Augmented and virtual reality mirror therapy system for hand rehabilitation in stroke patients

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***Abstract*—Nowadays, it is increasingly common for neurophysiological rehabilitation therapies to be carried out assisted by systems that allow friendly interactions with patients. Many of them are oriented towards challenges, games, or interactions that try to capture the patient's attention and generate a pleasant setting for performing routines. In this work, a system to conduct mirror therapy through different augmented and virtual reality games was developed, in which the movements of the healthy hand are replicated in a virtual hand. The patient can perform different routines focused on the movements of the shoulders, elbows, wrists, and fingers, which differ by the degree of mobility that the person has and the rehabilitation phase in which they are. In addition, the system includes a module that allows recording and consulting information about the patient's performance, making easier for specialists to carry out an evaluation and monitoring of the progress. The system is currently under evaluation by clinicians with patients, reaching satisfactory results in preliminary tests.**

***Index Terms*—virtual reality, augmented reality, mirror therapy, stroke, neurorehabilitation.**

I. Introduction

Traumatic brain injuries and strokes are one of the main causes of disability, and their consequences are manifested in lower excitatory responsiveness, general activity level, motivation, mood and cognition, among others [1]. When these conditions continue or increase over time, they produce problems in interpersonal relationships and social adaptation, causing a vicious circle of isolation, depression and anxiety [2, 3]. In order to minimize problems caused by neurological deficits and retrain the body, neurophysiological rehabilitation (NR) is used, in which individualized treatments help to manage specific issues with memory, attention, perception, problem solving, reasoning and executive functions, initiative and self-control.

Approximately two decades ago, the validity of the use of virtual reality (VR) in diagnostics and NR was beginning to be recognized [2] and today there is a very active community on this topic [4-7]. Some applications that have raised interest in the scientific community are related to phobias diagnosis and treatments, obsessive-compulsive disorders, post-traumatic stress disorders and hyperactive attention deficit syndromes. It is possible to list a series of advantages about the use of VR over traditional practices, such as reproducing a realistic daily environment in which patients can carry out interactions; exposing patients to controlled, safe and intentionally designed stimuli; focusing multisensory attention and avoiding distractions from the real world; defining hierarchies or levels in the stimuli and repeat them; guiding the stimuli to collaborate with psychological rehabilitation; generating instant feedback to the patient including playful and self-exploratory interactions to motivate the patient [2, 8, 9].

Hardware limitations and software standards have became less and less influential, and the massive access to videogame platforms has allowed progressing in this respect [9]. However, there are some aspects regarding the limitations that should be considered: the degree of realism and naturalness of the environment, the complexity and multimodality of sensory stimuli, and the inherent psychology of the individual that will lead to particular interpretations and interactions. In addition, as highlighted in [9], there is little data collection to generalize the results and validate the effectiveness of VR-based methods. Regarding interactive applications, there are different configurations that depend on the hardware and software used. A detailed review of commercial videogame and rehabilitation systems is presented in [10]. These applications can have 2D or 3D characteristics, they can be immersive or non-immersive [11], they can perform the setting through environmental or portable systems (wearable devices), they can interact with the user through touch commands/controls or with non-tactile technologies. In addition, it is possible to mention some desirable characteristics based on evidence collected in previous studies [11]. For example, presentation of the most important kinematic information in a simplified form, allowing a better interpretation by patients; the possibility for management of repetition and intensity; among others.

In [12], authors defined *mirror therapy* (MT) to help relieve "phantom limb" pain, when pain is still felt in the limb after amputation. Traditionally, a mirror box is used to create a reflective illusion of a limb that does not exist from the existing one (see Fig. 1). The hypothesis is that every time the patient tries to move the paralyzed limb, they receive sensory feedback through vision and kinesthesia. This neuro-rehabilitation technique allows the development of new neural connections for the control of hands and upper limbs through

Fig. 1. Mirror therapy. Image from 'Asociacion Medica Latinoamericana de Rehabilitacion' (https://www.portalamlar.org)

