introduce another way to interact with 3D models using hand-tracking and haptic devices [7].
- **Fitting.** It permits to create a curve/surface interpolating points cloud [3]. An algorithm has been developed to extract an ordered point cloud from a set of raw data (e.g., 3D scan or MRI volume). Therefore, the actual computer's power permits to define a NURBS model from the ordered points cloud in real time, and thus, without a complex approach to define the mathematical representation.
- **3D Rendering.** A set of methods has been developed to permit 3D rendering of the models. These modules are based on OpenGL primitives. Furthermore, an interface has been developed to use NURBS models within virtual environments based on VTK. The implemented interface permits to manage the 3D rendering in a very simple way avoiding involvement on low-level software development.
- **Data exchange:** This module has been developed using OpenCASCADE in order to obtain data exchange translators for IGES and STL. In fact, both AYAM and NURBS++ do not include this feature that is meaningful for our application field. This part of the suite is entirely developed using C++ language.

3.2. How to use SimplyNURBS

The upper layer of SimplyNURBS architecture is based on VTK. Each mentioned module is called within

a set of extended VTK classes, which can be used together with its classic kernel released from Kitware to manage NURBS models. VTK permits to manage each feature related to a 3D environment, such as definition and interaction with both scenes and 3D objects. The mind map [5] in Fig. 3. shows the software structure that permits to understand how the instructions have to be used. In particular, there are three main operations embedded into the upper layer:

- **Fitting.** This operation concerns the creation of NURBS models from a points cloud. It is a particular 3D object managed by VTK through the use of single instance. The defined instance automatically provides the generation of parametric model that is also initialized for 3D rendering using OpenGL primitives.
- **Interaction.** The interaction occurs using an extension of the VTK interactor-style that is based on the use of keyboard and mouse. A new module permits to modify NURBS models within the interactor-style by associating either the typical approach using mouse and keyboard or the tactile interaction. For example, this module permits to select a surface point using two fingers and to modify its position according to fingers position.
- **Export 3D NURBS model.** VTK makes available a set of classes permitting to export typical 3D

models in different formats, such as STL. We have added a new exporting class, which is able to export NURBS models in both STL and IGES.

4. VIRTUAL SOCKET LABORATORY

SimplyNURBS has been embedded into the new release of the socket modeling tool, named Virtual Socket Laboratory-VSL. Fig. 4. shows the mind map of the software architecture. The map portrays the different modules that compose the VSL software suite. In particular, it highlights the relationship between different steps of socket design and the software library.

Fig. 5 shows the VSL high-level architecture and its main components.

It includes modules to automatically reconstruct the patient's residual limb from MRI images, to model the socket by means a set of interactive virtual tools, and to analyze the pressure distribution at the socket-residual limb interface with a commercial FEA system. It emulates all phases of the socket development process starting from the digital model of the residual limb. The prosthetist is guided step-by-step by the system that applies in automatic or semi-automatic way design rules and procedures (e.g., where and how to modify the socket model) and makes available a set of interactive virtual tools to manipulate the

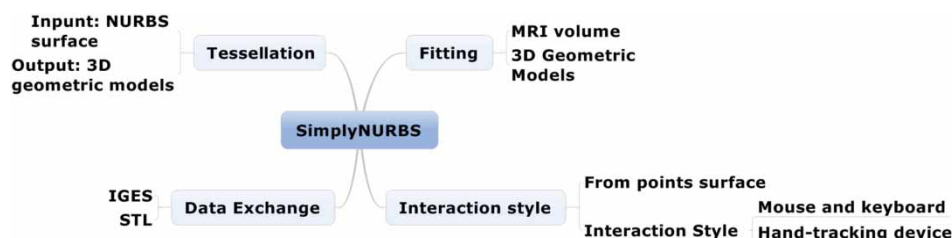


Fig. 3: Mind map of the software architecture.

