# Acquisition of customer's tailor measurements for 3D clothing design using virtual reality devices

ABSTRACT

Over recent years, various virtual prototyping technologies have been developed to innovate apparel industry. For each step of the garment design process one can find dedicated tools (from body acquisition to garment modelling and simulation) with the aim of making the process easier and faster. However, most of them are based on expensive solutions both for hardware and software systems. In this paper, we focus the attention on the first step of the made-to-measure garment design, i.e., customer's measures acquisition. We present a plug-in, named Tailor Tracking, which permits to get the measurements by interacting with the customer's avatar using hands as in the traditional way. Tailor Tracking has been developed using low cost devices, such as Microsoft Kinect sensor, Leap motion device and Oculus Rift, and open source libraries, such as Visualisation Toolkit (VTK) and Qt. The proposed approach is based on the use of multiple Kinect v2 to simultaneously acquire both customer's body and motion. This permits to emulate the customer's postures required to take the correct measurements. In addition, a virtual measuring tape is made available to replicate the one commonly used by the tailor. A men shirt has been considered as case study and a tailor and 14 people with no skills in garment design and different levels of experience in virtual reality technology have been involved to preliminary test Tailor

tracking. Finally, tests as well as results reached so far are presented and discussed. Results have been considered quite good; however, some critical measures have been identified as well as future developments. Anyway, Tailor Tracking can represent an alternative solution to the existing approach that automatically extract anthropometric measures from the customer's avatar.

**Keywords:** Clothing design, Garment measurements, Virtual Reality, Kinect sensors, Head Mounted Display, Hand-tracking device, Motion capture.

## 1. Introduction

During last decades, virtual prototyping has had an increasing impact since innovative technologies, such as 3D scanners, virtual and augmented reality, and additive manufacturing, have been made available for several contexts (Bartesaghi et al. 2015; Carulli et al. 2017, Tay et al. 2017; Geng & Bidanda 2017, Volonghi et al. 2018). For example, in fashion industry several efforts have been done to virtualize as much as possible the garment design process starting from body acquisition through dedicated body scanners (Wang 2005; Apeagyei 2010; Hsiao & Chen 2013) up to 3D modelling and simulation of garment wearability. For each step of the process, one can find dedicated tools with the aim of making the garment development process easier and faster. Most of them are based on expensive technical solutions for both hardware and software systems; moreover, they are not easy to use since they require specific skills not only in designing garments but also in computer graphics and modelling techniques. Even if commercial systems are available (e.g., Vitus SMART XXL or SYMCAD™ as body scanner or Clo3D and Optitex), many researches are still in progress to develop advanced

solutions and make them more suitable to the needs of the apparel industry (Volino &

Magnenat-Thalmann 2000; Wang 2005; Volino et al. 2005; Wang & Tang 2010; Hsiao &

Chen 2013). In addition, the attention is moving towards made-to-measure garments and this

means that the customer's body should be the key element around which the virtual cloth has

to be designed.

As an example, Figure 1 depicts the functional architecture of a virtual environment to

design made-to-measure garment developed within the framework of an industrial research

project, named BODY-SCAN, funded by the Italian Ministry of Economic Development. The

project consortium included academic and SMEs (Small and Medium Enterprises) partners.

Specifically, SMEs have been involved to engineer and experiment developed solutions for

virtual garment design.

**FIGURE 1**

Three main components can be identified corresponding to the main steps of the

garment design process:

(1) *Customer's acquisition*. This component exploits Microsoft Kinect sensors to

acquire the customer's 3D model (i.e., her/his avatar) and simultaneously

her/his movements to be used for both the interactive extraction of the

measures and analysis of garment comfort.

(2) *Measures extraction*. This step permits to extract in automatic or interactive

way the customer's measures to draw the 2D patterns composing a garment.

(3) *Garment modelling and simulation*. It comprises two commercial packages: a

2D CAD system and a 3D garment modeller. The first is used to draw the 2D

patterns (accordingly to the extracted measures) starting from scratch or from the company historical database. The 3D modeller permits to model and simulate the garment assembling the 2D patterns over the customer's avatar (Carulli et al., 2017).

This paper focuses mainly on the first and second steps, in particular, on the module, named Taylor Tracking, to get the customer's measurements interacting with the 3D model of the customer using hands. The underlying idea is to develop a virtual atelier where the tailor can take the measures using hands and interacting with the avatar as s/he traditionally does with human being. Tailor Tracking does not substitute the already existing solutions that automatically extract anthropometric measurements (Bragança et al. 2015; Markiewicz et al. 2017), but proposes an alternative approach suitable to design custom-fit garment and emulate tailor's manual operations when taking body measurements according to a specific request of the client. In fact, getting the right measures highly influences the custom-fit garment wearability.

The paper first introduces a brief overview of the scientific background in Section 2. Section 3 presents the body acquisition solution realised using low cost technology. Section 4 describes the Tailor Tracking plug-in, its main hardware and software components, and the design of Natural User Interface (NUI) to allow the interaction with the virtual environment. Finally, the experimentation and preliminary results reached so far are presented and discussed.

## 2. Scientific background

In the following, the traditional process and, then, an overview of the employed technologies are described, from body scanners and anthropometric measurement extraction to motion capture systems.

### 2.1 Traditional process for measures acquisition

Drawing 2D panels of a made-to-measure garment requires the acquisition of the customer's measures according to his/her needs and morphology (e.g., large or narrow shoulders, long or short sleeves) that can have an impact on the garment shape and wearability. In literature we can easily find the list of tailor's measures or measurements tables to realize a made-to-measure garment (Tailor Store). Traditionally, the tailor takes the measurements using a flexible tape and, depending on the measurement and the type of garment, the customer is required to assume specific postures.

This is a skilled task especially for made-to-measure garment; therefore, to meet our goal, we have analysed the operations traditionally performed by the tailor to identify her/his gestures and required customer's postures. Different types of garments have been considered for both men and women. As an example, Figure 2 lists some of main measures required to design a man shirt and related postures. The sleeve length measurement is taken from the point of the shoulder where one takes the shoulder width, following the bent arm down to where one wants the sleeve to end. The chest measurement is taken as a circumference measurement around the chest at the widest point, the customer standing in a relaxed posture and breathing out.

**FIGURE 2**

*2.2 Human body acquisition and measurements extraction*

3D scanners growth is visible in a broad range of commercial solutions with different costs depending on their precision, accuracy, operating principle and other features (Unver et al. 2016; Nguyen et al. 2018). Some examples for apparel industry are Vitus Smart XXL (Vitus Smart), SYMCAD^TM (SYMCAD) and [TC]² Body Measurement System ([TC]²), which also permit to extract the anthropometric measures necessary for garment design.

We considered low cost body scanners for both acquiring the 3D human avatar and detecting the skeleton for animations. Low cost 3D scanners come from video-gaming world and have been considered valuable after many research works, which demonstrated their potentiality in different contexts, industrial and not. Among them MS Kinect sensors v1 and v2 are the most representative (Newcombe et al. 2011).

3D acquisition systems can be subdivided according to position and number of devices. Many are based on a set of fixed devices positioned around the person to be acquired (Daanen & Ter Haar 2013; Hsiao & Tsao 2016), others on the use of a single fixed acquisition device and a rotating platform on which the person is located (Markiewicz et al. 2017). At present, this approach has been used in commercial solutions. GayGiano shop (http://www.gaygiano.com/en/) is an example of retailer that is currently using this technology where several Carmine sensors are positioned inside a cabin.

The last approach concerns the use of low-cost device as a classic 3D scanner. The operator acquires the human shape moving the device along the surface of the human body.

Occipital Structure Sensors and Microsoft Kinect v1 are some examples. They permit to scan the objects and elaborate the acquired triangular mesh using low cost software, such as Skanect (Skanect; Markiewicz et al. 2017).

