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REZUMAT TEZĂ DE DOCTORAT

A system for Neuromotor Rehabilitation using Virtual Reality

Sistem pentru reabilitarea neuromotorie folosind realitatea virtuală

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1 Introduction

1.1 Motivation

As medicine evolves, more solutions are found for various diseases. From vaccines that prevent disease, to new treatments and surgeries, the medical world is finding new ways of prolonging the lives of the human population.

Worldwide, according to a statistic of the World Health Organization (WHO)[1], approximately 15 million persons suffer a stroke each year, out of which approximately 5 million lose their lives, while other 5 million remain with permanent disability.

Technology can potentially assist the rehabilitation of physically disabled patients, and one very promising field in that aspect is Virtual Reality (VR). According to Burdea and Coiffet [1], Virtual Reality can be defined as a realistic-looking environment simulated through computer graphics, with which the user can interact in real-time.

This research was part of an extensive national project, TRAVEE (Virtual Therapist with Augmented Feedback for Neuromotor Recovery) that implemented a state-of-the art system dedicated to assisting the neuromotor rehabilitation process. The system creates a Virtual Environment (VE) - in which the patients are immersed - and tracks multimodal data: the movements of the patient, Electroencephalography (EEG) data, Electromyography (EMG). The system then analyzes the multimodal data and, based on this analysis, provides multimodal feedback: visual (visually augmented feedback), haptic (through vibrating motors), robotic (using a robotic glove), or electric - through Functional Electrical Stimulation (FES). This thesis presents my contributions to the TRAVEE project, focused around the functionalities of the Virtual Reality Central System component - the central server of the application - responsible with the main logic of the system and controlling the visual, robotic and haptic augmentation, as well as implementation of several functioning modes, specific for various types of input data and feedback methods. The research also included in-vivo and clinical testing of the implemented components. The testing results gave us a feedback of the patients involved and also a qualitative measure of the system efficiency.

Goals of the research

The goals of the research were to contribute to the implementation of several modules, mainly the Virtual Reality Central System that had multiple attributions: creating the VE in which the patients are immersed and are guided by the Virtual Therapist (VT), serving as the server of the system, that intermediates the communication between all the components while also implementing the main logic of the application and multiple functioning modes – depending on the used input and outputted feedback. The main original idea of TRAVEE – to which I also contributed in implementing – was that of visually augmented feedback. This is currently pending for patent under the title “System, method and computer program for augmenting human movements”.

All the goals of the research were fulfilled, the system was delivered according to the schedule and it successfully passed all the testing phases. The results of the testing phases were a promising feedback received from the patients and led to the discovery of several further research directions that must be studied as they could potentially have a significant impact in the evolution of the VR-based rehabilitation field.

[1] The world health report 2002 - Reducing Risks, Promoting Healthy Life. http://www.who.int/whr/2002/en/. Last Accessed June 2017.

1.2 The author's scientific publications in connection with the thesis

Papers published in conference proceedings

1. *<u>O-M. Ferche</u>, A. Moldoveanu, F. Moldoveanu, V. Asavei, A. Voinea, I. Negoi*, Challenges and Issues for Successfully Applying Virtual Reality in Medical rehabilitation. Proceedings of the International Scientific Conference on eLearning and Software for Education (eLSE), Bucharest, April 2015, vol. 1, pg. 494-501. WOS:000384469000073
2. *A.Voinea, A. Moldoveanu, F. Moldoveanu, <u>O. Ferche</u>*, ICT Supported Learning for Neuromotor Rehabilitation - Achievements, Issues and Trends, eLSE International Scientific Conference on eLearning and Software for Education, April 2015, vol. 1, pg. 594-601. WOS:000384469000086
3. *<u>O. Ferche</u>, A. Moldoveanu, D. Cinteza, C. Toader, F. Moldoveanu, A. Voinea, C. Taslitchi*, From Neuromotor Command to Feedback: a Survey of Techniques for Rehabilitation through Altered Perception, EHB International Conference on e-Health and Bioengineering, November 2015. WOS:00038039790010
4. *A.Voinea, A. Moldoveanu, F. Moldoveanu, <u>O. Ferche</u>*, Motion Detection and Rendering for Upper Limb Post-Stroke Rehabilitation, Proceedings of the 5th IEEE International Conference on E-Health and Bioengineering - EHB 2015, pg. 811-814. Iasi, Nov. 2015, Print ISBN:978-1-4673-7544-3, WOS:000380397900124.
5. *<u>O. Ferche</u>, A. Moldoveanu, M. Dascalu, C-N. Bodea, R. Lupu, D. Irimia, F. Moldoveanu*. The TRAVEE neuromotor rehabilitation system: In-vivo testing. ZINC, Zooming Innovation in Consumer Electronics International Conference, vol. 1, pg. 30-33, 2017. ISBN: 978-1-5386-0865-4. WOS:000392785700165
6. *<u>O. Ferche</u>, A. Moldoveanu, F. Moldoveanu*. The TRAVEE system for neuromotor recovery: Architecture and implementation. EHB E-Health and Bioengineering Conference, pg. 575-578, 2017. ISBN: 978-1-5386-0358-1. (IEEE) DOI: 10.1109/ZINC.2017.7968655.
7. *RG. Lupu, P. Herghelegiu, N. Botezatu, A. Moldoveanu, <u>O. Ferche</u>, C. Ilie, AM. Levinta.* Virtual Reality System for Stroke Recovery for Upper Limbs Using ArUco Markers. 21st International Conference On System Theory, Control And Computing (ICSTCC), vol. 1, pg. 548-552, Sinaia, Romania, 2017. (IEEE) DOI**:** 10.1109/ICSTCC.2017.8107092, WOS:000427419900090

Unpublished papers presented at conferences

1. *<u>O. Ferche</u>, A. Moldoveanu, F. Moldoveanu*, Brain Computer Interfaces for Neuromotor Recovery –Achievements, Issues, Trends. WPA 2015 Bucharest International Congress. June 2015
2. *<u>O. Ferche</u>, A. Moldoveanu, F. Moldoveanu, V. Asavei,* A Survey of Motion Tracking in Automated Neuromotor Rehabilitation after Stroke. WPA 2015 Bucharest International Congress. June 2015.
3. *<u>O. Ferche</u>, A. Moldoveanu, F. Moldoveanu*, An up to date survey of assistive technologies for neuro-motor rehabilitation using Virtual Reality. SpeD International Conference Speech Technology and Human-Computer Dialogue, October 2015.

Papers published in journals

1. *<u>O-M. Ferche</u>, A. Moldoveanu, F. Moldoveanu, M-I. Dascalu, R-G. Lupu, C-N. Bodea*. Deep Understanding of Augmented Feedback and Associated Cortical Activations, For Efficient Virtual Reality Based Neuromotor Rehabilitation, Revue roumain des sciences techniques, Série Électrotechnique et Énergétique, 2018, issue 2, pg. 233-239. (Impact Factor = 1.114) WOS:000428622400006

2. <u>O. Ferche</u>, *A. Moldoveanu, F. Moldoveanu*, Evaluating Lightweight Optical Hand Tracking for Virtual Reality Rehabilitation, Revista Română de Interacţiune Om-Calculator, 2016, vol. 9, no. 2, pg. 85-102. DOI: 10.5171/2017.155350
3. *C.A. Boiangiu, M. Zaharescu,* <u>O. Ferche</u>, *A. Danescu*, Automatic Correction of OCR Results Using Similarity Detection for Words and Fonts, International Journal of Applied Mathematics and Informatics. 2016, vol. 10, pg. 10-18.

Books

A. Moldoveanu, F. Moldoveanu, M-I. Dascălu, A. Ioniţă, <u>O-M. Ferche</u>, V. Asavei, A. Morar, UML Practic, Matrix Rom, 2014.

A. Moldoveanu, F. Moldoveanu, O. Balan, <u>O-M. Ferche</u>, TRAVEE - Raportare la Stadiul Actual al Domeniului. Abordare si Obiective Generale. Chapter in TRAVEE - studiu de caz - initierea unei cercetari ICT in recuperarea neuromotorie, volum colectiv editat de Alin Moldoveanu, Printech, 2014.

Prizes and awards

Distinguished Paper. <u>O. Ferche</u>, *A. Moldoveanu, M. Dascalu, C-N. Bodea, R. Lupu, D. Irimia, F. Moldoveanu*. The TRAVEE neuromotor rehabilitation system: In-vivo testing. ZINC Zooming Innovation in Consumer Electronics International Conference, 2017.

Annual BCI award 2018 nomination. Neuromotor Recovery based on BCI, FES, Virtual Reality and Augmented feedback for upper limbs. Robert Gabriel Lupu, Florina Ungureanu, Oana Ferche, Alin Moldoveanu. Awarded by BCI Award Foundation, Stanford University.

Research projects

TRAVEE – Virtual Therapist through Augmented Feedback for Neuromotor Recovery. National project, PN-II, ID. 1/2014(PN-II-PT-PCCA-2013-4-1580), 2014 – 2017

1.3 Thesis structure

The thesis is composed of 11 chapters. It begins with a first chapter presenting the motivation for my work during the doctoral studies as well as the resulting scientific publications. The second chapter briefly presents some details regarding the biology of cerebrovascular accidents and the hypotheses regarding cortical reorganization that support the potential of the ideas behind the thesis. Chapter 3 presents a survey regarding the use of Virtual Reality technology in the rehabilitation processes and the issues that may arise from it. Chapter 4 contains a survey of existing work in the field of rehabilitation through altering the perception of the patient. Chapter 5 analyzes existing rehabilitation solutions developed with various commercially available technologies. The thesis continues with a brief presentation of the TRAVEE project in Chapter 6, containing overviews of the functionality available for the patient and the therapist, the description of the rehabilitation movements included by TRAVEE as well as an overview of the system architecture. Chapter 7 presents my contributions to the TRAVEE system regarding the evaluation of available technologies for motion tracking and brain computer interfaces. Chapter 8 contains a presentation of my contributions to the implementation of the TRAVEE functionality. In chapter 9 I describe the results of the two in-vivo testing sessions with the initial prototype of the TRAVEE system, while chapter 10 presents the results obtained from the clinical trial with the final prototype.

