Remote monitoring and rehabilitation for patients with neurological diseases

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ABSTRACT
In this paper we present an upper-limb tele-rehabilitation solution suitable for patients suffering motor impairments due to neurological diseases (e.g. Parkinson's disease). The solution is based on *patient subsystems* connected to a *clinician subsystem* through a *secure cloud platform.* The patient subsystem is built around a novel Human Computer Interface (HCI) based on RGB-Depth camera (e.g. Kinect©), a monitor and soft gloves with color markers. Important features of the HCI are the accuracy of real-time and fine-grained three-dimensional (3D) tracking of hands and fingers, low cost, suitability for motor impaired patients and large working volume. The patient subsystem software implements both standard UPDRS motor tests and exergames, providing automatic evaluations of patients' performances about motor and cognitive functions. The clinician subsystem interface enables at any time the neurologists and the therapists to access data about their patients, evaluate their condition and get in touch with them if needed. Data produced by the patient-side subsystem during the rehabilitation sessions are stored in the data archiving sub-system on the cloud and can be reviewed by clinicians through the clinician subsystem.

Categories and Subject Descriptors
J.3 [**Computer Applications**]: Life and Medical Sciences, *Health*, I.4 [**Image Processing and Computer Vision**] , (http://www.acm.org/about/class/ccs98-html)

General Terms
Algorithms, Management, Measurement, Design, Reliability, Experimentation, Security, Human Factors, Verification.

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Keywords
Tele-rehabilitation, upper limbs, adaptive motor/cognitive training, real-time hand tracking, color glove, RGB-D camera, Kinect©, exergames, neurological diseases, automatic evaluation, motion analysis, ICT platform, Cloud, file sharing

1. INTRODUCTION
The aging of the world population is leading to an increment of the occurrences of neurological diseases (e.g. Stroke and Parkinson's disease - PD), and consequently of costs for the National Health Care Systems [1]. Rehabilitation therapies may improve cognitive and motor functions and independence by slowing down the progression of disability with benefits on gait and balance [3][12]. Nevertheless rehabilitation is expensive [1], because it requires the intervention of professional physical therapists to assess its progress and correctness, and also it impacts on the quality of life of the patients and their caregivers by requiring many trips to hospitals or ambulatories. These aspects have motivated the development of new low-cost tools, based on ICT technologies, able to deliver rehabilitation services in ambulatories or at home, with a minimum supervision of therapist. PD motor assessment is currently based on home diaries and neurological examination during a check-up at the hospital, with a large degree of subjectivity because assessment relies on the patient's memory and physician's experience.

Tracking the patient movements during rehabilitation sessions is necessary to assess the correctness of the rehabilitation process [5], and several technologies are currently applied based on virtual reality [14], wearable sensor networks [4], passive and active vision systems [8][10][13]. A limitation of existing wearable sensor systems based on inertial measurement units is their difficulty to provide accurate hand and finger positional data. Recently optical low-cost body tracking devices (RGB-D cameras) have been introduced in gaming market (e.g. Kinect©) and have found widespread use in new rehabilitation systems both for gait analysis, limbs motion tracking and gesture classification [8][11], but tracking accuracy of these devices on hand and fingers is very low. More accurate hand and finger tracking approaches are based on sensorized gloves [6][7][13], but they often encumber the natural movement of the hand. In neurologic

diseases monitoring and rehabilitation, hand and finger tracking is important to evaluate frequent patients fluctuations and to validate the improvements due to the therapy. In Parkinson's disease kinematic parameters of hand and finger movements are related to motor scores of the Unified Parkinson's Disease Rating Scale (UPDRS)[2], and they can be used to assess the patient motor functions [16][17].

In this work we present a tele-rehabilitation solution for upper limb rehabilitation based on a novel Human Computer Interface (HCI) build on RGB-Depth camera (Kinect©), a monitor and gloves with color markers. The HCI uses both color and depth info to overcome some of the limitations of the previously described approaches, such as inaccurate tracking of hands and fingers movements, cost, lack of comfort for motor impaired patients and small working volume. The details of the innovative solution, its performance and future developments are discussed. Sec. 2 provides an overview of its architecture and functionalities, while Sec. 3, 4 and 5 describes respectively the patient subsystem, the cloud platform and the clinician subsystem, then Sec. 6 illustrates some of the interactive exergames developed for the remote rehabilitation and finally in Sec. 7 the future work are discussed.