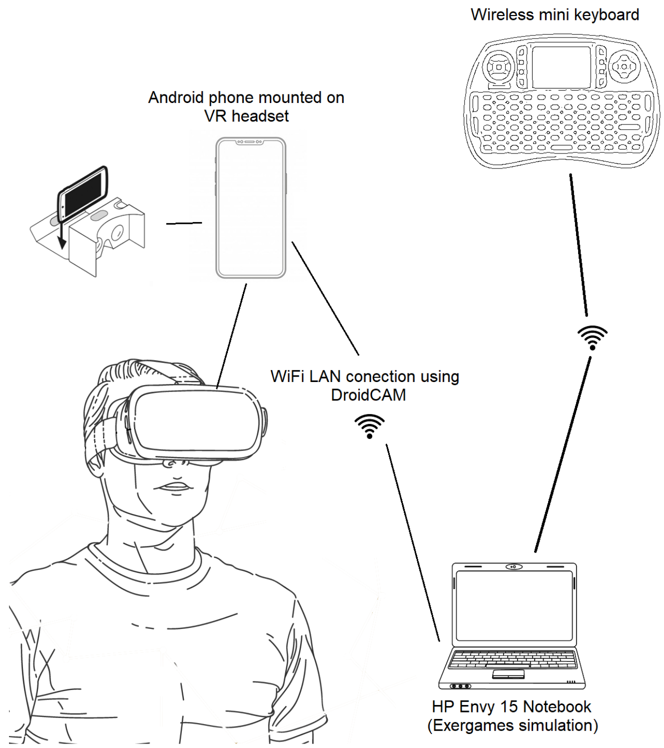

Fig. 2. Hardware setup.

positive feedback to the motor cortex that a movement of the affected limb has occurred. When applied to stroke patients, a mirror is placed in the midsagittal plane of the patient, thus reflecting the movements of the non-paretic side on the affected side. The visual illusion by which movement or touch of the intact limb can be perceived, affect the paretic or painful limb and have an effect on the activation of "mirror neurons" [13]. This is the process that is intended to be carried out by our proposal, virtually reproducing the movement of a healthy hand in the affected one, and thus achieving neuroplasticity stimulation to support the rehabilitation process of the affected hand.

Although there are some commercial applications for hand rehabilitation [14, 15], this development aims to be open source so that anyone can access it. We present here the advances in the development of a system that will assist physical therapists in the process of hands/wrists rehabilitation of stroke patients. It is intended to achieve an interactive system that improves the experience of patients when performing rehabilitation exercises and could be used in a telemedicine environment.

The rest of the article is organized as follows. Section II describes the setup of the system, the exergames designed for therapy with the increasing complexity of movements, and examples of the output from the patient's perspective. Section III presents the quantitative data collected from the experiences and the information that is available to the therapists. Finally, in Section IV the conclusions are drawn.

II. Materials and Methods

We present in Fig. 2 the scene design where the system will work. Patients have to wear virtual reality glasses to visualize the rehabilitation exercises. Regarding the devices, an Android cell phone, Google Daydream virtual reality glasses and a desktop computer are used.

First, the system receives as input the video frames from the cell phone camera using DroidCam through a WiFi connection. The video is pre-processed using OpenCV, and through the use of the Media Pipe Hands library, a segmentation of a pseudo-skeleton of the patient's hand is performed from the points of interest (see Fig. 3).

From these points, the position and the gesture that the patient is performing are determined, and different exergames are simulated using PyGame. These exergames use the positions of the hand and the gesture made for their game mechanics. Once the simulation is done, the video is sent to the mobile device via Wi-Fi streaming using Flask. A set of exergames were developed for different stages of the rehabilitation process, as detailed below.

A. *Exergame number 1*

Fig. 4 shows screenshots of the execution of exergame number 1. This exercise was designed for patients with reduced mobility in the hand and fingers, who are beginning their rehabilitation process. Its objective is to train the mobility of the entire arm including shoulders and elbow, without contemplating movements with the wrist or fingers. In this exercise, there is a rest area for the hand, where each interaction begins and ends (represented by the blue rectangle). During the execution, a white circle appears on the screen at a random location, which must be reached by the patient by moving their hand. When the circle is reached it turns green, confirming that

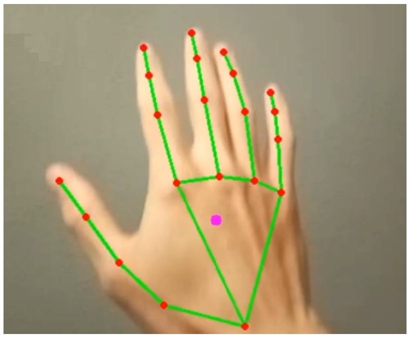

Fig. 3. Points provided by Media Pipe Hand's segmentation.