2 Stroke

According to information available on the *National Stroke Association* page[2], stroke is a disease of a region of the brain that appears as a result of an interruption of the blood stream towards it. Blood is responsible – among others – with transporting the oxygen necessary for cellular life towards the tissues in the body. If a region of the brain is deprived of the blood flow for a certain amount of time, the neurons in the respective region die, and with them, disappears – partially or totally – the set of abilities controlled by that region.

Depending on the cause that lead to the interruption in the brain blood flow to the affected brain area, stroke can be *hemorrhagic*, *ischemic* or *transient*.

Studies such as the one made by Schaechter et. al. [2] reveal the possibility of rehabilitation of patients that have lost the abilities associated to a certain area of the brain due to disease, through a process named *cortical reorganization*. This process is using the plasticity of the cortex and represents the possibility that new neural paths are built in order for the regions of the brain that are adjacent to the affected one to overtake its attributions, basically the patient re-learning the lost abilities.

For re-learning lost abilities, there were studies that revealed the potential of Virtual Reality to support this process by creating realistic visualizations to simulate lost abilities. A study regarding this subject was published in [3] and studied the available literature regarding the role played by fooling the brain through additional visual and motor feedback in the process of creating alternative neural pathways in rehabilitation.

3 Virtual Reality in Rehabilitation

Parts of this chapter have been presented at the 11th eLearning and Software for Education Conference (eLSE 2015) that took place in Bucharest, 23-24 April 2015 [17], or at the 8th International Conference on Speech Technology and Human-Computer Dialogue, October 2015 [7] (unpublished).

Physical rehabilitation is a branch of medicine that is dedicated to helping the patient re-learn behaviors and gestures that were lost because of an accident or disease. This often proves to be an overwhelming task for the patient and for the clinician. Many repetitions of the same movement may be necessary until it is re-learned and can be executed independently. This is one of the many reasons why technology and particularly Virtual Reality could be a major help in assisting the medical rehabilitation sessions: a VR environment could present the patients with an example of the correct movement that they have to execute, as well as create an interesting environment that would motivate them to continue the session without getting psychically tired or lose focus.

Studies made in the last few decades have proven that virtual reality enhanced rehabilitation sessions are more efficient than non-immersive ones [5]. Together with telemedicine (providing medical assistance from distance through technology), VR has the potential to deliver therapy services to patients in rural settings or therapy at home [4] for patients that would otherwise not be able to access these services. A comprehensive study of VR worlds is the one made by Moldoveanu et. al. [6].

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[2] National Stroke Association. Hope after stroke. „Understand stroke." http://www.stroke.org/understand-stroke/what-stroke. Last Accessed June 2017.

Although VR seems to be an enormous potential to the rehabilitation process, VR technology developers need to consider the potential issues that can arise from implementing technology for a medical field especially where disabled people are the targeted users. These problems are presented infthe following paragraphs.

Accommodation

The first issue with using VR for medical rehabilitation is that it needs a greater time for the patient to accommodate to the virtual reality that is very probably quite different from the reality the patient is accustomed to.

Transferring performance

One key issue with VR rehabilitation is pointed out by Holden et. al. [8] and refers to the transfer of the performance obtained in the virtual reality into the real world. In this article it is stated that many studies examine learning in a virtual environment but do not asses the degree in which the achievements from the virtual world can be used in the real world, as the two are not equivalent and the discrepancies between them may affect the rehabilitation sessions in a negative way.

Maintaining motivation

Although maintaining motivation seems to be one of the advantages of using VR enhanced rehabilitation solutions, the designers of such systems must take into consideration the fact that simply providing a virtual teacher that the patient must try to imitate is not sufficient. A regular rehabilitation session - assisted by a clinician - counts on the observation of the therapist for adjusting the performed exercises.

User interfaces

Another drawback of using VR in rehabilitation is that the existing user-interfaces [9] are not yet very user-friendly, especially for impaired users. Navigating through a VR is usually made using a joystick, a keyboard or a wand, but as these may be easy to use for the non-impaired, they may impose problems on the patient recovering from a stroke.

Usability

Another aspect that is also related to the user interfaces is that the system needs to be as easy to use as possible. This is especially difficult as the rehabilitation process is a very complex one, many parameters need to be taken into consideration, and it also needs to provide a variety of functionality and difficulty levels to adapt to the real sessions, therefore obtaining these results through a very simple graphical interface is a considerable effort.

Supervision

Even though VR rehabilitation systems have the potential to be used in a stand-alone at home environment, because they are still a relatively newly researched field, supervision by a medical professional with technical expertise is still advised thus affecting the advantage of at-home rehabilitation.

Device compatibility

VR rehabilitation is still a newly emerging field and a VR system for the disabled is a complex one, that generally includes at least a motion tracking system or another user input device, display and sound equipment, cameras, various vital parameters monitoring systems, or even a Brain Computer Interface (BCI) all connected and able to transmit information to a central system, for the rehabilitation session to take place safely and with the best results. Each of these components has its own interface, and standardization has not yet been achieved, thus the engineering effort of developing such a system.

Costs

There are two economic issues that must be taken into consideration: the profitability for the developer of VR rehabilitation systems and the cost for the end user.

As it is a challenge to estimate the costs of such a system, many are discouraged to tackle developing this kind of product.

Ethical issues

Ethical issues [11] must also be taken into consideration when using Virtual Reality in rehabilitation: the patients must be able to accept the virtual environment and to understand the immersion process in order to guard them from any emotional distress, and the patients must be asked to inform the therapist immediately if they feel discomfort or side effects.

Side effects

Holden et. al. [8] state that there seem to be no reports of negative side-effects from using a desktop version of a virtual reality system, and most of them are associated to immersive technologies created usually with head mounted displays. The possible side effects of the virtual reality therapy must be explained to the patient and to its tutors previously to starting the sessions and the therapy must be halted if any of them are present.

Legal issues

The legal issues that must be taken into consideration regard the currently applicable laws in the field of personal information, confidentiality, medicine and rehabilitation in the country where the system is used. Some of these issues generally concern [11]: informed consent, standard procedures (the clinician must also follow the standard procedure of the rehabilitation process when using Virtual Reality, the purpose of the technological system is to enhance the session, not to alter its fundaments), emergencies (the procedure in case of emergency must be very well established).

4 Rehabilitation through altering perception

Parts of the contents of this chapter were published at the EHB 2015 conference [3]. This paper studied the available literature regarding the possibility of “fooling” the brain by providing augmented feedback to detected motor actions or commands, thus possibly stimulating the cortical reorganization process, the brain associating the perceived (augmented) result with the performed efforts. The research included here were selected to contain the presentation of real tests, to describe the used system, and to focus on the rehabilitation of the upper limb, to evaluate the validity behind the TRAVEE system.

The augmented feedback in the TRAVEE system consists in presenting the movements of the patients in an augmented manner, to be more easily observed and to encourage the patients to continue their rehabilitation efforts. The methods used by the system to provide multimodal feedback are numerous: visual augmentation (increasing the movement amplitude), haptic (through vibrating motors that provide tactile feedback on certain key-points of the exercised limb), functional electrical stimulation (FES) and motor assistance through a robotic glove.

4.1 Virtual Reality Box

A classical rehabilitation method that uses visual augmentation is mirror therapy [12], that uses a mirror placed vertically in front of the patient in the sagittal plane, in such a manner that the movements performed by the healthy hand and arm are perceived as being performed simultaneously by the disabled one, as can be seen in Fig. 4-1. This technique was first introduced by Ramachandran et al. [12] where it was successfully used to eliminate or reduce the pain in phantom limbs of amputees of the upper limb. Such experiments suggest the utility of a virtual feedback in rehabilitation.

Fig. 4-1 Mirror therapy [13]

The technique was named "mirror box" as not only a mirror was used, but a box with a mirror placed as described, so that the patients would place the stump of the missing limb inside the box, hiding it from their sight, in order for the visual effect of the existing, functional limb placed inside the box to be achieved.

4.2 Functional Electrical Stimulation

Moseley and Flor [14] tested the hypothesis that chronic pain in a phantom limb can be relieved by stimulation in a functional context. This presumption was tested on upper limb amputees by applying electrical stimuli with various frequencies on the stump and training them to distinguish between them. The subjects were divided into a test group and a control group. The test group received the described treatment for 10 days, 90 minutes per day. After the final evaluation, it was observed that the test group reported decrease in phantom limb pain by more than 60%, the performance and tactile acuity improved, and in some cases, cortical reorganization reverted (certain areas of the brain regained their normal functions).

4.3 Augmented Reality

Regenbrecht et. al. [15] present a system designed to explore the benefits that come from fooling the brain into thinking that a movement was better than it actually was (such as amplifying a small movement). The study also validates a system, Augmented Reflection Technology (ART) that provides an augmented reality environment dedicated to support neuromotor recovery in stroke patients. The ART system consists of two cardboard boxes with curtains, lighting and web cameras, as well as a monitor with a keyboard and mouse for an operator to control the rehabilitation session. The patients place their hands inside the boxes and only see them on a screen; the images that appear to the patients are mediated by the system and the operator – thus allowing them to be controlled in various ways.

4.4 Virtual Reality

Feintuch et. al. [16] present and evaluate VirHab, a system that employs a motion capture system in order to process the image of the patients that see themselved in a virtual reality where small movements of the paretic arm are represented as full range ones of a healthy limb. The main purpose of the system is to accelerate the plastic recovery of the brain in order to treat chronic pain generated by conditions such as cerebrovascular accidents, traumatic brain injury or complex regional pain syndrome.

4.5 Conclusions

All of the analyzed systems and experiments were able to generate an improvement in the condition of the subjects by creating an altered visual feedback – either by using a mirror or a virtual or augmented environment. These findings are in accordance to the ideas that were implemented in the TRAVEE system: augmenting the feedback based on detected progress is highly probable to actually fool the brain into thinking the movements are real, thus supporting the process of relearning neural behaviors as well as increasing the motivation of the patients, as observable progress is most likely to be found encouraging.