As mentioned before, the second important issue for the virtualization of the garment design is related to anthropometric measure. Algorithms of mesh segmentation allow extrapolating main human districts and, starting from the segmentation, each part can be measured using a set of circumferences or distances between key points on the mesh usually based on a set of landmarks used for 3D scanning (Bragança et al. 2015). Tsoli at al. (2014) propose another method, which mixes the use of 3D body with a set of standard human avatars available from existing database for anthropometric measures (e.g., CAESAR) to evaluate several postures and increase the measurements precision. Other research works highlight how the emulation of human tissues (e.g., muscles) produces a high impact on the quality of the acquired measurements (Anguelov et al. 2005; Hirshberg et al. 2012).

Another innovative approach allows making the evaluation of anthropometric measurements an operation executed on the 3D avatar changing the initial static position. Zang at al. (Zhang et al. 2014; Zhang et al. 2014) use both the 3D acquisition of human body and its virtual skeleton for changing the initial position. They firstly acquire the raw point cloud of the human body used as input data for a body segmentation module. The segmentation permits to automatically recognize human body districts, which are used to define an ordered point cloud for creating a mesh useful for 3D garment fitting.

Wang at al. (Wang et al. 2012) use a single RGB camera to acquire the customer's point cloud. The solution has been designed to create a 3D acquisition system to be used in

house. The person has to turn him/herself in order to permit the acquisition of whole body. Even if the anthropometric measures are not very good, the 3D model can be used for futuristic on-line virtual garment shops.

Finally, other research works aim at obtaining accurate 3D human shape by starting from clothed 3D scanned people (Wuhrer et al. 2014; Yang et al. 2016). This means that customers are not obliged to dress tight clothes to get their correct measurements.

Ernst et al. 2016 present a research study where several commercial solutions have been compared to assess performances. Among them, there are commercial solutions allowing body scanning through the use of single or multiple RGB-D low cost sensors as well as automatic body measurements. Ditus MC by Human Solutions and Styku are the most important. The first one exploits twelve Asus Xtion Pro Live sensors and can scan the human body in only one second. The latter is based on a single Microsoft Kinect v2, which is inside a small tower. The client has to simply stand on the turntable and hold still for 30 seconds, while the platform spins.

Even if these solutions permit to automatically extract predefined measures at the best location on the human body with high precision and quality, made to measure garments often require measurements in different postures and further research is necessary to overcome barriers relative to dynamic postures and emulation of muscle mass.

### 2.3 Optical Motion capture systems

According to the aim of our research, we have considered optical Motion capture (Mocap) systems based on cameras. There are two main Mocap techniques: with or without markers

(Sharifi et al. 2017; Ong et al. 2017). In the first case the actor must wear markers in particular positions of the body (e.g., elbow, knee etc.) to facilitate the detection. The marker-based technology is widespread but has some disadvantages, such as high costs and usually a large installation space.

Marker-less Mocap systems do not use markers but exploit algorithms for identifying human shape and creating virtual skeletons following the acquired motions. The costs of these systems are more accessible than the previous ones. The cameras can be (Kraft et al. 2017):

- RGB cameras: the real light is separated by prisms and light filters into the three RGB primary colours feeding each colour into a separate video camera tube. Using charge-coupled device (CCD), the camera accumulates charge proportionally to the detected light. After a time interval, the data are sent to a memory buffer; then, CCD starts a new cycle and the information into the buffer is elaborated to generate the video. This solution is very cheap, and the system accuracy grows using multiple cameras. The disadvantage is that the system is not usable in environment with low light condition.
- IR (Infrared) cameras: these devices are able to create images using infrared radiation in order to use them in low light condition.

These two types of cameras can be combined for increasing the benefits of each technology.

As in the previous case, low-cost Mocap systems are mainly based on devices coming from the gaming world, such as Microsoft Kinect v1 and v2, PS Eye and Intel Gesture

Camera (Abdelnaby et al. 2017). With regard to apparel industry, marker-less Mocap systems have been exploited to emulate mirror of fashion shops and directly evaluate the virtual model of the chosen cloth on the body of the client (Yolcu et al. 2014; Saakes et al. 2016).

## 2.4 Head Mounted Displays and Hand-Tracking devices

In order to create a virtual environment for emulating tailor's work, we need a head mounted display (HMD) and a hand-tracking device. HDMs are helmets on which in front of each eye there is a tiny monitor that visualizes the virtual world. The position and lenses distortion of each monitor allow the emulation of depth sense of eyesight and, thus, the user perceives the visualization of a three-dimensional space to interact with using hands. Among many commercial solutions, the most important HMDs are Oculus Rift, HTC Vive and Google Cardboard (Carulli et al. 2016; Silva et al. 2016).

The interaction with the 3D application is only possible through hand-tracking device that can track hands/fingers inside the virtual world. Some examples are the Leap Motion device (Leap Motion), the Microsoft Kinect v2 (Kinect) and Duo3D (Duo3D).

At present, virtual reality applications have been exploited for collaborative design of customised garment to permit the customer's evaluation in a more realistic way (Basori et al. 2016). This approach has been mainly considered for classic fashion industry but also to design garments for disabled people with scoliosis. In this last case, the introduction of a virtual reality environment can help disabled people to interact with designers from their home (Hong et al. 2017).

**3. Customer acquisition: body and postures**

The Tailor Tracking plug-in needs the 3D model of the customer and his/her movements to take measures according to different postures. The adopted solution permits to simultaneously acquire both the customer's body and his/her movements. It comprises:

•        Three Kinect v2 arranged as shown in Figure 3. In the central area there is the walking area of 75x450 cm where all acquisitions are performed.

•        Three connected PCs (1 master and 2 slaves). Each Kinect sensor has to be connected to a PC and all PCs are connected through an Ethernet connection. One PC acts as master and manages the whole acquisition procedure. At the end, the acquisitions of the 3 sensors are merged into only one directly on the master PC.

**FIGURE 3**

The operative workflow is shown in Figure 4. Once the customer's body and his/her movements have been acquired, the avatar is reconstructed with automatic skeleton detection and animation generation. Then, an "animated" avatar is created associating the detected skeleton/animation to the customer's avatar by means of automatic rigging. Finally, the avatar can be animated to generate postures required to properly get measurements.

**FIGURE 4**

*3.1 Body acquisition and automatic avatar reconstruction*

The open source libraries LiveScan3D (Kowalski et al. 2015) and MeshLab (P. Cignoni, et al. 2008) have been used for body acquisition and automatic avatar reconstruction.

LiveScan3D is a framework for real time 3D reconstruction, which simultaneously uses multiple Kinect v2 sensors. The 3D reconstruction is a coloured point cloud where points from all the sensors are placed in the same coordinate system. The framework is able to detect the human shape and filters the ordered point cloud in automatic way. LiveScan3D has been customised an ad hoc module has been implemented to automatically perform the acquisition and generation of the 3D mesh of the point cloud (representing the customer's avatar) through the use of MeshLab, an open source system for processing and editing 3D triangular meshes. First, LiveScan3D acquires and filters the ordered point cloud of the body for few seconds. The acquisition frame rate of the Kinect device is 30 frames per second (fps) and, thus, 60 point clouds saved in different files in PLY format have been acquired. Then, starting from the 30th PLY file as input for MeshLab, the procedure automatically generates the 3D mesh exporting in OBJ format.

### 3.2 Movement acquisition: skeleton and animation generation

The acquisition of customer's movement relies on the use of the software platform iPiSoft (iPi Soft) able to track and elaborate data and come up with usable results. It permits to export a BVH file, which contains all information and data relative to both the skeleton and associated animation.

IPiSoft suite is able to manage acquisition and data elaboration respectively with iPi Recorder and iPi Mocap Studio. First, iPiRecorder starts simultaneously with LiveScan3D and the customer assumes the T-pose to permit an optimal generation of the virtual skeleton according to the customer's shape. Then, IpiMocap Studio allows managing the recorded

motion to extract a BVH file of the associated animation. The use of three Kinect v2 devices guarantees such a good acquisition that the procedure does not require manual filtering to rebuild the animation.