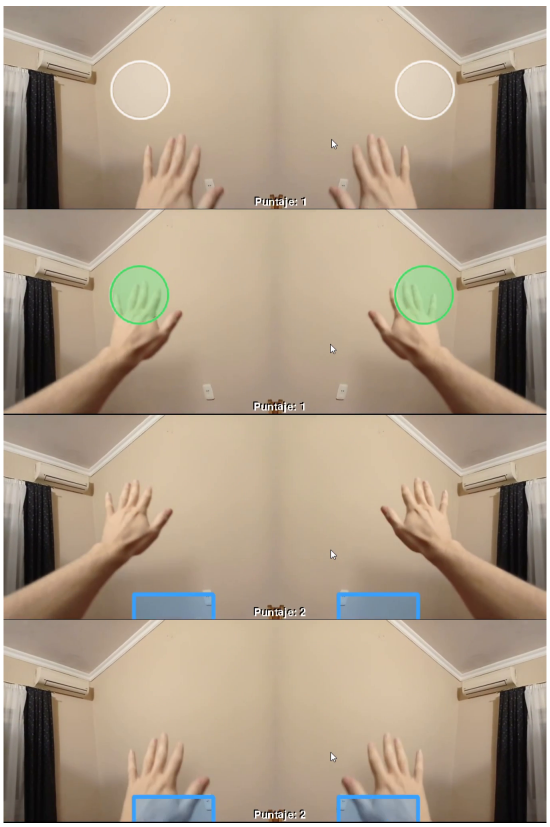

Fig. 4. Exergame number 1.

the objective was achieved, and adding a point. After a few seconds, the circle disappears and the blue rectangle indicates that it should return to the resting position. This process is repeated as many times as defined.

B. Exergame number 2

Screenshots of the execution of exergame number 2 are shown in Fig. 5. This mode of exergaming is aimed at patients who have already gained mobility in their arms and elbow, and are beginning to take the first steps to regaining mobility in their hand, as it requires the patient to open and close their fist and move their hands and arms. This exercise has the following dynamic: the patient must reach the mosquitoes that appear on the screen with the hand, starting from the rest position, and "catch" them closing their fist enough to "capture" them. When the goal is reached, a point is obtained and the player must return to the rest position. As in the other exergames, it can be repeated as many times as preset, and the position of the mosquito is chosen randomly.

Fig. 5. Exergame number 2.

C. Exergame number 3

This exercise requires good mobility in the fingers and hand, as well as coordination. The patient should have the ability to move their hands, even open and close the fist to pick up objects and move them (Fig. 6). The dynamic consists of reaching the position of a virtual ball and making the fist gesture to capture. The gesture must be maintained while moving the hand to the indicated position (white circle), and finally, the hand is opened to release the ball. If the exercise was performed correctly, the circle turns green, a point is obtained, and it is indicated to return to the rest area. The positions of the ball and white target are assigned at random in each execution.

D. Exergame number 4

Screenshots of the execution of exergame number 4 are shown in Fig. 7. This mode of exergame is aimed at patients who have already gained mobility in the arms and elbow, and have a good degree of mobility in the hands and a slight degree in the hands, fingers, and wrist, since different hand gestures are required. The objective is to train the fine mobility of the

Fig. 6. Exergame number 3.

Fig. 7. Exergame number 4.

fingers. The exercise presents a similar dynamic to exercise 1: the circles must be reached from the resting position and once the objective has been achieved, one returns to the resting position. The difference here is that, once the circle is reached, the patient must perform the indicated gesture within the circle and hold it for a few seconds. When both conditions are fulfilled simultaneously, the circle changes to green to indicate the success of the action, and then it is indicated that it must return to the rest zone. This can be repeated as many times as necessary, and each time both the location and the gesture are chosen randomly. The gestures available in this exercise are: open hand, closed fist, "peace", "Hawaiian greeting" (open thumb and pinkie), "rock" (open index and pinkie), thumb up, index up, and OK sign.

III. Results

A. Registered information from sessions

The relevant information and graphs for each therapy were determined together with the physical therapists, in an evolutive manner. After that, a scheme to store the information, how to save and present was proposed. Each recorded session includes the date, the objectives achieved, the exergame mode, and the total elapsed time. The objectives achieved represent the number of exercises properly performed during the session (for example, how many times could the patients open and close their fists, how many gestures did they do well, among others, depending on the exergame mode). The system also keeps a record of the positions of the center of mass of the hand throughout the session, to analyze the dynamic made by the patient. For this, the specialists requested the implementation of two graphs that represent the horizontal and vertical position of the hand. Using all information, the specialist can assess whether the patient has performed the required exercises and carry out quantitative monitoring of their progress. To make easier the visualization, a web system was developed with a graphical interface to cross-check data stored in the different sessions. This was implemented using Flask and Dash[1].