5 Rehabilitation solutions with commercially available hardware

In this chapter we discuss about several hardware devices that are affordable and may be used for at-home motor rehabilitation. For each identified device, one or more rehabilitation experiments that use the device are described.

Microsoft Kinect
Cho et. al. [18] present a virtual version of the classical test, a Virtual Box and Block game, developed in the Unity game engine. The conclusions of the experiment taken on 9 stroke patients with an age average of 67 ±8 years found correlations between the scores obtained in the BBT and in the VBBT but the scores in the virtual environment were found to be significantly lower, the authors concluding that this fact could be related to the interaction with the virtual reality.

WiiFit
Yeh et. al. [19] describe a VR system designed for vestibular rehabilitation. The system contains two subsystems: a training and an assessment system. The assessment system consists of a WiiFit used to determine the center of gravity of the patient in real time in order to observe the changes during the training. Over 50% of the 17 patients recorded progress in terms of evaluating balances indexes as a result of the training sessions.

ioTracker
Schonauer et. al. [20] evaluated a system dedicated to chronic pain rehabilitation through serious games. The hardware setup includes a professional passive marker based infrared optical motion capture system (iotracker [21]) that calculates the 3D position from images taken by several cameras.

The six patients with chronic pain involved in the testing of the system reported a decrease in pain level (from 62 to 52 on a Visual Analog Scale of pain – a variation equal to or greater than 13 is stated to be clinically relevant) after four weeks of gaming

Qualisys
Ustinova et. al. [22] present the testing of the results obtained through short term practice with a 3D immersive video game (Octopus) for patients with traumatic brain injury (TBI). The system consisted of a

PC integrated with a 6-camera system for motion tracking (Qualysis AB, Gothenburg, Sweden) using three markers attached to each hand.

Six participants with mild-to-moderate TBI were involved in the experiment. All participants recorded improvements in game score during the sessions. After completion of the session, five out of the six participants displayed improved reaching distance.

Playstation and EyeToy

Sandlund et. al. [23] evaluated the efficiency of a low-cost at-home game-based rehabilitation system for children suffering from cerebral palsy (CP). The proposed solution consists of a Sony PlayStation2 equipped with the game EyeToy Play 3. The fifteen children involved in the experiment, aged 6-16, were asked to play the EyeToy game for 20 minutes per day during the four weeks intervention period, and were evaluated before and after this trial period. For the evaluation, the kinematics were captured using five camera analysis system (Proreflex, Qualisys AB, Gothenburg, Sweden) that uses infrared light and 27 markers. The data was recorded in two different conditions: virtual – when the children played the EyeToy game – and real – while they were performing a non-exercised real-world task, reaching for real objects.

The results of the experiment showed decreased peak velocity in both scenarios. The smoothness of the movements was increased in real-world tasks without differences in the virtual world, while movement precision improved in the virtual world without affecting the real-world tasks.

Myo armband

Lipovsky et. al. [24] described an experiment with a proof-of-concept system designed at the University of Lisbon that is dedicated to hand rehabilitation using video games – named “hand therapist”. The system consists of a Myo armband, a home-made robotic glove and the Unity 3D engine for game development.

The system has only been tested with healthy subjects so far, but it shows great potential for a low cost (under 500 euros) rehabilitation system.

Head Mounted Display

The Head Mounted Display is a device that – when placed on the head of the user – has two small monitor screens, one in front of each of the user’s eyes, thus it can provide a convincing 3D sensation and a great degree of immersion for virtual environments. The HMDs are not necessarily a good option for VR- based rehabilitation systems because they are usually not comfortable – especially for a disabled patient who is already in a distressed state of mind.

Gamito et. al. [25] present a research regarding cognitive recovery of memory and attention deficits for patients following stroke by using a VR training program. Two patients with both deficits (memory and attention) as a consequence of an ischemic stroke were selected for the trials and were subjected to ten sessions of VR enhanced rehabilitation sessions using a system consisting of an eMagin Z800 Head Mounted Display[3] and a mouse for exploring the virtual environment. The results of the experiment showed significant improvement on both the WMS (from 37 to 45) as well as on the TP scale (from 65 to 107).

SeeMe

Sugarman et. al. [26] validated the feasibility of a Virtual Reality system for the treatment of unilateral spatial neglect (USN). The employed VR system is the SeeMe, a projected video capture system which does not require any specialized hardware, just a webcam and a computer and can be used while standing, moving or sitting. The subject involved in the experiment was a 66-year-old woman who had suffered a

[3] Products – eMagin. http://emagin.com/products/. Last accessed March 2018.

right hemisphere stroke 15 months previously. For the evaluation, the React task of the SeeMe system was used, which require the patient to touch a presented ball within a given amount of time and records the hits and the misses. At the end of the experiment the movement times decreased for both sides.

Data gloves
The 5DT Data Glove[4] (with a price estimated at $995) was used in the experiment described by Tunik et. al. [27] that studied whether mirror feedback in VR could stimulate ipsilesional cortex activation in chronic stroke patients. Tunik et. al. [27] replaced the mirror with a virtual environment in which the patients can see their hands from a first-person point of view.

The experiment involved five chronic stroke patients that were scanned using functional Magnetic Resonance Imaging (fMRI) while an MRI (Magnetic Resonance Imaging) compatible VR device recorded the movements of the healthy hand in order for the real time virtual reality to be updated accordingly. For data acquisition, an MRI compatible 5DT Data Glove 16 MRI (Fifth Dimension Technologies) was used, interfaced with a virtual environment developed with Virtools software. The study concludes that mirrored feedback in a VE can significantly activate the motor cortex of the lesioned hemisphere, activations that are clearly related to the presented visual effect.

Webcams
Borghese et. al. [28] tackled neglect rehabilitation with Virtual Reality using a low-cost system consisting of a personal computer (PC), a webcam and a projection system. Patients suffering from neglect disregard the side of their body that is opposite to the side of the brain that suffered a lesion

The experiments were performed on a 65 years old patient for a duration of one month, thirty minutes a day for five days a week. After the treatment, the patient showed improvement in his global cognitive function (Mini-Mental State Examination).

6 The TRAVEE Project

TRAVEE (Virtual Therapist with Augmented Feedback for Neuromotor Recovery) is a national PNCD-II project, aimed at developing an original system to help rehabilitation of the upper limb of patients with impairment because of brain damage, through stroke, trauma or other brain injuries.

The main original idea of TRAVEE is that of creating a system that provides augmented feedback to the patient to stimulate recovery through neuroplasticity. The purpose of the system is to help in fulfilling the *causal chain/loop* of recovery, consisting mainly of three steps:

1. The **attempt** of the patient to perform the desired movement;
2. The **observation** – by the patient – of the resulted effects;
3. The **association** of the observed effects with the efforts made in the first phase – this phase takes place at the level of the patient cortex and – in time, with repetition – may lead to the re-learning of the lost ability.

[4] 5DT | Training Simulators and Virtual Reality. http://www.5dt.com/

TRAVEE attempts to close this loop by providing additional feedback that reinforces the association phase. It also implements an innovative method of communication with the patient, through the Virtual Therapist – a virtual avatar that executes the movements that the patient needs to reproduce in the real world.

In order to fulfill its goals, TRAVEE uses several modern technologies:

- Virtual Reality for an improved immersion sensation,
- Optical tracking devices to follow the movements of the patient in real life,
- Brain-Computer Interface (BCI) through an Electroencephalography (EEG) helmet to detect intention of movement of the affected limb,
- Electromyography (EMG) to detect muscle activation in the limb,
- Functional Electrical Stimulation (FES) to artificially stimulate the muscle and perform the movements,
- Robotics – a robotic glove, part of another project at POLITEHNICA University of Bucharest (PUB) - project IHRG (Intelligent Haptic Robot Glove for Patients Suffering Cerebrovascular Accident), led by prof. Nirvana Popescu. This has the role of supporting mechanical movement when necessary,
- Haptic – vibrating motors attached to the exercised limb that provide feedback through vibrations.

In the following chapters are presented the contribution brought through this research to the TRAVEE system.

6.1 Functionality overview

The description presented in this chapter was also presented at the EHB IEEE Conference on e-Health and Bioengineering that took place on June 22nd-24th 2017 in Sinaia, Romania [34].

From a user's point of view, TRAVEE has two main components: one that is dedicated to the patient that undergoes the rehabilitation process after stroke, and one that is dedicated to the therapist – the clinician that guides the rehabilitation session.

The complex component dedicated to the patients involves devices and software that immerse them in a Virtual Environment to identify themselves with the presented avatar, as well as devices dedicated to supporting their movements and providing complex feedback during the exercises.

The component for the therapist is aimed mostly at providing intuitive tools for configuring the rehabilitation session composition and the devices used for each exercise, as well as to monitor the activity of the patient.

6.1.1 TRAVEE for the patient

The main features of the TRAVEE system are dedicated to the patient – the subject of the upper limb rehabilitation process. The patient is immersed in a Virtual Environment where there is an avatar (a 3D humanoid) representing the therapist, that exemplifies the movement that the patient needs to try to reproduce in the real environment, and a second avatar – viewed from a first-person point of view, representing the user – that mimics the real-life movements of the patient.

Fig. 6-1 The VE, the patient from a first-person point of view, with the therapist exemplifying the correct current movement

Other devices that the patients interact with are: the Oculus Rift[5] Head Mounted Display placed on their head, where they see all of the above; a robotic glove (IHRG project [35]) that supports the execution of certain movements and a Haptic device (whose hardware and software was developed at the "Gheorghe Asachi" Technical University of Iasi) that provides vibrations on certain key-points of the upper limb during each exercise, as a form of feedback.

To track the body of the patient, TRAVEE uses two low-cost devices [36]: Microsoft Kinect v2 for the movements of the shoulder and elbow joints, and Leap Motion[6] for the fine movements of the hand and fingers. Kinect v2 tracks up to 25 joints of the body. For our project, we used Kinect for tracking movements of the shoulder and of the elbow. Leap Motion provides tracking of the rotation of the elbow joint, palm joint, and for each phalange in the five fingers of both hands. We used Leap Motion for tracking of the rotations of the palm and for the movements of the fingers.

