Arm prosthesis simulation on a virtual reality L-shaped workbench display system using a brain computer interface

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ABSTRACT

The work being described in this paper is the result of a cooperation project between the Institute of Visual Computing at the Bonn-Rhein-Sieg University of Applied Sciences, Germany and the Laboratory of Biomedical Engineering at the Federal University of Uberlândia, Brazil. The aim of the project is the development of a virtual environment based training simulator which enables for better and faster learning the control of upper limb prostheses. The focus of the paper is the description of the technical setup since learning tutorials still need to be developed as well as a comprehensive evaluation still needs to be carried out.

1. INTRODUCTION

The first prosthetic replacement was reported in the book “Vedas” written in Sanskrit in India, being compiled between 3,500 and 1,800 B.C. (Vanderwerker, 2013). For many centuries, the use of prosthetics was limited only to correct the appearance of the missing human limb by means of wood or metal. Nowadays, not only the appearance and the materials of the prosthetic limbs improved significantly. Since the 1960’s medical research focused on the substitution of the functionality of the missing limb, too.

Usually, arm prostheses with grasping functions consist of an underlying mechanical structure being covered by a polyvinyl chloride (PVC) skin cover which is quite robust and appears more human skin-like than other materials. The connection to the human body is used for control.

This can be done by means of myoelectric signals or even brain-computer interfaces as described in the related work section. However, when using myoelectric signals derived by surface electrodes from either the breast muscles or from the remaining part of the arm, controlling gets complicated. Due to the high weight of the prostheses and the associated pre-stress of the muscles being used, signal processing algorithms usually fail by filtering the noise caused by the pre-stress from the intended signal for controlling the prosthesis. Especially in the beginning, when the prosthesis is new to the patient, this can cause an additional psychological burden. The result is a very flat learning curve for the patient.

However, up to now, learning the control of arm prostheses is possible by the intensive supervision of physiotherapists. Hence, the learning phase is accompanied by high costs, too. Therefore the main motivation for the project being described in this paper was to transfer the first learning steps with the prosthesis into a virtual environment, where the prosthesis itself is represented by a weightless graphical representation. The virtual environment itself would provide the means for aligning the virtual prosthesis with the remaining arm. The assumption was that if the graphical representation is of high quality and both, the remaining arm and the prosthesis, are perfectly aligned, then training would become much easier, especially in the beginning.

However, the simulation does not intend to replace the conventional training which obviously is absolutely crucial. But it would allow for an easier learning experience especially in the beginning when the patient’s psychology shows the highest impact on the success of the training.

This paper is describing early research results. Hence it focuses on the technical description of the used setup and provides the results of a system evaluation with healthy users. The authors of the paper as well as the cooperation partners intend to develop appropriate autodidactic learning tutorials for the patient using the virtual reality based prosthesis simulator. In addition a comprehensive user evaluation is planned too.

2. RELATED WORK

Prosthetic limbs can be categorized from different perspectives. For example Disabled-World - an independent Health and Disability news source (Langtree and Langtree, 2013), categorizes prostheses by the relative connection place of the prosthetic limb such as below/above the elbow or the knee. Steven Lam (Lam, 2010) used the functionality criterion to categorize prostheses in three groups: cosmetic, body-powered and externally powered prostheses. Considering the purpose of usage, all prosthetic kinds have their own advantages and disadvantages in terms of costs, appearance, functionality and comfort. Cosmetic prosthetics are the cheapest and lightest kind. Their functionality is very limited and mostly they only have been used for correcting the natural appearance of the human body. On the other hand the body-powered prosthetics have more degrees of movement but at the same time they are more expensive and heavier. In comparison to the previous two kinds, externally powered prosthetics focus more on substituting the natural functionality of missing limbs rather than their appearance. Among this type, myoelectric prosthetics use technology like Electromyography (EMG) (Hiraiwa et al, 1989, Huang et al, 2008, Schultz and Kuiken, 2011) for signal acquisition and lightweight electro-motors and batteries for mimicking the functionality of the missing limb.