2. AN OVERVIEW OF THE PROPOSED SOLUTION

The solution here presented is intended for patients suffering motor impairments due to neurological disease (e.g. Parkinson's). It delivers at home both standard neurological tests (UPDRS) and suitable exergames, providing an estimate of parameter values related to motor/cognitive impairments (See. Sec. 3) which are used to evaluate the patients' fluctuations. Additional services are supported, such as video tutoring and text-messaging with therapist. Several rehabilitation platforms suitable for neurological diseases have been proposed: wearable sensors [15], immersive devices for virtual environment [14], exoskeletons [21]. Recently RGB-Depth cameras (e.g. Kinect©) have been introduced in rehabilitation systems [8][10] and in exergame based system for rehabilitation [11].

The novelty of our solution is mainly related to the HCI, based on an innovative approach, which integrates color and depth information (see Sec. 3) and outperform most of the other solutions, in term of accuracy of real-time 3D hand/fingers motion tracking, size of the working volume, comfort, usability and cost effectiveness. As illustrated in Fig.1, the overall solution includes three main components: the *Patient Subsystem*, the *Clinician Subsystem* and the *Platform Management*.

The HCI automatically collects data about movements and choices of the patient, acquired while the rehabilitative exergames are performed. The level of difficulty of each delivered exergame is adapted to the patient status, which is preliminarily evaluated by means of UPDRS tests performed by means of the same HCI. Hand motion data are elaborated to extract information about patient condition and the results are sent to a secure cloud platform along with videos captured during the exergames execution. At any time the clinicians can access this information through a suitable web application and evaluate the conditions of their own patients. The following sections describe each of these components, focusing on the most innovative part, that is the hand tracking and motor parameters evaluation implemented in the patient subsystem.

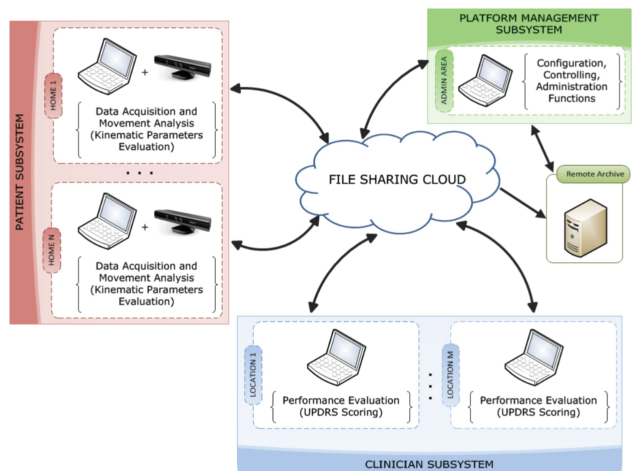

Figure 1 The sub-systems of the proposed solution

3. THE PATIENT SUBSYSTEM

The patient subsystem is composed of the HCI, the patient Graphical User Interface (GUI) and the software modules responsible for the two-way text messaging between patient and the clinician, data acquisition, data analysis and automatic scoring of the tests and exergames performed by the patient. During the rehabilitation session the GUI provides menus and submenus to select the type of activity (i.e. test or exergame) and the activity itself (e.g. finger-tapping) along with a simple questionnaire to input information about the self-perceived status (i.e. ON/OFF) and time from last drug assumption. All the selections and data input are performed by hand gestures and finger pointing through the HCI, hence avoiding keyboard or mouse input. This is an important aspect for patients suffering motor impairment and presumably with limited familiarity with PC and input devices. For those more skilled with technology and with minor motor impairments, a keyboard support is provided for messaging with clinicians. The GUI also supports video acquisition of the rehabilitation sessions and provides video, audio and textual guides to help the patients to perform correctly the rehabilitation sessions.

3.1 HW description

Our acquisition system consists of an *optical 3D device*, e.g. Kinect© from Microsoft©, providing synchronized RGB/DEPTH streams with 640x480x30fps resolution, connected via USB port to a medium-high performance PC or notebook. Additional equipment consists of *comfortable gloves with colored markers, shown in* Figure 2: each marker is in correspondence with a reference point of the hand (e.g. fingertips) and they are used to track their movements (3D trajectories) or to perform specific system functionality (e.g. light calibration or menu hand selection).