6.1.2 TRAVEE for the therapist

The TRAVEE functionalities dedicated to the therapist are related to patient and session configurations (patient profile, session content and length, selecting the devices used by each exercise and their configuration) and to session supervision, through graphs that represent in real time the essential parameters regarding the session.

The available exercises were selected by the doctors in the project consortium, to cover the most common rehabilitation exercises. These include the Finger Flexion-Extension, the Palm Flexion-Extension, the Forearm Flexion-Extension and the Arm Adduction-Abduction movements.

6.2 Rehabilitation movements

The rehabilitation movements implemented by the TRAVEE system were chosen by the doctors in the project consortium. The selected movements are:

Forearm Flexion-Extension

This movement exercises the elbow joint, requiring the patients to bring their forearm towards the anterior side of their upper arm, followed by the extension, that brings the forearm back on the direction of the upper arm.

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[5] Oculus DK2. https://www3.oculus.com/en-us/dk2/. Last accessed May 2017.

[6] Leap Motion Home Page. https://www.leapmotion.com/. Last accessed May 2016.

Forearm Pronation-Supination

This movement consists of a rotation of the palm around the axis of the forearm, clockwise and counterclockwise.

Palm Flexion-Extension

This movement exercises the wrist joint, by bringing the palm closer to the anterior side of the forearm, followed by the extension, that brings the palm closer to the posterior side of the forearm.

Fingers Flexion-Extension

This movement requires closing the palm, by flexing all the fingers, followed by the extension of the fingers.

Thumb Opposition

This movement exercises the thumb, consisting of successive flexions that bring the tip of the thumb finger towards the base of the pinky finger, followed by extensions of the thumb away from the palm.

Thumb Touches

These movements exercise the "pinch" movement, consisting of successive flexions of the thumb and one of the other four fingers, that bring the tip of the thumb finger to touch the tip of the opposing finger, followed by extensions that straighten the fingers.

Arm Abduction-Adduction

This movement requires that the arm is moved in a frontal plane, away from the body for abduction and towards the body for adduction.

Arm Anteduction-Retroduction

This movement also exercises the shoulder joint, consisting of a movement of the arm in a sagittal plane, away from the body for anteduction and towards the body for retroduction.

Shoulder Raise

This movement exercises the shoulder joint, consisting of successive movements of raising and lowering the shoulder.

6.3 TRAVEE architecture overview

This chapter presents briefly the architecture of the TRAVEE system. Parts of it were published in the proceedings of the 6th edition of the EHB IEEE Conference on e-Health and Bioengineering that took place on June 22nd-24th 2017 in Sinaia, Romania [34].

The preliminary architecture for the TRAVEE system was presented by Caraiman et.al. [37] but as the project evolved, the architecture was improved and updated to better fit the purpose of TRAVEE.

The figure below presents a simplified diagram of the main components and devices.

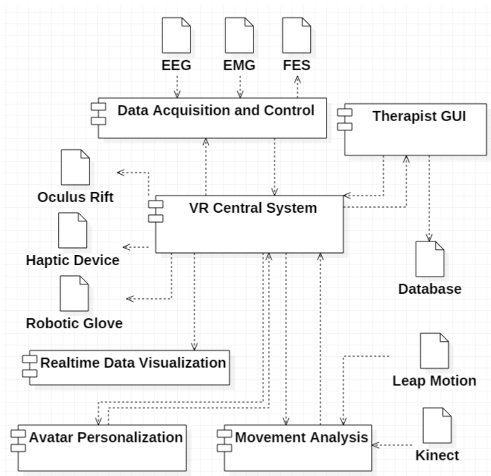

Fig. 6-2 TRAVEE architectural overview

As can be seen in the diagram, the system has one central component, the VR Central System, which communicates with the other two main components - Therapist GUI and Data Acquisition and Control components to ensure the correct functionality of TRAVEE.

The Data Acquisition and Control component

This component is in charge with taking data from the BCI (Brain Computer Interface – the EEG device) and the EMG sensors and controlling the FES device. This module receives commands from the Central System and provides data received from the controlled acquisition devices. It was implemented by the team at "Gheorghe Asachi" Technical University in Iași.

The Therapist GUI

The Therapist GUI (Graphical User Interface) is the control interface dedicated to the therapist. Here the therapist is able to add patients into the system, to define rehabilitation sessions as well as control the functionality of the entire system, through start, stop, pause type actions that are sent to the Central System. This component is also connected to a database, where it stores information regarding the patients, the defined sessions and the executions. This component was implemented by the OSF Global Services Bucharest project partner.

The VR Central system

The Central System is also named here VR Central System because it was implemented using the Unity game engine[7] that allows fast creation of VEs and is easily integrated with Oculus Rift. In Unity we used the C# language with the .NET framework[8] to write all the necessary scripts for the TRAVEE functionality. It was implemented at the POLITEHNICA University of Bucharest, and – apart from the Avatar personalization module, which was developed upon an existing solution – represents my original work.

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[7] Unity. https://unity3d.com/. Last accessed May 2017.
[8] .NET framework. https://msdn.microsoft.com/en-us/library/ z1zx9t92 .aspx. Last accessed May 2017.

It is the central component that connects all the components together, it communicates with the Therapist GUI, receiving the commands from the interface, it communicates with the Acquisition and Control system, sending commands for the controlled devices and receiving data to be sent to the Visualizations module. It also interacts with the Movement Analysis and the Avatar personalization modules and controls the Haptic device and the Robotic Glove.

Movement analysis

This component is in charge with analyzing the data taken from the motion trackers: the Kinect and the Leap Motion. Based on the calculations made in this module, the Central System decides taking actions such as providing any of the available forms of feedback.

The data taken from Leap Motion and Kinect consists of rotations for the joints involved in the movement: shoulder, elbow, palm, and for each phalange in the fingers. For each movement, we chose one or more joints that are of interest. On the joint of interest, we made an evaluation of the degree up to which the movement is performed based on one or more parameters (angles and distances). The system allows the users (therapists) to define a set of threshold values for these parameters (a degree of execution) up to which they consider the movement needs improvements. As long as the movement is evaluated to a degree of execution below the threshold, the patients see an improved version of their real movement.

Movement analysis is detailed in the dedicated chapter.

Real-time Data Visualization

This is a separate component with the purpose of displaying graphical representations for the data acquired by the system during the sessions. It receives data from the Central System and creates the graphs in real-time. It is dedicated to the therapist, that – based on the info presented here – may decide to make changes and adapt the session to the performances of the patient.

Avatar personalization

The avatar personalization is a module dedicated to creating a better immersion sensation for the patient by changing certain elements in the aspect of the avatar, such as gender, size (Small, Medium, Large), clothes, hair, etc.

Components communication

The components communicate with one another through messages with an established format, in JSON serialization, through TCP sockets.

Each command has a generic format, containing a name and a set of parameters with either a string or numeric value. The generic format allowed us to communicate between heterogenous technologies.

This way of communication was chosen because it allows each component to run on a different computer – thus decreasing the processing overload on a single computer. Also, the implementation of the components was assigned to various members of the consortium, and an increased modularity provided separation of tasks, that could be implemented at various sites, with periodical meetings for integration tests.

Configuration

The contents of this chapter were presented at and published in the proceedings of the ZINC – Zooming Innovation in Consumer Technology 2017 conference that took place in Novi Sad, Serbia [38].

Due to its complexity (high number of available technologies for feedback), TRAVEE allows the doctor to select – from the dedicated GUI - the desired devices to be used for each configured rehabilitation exercise that will be included in each defined session.

For example, some of the available configurations allow the FES to be controlled exclusively from the detected EEG signals, while others may control the FES depending on the movements detected from the optical tracking devices, EMG signals, or any of these combined [39].

7 Contributions to the evaluation of the available technologies for TRAVEE project

One of my initial tasks for TRAVEE were to study available technologies in the areas of BCI and hand tracking, in order to choose the most appropriate ones (medically, technologically and financially) for the purpose of the system.

7.1 Hand tracking technologies

The analysis presented in this chapter was disseminated within the International Congress World Psychiatric Organization (WPA) 2015 that took place in Bucharest [29].

The purpose of a motion tracking system is to assess and represent in real time the pose changes of the body or of a part of the body of a subject.

Classification of motion tracking technology:

1. Non-visual: inertial, magnetic
2. Visual: optical sensors

Motion tracking using non-visual tracking devices

Xsens MTw. According to the producer specification[9] it is a digital inertial measurement unit that measures: 3D rate of turn, acceleration and earth magnetic field (3D angular orientation to 1 degree precision). Up to 32 devices can be used to track key points.

TRIVISIO Colibri Wireless[10] consists of an IMU with accelerometer, gyroscope and magnetometer. Up to 10 devices can be used in a setup. The output is represented as quaternions.

Polhemus Patriot[11]. Magnetic sensor that provides 6 degrees of freedom and runs with up to 50 updates per second. Among the uses of Polhemus technology: simulations of weightlifting motion at the US Olympic Center[12] and measuring hand tremor for Parkinson's patients[13].

Table 7-1 Comparison of non-visual tracking technologies

	Price	Number of measuring units	Maximum distance
Xsens MTw	6350 EUR	6	20 meters
TRIVISIO Colibri	700 EUR	1	10 meters
Polhemus Patriot	2000 EUR	4	3 meters

[9] xSens MTw Awinda. https://www.xsens.com/products/mtw-awinda/. Last accessed July 2017.
[10] TRIVISIO Colibri Wireless – Inertial Motion Tracker (Wireless). https://www.vrlogic.com /Downloads/VRLOGIC_TRIVISIO_Colibri_Wireless.pdf. Last accessed July 2017.
[11] Polhemus Patriot. https://polhemus.com/motion-tracking/all-trackers/patriot/. Last accessed March 2018.
[12] Polhemus – innovation in motion. Case study: Assisting olympic weightlifting with motion tracking. http://polhemus.com/case-study/detail/assisting-olympic-weightlifting-via-motion-tracking-at-the-u.s.-olympic-tra. Last accessed July 2017.
[13] Polhemus – innovation in motion. Case study: neuroscience application powered by Polhemus tracking. http://polhemus.com/case-study/detail/polhemus-motion-trackers-enable-measurem ent-of-the-effectiveness-of-brain-s. Last accessed July 2017.