However, the externally powered prosthetics are not perfect yet. They are the most expensive kind due to special design, and heavier because of the electro-motors and battery weight. From the functional perspective the externally powered prosthetics are the most preferable kind, but due to the special control system, these prostheses are difficult to learn and use (Takeuchi et al, 2007, Anderson and Bischof, 2012). For controlling them patients need to produce electrical muscle activity by moving one or more special skeletal muscles. This work by itself is an extremely hard and time consuming procedure and needs high mental effort as well as motivation, especially during the initial months of training. By considering the stress which is caused by the prosthesis weight and the uncomfortable feeling around the attachment area, it is evident that the training procedure becomes a hard and long way of learning with a very flat learning curve.

It has been proven that VR/AR-based training systems have got good capabilities to significantly improve training performance of many kinds. In order to understand the distinction between VR and AR, VR (virtual reality) refers to systems where the user is immersed almost totally in the artificial environment and just sees virtual objects. The real world reference frame vanishes in the background. The term AR (augmented reality) refers to systems where the user still sees the real world into which virtual objects are placed. However, in many applications this distinction is not easily to make since in projection based virtual environments the user still sees his own body parts and therefore, per definition, these might not be considered to be true virtual reality environments. This is the reason why a third term MR (mixed reality) was introduced, which combines the former two and tries to bridge between VR and AR by a continuum of mixed application possibilities where either virtual or real world objects are prevalent.

In order to improve the control over the muscular activity and decrease the training time, many researchers proposed different training systems. For instance, (Merians et al, 2002) developed a haptic system called “Rutgers-II ND hand master glove” for hand rehabilitation. Otto Bock HealthCare (Otto-Bock, 2012) devised a commercial product called “Myoboy training suit” for measuring EMG signals to find better electrode settings. (Armiger and Vogelstein, 2008) and (De la Rosa et al, 2008) used a game environment to provide engaging and motivating training sessions for individuals.

Among these training systems, the VR and AR based ones are the most popular which were used for training purposes (Takeuchi et al, 2007; Anderson and Bischof, 2012; Luo et al, 2005a; Luo et al, 2005b; Murray et al, 2006; Cole, 2008; Al-Jumaily and Olivares, 2009; Lamounier et al, 2010; Lamounier et al, 2012). The reason is simply that VR/AR-based training systems provide more realistic and natural feedback about the quality of the patient’s interactions with the prosthesis and with the environment, respectively. Contrary to this, haptics-based systems are very limited to motor rehabilitation rather than prosthetic limb rehabilitation, and game-based ones do not provide the natural feedback and interaction of the missing limb..

3. SYSTEM SETUP AND APPLICATION

The main part of the prosthesis simulation system used in this project consists of an L-shaped workbench. It is composed of a 1.71 m high and 1.41 m wide metal frame. Two 0.49 m high and 0.67 m wide projection displays are embedded in that frame, expanding a virtual work volume of about 0.17 m^3 size. Two stereo-projectors project the scene onto the corresponding display screens. Two mirrors are used for reducing the projection distance to the screens (see figure 1).