This solution responds to low-cost, real-time, non-invasive and user-friendly requirements, with an high performance in terms of accuracy and precision of movement measurement. This is achieved thanks to RGB-DEPTH data fusion, as described in the next subsection.

Figure 2 The Human Computer Interface Hardware

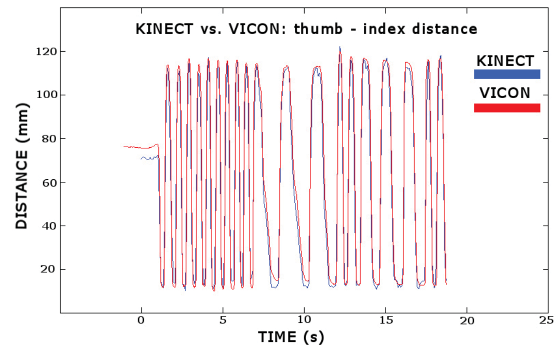

Figure 3 HCI vs. optoelectronic system comparison of measured finger distance during the Finger Tapping exercise

3.2 The motion tracking algorithm

The solutions based on optical devices are characterized by some limitations related to occlusions and ambient-light conditions. Therefore, usually they are not applied in uncontrolled environment.

In our solution we use soft and light gloves, suited for movement-impaired subjects. The gloves are black and have a set of colour markers (i.e. colour, shape and position), designed to be easily tracked in different environmental light conditions by a light-compensation algorithm. The colours of the marker are chosen to be maximally separated in the HSV colour space [22] to allow accurate recognition by means of colour-threshold segmentation algorithms.

Colour segmentation requires a coarse, preliminary image brightness adjustment obtained by tuning the gain of the RGB camera. Then a fine adjustment is performed according to the average brightness measured on the white circular marker on the palm. Its 3D centroid is used as starting hint for hand detection and tracking by the middle-layer library (e.g. OPENNI) from the DEPTH camera information.. Hand centroids are used to determine 2D and 3D bounding box of the hand in both colour and depth images. This allows to run colour-segmentation algorithms only in a limited area of interest, reducing computational costs. The brightness of the white circular marker and its apparent colour due to the temperature of the environmental lighting are also used in image segmentation by loading the most appropriate set of HSV colour thresholds, which were experimentally estimated.

To improve performance of colours segmentation, the CamShift algorithm [22] is applied. A cumulative histogram made from the thresholded pixels is used to track in the 2D images the blobs of pixels belonging to the glove or to the different colour markers. A robust 2D position of the colour marker is then estimated as the centroid of the corresponding colour blob. The 3D position of each marker is obtained from the corresponding 2D one by the calibration parameters of the RGB-D camera.

3D trajectories of the markers have been proved to be consistent with those obtained by the optoelectronic system (VICON© MX, 6 TVC 100 Hz) as shown in Fig.3.

3.3 The evaluation of motor functions

In the previous subsections we have described the motion tracking system and proved its accuracy for real-time evaluation of hands and fingers trajectories in the 3D space. Consequently a number of kinematic parameters can be calculated in order to characterize the motor functions, for example in term of movement smoothness, average speed and correct execution of movements. Since an important goal of this system is the remote evaluation of the patient conditions, we developed a statistical model to support an automatic evaluation of a subset of UPDRS tasks, selected by a pool of neurologists from Istituto Auxologico Italiano, involved in the Vrehab project, namely: finger tapping, hand prono-supination and opening-closure. The first step is the selection of kinematic parameters to be used for getting evaluations as close as possible to those provided by neurologists when they apply this semi-quantitative evaluation scale. To this aim we applied the Principal Component Analysis (PCA) to data related to specific UPDRS tasks to retain the most representative parameters. For example in the case of finger tapping, we reduced the parameters from the original 19 to a set of 5 (linear combinations), still retaining the 95% of the overall information. PCA was applied to data collected by means of our HCI from a pool of 80 Parkinson's patients, while they were performing the above mentioned type of tests. For each execution we also collected the UPDRS score assigned by the neurologists.