Motion tracking using visual tracking devices

Microsoft Kinect v2. RGB camera with infrared depth sensor for human body identification and motion tracking. Detects 25 joints, finger movement, face expressions. Errors 1mm-2.5mm.

Leap motion. Close-range movement detection of the hand and lower arm. Accuracy of approximately 0.7mm of the detected movements.

Intel Realsense. A small device that can track close-range movements of the hand, having also other features, such as face detection, 3D scanning, object tracking.

Video camera + markers. Acquires high resolution video data and determine the current body position by identifying known markers in the images and based on a known human body model.

Table 7-2 Comparison of visual tracking technologies

Device	Price	Range	Markers
Kinect v2	200 EUR	Long range	no
Leap Motion	70 EUR	Close range	no
Intel RealSense	130 EUR	Close range	no
Video camera	150 EUR	Both	yes

Conclusions

One of the key issues of computer assisted rehabilitation is tracking as accurately as possible the movement of the patient's body, in general, or a disabled limb, in particular.

The analyzed solutions have great potential in the area of rehabilitation as the cited experiments prove, but improvements need to be made regarding the accuracy of the measurements.

Out of the multitude of options, we chose to integrate several motion tracking technologies – given the sensitivity of the medical rehabilitation field.

7.2 Brain-Computer Interface devices

The contents of this chapter were also presented within the International Congress World Psychiatric Organization (WPA) 2015 that took place in Bucharest [30].

TRAVEE desires to use BCI as an additional communication path for the patient recovering after stroke, by detecting his/her intention of executing a movement and using robotics or FES to aid the patient in executing the desired movement.

Issues of using BCI in rehabilitation

The main challenges of using BCI in rehabilitation are related to:

1. Cost vs. Precision and Connectivity
2. Comfort
3. Prohibitions imposed by producer regarding medical use

BCI

Out of the several options for monitoring cerebral activity (EEG, MEG, fMRI etc.) the most commonly used is EEG (electroencephalography).

According to Wolpaw et. al. [31], an efficient communication involves two phases:

1. The user encodes his/her intentions into neural signs
2. The system decodes these signals translating them into the associated command.

BCI can be classified by whether the electrodes that measure the electric impulses are implanted onto the surface of the brain or are placed on the scalp of the user.

Analyzed solutions

Taking into account the challenges BCI faces in medical rehabilitation, the available signals that should be detected and the published experiment results, three BCI solutions were considered for the purpose of TRAVEE [32]:

Emotiv

- EPOC EEG headset[14], dedicated SDK libraries for detecting mental commands and facial expressions. Accessible price. Limited by connectivity issues.

Biosemi ActiveTwo[15]

- Very good quality EEG measurements, low noise, electrodes can be placed according to the 10-20 electrode location systems. Very prohibitive costs and not intended to be used for medical purposes, according to manufacturer. Cannot be worn in bed position as needed by TRAVEE project.

g.Tech Nautilus[16]

- Wireless EEG recording system, with high signal to noise ratio, many channels, but a high price.

Table 7-3 Comparison of BCI technologies

	Price	Number of electrodes	Wireless
Emotiv	700 EUR	14	yes
ActiveTwo	11000 EUR	24	no
Nautilus	6000 EUR	32	yes

Discussion

From the analyzed solutions the most appropriate was determined to be the gTech Nautilus. It would provide a great accuracy – that is much needed in a rehabilitation system as TRAVEE – and the cost – although very high – is good for the performances that it provides.

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[14] Emotiv Epoc+ - 14 Channels Wireless EEG Headset. https://www.emotiv.com/epoc. Last accessed March 2018.
[15] Biosemi EEG ECG EMG BSPM NEURO amplifier electrodes. https://www.biosemi.com/products.htm. Last accessed March 2018.
[16] G.Nautilus – g.tec's wireless EEG system with active electrodes. http://www.gtec.at/Products/Hardware-and-Accessories/g.Nautilus-Specs-Features. Last accessed March 2018.

7.3 Comparison between Leap Motion and Intel® RealSense hand tracking devices

The contents of this chapter were published in the Romanian Journal of Human-Computer Interaction [33].

7.3.1 Motivation

The TRAVEE project requires a device for a precise tracking of the movements of the human hand. We concluded that the most appropriate for our purpose (due to its lightweight design and ease of use) would be a solution based on optical tracking. We evaluated two such optical tracking devices: Leap Motion and Intel RealSense. We used this method because we believe it fits the best our particular scenario.

As the TRAVEE system wishes to be affordable and easy to use by people without technical background, we focused on lightweight, low cost solutions. We chose the Microsoft Kinect for body tracking, but for more detailed movements of the hand we found it did not provide enough detail (only the direction of the forearm, the palm and that of the thumb[17].) For detailed tracking of each finger we found two solutions that would fit our system: Leap Motion and Intel RealSense.

This chapter presents the rehabilitation exercise movements that are considered in the TRAVEE system and identifies – for each movement - a placement that we thought would be best for each of the two tracking device, discussing the results.

7.3.2 Evaluated movements

The TRAVEE system implements 10 rehabilitation movements, out of which only four involve movement of the fingers and are thus relevant for this research:

- Finger flexion-extension

- Thumb flexion-extension

- Palm flexion-extension

- Thumb touches

7.3.3 Evaluation methods

In order to determine the most appropriate configuration for our system we applied two evaluation methods that we believed are sufficient for a decision in our particular situation.

In the first method we established classes of movements –approximate angles to which we bent four fingers (index, middle, ring, pinky) and the thumb respectively – in order to observe the detection of movements of smaller or greater amplitude with each of the selected devices (30 repetitions of each movement).

In the second method we executed each movement of the four movements of the hand included in the TRAVEE system and observed the accuracy with which the tracking follows the movement for a longer period of time (50 repetitions). One execution was considered correct if the subjects felt that the movement of the virtual hand represented their own to an immersive degree.

[17] MSDN, Jointype Enumeration. https://msdn.microsoft.com/en-us/library/microsoft. kinect.jointtype.aspx. Last accessed May 2016.

Tracking for movements with various amplitudes

As we are interested in the detection of the movement by the tracking devices, we considered that an approximate approach would suffice for determining whether various degrees of movement are detected by the devices.

Device placement

We selected the positions of the devices so that the movement is performed in the distance range recommended for the devices, as we mentioned in their description. As for the actual location of the device, we chose it so that all the important elements of the movement would be visible to the IR cameras, for the device to observe the differences in depth – as we thought would be most appropriate.

Conclusions

From observing the accuracy of the tracking process (visually – comparing the movements in the real world with those indicated by the visualization software provided by the producers) and by the feedback we received from our subjects, we determined that for the movements that must be tracked by our system, the best placement for the Leap Motion device is the classical one, with the hand directly above the controller, especially if the movement involves keeping some of the fingers together. For the RealSense we evaluated a similar placement, with the hand parallel to its surface.

We also found out more information regarding the way the two devices track our desired movements and the opinion of a healthy subject that tries to perform them while being immersed in a VE.

8 Contribution to the implementation of the VR Central System

Parts of the contents of this chapter were published in the proceedings of the ZINC – Zooming Innovation in Consumer Technology 2017 conference that took place in Novi Sad, Serbia [38].

My main contributions to the TRAVEE system are included in the VR Central System. I contributed to the following activities/components, mainly on the implementation and testing parts:

- Definition and server-side implementation of the communication protocol between the system components and the VR central system
- Body tracking for the patient avatar
- Recording of body movements for the therapist avatar
- Contributions to the avatar personalization module
- Rehabilitation session execution
- Visual movement augmentation
- Haptic movement augmentation
- BCI controlled mode
- Robotic hand controlled mode

The contributions are detailed in the following chapters. The entire implementation was made using C# scripts in the Unity engine.

8.1 Communication protocol between the VR central system and other system components

The messages and commands to be exchanged between the main components of the TRAVEE system were defined by the consortium in meetings held in the phase II of the project. It was decided that the system will have a client-server architecture, the VR central system being the server and the Therapist GUI and the Acquisition & Control components being the clients.

I proposed a communication between the three components based on TCP sockets[18] with messages being sent in a serialized JSON format[19] due to its understandability and ease of use with the .Net framework through JSON serialization and deserialization libraries (in particular I used JSON.NET by Newtonsoft[20] in my implementation). I also defined a standardized format of all messages in order to simplify the serialization and deserialization process.

Another contribution was the implementation of the server within the VR Central system. Using C# scripting, I implemented a socket server that listens for connections from clients. The communication with each main component is made on a different port. As soon as the connection is established, the server listens for and sends commands, as necessary, according to the communication protocol.

The server listens for connections from clients on three ports, one for the Therapist GUI, one for the Data Acquisition and Control and one for the Data Visualization Tool. Each listener has its own thread, waits for connections from clients ant then serves their requests as long as the client remains connected.

8.2 Patient body tracking

The body tracking of the patient avatar was made using two Unity assets: Kinect v2 Examples with MS-SDK[21] created by RF Solutions for the movements detected by the Kinect v2 device and Avatar Hand Controller for Leap Motion[22] created by Ivan Bindoff for the movements detected by the Leap Motion.

Kinect tracks over 20 joints, giving the general position of the body, while Leap Motion provides detailed data for the joints of the hand fingers, as presented in the figure below. As a result, for each exercise only one of the devices is necessary for tracking.

Each movement was classified as either a Kinect movement or a Leap Motion movement, based on the segments of the hand that require tracking.

The classification of the TRAVEE movements according to this criterion is presented in the table below.

Table 8-1 Classification of TRAVEE movements based on the tracking device used for detection

Kinect movements	Leap Motion movements
Forearm flexion-extension Arm adduction-abduction Arm anteduction-retroduction Shoulder raise	Palm flexion-extension Finger flexion-extension Thumb opposition Thumb touches Forearm pronation-supination

[18] TCP and UDP Socket API. https://www.w3.org/TR/tcp-udp-sockets/. Last accessed March 2018.
[19] JSON. http://json.org/. Last accessed March 2018.
[20] Json.NET – Newtonsoft. https://www.newtonsoft.com/json. Last accessed March 2018.
[21] Kinect v2 Examples with MS-SDK. https://assetstore.unity.com/packages/3d/characters/kinect-v2-examples-with-ms-sdk-18708. Last accessed March 2018.
[22] Avatar Hand Controller for Leap Motion. https://assetstore.unity.com/packages/tools/input-management/avatar-hand-controller-for-leap-motion-29806. Last accessed March 2018.