IpiSoft has been also used to create the database of movements that can be applied to the human avatar in order to generate different postures. The database is a set of BVH files, which contains the animations emulating traditional movements to generate the customer's postures required by tailor.

### 3.3 "Animated" avatar

To generate the postures, a module able to associate the human body model with motion data has been developed. Automatic rigging is the crucial issue (Figure 5). It has been implemented using the open source 3D modelling and animation application Blender (Blender) as a SDK. It permits to manage the body animations and the automatic association of an animation to the 3D human avatar and, thus, define the different body postures (Baran & Popovi 2007).

The 3D rigging arranges the human body mesh with an acquired movement organizing the mesh points in vertex groups. Each vertex group can change its position and orientation according to the motion available by the animation. The automatic procedure, based on Blender, permits the automatic association of an animation to the 3D model of the human body. First, the acquired skeleton (Figure 5.a) is linked to the 3D human avatar (Figure 5.b) in the correct position (Figure 5.c). Then, the vertex groups are generated and populated according to the position of each vertex to the nearest bone of the skeleton (Figure 5.d-f).

When the automatic 3D rigging is completed, the skeleton can be moved and the 3D human avatar is animated accordingly. Finally, Blender permits to export/import the 3D models in several animation formats, such as BVH, C3D and DAE.

FIGURE 5

## 4. Tailor tracking plug-in

The Tailor Tracking plug-in is a virtual reality application that makes available a virtual atelier where the tailor can take measurements by means of a virtual measuring tape and interacting with the "animated" customer's avatar previously described using hands. A low-cost philosophy for both hardware and software components has been adopted for its development.

### *4.1 Hardware and software architecture*

Two hardware configurations have been considered (Figure 6). The first one (Figure 6.a) foresees the use of a hand-tracking device, i.e. the Leap Motion, to interact with the customer's avatar using hands; the second one considers also the Oculus Rift to create an immersive virtual reality application (Figure 6.b). In the latter the Leap motion is mounted on the front side of Oculus Rift.

FIGURE 6

Tailor Tracking has been developed in C++ language and the software architecture exploits a set of SDKs according to above-mentioned devices (Figure 7):

- Leap Motion SDK for hand tracking. It makes available a set of modules to easily detect various types of gestures. The developed NUI is based on the SDK of Leap Motion as well as on an ad-hoc developed module that extends the C++ classes of VTK (Colombo et al. 2016) to interact with the virtual environment.

- Oculus Rift SDK 2.0 for immersive vision inside a 3D virtual world (Oculus Rift). The Taylor Tracking environment is automatically visualized in the user's field of view of the Oculus Rift when the 3D body shape is detected and, thus, the tailor can start to take measurements using hands/fingers detected by the Leap Motion.

- Visualization Tool Kit (VTK). The Taylor Tracking is composed by a set of widgets. In particular, the virtual measuring tape is a widget based on the use of a 3D line. The user takes the measurement by pinching the initial point and moving the line representing the tape along the human avatar until s/he reaches the ending point. Once the virtual tape measure has been properly placed, the associated measurement is calculated and visualized in the field of view of the environment.

- Qt (Qt), a SDK to develop Graphic User Interfaces (GUI).

FIGURE 7

The application requires the synchronization of mentioned devices; therefore, a software framework, named FrameworkVR, has been developed to manage the synchronization. It is general purpose and a fully independent platform. FrameworkVR has been developed to permit an easy integration of new modules related to other important issues for virtual garment design, such as emulation of muscles, 3D human shaped estimated from

clothed 3D scanned person and import/export of different file formats used by commercial
CAD systems. Furthermore, it includes a set of extendable software modules, which permit to
design NUI for a custom virtual environment based on VTK.

## 4.2 FrameworkVR and NUI design

As mentioned before, FrameworkVR has been developed for managing the synchronization
among the 3D environment of VTK, Leap Motion and Oculus Rift. Usually, each device uses
a coordinate system that can be different from each other. FrameworkVR orients and
translates 3D virtual objects according to the coordinate system of the Oculus Rift in order to
obtain the correct visualization of the human body loaded through VTK and of the
hands/fingers tracked by the Leap Motion.

The SDKs have been exploited to develop a more complete software framework to
simplify the design of the application, which requires the device synchronization, the
management of triangular mesh models, the animations and the emulation of the virtual tape
measure.

Among the several research fields related to virtual reality applications, the design of a
NUI is one of the most important challenges (Wigdor & Wixon 2011; Colombo et al. 2015).
Too often, NUI design is limited to create a lot of gestures without thinking if chosen gestures
are natural or not. A good NUI should allow the user to be mainly concentrated on the
achievement of the final goal instead of monitoring the correct execution of the gesture.

On this basis, FrameworkVR encapsulates a set of guidelines to design NUIs and
permits to develop interaction styles for virtual reality applications. The modules are general

purpose and a set of virtual widgets, such as buttons, sliders and icons, has been made available. The finite state machine (FSM) pattern has been adopted and customised.

Figure 8 depicts the FSM relative to FrameworkVR. The FSM starts from the Idle state indicating that there are no hands inside the field of view (FOV) of the user. When one or two hands is/are detected by the Leap Motion, the FSM moves to "hands state", which allows interacting with virtual widgets. The use of a virtual widget permits the FSM to translate from "hands state" to "focus state". If the FSM is in the "focus state", the widget may be selected and a particular action can be executed inside the application and the "selected state" is achieved. The transition among these four states is possible also according to the rules of the guidelines embedded in FrameworkVR.

FIGURE 8

Its high modularity allows the extension with new software modules to customize the NUI for a particular application, as shown in the following section.

### 4.3 Tailor Tracking NUI

By starting from the basic FSM of FrameworkVR, a customised NUI for Tailor Tracking has been designed through a new FSM model (Figure 9) extending the one shown in Figure 8. The customised FSM presents a new set of states describing the modes with which the user can interact when using the virtual tools. The new states are based on gestures done with one or two hands. Each gesture has an initial state (**Starting mode**) that may go into three different states according to the interaction style as described in the following:

- **Toggle Image mode** that permits to interact with the virtual widgets (e.g., sliders and buttons) inside the activated virtual tools.

- **Tape measure mode** that is activated when the user wants to apply the virtual contour widget to get measures.

- **Camera mode.** Both sub-states of camera mode allow executing operations relative to the visualization of the model, such as rotation and zooming.

The customised NUI allows also the interaction with the virtual tape measure, which has been developed for taking measures using hands as in the traditional way.

FIGURE 9

### *4.4 Virtual tape measure*

From the analysis of the tailor's work (§2.1) a set of basic gestures has been identified as shown in Figure 10. The specific widget "virtual tape measure" has been developed to emulate the tailor's tape measure. It allows an interaction based on a set of nodes along its path and a node can be added, moved or deleted. When the user interacts with a control node, the measurement is automatically calculated and visualized inside the 3D scene of the Tailor Tracking. In this way, the tailor can compare and evaluate their correctness in an easy way. Figure 11 shows some examples of measures taken for a men shirt.

FIGURE 10

FIGURE 11

*4.5 Postures database*

The Tailor Tracking can be used starting from either 3D human bodies acquired with Microsoft Kinect v2 or standard 3D mannequins; therefore, it makes available:

•        A set of body animations, i.e., a 3D animation library composed by BVH files to generate different avatar postures. Once defined the correct posture, the tailor can take the measurements necessary to design the garment. The library is composed by several subsets of animations according to the type of garments. Involving people who executed useful postures (Figure 12) to design shirt, pants, jacket and skirts has generated the database.

•        A set of standard mannequins for clothing design whose sizes meet the Europeans standards for both males and females. The 3D models are available in OBJ format and can be used instead of acquiring the 3D human avatar of a specific customer.