Figure 4 shows a radar chart based on the initial 19 kinematic parameters used for finger tapping. In this chart each colored line corresponds to an UPDRS score, while each parameter value X_i represents the average of the parameter values of patients which got a specific UPDRS score out of the overall pool of Parkinson's patients. These averages are normalized and scaled with respect to the average of healthy subjects, as shown in the following equation:

$$z_i = \frac{X_i - \mu_i}{\sigma_i} \qquad i = 1..19 \qquad \begin{cases} \mu_i - \text{mean of } i-\text{th parameter on all healthy subjects} \\ \sigma_i = \text{standard deviation of the } i-\text{th parameter on all healthy subjects} \end{cases}$$

Three different approaches, i.e. Naive Bayes, Linear Discriminant Analysis and Ordinal Logistic Regression Model [16], were used to train a classifier on the 80 patients by using the patient UPDRS scores assigned by 3 neurologists and the 5 parameters selected by the PCA. The Naive Bayes Classifiers (NBC) [23] gave the best results. The accuracy of the NBC classifier in assigning

correctly the UPDRS scores was tested by using the *leave-one-out* cross validation method, and it was found to be 46%. This is not surprising, considering that several neurologist scores differ of 1 UPDRS level, with an Intra Class Correlation (ICC) of 0.63 (*moderate* to *substantial* correlation). Strategies to increase the inter-rater reliability (e.g.as in [25]) are currently under consideration and they will be adopted in the future works. In our solution the UPDRS motor score is evaluated by the application shown in Fig.5. This score is used at the beginning of each remote rehabilitation session to set accordingly the exergame difficulty level and to scale the exergame scores, as illustrated in Sec. 6.

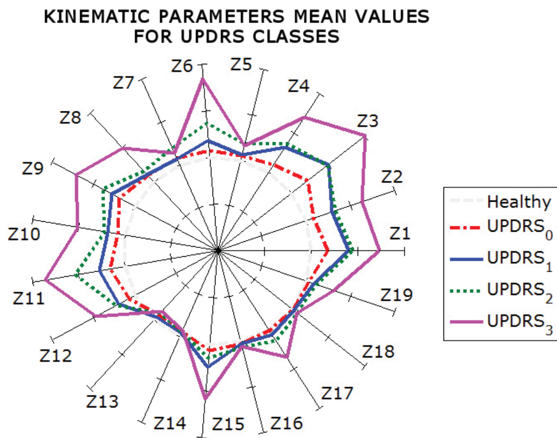

Figure 4 Kinematic parameters vs. UPDRS scores

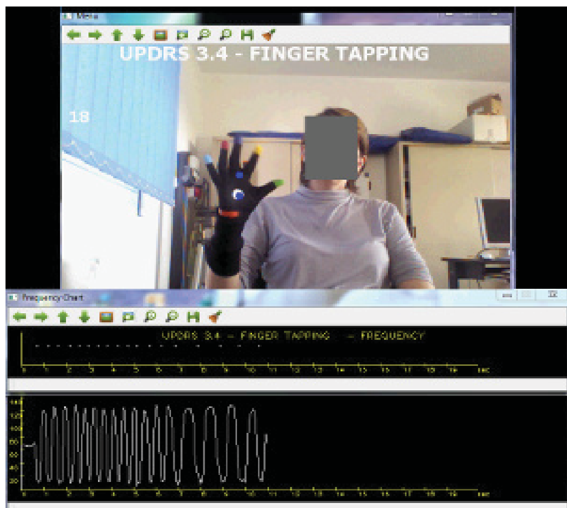

Figure 5 The patient GUI and the finger distance evaluated from finger trajectories (not shown to patients)

4. THE CLOUD PLATFORM

A fast prototyping approach was used to implement the main functionalities of the tele-monitoring and tele-rehabilitation service to evaluate its feasibility and to identify potential problems related to patient-to-clinician communication, the design of the database, the subsystems GUI usability and the engagement of the patients.

In this preliminary phase the data archiving was implemented on the Cloud by a commercial multiplatform file hosting service (Dropbox©) managed by the platform management sub-system. However our final goal is the integration of the patient subsystem, described in Sec. 3, in Nuvola IT Home Doctor, the cloud platform of Telecom Italia for e-health [18], along with other tele-rehabilitation solutions [19] currently under development. This will address the requirements of scalability and standard compliance, which have not been taken into account yet in this work.

The data produced by the patient subsystem during the rehabilitation sessions include videos, kinematic parameters, scores and messages. This data are automatically encrypted and stored in the file sharing cloud. The data produced by the clinicians subsystem may include UPDRS evaluations, messages to the patients and annotations.