8.3 Recording of body movements for the therapist avatar

For the recording of the therapist body movements I created a separate Unity project, containing only the avatar of the therapist, connected to the body tracking assets. This component is necessary to create recordings with the correct movement execution to be played continuously on the therapist avatar during sessions, for the patients to observe the correct movement they need to perform.

Each asset has a record and play functionality, but for TRAVEE we needed a common recording format for all movements, with all the tracked joints. As a result, I created the TRAVEE Recordings project that is dedicated to recording movements of the therapist. In recording mode, all the movements of the therapist are recorded in a file, by serializing the position, rotation and scale of each tracked joint in its skeleton.

In the TRAVEE scene, when the movements are played on the therapist avatar, the recording file is de-serialized and the stored positions are applied to the avatar frame by frame.

8.4 Contributions to the avatar personalization functionality

My contributions to the avatar personalization module were brought upon an existing prototype solution implemented by another colleague at UPB, Alexandra Voinea, that allowed the user to personalize the Gender and Age of the avatar (five options), the Weight of the avatar (5 options), the Height of the avatar (6 options), the Hair color and the Skin color. The existing solution was not integrated with the TRAVEE system, as it was still a standalone project designed specifically for personalizing the patient avatar.

My contributions to this module were: integrating it with the TRAVEE system and adding two options of clothing and two options of hairstyle for each gender, removing the Height changing option as it seemed less relevant in the TRAVEE scene where the user had no elements of rapport to approximate the avatar's height. I also optimized the number of necessary models for the customizations.

8.5 Rehabilitation session execution

A session consists of a list of exercises. Each exercise has an associated: body side (either left or right), a duration and an associated list of devices or features that will be used for it. The available devices and features in the TRAVEE system are: visual augmentation, vibrations, Functional Electrical Stimulation (FES), Electromyography, Brain Computer Interface, Robotic glove.

The therapist defines the list of exercises to be executed in the current session and then navigates to the Session control form by pressing the Start session button. This will redirect the therapist to the Session control screen that provides controls to start, stop, pause or continue the session, as shown in Fig. 8-1.

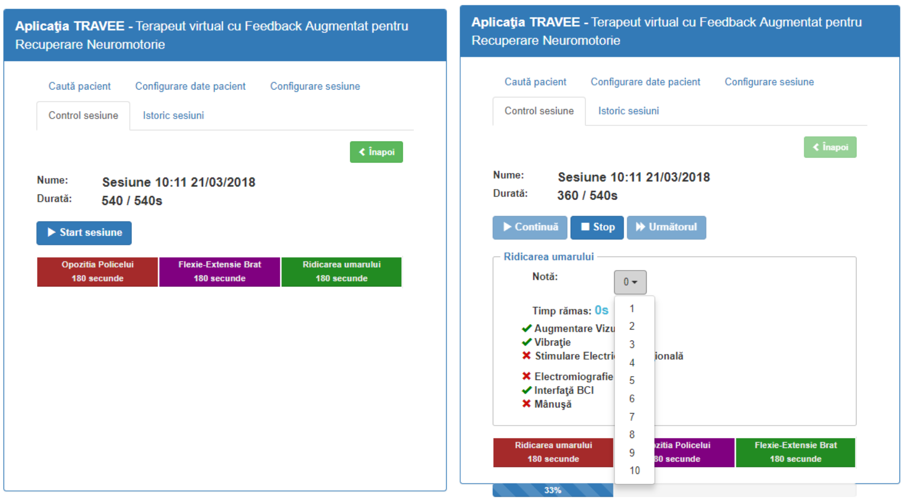

Fig. 8-1 The Session control screen of the Therapist GUI

From the Session control screen, when the user clicks the Start session button, the rehabilitation session is started and a CONFIGURE_SESSION message is sent to the Virtual Reality Central System with all the data about the current session.

The VR Central System receives the message and as a result builds its own current Session object that contains all the received information regarding the contents of the currently executed session.

Initialize current session

Within this activity, the server initializes the current session with the information received from the Therapist GUI and initializes the current exercise.

Session running

While the session is running, the following operations are continuously performed:

- The pose of the therapist avatar is updated according to the corresponding recorded file.
- The movement of the patient is analyzed and augmented according to the settings established by the therapist for the current exercise, based on information received from the Acquisition and Control system, as well as on the tracking data.

My contributions to the rehabilitation session execution feature were in the implementation of the server-side logic and functionality. I implemented the socket server on the VR central system, that listens for connections from the Therapist GUI. After the Therapist GUI is connected it can send any of the commands that will be interpreted and executed accordingly.

8.6 Movement analysis

While the session is running, tracking data is provided by the tracking devices at each frame. I will refer to the current data from the tracking devices as the current *pose* of the patient, meaning the positions, rotations and scales of all the joints in their body – as observed by the tracking devices. The VR Central System knows the current movement in the session, that the patient must try to execute, and, using the Movement Analysis component – that is tight coupled with the VR Central System - it analyzes the current pose to determine to which degree the movement was performed.

The evaluation of the degree to which a movement was performed differs for each movement: for each movement we identified a joint or a set of joints that are most relevant and used them to calculate a score. The score is represented by a number whose values vary for each movement, as it can be represented by a relevant angle or a distance between two bones or joints of the hand.

The joints used for the movements are presented in Fig. 8-2 and Fig. 8-3. As the system knows what the current exercise is, for each pose, it evaluates the current relevant angle or distance. This value is considered to be the score for the movement. Each type of movement has a series of predefined parameters – that were refined based on the information discussed with the medical partners:

- A maximum score up to which the movement is considered to be needing visual augmentation
- An augmentation factor.

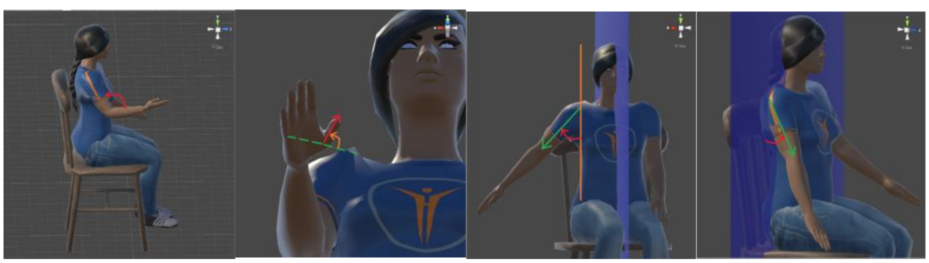

Fig. 8-2 The angles considered for evaluating the movement score for Forearm Flexion-Extension, Thumb Opposition, Arm Adduction-Abduction, Arm Anteduction-Retroduction

Fig. 8-3 The angles considered for evaluating the Palm flexion-extension, Forearm pronation-suppination, Finger flexion-extension and Shoulder raise movements

8.7 Visual augmentation of movements

During the rehabilitation session execution, the data from the input devices – tracking devices, BCI, EMG – is analyzed by the VR Central System and, if the system decides it is necessary, the movement is visually augmented.

Movement visual augmentation based on tracking data within the TRAVEE system is the process through which, during the execution of a certain movement in a rehabilitation session, the movement detected by the tracking devices is improved before being applied to the virtual avatar of the patient. This means that the patient tries to execute correctly the current movement in the session – exemplified by the therapist avatar – and the movement the patient observes on the patient avatar will be a slightly improved version of the real movement, as detected by the tracking devices.

The movement visual augmentation based on movement tracking data uses the score calculated for the movement and a previously set threshold. The movement is augmented if the score is below the threshold with a factor given, which is calculated with a quadratic or exponential formula such that the augmentation factors are inversely proportional with the current score, becoming zero at the established threshold. A graphical representation for the desired variation of the augmentation factor is represented graphically in Fig. 8-4.

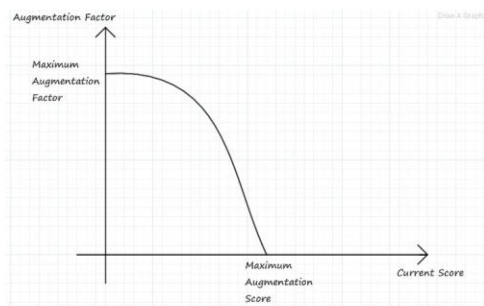

Fig. 8-4 The desired shape of the variation graph for the augmentation factor

Several functions for calculating the augmentation of various parameters in the movement were evaluated, but the one that was determined to be most appropriate for the idea of TRAVEE would have the following form:

$$\begin{cases} threshold \times \left(1 - e^{-\frac{x}{augmentationFactor}}\right), x \leq threshold \times \left(1 - e^{-\frac{x}{augmentationFactor}}\right) \\ x, x > threshold \times \left(1 - e^{-\frac{x}{augmentationFactor}}\right) \end{cases}$$

Such a formula would determine a more or less abrupt variation in the augmented parameter (which can be either an angle or a distance involved in the movement, whose augmentation would be appreciated as an improved movement) depending on the chosen augmentation factor (in the formula marked as *augmentationFactor*). A smaller augmentation factor determines a more abrupt increase of the augmented parameter, can be observed in the graphical representations below.