FIGURE 12

## 5. Experimentation and preliminary results

The design of a men shirt has been considered as case study to preliminary evaluate the usability of the application and verify if necessary postures can be easily generated and right measures taken.

The tests have involved 14 people (13 male and 1 female) with no experience in garment design and with three different levels of experience in virtual reality environment:

• Skilled user (S): s/he knew how to interact with a virtual reality environment.

- Average user (A): s/he had used some simple virtual reality application but had never tried a long-lasting interaction to achieve a specific aim.

- Inexperienced user (I): s/he had never used a virtual reality application and did not know how to interact with a virtual environment.

A tailor has been asked to show the testers how he traditionally takes the measurements. Measures taken by the tailor have been considered as reference (Table 1).

TABLE 1

The test procedure has been subdivided in two phases. In the first step, each tester was asked to see a video tutorial describing the basic actions to interact with the virtual environment and how to use the virtual tape measure. During the tutorial the user had to emulate the basic actions made by hands and fingers.

Second step concerned the use of the Tailor Tracking. Initially, the user had to familiarize herself/himself through the visualization of the 3D environment and the interaction by trying to repeat the actions previously shown by the video tutorial. When the user's interaction was good enough, s/he started taking measures to design a men shirt.

Each tester has had to take six measurements in the following order: neck (NM), shoulders (SM), chest (CM), waist (WAM), arm (AM), and wrist (WIM). Table 1 shows the measures taken by each tester, her/his related degree of experience and the time of completion of the task.

Analysing Table 1, we can observe that:

- Skilled and average testers have been able to get all measures. They are comparable to the tailor's ones and, in general, the differences are no more than +/- 5 mm (considered acceptable by the tailor) except for wrist (up to -2,5 cm). Neck, chest and arm measures are the same or very close to the reference ones.

- Inexperienced testers have been able to get all the required measures except for neck and wrist (marked with "-" in the Table 1). In detail, two users have found difficulties to take the measures of the neck while six testers the measurement of the wrist. In general, the difference between acquired values and tailor's ones are higher than those taken by skilled and average testers (especially for the waist), except for the arm.

- Execution time is higher than tailor's one even if skilled testers acquired all measures in a time interval close to the execution time reached by the tailor following the traditional approach.

Summarizing, the most critical measures are the wrist for all types of users and, in addition, the neck and waist for inexperienced users. The error related to wrist measure is mainly due to the quality of the acquired mesh in the related body district. In general, the other measurements are very close to the real ones and differences mainly depend on the difficulties of interaction with the virtual environment.

Moreover, the execution time suggests that further improvements of the NUI are necessary to simplify the interaction style and make the task easier. Anyway, we should

remember that all testers have no experience in garment design and this has partially influenced their capacity to get the right measure.

Measurements have been taken with the customer wearing light clothes or only underwear according to what the tailor traditionally does. At present, we haven't considered customer with heavy clothes since they can influence the accuracy of the measurements. We will face this problem developing a physically based model of the customer or applying an algorithm for automatic clothing removal (Wuhrer et al. 2014).

Some preliminary tests have been also carried out to compare Tailor Tracking with the module for automatic measures extraction, which is part a virtual environment to design made-to-measure garment shown in Figure 1 and still under refinement. Chest and waist values are comparable and there are small differences. The most critical measures have been the base of the neck, wrist and the shoulder. One reason is still the quality of the mesh but we should take into account that a tailor is highly skilled, get and accommodate measures according to customer's morphology and with different postures.

The solution for body acquisition has demonstrated a good potential for a real use in the future. The number of Kinect v2 can be increased to obtain a customer avatar in a more accurate way, faster and more similar to the commercial ones described in §2.2. A higher number of Kinect v2 permits to get a more precise acquisition of human body districts, such as hands, arms and legs, and of occluded zones (e.g., internal part of the legs). With our solution, the human body has been acquired in 120 seconds and the automatic reconstruction of the mesh has been executed in 15 seconds. By the way, the high modularity of proposed solution permits to consider faster and more accurate 3D scanning systems based on RGB-D

sensors (Ernst et al. 2016, Geng & Bidanda 2017). Furthermore, it can be integrated into existing solutions in order to permit both automatic measurement extraction and take specific customer measurements interacting with the customer's avatar using hands.

Finally, the database of animation allows defining all necessary postures for customer's measurements. Some problems have been identified with regard to the mesh deformation, in particular for the upper arm. In addition, considering the variety of garments (e.g., pant, skirt, and dress) different avatar postures are necessary. New modules will be added to manage a database of postures and movements to be automatically applied to the customer's avatar and guide the users during measures detection.

## 6. Conclusions

This paper presents the Tailor Tracking system to acquire the customer's measures by virtually interacting with the customer's avatar using hands as the tailor traditionally performs with the client. At present, it has been preliminarily experimented involving a tailor and a number of testers. The tailor considered positively results reached so far as well as the testers the interaction with the virtual environment; however, further improvements are necessary. They concern the 3D scanning procedure to generate a more refined mesh of the avatar, the NUI to simplify the interaction style making easier the measurements task, and the postures database to fully consider the variety of men and women garments. We have also planned to test Tailor Tracking with different clothes and embed tailor's knowledge within the system to train novice tailors.

Tailor tracking can represent a cheaper alternative to the existing approach that automatically extract anthropometric measures from the customer's avatar and has been specifically designed to allows the tailors to get the measures ad s/he traditionally performs. Future tests have been planned in order to evaluate the Tailor tracking with other commercial solutions and compare performances in terms of effectiveness and usability. Anyway, the two approaches can be combined. We are also investigating the possibility to include a module for muscle simulation as well as to estimate human body shape under clothing. Furthermore, haptic gloves are under evaluation for a force feedback when the tailor interacts with 3D mesh.

Finally, the system is independent from any specific garment modeller since considered data formats (.stl for the avatar mesh, and *.bvh, .C3D* and .dae for data acquired with the Mocap system) are those ones commonly used by 3D commercial garment modellers. Therefore, integrated with a 3D clothing system, it will permit to fully virtualize the garment development process and emulate a virtual atelier.

**Acknowledgements**

# References

Abdelnaby, M. et al., 2017. Augmented reality maintenance training with intel depth camera. *In Proceedings - 2017 International Conference on Machine Vision and Information Technology, CMVIT 2017*. 116–122.

Anguelov, D. et al., 2005. SCAPE: Shape Completion and Animation of People. *In ACM Transactions on Graphics*. 408–416.

Apeagyei, P.R., 2010. Application of 3D body scanning technology to human measurement for clothing fit. *International Journal of Digital Content Technology and its Applications*, 4(7), 58-68.

Bartesaghi, S., Colombo, G. Morone, S., 2015. Spatial Augmented Reality and Simulations to Improve Abdominal Aortic Aneurysm Diagnosis and Monitoring. *Computer-Aided Design and Applications*, 12(6), 803–810.

Basori, A.H. et al., 2016. An overview of interactive wet cloth simulation in virtual reality and serious games. *Computer Methods in Biomechanics and Biomedical Engineering: Imaging and Visualization*, 6(1), 93–100.

Bragança, S., Arezes, P.M. Carvalho, M., 2015. An overview of the current three-dimensional body scanners for anthropometric data collection. *In Occupational Safety and Hygiene III - Selected Extended and Revised Contributions from the International Symposium on Safety and Hygiene*, 149–154.

Carulli, M., Bordegoni, M. & Cugini, U., 2016. Integrating Scents Simulation in Virtual Reality Multisensory Environment for Industrial Products Evaluation. *Computer-Aided Design and Applications*, 13(3), 320–328.

Carulli, M. et al., 2017. ICT technology for innovating the garment design process in fashion industry. *In Smart Innovation, Systems and Technologies*. 525–535.