Records table (Fig. 8): the rehabilitation sessions are displayed including the session ID, date, exergame mode, number of completed objectives and the total time in seconds. The average time for completing objectives is also added, dividing the total time by the number of objectives completed, thus allowing the specialist to quickly evaluate the patient's performance. By clicking on a row in the table the details of the positions of the center of mass of the hand during a session can be seen.

Graph of achieved goals by date (Fig. 9 (top)): presents the number of achieved goals by date considering any exergame mode. This graph allows the specialist to quickly analyze the days in which the required exercises were not fulfilled, that is, fewer exercises were performed than those suggested for

[1]Accessible at https://dash.plotly.com/ and https://flask.palletsprojects.com/

Session ID	Date	Exergame mode	Completed objectives	Session duration (sec)	Average time per completed objective (sec)
1	2021-08-31 01:14:28	Mode 1	4	37	9.25
2	2021-09-01 01:17:37	Mode 1	6	37.1	6.18
3	2021-09-02 00:24:42	Mode 1	24	94.2	3.92
4	2021-09-03 00:27:47	Mode 1	14	42.7	3.05
5	2021-09-05 00:30:17	Mode 1	16	56.2	3.51
6	2021-09-07 00:31:47	Mode 1	6	27.8	4.63
7	2021-09-08 00:37:30	Mode 1	2	8.4	4.2
8	2021-09-09 00:37:52	Mode 1	2	8.2	4.1

Fig. 8. Records table.

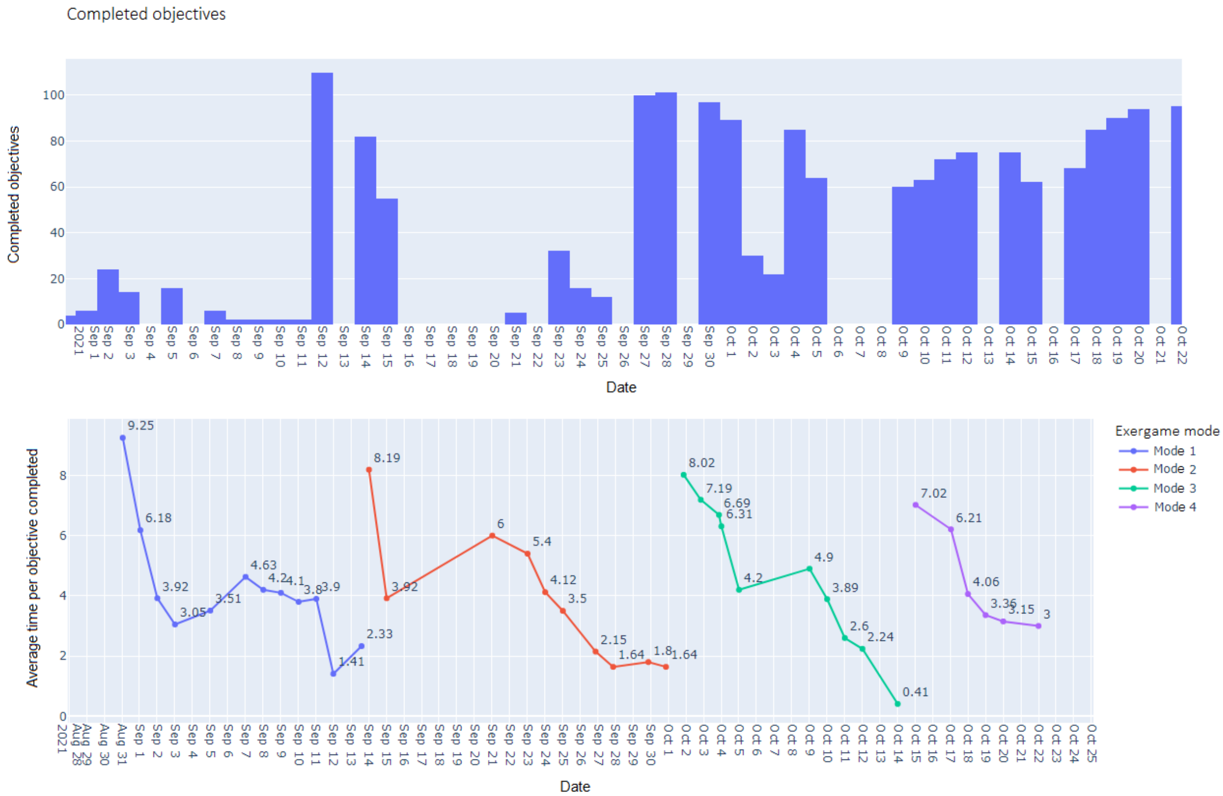

Fig. 9. Graph of goals met by date (top), Graph of the evolution of the average time per objective by dates (bottom).

therapy.