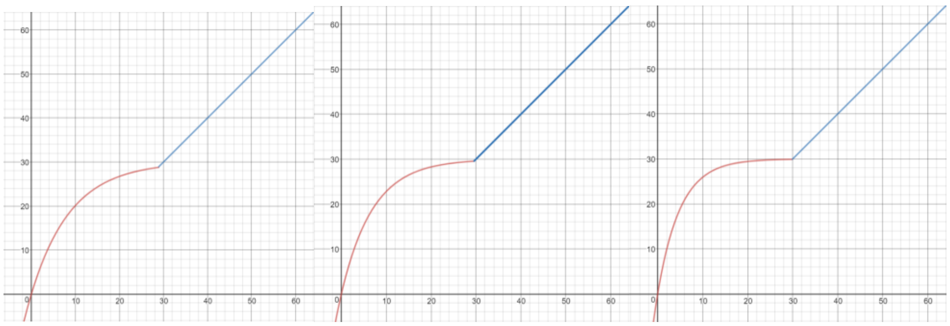

Fig. 8-5 Graphical representations of the augmentation functions with a threshold of 30, and augmentation factors of 9 (left), 7 (center), 5 (right)

The augmentation algorithm is the following:

- Calculate the score for the currently executed movement.
- If the score is beneath the threshold for the currently executed movement, calculate the augmented value for all the parameters involved in the movement before applying them onto the virtual avatar of the patient.
- Otherwise, display the avatar in the position that was detected by the tracking devices.

The process of visual augmentation based on body tracking is pending for a patent with the title: "System, method and computer program for augmenting human movements".

8.8 Haptic feedback

The haptic feedback for a movement is realized by applying vibrations on certain key areas of the exercised limb when the degree of realization of the current movement passes of a certain pre-established threshold. This is used as an additional feedback, to inform the patient of his or her progress, and to stimulate the continuation of the rehabilitation process.

The vibrations are applied using a device built at the "Gheorghe Asachi" Technical University in Iasi. This device has two small engines that vibrate, attached to electrodes that are placed on the surface of the skin. The placement of the haptic device was decided by the doctors at the moment of testing.

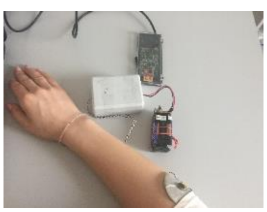

Fig. 8-6 Haptic device placed on the forearm

This feature was implemented by considering predefined parameters for each movement. The evaluation of each movement is made using the previously described method. The predefined parameters define the threshold that determines whether the vibrations are active or not. The poses detected by the optical tracking devices are monitored. When the calculated score for a pose increases above the threshold, the haptic device is started, in order to apply the vibrations as a form of feedback. The haptic device vibrates for as long as the detected pose has a score for the currently executed movement that is above the predefined threshold.

8.9 BCI and visual augmentation

In BCI controlled mode, the VR Central System receives from the Acquisition system data taken by an EEG device.

The VR Central System presents the patient with the rehabilitation scene, in which the patient sees the patient avatar from a first-person point of view. The VR Central system receives values from the Acquisition system and based on the received value may decide to play a pre-recorded movement on the avatar of the patient on either the left or the right hand, based on the following algorithm.

8.10 Robotic hand controlled mode

This mode is dedicated to patients with less motor control of their hand. In this mode of functioning, the patient is immersed in the virtual environment, while the movements of the palm are detected by the Leap Motion device.

First IHRG glove and initial integration with the TRAVEE system

The robotic glove is part of the IHRG project. Initially, I integrated the original IHRG glove with the TRAVEE system.

In the initial implementation of this functionality, I used the API of the IHRG glove to send commands on the serial ports for each movement. The API of the glove, as implemented by the IHRG project of Prof. Nirvana Popescu at POLITEHNICA University of Bucharest, includes several one-byte codes that – when sent to the glove via the serial port, determines an activation of the 5 motors placed on the wrist of the hand in the correct configuration and sequence to provoke one movement.

The integration of the initial IHRG glove consisted in the following mode of functioning of the TRAVEE system:

- The patients – wearing the IHRG glove - are immersed in the virtual environment, where they see the patient avatar that moves according to the movements detected by the Leap Motion device – without visual augmentation.
- When an exercise that includes the IHRG glove as a form of augmentation is played, the system periodically sends – via the serial port – a code representing the currently executed movement, that determined the glove to perform one repetition of the selected movement. In this manner, the glove continuously assists the patient hand in performing the current movement.

TRAVEE-dedicated IHRG glove and final integration with the TRAVEE system

After the integration of the initial IHRG glove with the TRAVEE system, there were several ideas of improvement, suggested by the teams at UBP and INRMFB regarding the way of functioning of the glove. Therefore, a glove dedicated to the TRAVEE system was created by prof. Nirvana Popescu’s team, that was more in sync with the purposes of TRAVEE.

The main changes that were brought to this glove compared to the one initially integrated are:

- The initial glove assisted the patient in the flexion movement. The TRAVEE-dedicated IHRG glove has the actuating motors placed on the upper side of the wrist, assisting the extension of the fingers.
- New commands were added that were more appropriate for the new mode of functioning within the TRAVEE system.

8.11 Session recording

In order to be able to analyze the data generated during the sessions with the patients, the VR Central System of TRAVEE also includes a recording functionality. This functionality is integrated with the VR Central System and stores all the relevant information for each session in a .session file.

The data stored in the recording files was fundamental for the analysis that was performed regarding the performances of the patients during the clinical tests with the TRAVEE system.

8.12 Session analysis

This functionality was implemented to obtain data regarding the evolution of each of the patients tested using the VR Central System functionalities during the clinical trial that took place in April-May 2017. For this purpose, the session analysis tool can analyze automatically many session recording files that have the format previously described, and extract from them synthetic data, so that the therapist can gather information without visually inspecting all the sessions.

Using the variation of the scores, and the other information in the files, it determines the following information:

- The execution times for each session
- For each execution of an exercise in a session:
    - The number of repetitions, as perceived by the system through the variations of the calculated scores for the tracked poses sequences
    - The average score for all the poses detected for the execution of a given exercise In-vivo tests

9 In-vivo tests

9.1 The first set of in-vivo tests

In this set of tests, November 2016, one patient has tested the BCI and VR visual augmentation functioning mode, and three patients tested the VR and optical tracking with visual augmentation functioning mode.

Results

The patients were asked to answer several questions regarding their experience with the TRAVEE system. The questions referred to their comfort during the session, the quality of the images presented on the HMD and of the avatars and their movements as well as their opinion regarding the utility of such a rehabilitation system. Each question had five answer options, on a scale from 1 to 5.

Conclusions

The patients reported that they felt tired after the session with an average of 2.33 out of 5. Two of the patients reported dizziness from the visuals on the virtual reality glasses, but they perceived no nausea and very little anxiety. The image of the virtual environment was quite clear, as they rated it above average, with 3.33. No major discomfort was reported. The movements of the avatar needed improvements as two of the patients did not think they looked realistic. None of the patient was disturbed by the visual augmentation of the movements, therefore we concluded it was well applied, in a non-disruptive manner. The virtual therapist needed improvement, and that fact was also remarked by the patients.

The conclusions of this round of testing were that the system can be used in a medical rehabilitation session for patients with various degree of disability, but there were also certain improvements to be made.

9.2 The second set of in-vivo tests

The contents of this subchapter were presented at and published in the proceedings of the ZINC – Zooming Innovation in Consumer Technology 2017 conference that took place in Novi Sad, Serbia [38].

In December 2016, the second set of In-vivo tests took place at the INRMFB in Bucharest. The tested system included the VR Central System with optical tracking devices, the HMD and provided visual and haptic feedback.

Results
The three patients were asked to answer several questions regarding their experience with the TRAVEE system. The questions regard their comfort during the session, the quality of the images presented on the HMD and of the avatars and their movements as well as their opinion regarding the utility of such a rehabilitation system. Each question had five answer options, on a scale from 1 to 5.

Conclusions
All the patients seemed to accept all the components of the system, as they graded the discomfort levels to be very low. Only one of them reported a level of tiredness, none of them experienced dizziness, nausea or anxiety – as we knew might happen when using such technologies in rehabilitation [17].

The image on the HMD seems to be clear in most cases and the patients seem to be able to identify easily with the avatar and to recognize the movements as their own at an acceptable level.

Because of the feedback received from the patients from this testing session, as well as our own observations during the tests, we have pointed out another improvement that had to be included in the final prototype.

10 Clinical trial

The clinical trial took place between 28th April 2017 and 19th May 2017, at the National Institute for Rehabilitation, Physical Medicine and Balneoclimatology (INRMFB) in Bucharest. The tested configurations were chosen based on the degree of disability of each patient and included BCI, FES, VR and robotic glove.

A total of 21 patients tested the TRAVEE system with visual augmentation. The patients or their representatives had given their accord for participating in the experiments, and an approval was obtained from the ethical council of the INRMFB.

The recordings of the sessions were analyzed using the Session analysis component, as previously described. The number of repetitions was determined automatically, based on the number of changes in the direction of variation of the calculated score for each movement.

10.1 Questionnaires

The patients that participated in the clinical trial received a questionnaire containing 12 questions. Each question had five answer options, on a scale from 1 to 5. The questions and the answers given by the patients are presented below.

Questions

Q1. During the training sessions, what was the perceived level of tiredness?
Q2. During the training sessions, did you feel dizziness? If so, how intense?
Q3. During the training sessions, did you feel nauseous? If so, how intense?
Q4. During the training sessions, did you feel any anxiety or fear? If so, how intense?
Q5. During the training sessions, how clear was the image perceived on the virtual glasses/monitor?
Q6. During the training sessions, did you feel physical discomfort due to the system components? If so, how intense?
Q7. During the training sessions, did you feel pain? If so, how intense?
Q8. During the training sessions, how real did the avatar movements seem to you?
Q9. During the training sessions, how well did you identify your movements to those of the avatar?
Q10. During the training sessions, did you feel that the movements of the avatar were different than yours (greater)? If so, how much different?
Q11. During the training sessions, were the indications of the virtual therapist useful for the exercise execution? If so, how useful?
Q12. Do you consider that the training sessions with this system were useful for your rehabilitation? If so, how useful?