Colombo, G. et al., 2015. Low cost hand-tracking devices to design customized medical

devices. *In International Conference on Virtual, Augmented and Mixed Reality*. 351-360.

Colombo, G. et al., 2016. Mixed reality to design lower limb prosthesis. *Computer-Aided Design and Applications*, 13(6), 799-807.

Daanen, H.A.M. & Ter Haar, F.B., 2013. 3D whole body scanners revisited. *Displays*, 34(4), 270–275.

Duo3D. Available from: https://duo3d.com [Accesed 20 April 2018]

Ernst, M. et al., 2016. Rapid Body Scanning Technology for a Virtual Mass Customization Process in Garment Industry. *In Proceedings of the 7th International Conference on 3D Body Scanning Technologies, Lugano, Switzerland, 30 Nov.-1 Dec. 2016. Ascona, Switzerland: Hometrica Consulting - Dr. Nicola D'Apuzzo*, 159–169.

Geng, Z. and Bopaya. B., 2017. Review of reverse engineering systems-current state of the art. *Virtual and Physical Prototyping*, 12(2), 161-172.

Hirshberg, D.A. et al., 2012. Coregistration: Simultaneous alignment and modeling of articulated 3D shape. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 7577(6), 242–255.

Hong, Y. et al., 2017. Virtual reality-based collaborative design method for designing customized garment for disabled people with scoliosis. *International Journal of Clothing Science and Technology*, 29(2), 226–237.

Hsiao, S.-W. & Chen, R.-Q., 2013. A study of surface reconstruction for 3D mannequins based on feature curves. *CAD Computer Aided Design*, 45(11), 1426–1441.

Hsiao, S.-W. & Tsao, Y.-C., 2016. Applying Multiple Kinect on the Development of a Rapid 3D Mannequin Scan Platform.*International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, 10(7), 1185–1189.

Vitus Smart. Available from: http://www.human-solutions.com/fashion/. [Accesed 20 April 2018]

iPi Software. Available from: http://ipisoft.com/ [Accesed 20 April 2018]

Kinect. Available from: https://developer.microsoft.com/en-us/windows/kinect [Accesed 20 April 2018]

Kowalski, M., Naruniec, J. & Daniluk, M., 2015. Live Scan3D: A Fast and Inexpensive 3D Data Acquisition System for Multiple Kinect v2 Sensors. *In Proceedings - 2015 International Conference on 3D Vision, 3DV 2015*, 318–325.

Kraft, M. et al., 2017. Toward evaluation of visual navigation algorithms on RGB-D data from the first- and second-generation Kinect. *Machine Vision and Applications*, 28(1–2), 61–74.

Leap Motion. Available from: https://www.leapmotion.com/ [Accesed 20 April 2018]

Markiewicz, Ł. et al., 2017. 3D anthropometric algorithms for the estimation of measurements required for specialized garment design. *Expert Systems with Applications*, 85, 366–385.

Newcombe, R.A. et al., 2011. KinectFusion: Real-Time Dense Surface Mapping and Tracking. *In IEEE ISMAR*. 127-136.

Nguyen, W.L.K. et al., 2018. Morphological Box Classification Framework for supporting 3D scanner selection. *Virtual and Physical Prototyping*, 0(0), 1–11.

Skanect. Available from: http://skanect.occipital.com/ [Accesed 20 April 2018]

Oculus Rift. Available from: www.oculusrift.com [Accesed 20 April 2018]

Ong, A., Harris, I.S. & Hamill, J., 2017. The efficacy of a video-based marker-less tracking system for gait analysis. *Computer Methods in Biomechanics and Biomedical Engineering*, 20(10), 1089–1095.

P. Cignoni, M. Callieri, M. Corsini, M. Dellepiane, F. Ganovelli, G.R., 2008. MeshLab: an Open-Source Mesh Processing Tool. *In Sixth Eurographics Italian Chapter Conference*. 129–136.

Qt. Available from: https://www.qt.io/ [Accesed 20 April 2018]

Saakes, D. et al., 2016. Mirror Mirror: An on-body T-shirt design system. *In Conference on Human Factors in Computing Systems - Proceedings*. 6058–6063.

Sharifi, A., Harati, A. & Vahedian, A., 2017. Marker-based human pose tracking using adaptive annealed particle swarm optimization with search space partitioning. *Image and Vision Computing*, 62, 28–38.

Silva, A.R. et al., 2016. An indoor navigation system for live-action virtual reality games. In Brazilian Symposium on Games and Digital Entertainment, SBGAMES, 1–10.

SYMCAD. Available from: http://www.symcad.com/eng/technology.htm [Accesed 20 April 2018]

Tailor Store. Available from: https://www.tailorstore.com/mens-body-measurements.pdf [Accesed 20 April 2018]

Tay, Y.W.D. et al., 2017. 3D printing trends in building and construction industry: a review. *Virtual and Physical Prototyping*, 12(3), 261–276.

TC2. Available from: https://www.tc2.com [Accesed 20 April 2018]

Unver, E., Taylor, A. & Ball, A., 2016. Comparative Analysis of Mobile 3D Scanning Technologies for Design, Manufacture of Interior and Exterior Tensile Material Structures and Canvasman Ltd. Case Study.

Volino, P. & Magnenat-Thalmann, N., 2000. Virtual Clothing, Berlin, Heidelberg*: Springer Berlin Heidelberg.*

Volino, P., Cordier, F. & Magnenat-Thalmann, N., 2005. From early virtual garment simulation to interactive fashion design. *CAD Computer Aided Design*, 37(6), 593–608.

Volonghi, P., Baronio, G. & Signoroni, A., 2018. 3D scanning and geometry processing techniques for customised hand orthotics: an experimental assessment. *Virtual and Physical Prototyping*, 0(0), 1–12.

VTK. Available from: http://www.vtk.org/ [Accesed 20 April 2018]

Wang, C.C.L., 2005. Parameterization and parametric design of mannequins. *CAD Computer Aided Design*, 37(1), 83–98.

Wang, C.C.L. & Tang, K., 2010. Pattern computation for compression garment by a physical/geometric approach. *CAD Computer Aided Design*, 42(2), 78–86.

Wang, R., Choi, J. & Medioni, G., 2012. Accurate full body scanning from a single fixed 3D camera. *In Proceedings - 2nd Joint 3DIM/3DPVT Conference: 3D Imaging, Modeling, Processing, Visualization and Transmission, 3DIMPVT 2012*. 432–439.

Wigdor, D. & Wixon, D., 2011. Brave NUI World, *Communications of the ACM*, 54(12), 14-16.

Wuhrer, S. et al., 2014. Estimation of human body shape and posture under clothing. *Computer Vision and Image Understanding*, 127, 31–42.

Yang, J. et al., 2016. Estimation of Human Body Shape in Motion with Wide Clothing. *In B. Leibe et al., eds. Computer Vision -- ECCV 2016. Cham: Springer International Publishing*, 439–454.

Yolcu, G., Kazan, S. & Oz, C., 2014. Real time virtual mirror using kinect. *Balkan Journal of Electrical and Computer Engineering*, 2(2).

Zhang, D., Wang, J. & Yang, Y., 2014. Design 3D garments for scanned human bodies. *Journal of Mechanical Science and Technology*, 28(7), 2479–2487.