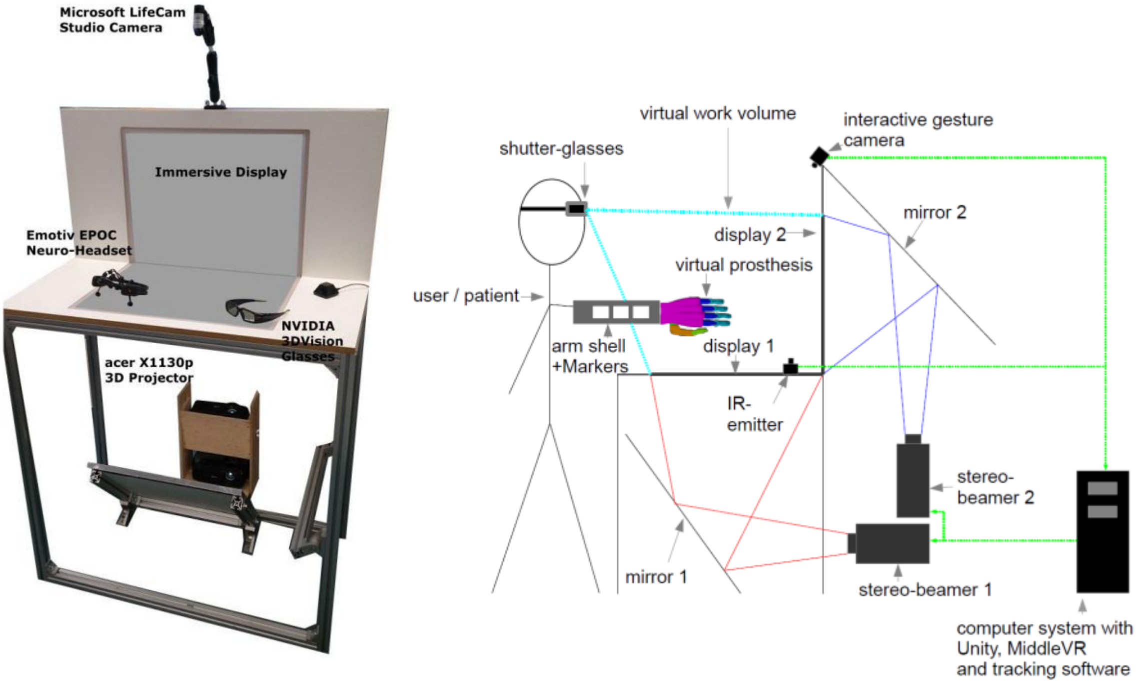

Figure 1. *System setup and L-shaped workbench at the Bonn-Rhein-Sieg University. The right part of the image shows all components being used. The virtual prosthesis model is shown as an extension of the user's arm shell with markers.*

Rendering is implemented by using the Unity game engine (Unity). The choice for Unity was mainly influenced by its huge range of rendering options, animation sequencers and a physics library, detecting and handling object collisions. However, since Unity is not natively supporting stereoscopic output we decided for the additional MiddleVR plugin (I'm in VR, 2013). MiddleVR allows for configuring different display setups as in this case a two orthogonal sided setup of the L-shaped workbench. The setup is stored in a configuration file which again is read and interpreted by Unity. For stereoscopic perception of the images, the NVIDIA 3D Vision set is used, that consists of shutter glasses and an infra-red emitter. The infra-red emitter is responsible for triggering the shutter mode of the 3D stereo glasses which in turn have got an infra-red sensitive sensor. Stereo viewing of the 3D prosthesis model with Unity on the L-shaped workbench is possible now. The remaining issue is the control of the virtual prosthesis model in the virtual environment. For the purpose of aligning it with the user's remaining arm stump the tracking has to be solved by using an arm shell including markers (see figure 2). The arm shell consists of carton on which an AR fiducial marker board is attached for tracking purposes. The board itself is a composition of several single fiducial markers. These markers are recognised by the camera looking down onto the shell from the top frame of the workbench display. The camera is operated by a self-developed tracking application (C++) that recognizes the fiducial markers and computes the translation and orientation (pose) of the entire arm shell. For computation purposes, the C++ tracking application uses the ALVAR (A Library for Virtual and Augmented Reality) (Alvar, 2014) and OpenCV library. ALVAR detects the markers, recognizes them and computes their translation and orientation coordinates by means of a transformation matrix.

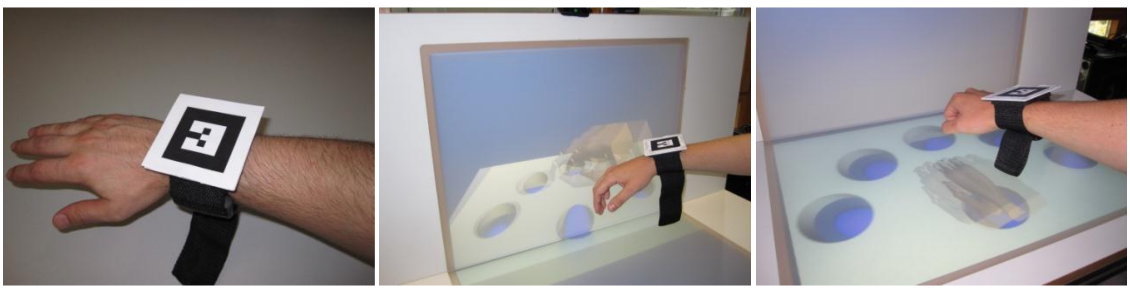

Figure 2. *This simple arm shell is attached to the user's remaining arm stump using fiducial AR markers for tracking.*