The platform management sub-system is intended for supervising the file sharing systems, where patients and clinicians data, accounts and rights may be created, deleted and grouped. To reinforce the confidentiality of data, the identity data of patients where replaced with nicknames.

5. THE CLINICIAN SUBSYSTEM

The clinician subsystem implements the supervision and the validation of the rehabilitation sessions. Neurologists use a GUI (Fig.6) to access data about kinematic parameters, automatic scores, videos of the rehabilitation sessions, to manage messages from/to their patients and to configure exergames. Moreover, they can score UPDRS test performance.

Apart from medical evaluation, this score can be used to further train the algorithm used for the automatic UPDRS score estimation.

The input data of the clinician subsystem is automatically encrypted and stored in the file sharing cloud.

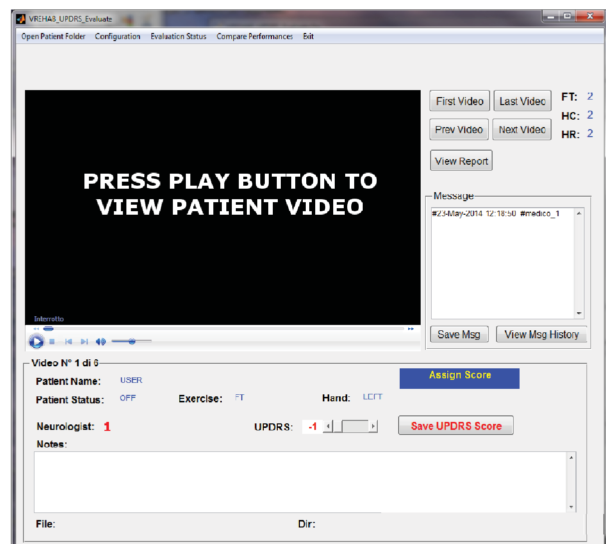

Figure 6 The neurologist GUI

6. REMOTE MONITORING TESTS AND REHABILITATION EXERGAMES

The solution described in the previous Sections can be used both for monitoring and rehabilitation purposes.

As discussed in Sec. 3.3, the Patient Subsystem can be used at any time to estimate the UPDRS score of upper limb motor tasks (e.g. Finger tapping). . This automatic assessment can be aimed at the remote monitoring of motor fluctuations or at adapting the exergame settings.

In the first case the remote monitoring data are stored in the Cloud Platform together with the neurologist evaluations, made during the outpatient check-up in the medical office. This is used by the neurologist to track the long-term evolution of the motor symptoms and accordingly modify the prescriptions about the therapy and the rehabilitation. In the second case, the estimate of the UPDRS score is used to set the level of the exergames: a too simple level can result boring and useless, while a too difficult level can be frustrating. Moreover, based on the patient conditions the score of the exergames can be suitably weighted, to prevent patient demotivation.

Exergames are widely employed in neurorehabilitation [9][20], with evident benefits for patients [12][13]. Some of the games commonly used by physical therapists during neurological rehabilitation sessions were extended to be played at home, without any therapist assistance. These new exergames were designed by a pool of neurologists of the Istituto Auxologico Italiano, by leveraging the 3D tracking and measurement capabilities of the HCI. The goal is to investigate additional motor and cognitive functions and to explore interaction between motor and cognitive impairments.

The current exergames are quite simple but they still require both motor and logical abilities. The patient plays the game by moving hands and fingers in the 3D space to perform a given task, taking into account the scene shown on the monitor. Typically the scene includes a number of lines and objects and the patient must follow them according to well defined rules: the characteristics of the objects, such as shape, size and colors, and the logical complexity of the rules can be set according to the estimated condition of the patient, to make the game challenging but not frustrating (Fig.7). Textual and audio support is available to help the patient. During the execution of an exergame, a number of relevant kinematic parameters are acquired, along with errors in logic, full accomplishment and duration of the game. These data are combined and suitably weighted to get the final *personalized* score. The exergame sessions are recorded and stored in the cloud platform: in this way the clinician can see at any time the video of the patient while he/she is executing the game, synchronized with the GUI seen by the patient, as illustrated in Fig.8 for the Spiral game. For each run, the clinician is provided with a number of kinematic parameter values and a diagram where the optimal trajectory is superimposed to the patient trajectories, as illustrated in Fig. 7b and Fig. 8b for the same game.