Graph of the evolution of the average time per objective by dates (Fig. 9 (bottom)): shows how the average time for fulfillment of objectives by dates evolves, according to the exergame mode. The values presented decrease when the patient obtains a better performance in their sessions, and increase when it takes longer to reach the objectives. The combination of this graph and the previous one allows us to evaluate how the average time of meeting objectives varies when patients carry out or skip sessions.

Graphs of the evolution of the average time per objective throughout the sessions (Fig. 10): present the time used to accomplish an objective (individualized by exergame mode), allowing analysis of how long each exercise takes and the progress in the rehabilitation. The graph includes a horizontal line (whose value must be determined by the specialist) that indicates an average time threshold for objectives. When the patient obtains times below the threshold during several sessions, it could indicate that he is ready to move to the next level.

Graphs of horizontal and vertical positions of the center of mass of the hand: they show the horizontal and vertical movements made by the hand throughout the session, and allows specialists to analyze the mobility of the arms and elbows.

Several evaluations were made regarding both technological aspects of the system and the feasibility of developing a product from the current setup. For this, the temporary delays in the system, streaming, and user experience were taken into account. Also, meetings with specialists in mirror therapy and rehabilitation were carried out to evaluate the potential use with patients and the general experience of using the system.

These initial evaluations obtained satisfactory results regarding the feasibility of developing a useful product, as well as its use with real patients in rehabilitation centers. The mean delay between image acquisition and presentation on

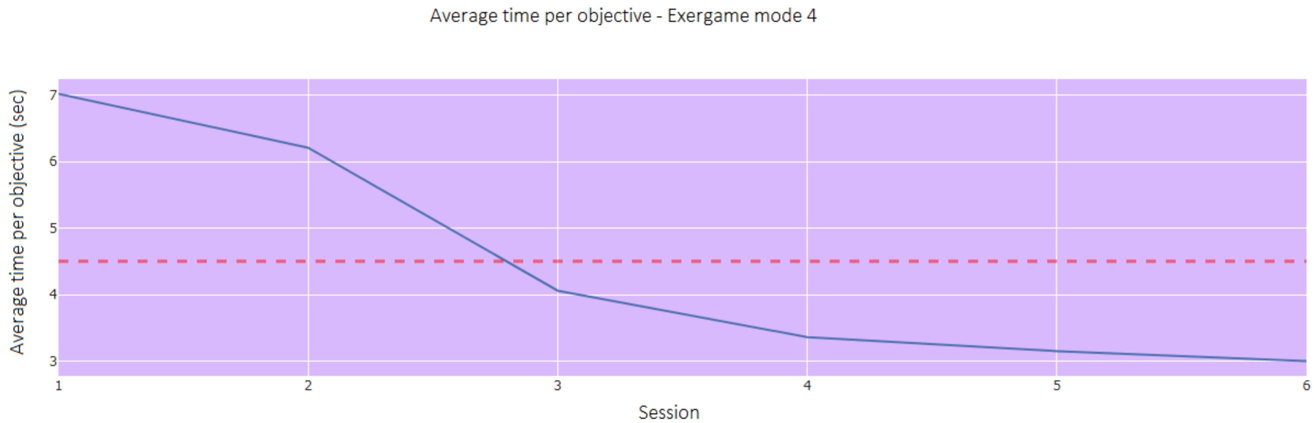

Fig. 10. Graphs of evolution of the average time per objective throughout the sessions.

the screen was high, so it is necessary to put some effort on optimizations to the system and look for alternatives that improve the processing times. Also, new hardware components or minicomputers should be explored that allow the system to run in real-time without requiring a PC, so that patients can take the system home.

IV. Conclusions

In this work, a therapeutic assistance system was implemented for the rehabilitation of hands/wrists of stroke patients through different exergames. Using a mobile camera, the system implements the detection of the healthy hand and the recognition of gestures using state-of-the-art neural networks. An augmented image is generated in real-time to provide a virtual reality environment that stimulates the rehabilitation process.

In qualitative tests, it was positively evaluated by the therapists of a local rehabilitation center. The system was very useful in the daily routine when dealing with several patients at the same time, it follows the structure of exercises performed in conventional sessions and manages to capture the patient's attention through the use of exergames. Besides, the quantitative data gathered greatly improved the information that specialists use to follow the treatment of each patient.

The development will continue with the aim of obtaining a mobile system that can be used in therapy in medical centers and also at home. To reach that, some initials works are nowadays in progress with the inclusion of a minicomputer (Raspberry Pi 3) to run the main software.

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