After the computation, the pose is sent to the rendering program Unity. Unity now updates the position and orientation of a virtual prosthesis model with respect to the new pose. For doing so, the library ZMQ (ZeroMQ) is used to open up a TCP connection to Unity. ZMQ transfers strings over a network or within a single computer system to any subscribed process. Therefore, we converted the coordinates to string type and ZMQ sends them to localhost since Unity runs on the same graphics PC. However, any IP address can be specified and used by ZMQ. This allows for maximum flexibility if, at a later stage of the project, it will be decided to run the tracking application on a separate machine. As soon as the coordinates are received by the subscriber service of Unity, a script is needed to convert the string data back into a floating point translation and orientation data stream of the arm shell. With the help of this it is possible to update the orientation and position of the virtual prosthesis model represented by a game object in Unity. Since we are importing the tracking data 1:1, the alignment is automatically done and the prosthesis model is located at the same position as the user's arm shell. Hence we are ready to practice controlling the arm prosthesis model which itself follows each movement of the user's remaining arm stump.Figure 3 provides an overview of the software architecture of the project.

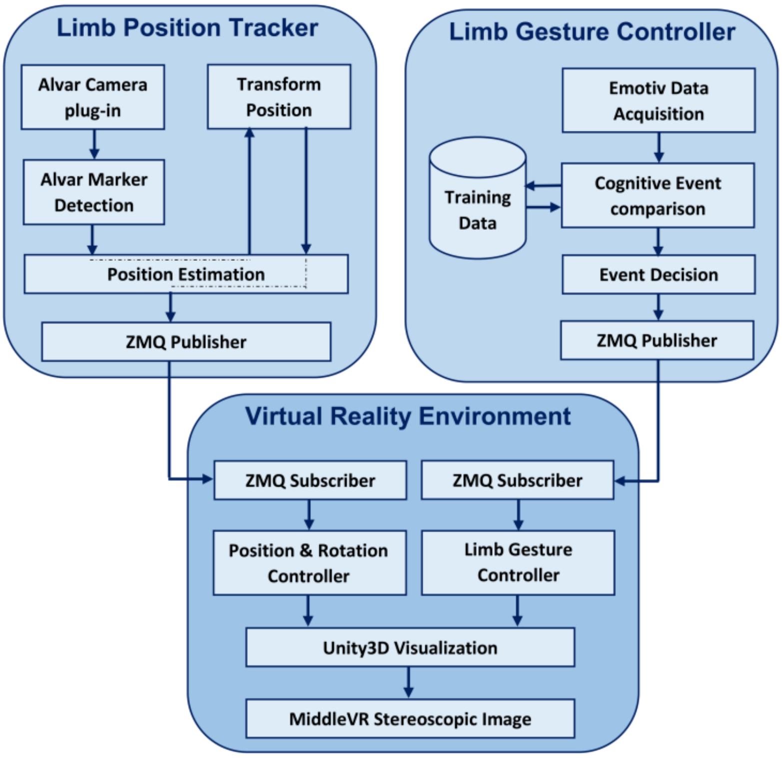

Figure 3. *The Software architecture of the simulator.*

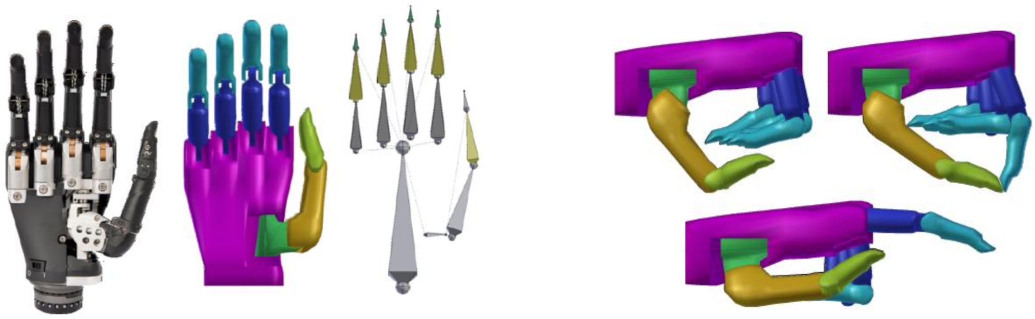

Figure 4. *From right to left, a real prosthesis (i-limb ultra from TouchBionic), a virtual prosthesis model and a kinematic chain created in Blender are shown. Each of the five fingers has got two limbs only. The kinematic model was also created in Blender (left part of the image). The right part of the figure shows the gestures being allowed. These are pointing and two different types of grasping. These gestures can be triggered by using the Emotiv EPOC brain computer interface.*

Proc. 10th Intl Conf. Disability, Virtual Reality & Associated Technologies
Gothenburg, Sweden, 2–4 Sept. 2014
©2014 ICDVRAT; ISBN 978-0-7049-1546-6

The virtual prosthesis itself, being modelled in Blender, consists of five two-limbed fingers and a palm of the hand as shown in figure 4. All fingers can be moved separately up to a certain degree since an underlying kinematics model was added in Blender that ensures no child segment can be moved independently from its parents. However, in a first version of the project we did not intend to allow for entire prosthesis control. Instead we implemented animation sequences for grasping and pointing gestures which can be triggered by the user wearing a BCI (brain computer interface) from Emotiv *(*Emotiv, 2013*)* (see figure 4).