Zhang, Y., Zheng, J. & Magnenat-Thalmann, N., 2014. Cloth Simulation and Virtual Try-on with Kinect Based on Human Body Adaptation. *Simulations, Serious Games and Their Applications*, 31–50.

| # Tester | Gender | Age | Level | NM [cm] | SM [cm] | CM [cm] | WAM [cm] | AM [cm] | WIM [cm] | Time [min] |
|---|---|---|---|---|---|---|---|---|---|---|
| *Measures taken by the Tailor* | | | | 38 | 46 | 95 | 93 | 88 | 16,5 | 6 |
| 1 | M | 25 | S | 38 | 46 | 94,5 | 94 | 87,5 | 15 | 10 |
| 2 | M | 29 | S | 38 | 45 | 95 | 93 | 87,9 | 14 | 9 |
| 3 | M | 27 | A | 37,5 | 45 | 95,5 | 93 | 88,5 | 15 | 13 |
| 4 | M | 26 | A | 38 | 46 | 95 | 92 | 87,5 | 14 | 25 |
| 5 | M | 39 | I | 36 | 45 | 96 | 94 | 87 | - | 15 |
| 6 | M | 28 | I | 37 | 47 | 95 | 94 | 88,5 | - | 15 |
| 7 | M | 40 | I | 39 | 47 | 94 | 96 | 88 | 14 | 17 |
| 8 | M | 23 | I | 36 | 46 | 94 | 95 | 89 | 14 | 16 |
| 9 | F | 24 | I | - | 47 | 95,5 | 95 | 87 | - | 20 |
| 10 | M | 24 | I | 37 | 45 | 96 | 94 | 88 | - | 19 |
| 11 | M | 24 | I | 36 | 46 | 94 | 94 | 87 | - | 21 |
| 12 | M | 23 | I | 39 | 47 | 95 | 93,5 | 86 | - | 20 |
| 13 | M | 27 | I | 38 | 44 | 93 | 93,5 | 88,5 | 14 | 24 |
| 14 | M | 31 | I | - | 45 | 96 | 93 | 86 | - | 22 |

Table 1. Summary of measures acquired by the tailor and 14 testers.
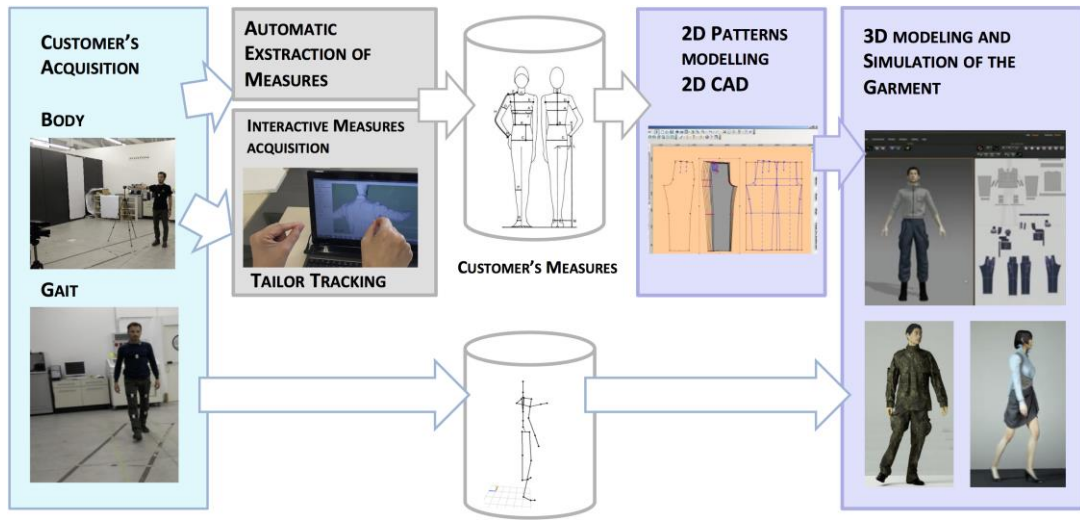
Figure 1. BODY-SCAN Virtual environment for made-to-measure garment design.
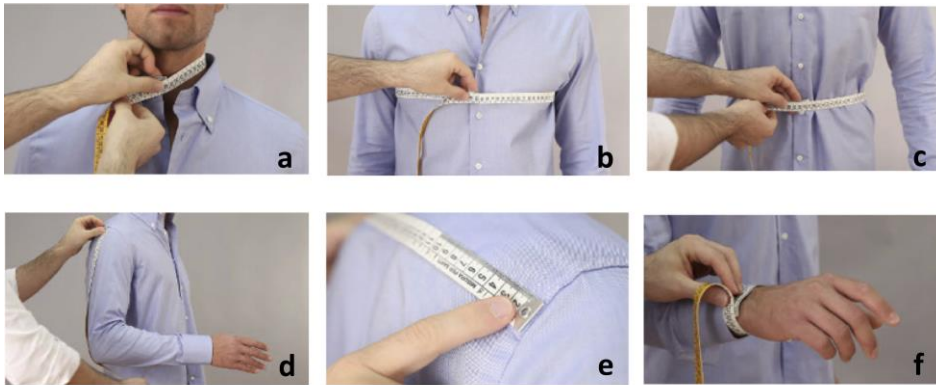


Figure 2: Examples of measures for man shirt. a) Collar: measure around the base of the neck;

b) Chest: measure around fullest part standing wright; c) Waist: measure around body at the

natural waist level; d) Sleeve: measure from shoulder to wrist with arm bent at 90°; e)

Shoulder: measure from tip of left shoulder point to the right one: f) Wrist: measure around

wrist bone.
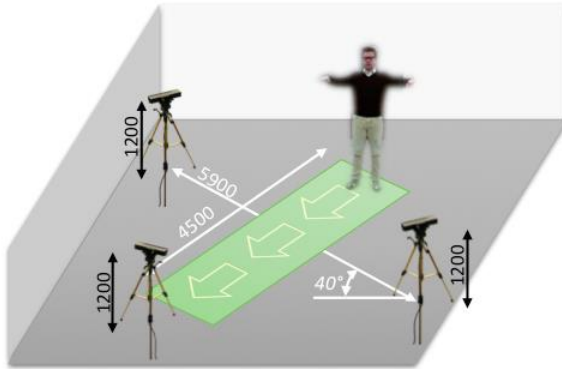
Figure 3. Layout of the Motion capture system based on three Microsoft Kinect v2.
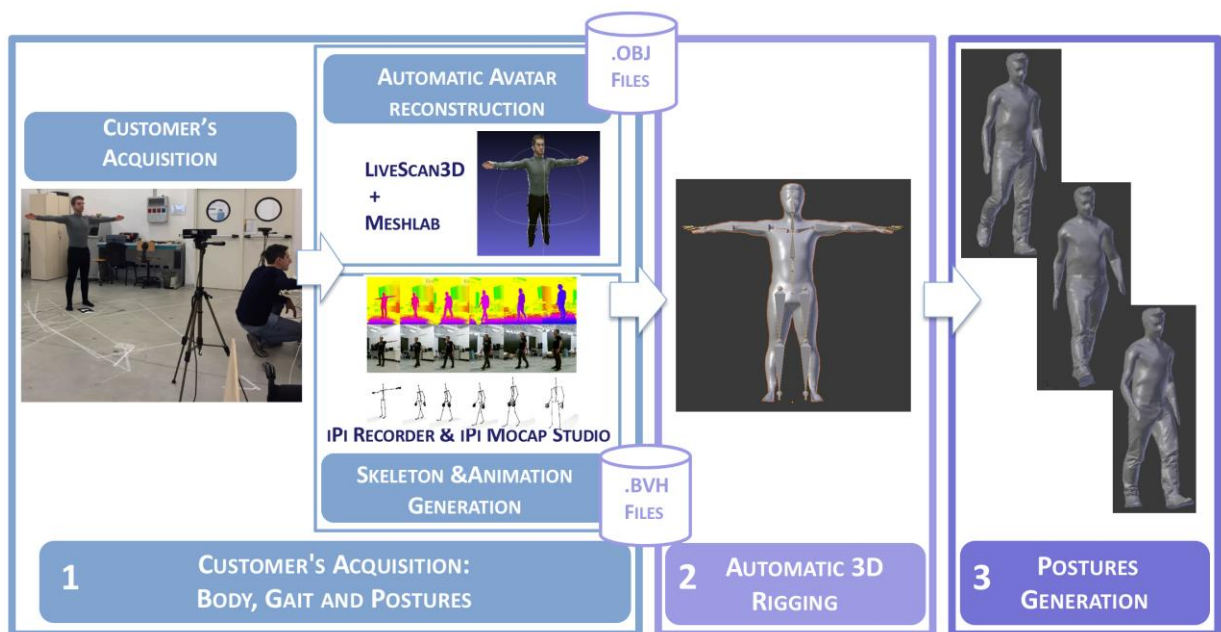