Answers

Table 10-1 Questionnaire answers of the patients participants to the clinical trial with the TRAVEE system

Patient	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
1	2	2			3	4	1	2	3	2	2	3
2	2				3	3	2	3	3	3	3	3
3	3	2	1	1	3	4	1	2	3	2	4	3
4	3	2			3	3	1	2	2	4	2	2
5	4	2	1	1	3	3		2	3	4	2	2
6	4	2	1	2	3	4	1	1	2	4	2	2
7	2	2			3	4	1	2	2	2	2	3
8	3	2	1		3	3		2	3	2		3
8	4	3	2	3	3	4	3	2	3	4	3	3
10	2				3	4	1	2	2	4	2	3
11	2				4	3		3	3	2	4	3
12	4	3	2	3	4	4	3	2	2	3	2	2
13	2				4	3		3	3	2	3	3
14	4	1			3	3	2	3	3	1	3	2
15	4	2	1		2	3	3	3	3	2	3	2
16	2	2		1	4	3	1	3	3	2	3	2
17	4	2	1	1	2	3	1	2	3	2	3	3

18	2				3	3		2	3	3	2	2
19	4	1			3	3		3	2	2	2	2
20	2	2			3	1		3	3	2	2	3
21	4				3	4		3	3	2	3	3
Average	3.00	2.00	1.25	1.71	3.10	3.29	1.62	2.38	2.71	2.57	2.60	2.57

10.2 Discussion

The results of the clinical trial are specific to a qualitative study and not a clinical one, because of the reduced number of sessions with each patient. We used the responses received to draw several conclusions regarding the TRAVEE system.

Tiredness (Q1)

The responses of the patients revealed an above-the-average level of tiredness. Considering that for many of the patients the system was the first interaction with VR, and the equipment included an Oculus Rift placed on the head of the patient, which weights 440 grams[23], that could generate tension and pressure on the head of the patient and a tiredness feeling. Also, that could also be a sign of motivation for the rehabilitation session, but further research should take place before any conclusions are drawn.

Dizziness (Q2)

Relatively low degrees of dizziness were reported. The fact that the sessions were generally no longer than 5 minutes, and that between the sessions the VR equipment was removed, to allow the patient to relax, could be explanations of the low rate of dizziness experienced by the patients.

Nausea (Q3)

With an average of 1.27 it seems that the patients did not have intense feelings of nausea, which is encouraging for a system using VR in a rehabilitation environment, as it appears it did not create such an intense discomfort.

Anxiety or Fear (Q4)

Low scores were reported for feelings of anxiety or fear. The patients were informed regarding the process of rehabilitation involving the TRAVEE system, to ensure the experience will not produce anxiety, and it seems that the dialogue with the patient as well as the fact that the sessions were initially performed in the presence of the patient’s doctors had a good impact for lowering stress levels.

Image (Q5)

With an average of 3.1 out of 5 it appears that the image perceived by the patients on the HMD was mostly a clear one and that the positions of the avatars in the scene was good, as the patients did not have trouble in observing the scene.

Physical discomfort (Q6)

The reported physical discomfort of 3.29 out of 5 reflects that the system components are not yet as comfortable as they should be for a rehabilitation system. A lower-weight alternative should be found for the Oculus Rift DK2 used, as well as a more optimal solution for the optical tracking – keeping the hand in

[23] Oculus Rift Specs – DK1 vs DK2 comparison – Rift Info. https://riftinfo.com/oculus-rift-specs-dk1-vs-dk2-comparison. Last accessed March 2018.

the field of detection of the Leap Motion device was a challenge, and it often required that the patients hold their hand in a less comfortable position, as it was placed on the HMD, at eye level.

Pain (Q7)

As the average score for the perceived pain during the sessions is 1.62 out of 5, it is a positive observation that the patients, although they felt a degree of physical discomfort it was not as intense as to produce pain.

Avatar movements – realism, immersion (Q8, Q9)

With scores of 2.38 and 2.71 out of 5, the degree of realism of the avatar movements was perceived on average as moderate, while the immersion was evaluated to be slightly above an average of 2.5. The realness of the movements could be improved by using other tracking devices and methods, with a wider range of detection and improved precision. As TRAVEE desired to be a low-cost solution for VR rehabilitation - the devices used provided acceptable tracking capabilities.

Augmentation (Q10)

The obtained average for the evaluation of the observability of the visual augmentation effect is slightly above the middle of the interval, 2.57 out of 5. The purpose of the visual augmentation implementation was for it to not be observed by the patients, and we evaluate that it is a low enough score but that also reveals a point where the system could also be improved substantially, to create a more seamless visual augmentation effect.

Virtual Therapist (Q11)

The usefulness of the indications of the Virtual Therapist were evaluated with a 2.60 out of 5, a good score but one that shows that the indications could be improved, possibly by using a distinct perspective or a different position of the avatar of the Virtual Therapist.

System utility (Q12)

The overall utility of the system was also evaluated above 2.5 with an average of 2.57. Further improvements are needed for the system to be able to be used on a larger scale, and further research needs to take place – extensive testing sessions, with more sessions per patient, to draw a clear conclusion regarding the utility of the ideas implemented by the TRAVEE system. Given the small number of sessions performed by the patients during the clinical trial, we find that the obtained score for this question is encouraging, showing the enormous potential behind such a system.

11 Conclusions and future work

This chapter includes my conclusions about the TRAVEE system, a summary of my contributions to its development and some future work directions as a continuation of my doctoral research.

The TRAVEE project fulfilled all of its purposes: designing and developing a relatively low cost rehabilitation tool for the upper limb, with multiple use modes, multimodal input and feedback, novel ideas through the presence of the Virtual Therapist and the use of visually augmented feedback, as well as validating this complex system through tests in a medical environment. My perception is that TRAVEE was a great opportunity to design, implement and test a multitude of possible tools that could enhance a rehabilitation session, and that each of them has great potential if it were integrated into a commercially available system.

TRAVEE was also an exercise of collaboration between heterogenous teams from various environments. Engineers, doctors, rehabilitation therapists, both from academia and from industry brought their contribution to the system in all of its phases. The result has a great potential, from all of its perspectives.

TRAVEE is a state of the art system, combining multiple new and heterogenous technologies in a complex architecture : VR, robotics and haptics, real time data acquisition from an EEG device monitoring the patient, and others. There were many technical challenges that had to be overcome for the system to become viable. Medically, TRAVEE proved to be a system that can be used practically in rehabilitation; it was easily accepted by a variety of patients, with feedback that is generally positive. It also aggregates all the data acquired during the sessions, and obtains a synthetic representation that can be interpreted by doctors, while also providing a tool to organize and retreive information regarding patients and their sessions.

Parts of this chapter are published in the journal *Revue Roumaine des Sciences Techniques Série Électrotechnique et Énergétique*

Commented [FM1]: Sunt niste fraze generale, nu cred ca este cazul sa spui ca le-ai publicat

11.1 Summary of the original contributions

My original contributions included in this thesis are especially linked to the design and implementation of several key parts of the TRAVEE system. Also, I contributed to the study of the state of the art in the field and to the selection of the most appropriate technologies to be used in the implementation of the system. Other important contributions are to the system testing: test cases conception, questionnaires conception and the qualitative study based on user answers, conducting to the two in-vivo testing sessions and the clinical trial.

Contributions to the design and implementation of the VR Central System:

- The definition and implementation of the communication protocol between the VR Central System and all the other components of the system. The results were disseminated at the EHB E-Health and Bioengineering Conference, Sinaia, Romania, 2017 [34].
- The implementation of the rehabilitation session execution on the VR Central System. The results were disseminated at the EHB E-Health and Bioengineering Conference, Sinaia, 2017 [34].
- The implementation of the Movement analysis component, that is coupled with the VR Central System.
- The implementation of the visual augmentation of the movement, based on the movement analysis. The results of this implementation are included in a pending patent with the title: “System, method and computer program for augmenting human movements”.
- The implementation of the haptic feedback control and logic, using the existing haptic device. The results were disseminated at the ZINC, Zooming Innovation in Consumer Electronics International Conference, Novi Sad, Serbia, 2017 [38].
- The implementation of the BCI with visual augmentation functioning mode of the TRAVEE system.
- The implementation of the robotic hand-controlled functioning mode of the TRAVEE system. The results were briefly disseminated at the ZINC, Zooming Innovation in Consumer Electronics International Conference, Novi Sad, Serbia, 2017 [38].
- The implementation of the session recording module.
- The implementation of the session analysis module.

- Several contributions to the avatar personalization module.

Contributions to the TRAVEE system testing

- Test cases conception for the two in-vivo testing and the clinical trial
- In vivo testing during two short testing sessions. The results were disseminated at the ZINC, Zooming Innovation in Consumer Electronics International Conference, Novi Sad, Serbia, 2017 and at the EHB E-Health and Bioengineering Conference, Sinaia, Romania, 2017 [38].
- Questionnaires conception
- In vivo testing during a clinical trial.
- The qualitative study based on user answers

Contributions to the dissemination of the TRAVEE project

Throughout all the phases of TRAVEE, my contributions in this area consisted of disseminating the following:

- the research I made in the initial phases of the project, through:
  - state of the art research regarding technologies used in similar projects [7][29][30],
  - issues that may arise from implementing VR and ICT solutions for rehabilitation [17],
  - the use of similar ideas for stimulating the rehabilitation process [3],
  - comparisons between two finger and hand tracking technologies [33].
- the chosen solution, architecture and implementation details [34][38];
- the summarized and processed results of the testing sessions [34][38];
- possible future directions of research that could be derived from the work in TRAVEE [40].

11.2 Future work

Possible future directions for the continuation of the work started by TRAVEE include:

- Optimization of the augmentation of the feedback sent to the patient by observing the differences between the classical and augmented rehabilitation and understanding the cerebral mechanisms that create these differences.

- Analyzing the importance of variations in the augmentation factors and the evolutions of the patients. Finding the reasons why the changes in the patient's evolution took place during the TRAVEE clinical trial, and whether these are consistent and with medical relevance.

- Testing the utility of augmentation for patients with spasticity, which is a condition that often appears as a result of the interrupted communication between the brain and the muscle that causes it to contract involuntarily for long periods of time[24].

- Studying the influence of the rehabilitation environment on the evolution of the session and the emotional state of the patient. The TRAVEE system only implemented one scene that presented only the patient and therapist avatar.

[24] What is spasticity? http://www.stroke.org/we-can-help/survivors/stroke-recovery/post-stroke-conditions/physical/spasticity. Last Accessed February 2018.

- Comparing the results obtained with visual augmentation versus robotic support of the movement.

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