The Limb gesture controller is the component that is responsible for the data acquisition from the BCI sensors. It compares the sensor data with training data. Each user was trained to generate at least 4 events (left/right smirk, rise brow and pushing tooth) by using facial expressions. While the output of the Emotiv SDK is an integer in the range from 0 to 100 and also is changing due to other events because of false-positive event decisions, an exponential moving average method was applied to solve this issue. At the end, the selected events are sent over the ZMQ socket to Unity.

4. SYSTEM EVALUATION

In order to evaluate a prosthesis training system, the participants are divided into three groups. The first group uses the actual hardware, the second group uses a remotely controlled training system and the third group uses the proposed training system. While the training takes place, all participants should perform a test to check their performance from start to end of the test period. Then the results of all three groups can be compared to each other. Since the aim of this project is to improve the naturalness of the interaction in the training environment and no individual disabled from upper limb was accessible, we focused on the evaluation of the naturalness of the interaction. In this regard, two test scenarios have been developed, one for model alignment and the other for depth perception.

4.1 Alignment Test

The objective of the alignment test is to find out how the limb model aligns with the remaining physical limb from user perspective while the user interacts with the environment. For this purpose, the following scenario was developed in order to test the alignment:

- The limb model will appear in the pointing gesture.
- 9 targets will appear sequentially in different predefined positions, each one two times.
- The user should point onto the target and shoot a virtual laser beam from index finger through target.
- A proper facial event (smile event) will be used to generate a trigger for shooting the laser beam.
- The laser beam will be visible for 0.2 seconds, which helps the user to correct the model orientation.
- The transformation of the limb model and the target will be used to calculate an error ratio of alignment by the angle between laser beam and the targets.