Figure 4. Operative workflow to acquire customer's postures.
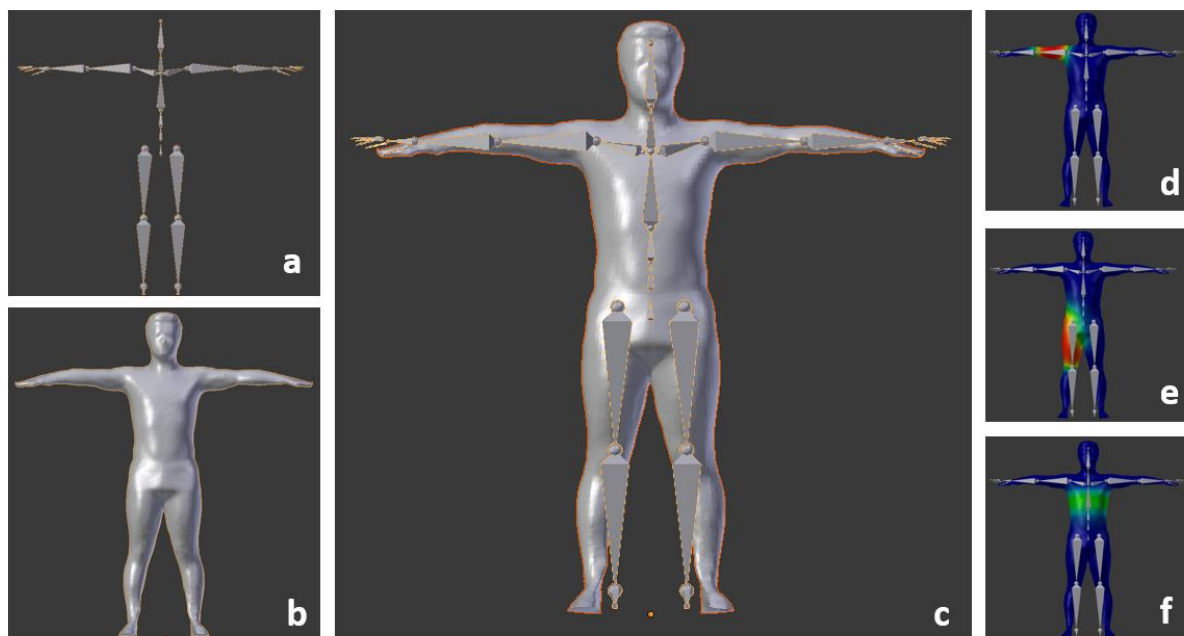
Figure 5. Automatic 3D rigging procedure.
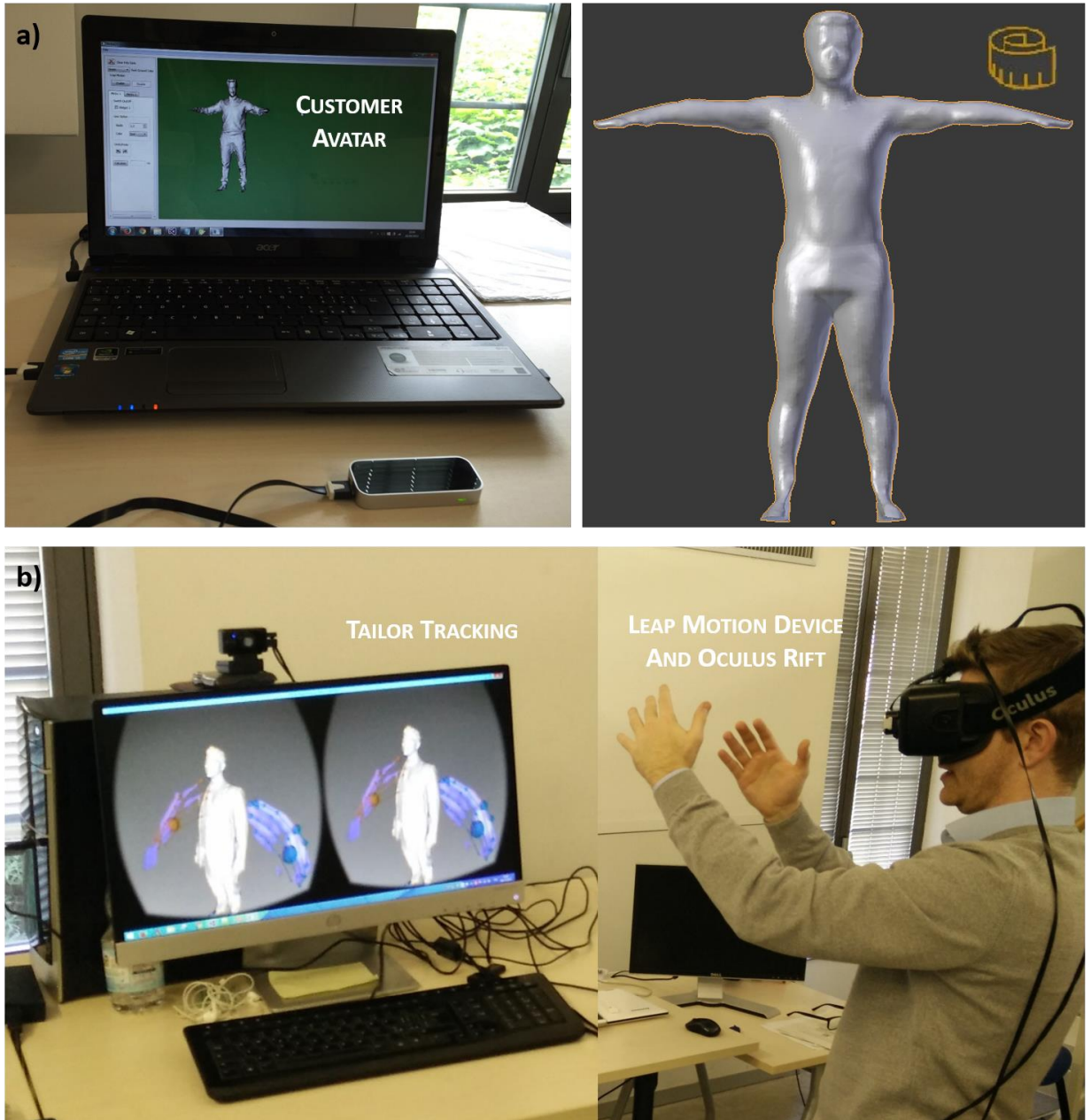
Figure 6. a) Solution with only hand tracking device; b) Virtual reality solution.
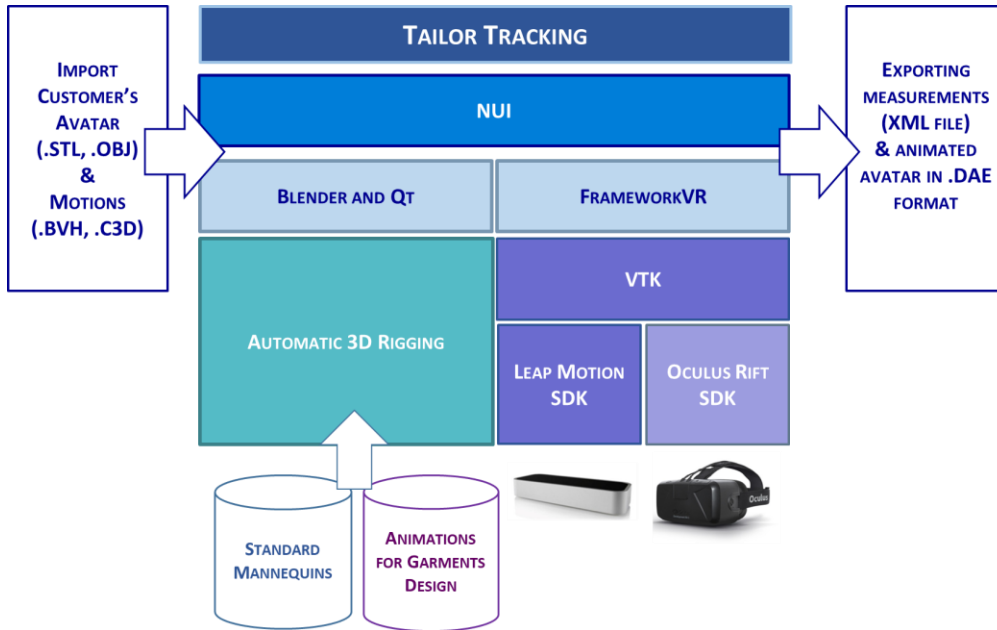
Figure 7. Software architecture of proposed solution.
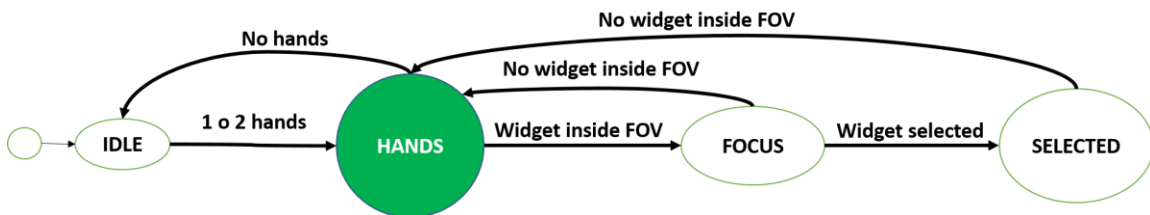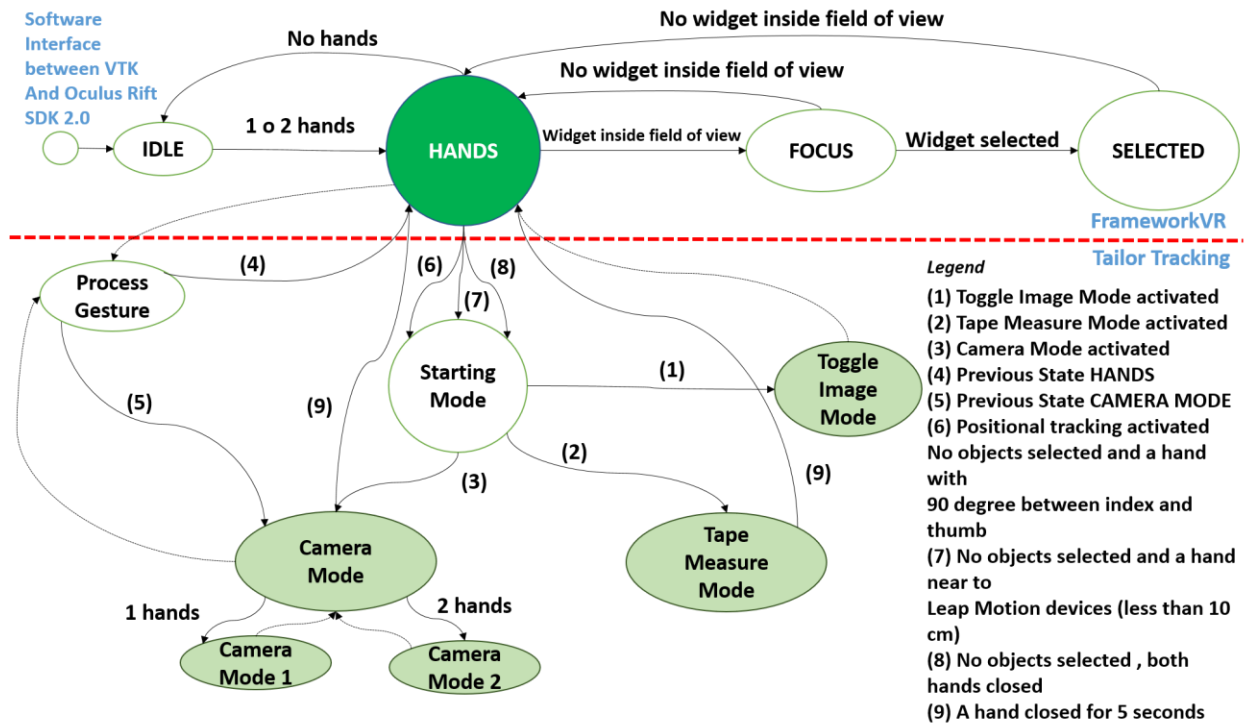