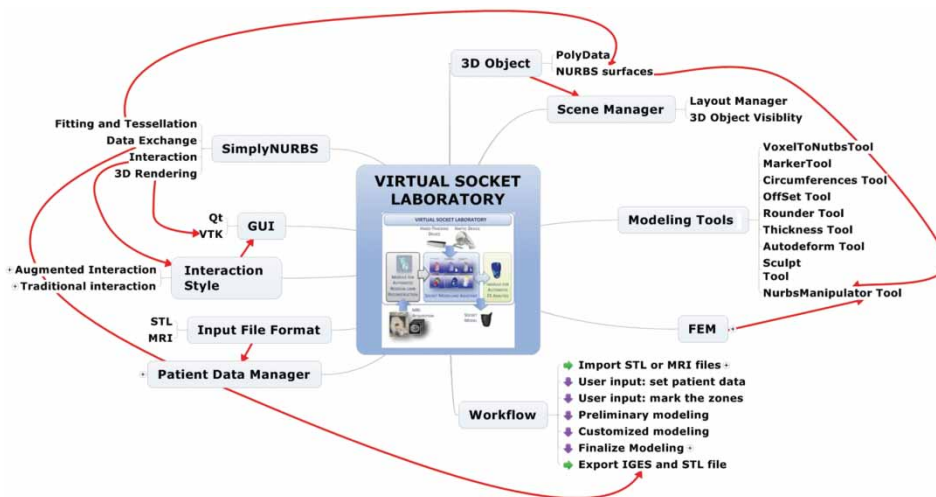


Fig. 4: Mind map of VSL software architecture.

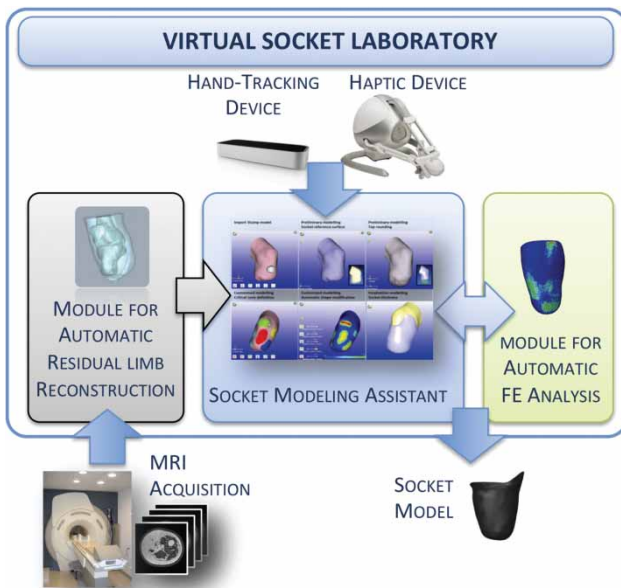


Fig. 5: VSL high-level architecture.

socket shape according to traditional procedures. Furthermore, VSL includes an interaction module, which permits to convey the interaction more natural and similar to the traditional one through the use of hand-tracking and haptic devices.

4.1. Use of SimplyNURBS within VSL

SimplyNURBS tools have been mainly used to:

- Create the external skin and bones models through surface fitting of the points cloud automatically extracted from MRI images. The developed algorithm is subdivided in four phases [7]. Initially, an edge detection algorithm is applied to each MRI image that allows extracting the boundary of both bones and residual limb shape. Then, a 3D segmentation is executed on voxels in order to separate the meaningful parts of MRI volume, such as bone and

residual limb. Afterward, a set of circumferences is defined around the filtered data. For each circumference, each control point is moved toward the center of the circumference itself until the point intersects the first voxel, which lies on the external surface of the filtered voxel volume. This procedure allows extracting an ordered points cloud for each model used to generate NURBS surfaces. Furthermore, a tessellation can be achieved in order to obtain geometric models with triangular or quadrangular facets.

Fig. 6 shows the main steps of the algorithm applied to a test case. The test considered a set of 150 MRI images, each 288×288 pixels (Fig. 6(a)). Segmentation phase permitted obtaining the boundary of both femur and residual limb, which are respectively composed of 74,007 voxels and 135,888 voxels (Fig. 6(b)). Fig. 6(c). and Fig. 6(d). shows respectively the extracted ordered points cloud of the residuum and the femur. Finally, Fig. 6(e) the tessellated model composed of 33,671 triangular facets.