Table 1. *Target appearance order during the alignment test.*

Target number	1	2	3	4	5	6	7	8	9
Target appearance order	1-9	5-13	3-10	7-15	4-11	14-18	2-6	8-16	12-17

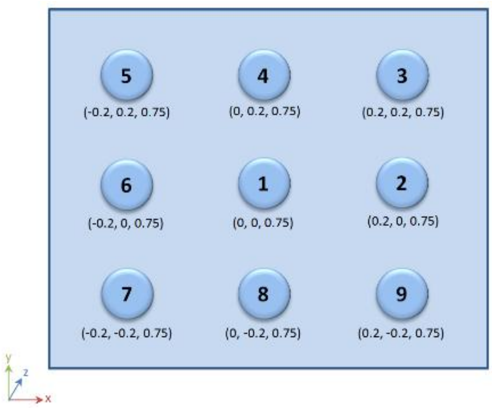

Figure 5. *The targets' numbering and their position relative to Unity3D left hand coordinate system.*

4.2 Alignment Evaluation

The number of participants for this test was 15. The maximum angle illusion is 7.65 degree for target number 2, and the minimum angle illusion 3.97 degree for target number 7. The general observation shows that the targets in the upper right corner have smaller angle illusion whereas the targets in the lower left corner have a larger angle illusion, as shown in figure 7. Considering the point that all participants were right handed, one may conclude that it becomes harder to point correctly to the targets on left side where the eye direction moves away from the limb model. The main issue that has been reported from all participants is that, without having control over the wrist, it is difficult to correct the orientation of the limb when displayed on the lower part of the display.

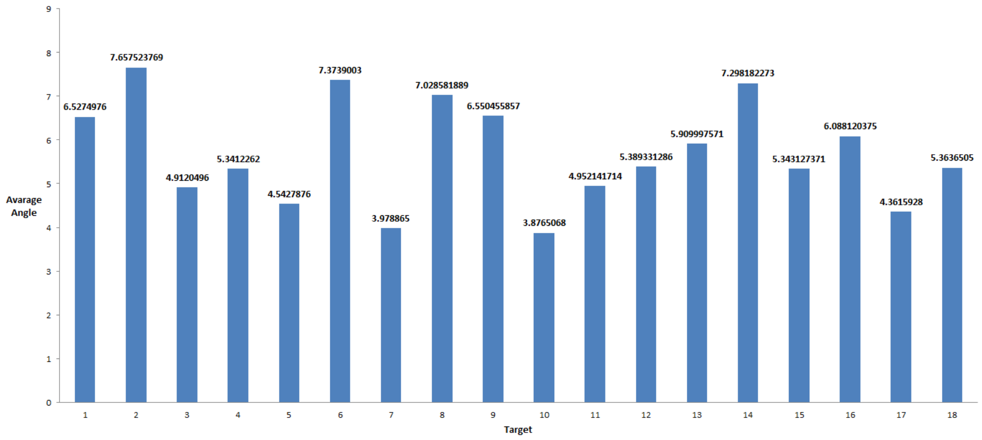

Figure 6. *Total average of the angle illusions for each target in each appearance.*

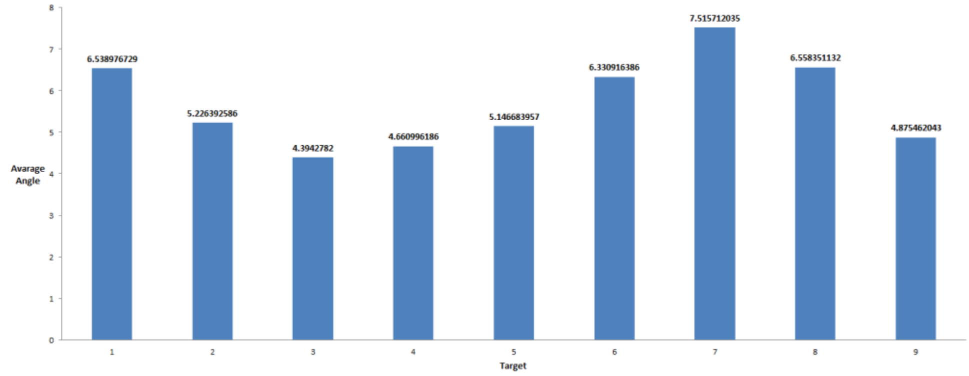

Figure 7. *Total average of the angle illusions for each target.*

Another problem that has manifested itself during the tests, were the fixed position and the orientation of the camera used for rendering. While moving and pointing with the limb model, the users moved body and head, and also rotated their eyes. Since the camera transformation was fix and no tracking was applied to head position and eye orientation, the targets' appearance became increasingly unnatural according to the change in head position and eye orientation.