Figure 8. FSM of FrameworkVR.

Figure 9. Customised FSM for Tailor Tracking, which extends the basic FSM of FrameworkVR shown in Figure 8.

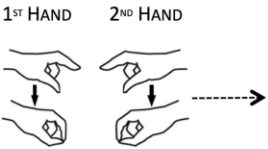| ACTION | GESTURE | DESCRIPTION |
|---|---|---|
| **BASIC INTERACTION** | | |
| From basic interaction to acquisition of measures | | This neutral gesture changes possible actions the user can execute on the virtual human body. Two interaction modes are available: the *Camera mode* for changing the visualization of 3D model, such as rotation and zooming, the *Tailor mode* for taking measurements. |
| Moving 3D human avatar | | The 3D virtual human follows the palm orientation. Zoom-in/zoom-out of the human body has been done through horizontal motion of a palm |
| **BODY MEASURES OPERATIONS** | | |
| Create a measuring tape to get a body measure. | 1ST HAND 2ND HAND | The double pinch action permits to activate the measuring tape and get a measurement along the surface of the client's avatar. The initial pinch action defines the starting point of tape measure, while the second one defines the initial path of the tape |

Figure 10. Identified gestures for interacting with virtual environment of Tailor Tracking.
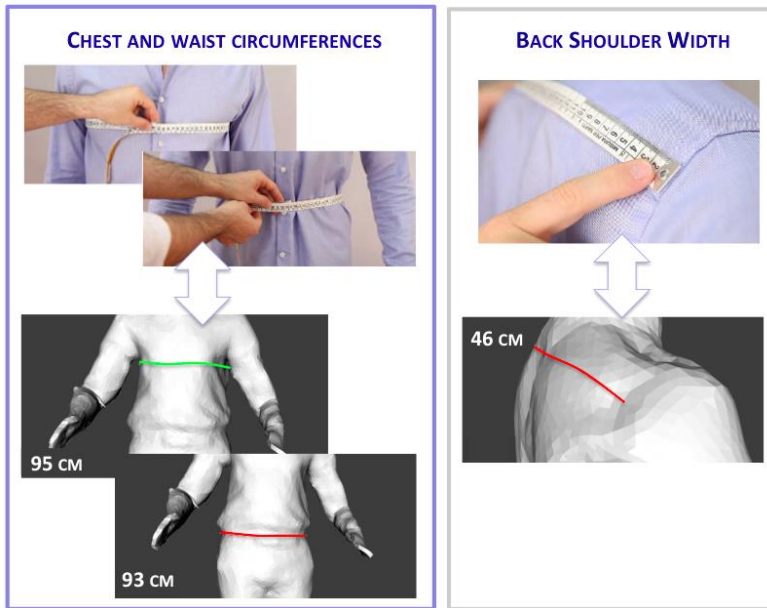
Figure 11. Example of measures taken on the customer's avatar.



Figure 12. Example of human avatar postures.