- Manipulate the socket shape interacting directly with surface points through a set of interactive tools that emulate the traditional tasks performed by the prosthetist. Among them, the most important is the Sculpt tool. It permits the technicians to manage the critical zones of the socket surface in order to obtain the most ergonomical shape for the socket. It emulates the operation of adding or removing materials usually performed by the technicians on the plaster cast to create load and off load zones. Fig. 7 shows an example where the user modifies socket shape through the Sculpt tool. Another one, named NURBS modeling tool, permits to shape the upper part of the socket directly acting on the surface points. In this way the technicians do not need to know details about the underlying mathematical models. The manipulation can be carried out using both traditional devices and hand-tracking devices (e.g., Leap Motion device). The use of hand-tracking devices

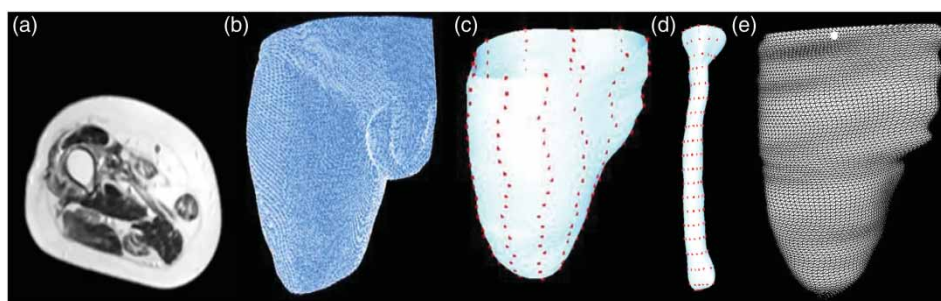


Fig. 6: Main steps of automatic 3D reconstruction of the residuum from MRI images.

has been introduced in order to emulate operations manually performed by technicians during traditional design process of socket model. The idea is to make available a set of virtual modeling tools that permit to emulate operations manually performed and to interact with 3D model of socket in a more natural way. Fig. 8 shows the use of fingers to select the surface points and move them to modify the upper profile.

- Export and import the geometric models of the socket and residuum in IGES or STL formats.

The system generates the geometric models in IGES format required by the FEA system to automatically execute the simulation and analyze the socket-residual limb interaction [6]. Then, results are imported within the modeling environment and represented through a color map. Fig. 9(a) shows the two models imported and meshed for FE analysis and Fig. 9(b) the simulation results. Furthermore, the socket model or its positive model can be exported in STL format (Fig. 9(c)), which could be used for 3D printing.

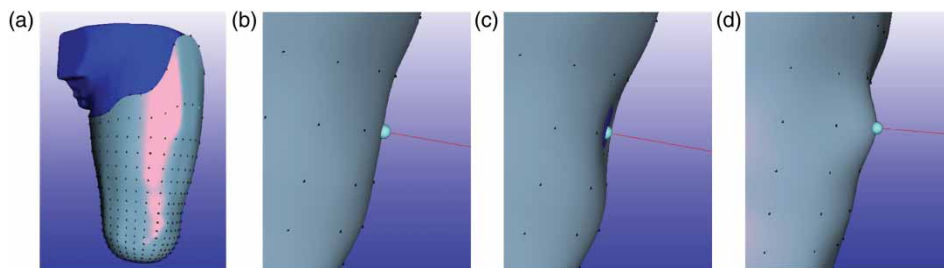


Fig. 7: (a) socket model, (b) surface detail, (c), and (d) modification of socket surface to create respectively load and off-load zones.