4.3 Depth Test

The objective of the depth test is to evaluate the aim accuracy for objects in different depths from the user perspective in the training environment. In order to apply this test, the following scenario is created and applied:

- The limb model appears in idle gesture.
- A table with 6 buttons was designed in Blender (a free 3D modelling and animation toolkit) and exported to the Unity3d environment.
- The first button B is an activation button, which is positioned in the center of display and in the nearest depth from the user perspective.
- The other 5 buttons are the targets that will show up in a pre-defined sequential order, each one after the activation button was pressed. They are positioned from left to right by 30 degrees relative to the activation button as shown in figure 8.

- The time between activation and all target hit attempts is recorded.
- The number of failed hit attempts for each target is counted.

Table 2 shows the appearance order of all targets. The user must hit the activation button B after which (according to table 2) the target will show up and the activation button will disappear. After a successful hit, the target will disappear and the activation button will appear again. This procedure continues 3 times for each target until the last target is hit.

Table 2. *The target buttons' appearance order during depth estimation test.*

Target number	1	2	3	4	5
Target appearance order	2-6-12	5-9-14	3-8-15	1-10-13	4-7-11

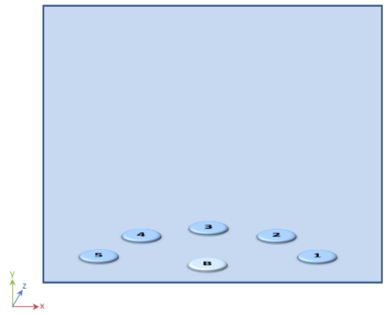

Figure 8. *The target buttons numbering and their position relative to Unity3D left hand coordinate.*

4.4 Depth Evaluation

The test was applied to 15 participants and the result that can be concluded from the test data is almost the same as from the alignment test. The maximum average time before a hit was found for target number 3 with 1.72s. The minimum average time was found for target number 2 with 1.15s, as shown in figures 9 and 10. While it seems obvious from the experimental data that target 3 seems to be most difficult to hit (indicated by the maximum delay time for a hit and the maximum number of misses - see table 3), this finding is not easy to interpret. It might as well result from a perspective issue related to the lower left display region as from a depth estimation problem.

Table 3. *The number of missed hit attempts during depth estimation.*

Target number	1	2	3	4	5
Number of misses	3	0	5	3	2

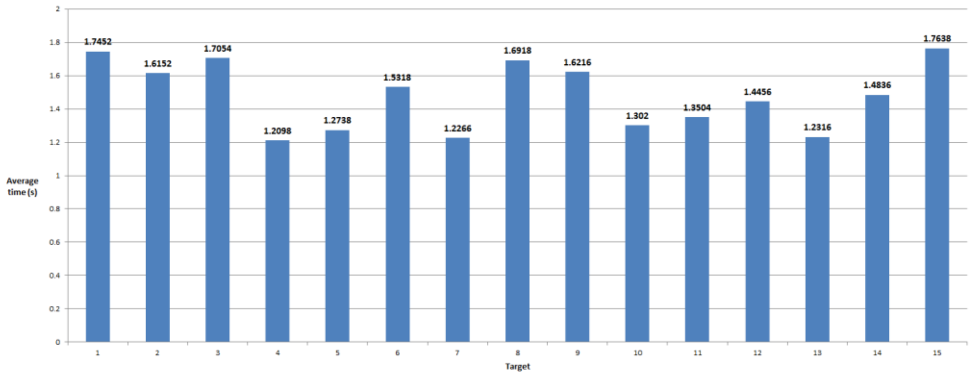

Figure 9. *The average time of each hit action for all target appearances.*

Another important issue that has been observed during depth testing was a significant tracking delay. The marker tracking is a standalone application which sends much less position and orientation data per second over the socket, than data is sent from the tracking component to the visualization component which itself renders at a high frame rate. This is the reason for a clearly observable visualization delay in case of fast limb movements.