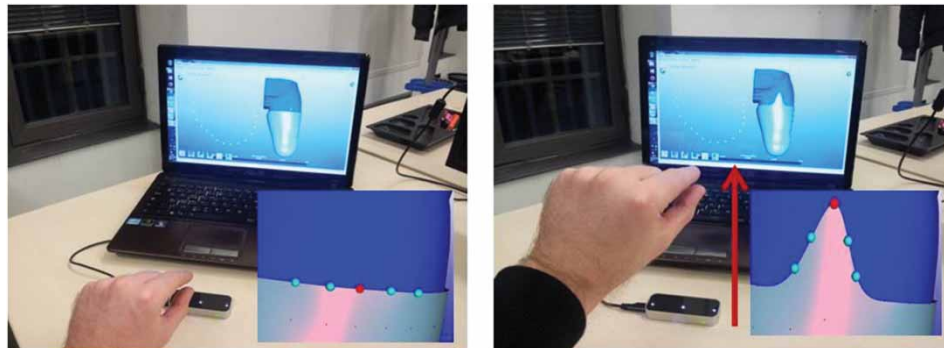


Fig. 8: Augmented interaction to model socket shape.

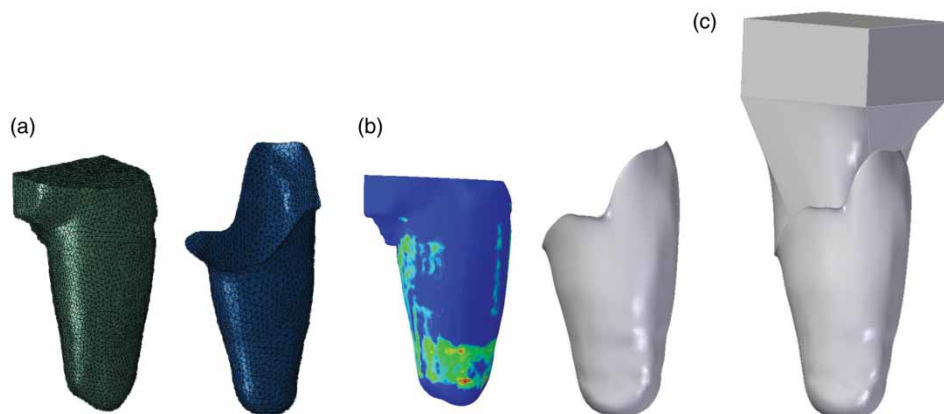


Fig. 9: (a) Meshed models of residual limb and of the socket, (b) FEA results, and (c) models of socket model and the positive plaster cast.

4.2. Results and Discussion

A set of tests has been carried out to evaluate the new modeling suite implemented using SimplyNURBS according to requirements identified in section 2.

Fitting has been tested with different dataset of point clouds. First, we considered sets of MRI images acquired for different patients and we automatically reconstructed the 3D NURBS models. Later, they have been used to generate the NURBS surface, which describe the socket shape. The results reached so far have been compared with those of previous version. It has been highlighted that all NURBS surfaces were properly created and problems mentioned in section 2 have been solved (Fig. 10.). In addition, the correct import of modes in IGES format has been verified.

Another test has been performed starting from a points cloud of the residuum acquired with Microsoft Kinect and Skanect (<http://skanect.manctl.com/>) software. Fig. 11(a) shows the residuum of the transfemoral amputee we have acquired; while Fig. 11(b) and Fig. 11(c), respectively the points clouds and surface model. Also in this case, the residuum surface has been properly generated with an adequate accuracy. However, at this stage of development, the procedure is not completely automated, but the points cloud has been manually filtered to get the anatomical district of interest.

Regarding interaction, the previous version of the socket modeling tool adopted a traditional interaction paradigm and no specific problems were identified. Therefore, tests mainly concerned the modification of surface points using the hand-tracking devices since this is one of the new implemented features. Fig. 8. shows an example. The results demonstrated the feasibility of the approach, but some problems related to gesture and points detection have been identified. In fact, a long lasting interaction can cause uncomfortable postures and fatigue. Therefore, in collaboration with the technical staff of an orthopedic lab we have planned to study and identify more ergonomic gestures and posture. At present, it is under development a new version to obtain a more natural and effective augmented interaction.