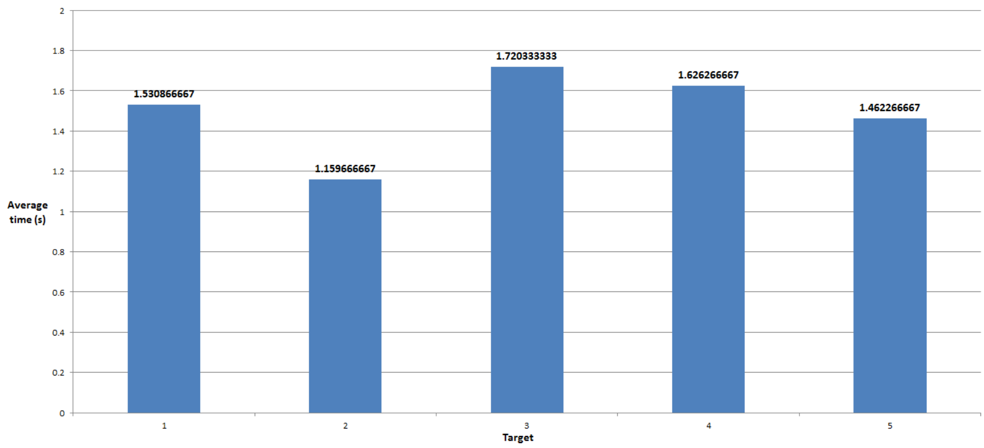

Figure 10. *The total average time of the hit action for all targets.*

6. CONCLUSIONS

With the help of the setup described in section 4, a system was implemented that allows for displaying arm prostheses in a virtual environment being aligned with the remaining arm stump of a user. Hence the technological basis was created for further implementations such as learning tutorials that will potentially support the learning of how to control the prosthesis. It is evident that the quality of that VR training system has to be evaluated by real patients prior to draw important conclusions about the system's usability aspects. However, while working with the system during initial usability tests with healthy users, first feedback was provided.

The first feedback about the system concerned the display system. Even though the frame of the L-shaped workbench display system is made of high-quality welded aluminium profiles (compare figure 1), it was not resistant enough to bending and distortion. The reason for that were recesses impairing the stability. Hence the authors decided to additionally add front and side walls made of reinforced steel profiles. The second feedback about the system concerned the camera tracking. Obviously the camera tracking shows a few real disadvantages such as the constant need for calibration, the need for high camera resolution due to the required high accuracy of the alignment as well as the steep visibility angle, since the camera needs to be mounted on the top of the display frame. Hence, for the future, the authors decided for using a Leap 3D motion controller from the company LeapMotion Inc.. The potential improvements with that tracking device are simply that fiducial makers are not needed anymore and the tracker itself can be easily placed at the bottom side of the display system looking upwards to the remaining arm stump of the user.

As already mentioned, future work will deal with the implementation of electromyographic control. This includes the crucial signal processing algorithms as well as interfacing with the control unit of the prosthesis itself. Furthermore autodidactic learning tutorials will be added. At the moment when this paper is written the authors intend to implement, add and display animated sequences of hand gestures that the user tries to copy. The idea is such that an automatic feedback mode will provide information about the quality of the copied gesture as well as some key performance indicators such as for example time on task. Using Unity 3D as the visualisation platform allows for adding virtual, graspable objects to the virtual scene and rendering the accompanying collision recognition and collision control of the virtual objects with the virtual hand prosthesis. Hence the authors assume that this will significantly improve the psychological acceptance of the virtual prosthesis by the user as well as allow for better control.

Acknowledgements: This work has been supported financially by the Institute of Visual Computing at Bonn-Rhein-Sieg University of Applied Sciences. The authors also would like to acknowledge the project cooperation partner from the Laboratory of Biomedical Engineering at the Federal University of Uberlandia, Brazil for their great input and system evaluation.

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