Last tests concerned the export of the IGES models of the socket and residual limb to the FEA package. These tests permitted to verify if the IGES models could be automatically processed by the simulation procedure to generate the corresponding FE models and simulate the socket-residuum interaction without the end user's intervention. Case studies, related to both transfemoral and transtibial patients, have been considered. The procedure completed all simulation steps and no problems have been detected with regards models representation.

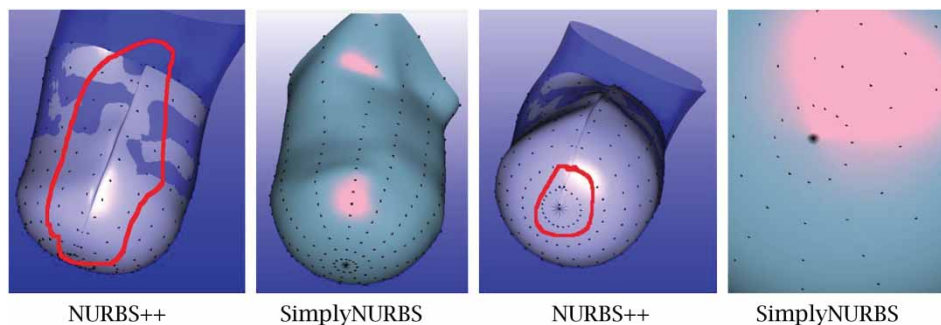


Fig. 10: Comparison between NURBS ++ and SimplyNURBS.

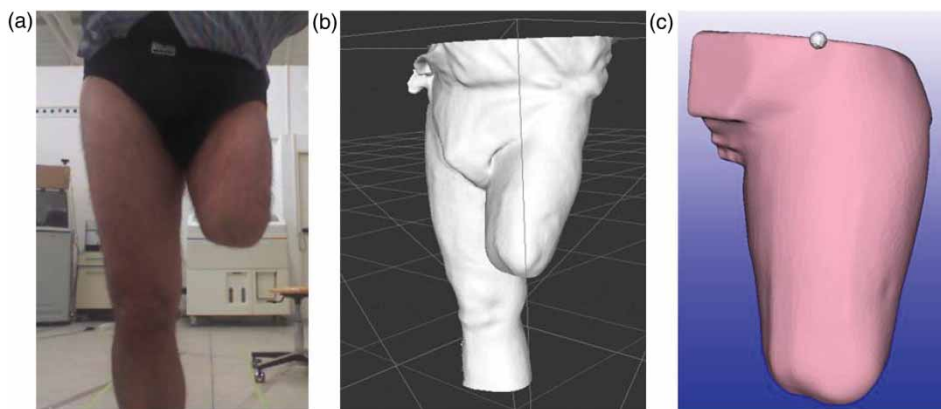


Fig. 11: (a) anatomical district of a transfemoral amputee, (b) points cloud, and (c) residuum surface.

5. CONCLUSIONS

This paper presented an open source NURBS library, named SimplyNURBS, developed to implement an ad hoc modeling tool for the prosthetic field. SimplyNURBS has been based upon AYAM modeling suite, OpenCASCADE and NURBS++ libraries. In addition, standard release of VTK does not permit to fully exploit NURBS surface modeling. SimplyNURBS, as free solution, could be easily added to VTK suite to make available NURBS modeling.

The VSL has been tested with different case studies to verify that the SimplyNURBS permits to meet the requirements of the considered domain. Particular attention has been put on fitting, export/import and surface manipulation/interaction and results reached so far were positive. Regarding interaction using hand-tracking devices, the tests results have been considered interesting also by prosthetists, but further enhancements are necessary to improve detection of gesture and surface points. In addition, it has been also experienced the use with haptic devices. In fact, it is under development a haptic mouse at low-cost to make it affordable also by small orthopedic labs and results of preliminary tests are promising.

Finally, SimplyNURBS, has been initially developed for application in the prosthetic domain, but it can be used for other applications, which usually require computer-aided tool to model products around the human body, or anatomical district and organs. In fact, the authors have planned to use the library to develop application for 3D clothing design and simulations.

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