Some of the games, such as the Spiral game, are challenging for the motor aspects, but pretty simple concerning the cognitive aspects. In this case, the patient is requested to follow a spiral trajectory which appears on the screen with his/her finger tip, represented for visual feedback by a white dot in the GUI (see Fig.8c). The parameters evaluated are the ratio of the 3D path length to the ideal 3D path length (i.e. the spiral length) and the time to complete the game. Different level of difficulties is obtained by modifying the line depth and the number of turns of the spiral.

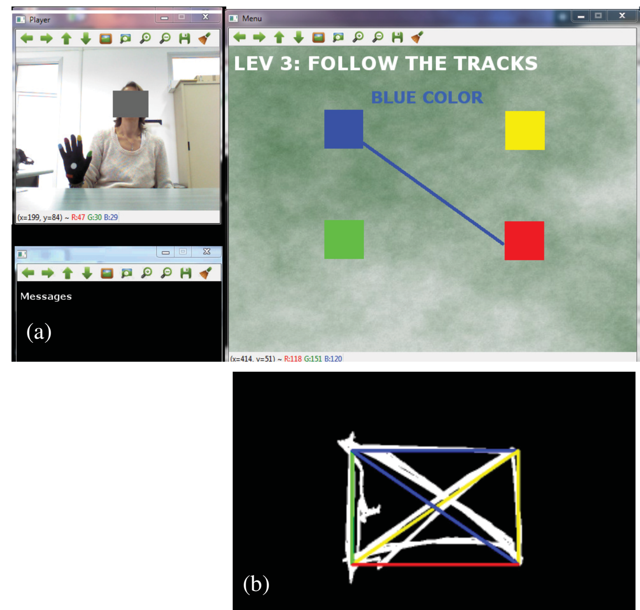

Figure 7 The cube tracing exergame and the associated finger trajectories

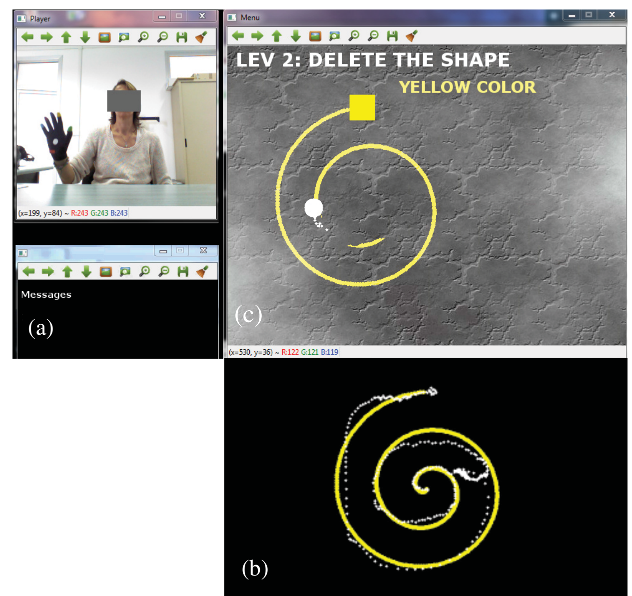

Figure 8 The spiral tracking exergame and the associated finger trajectories (white dotted)

An example of motor and cognitive challenge is provided in the game illustrated in Fig.7a. In this case the patient is requested to move his/her index following the blue objects: he/she must position his/her finger on a blue object and move his/her finger as fast as possible to reach the next blue object, when it appears on the screen. Different levels of difficulties can be obtained by increasing the number of objects represented at the same time in the scene, changing the dimension and color of the objects or their persistence in the scene. In this case the used metrics are the ratio of the number of correctly “taken” objects to the total number of objects, the index of curvature, calculated as the ratio between the

3D path length and the linear distance between to targets, and the statistics about the reaching time.

Finally we mention a game which involves 3D movements. When an object appears on the screen, the patient must position the index of a hand in correspondence of it (without touching the screen) and push it until it reaches the background. The objects are then dynamically resized accordingly. Different levels of difficulties can be obtained by changing the dimension of the objects and the range of motion required. The used metrics are the ratio of the number of correctly "pushed" objects to the total number of objects, the index of curvature, calculated as the ratio between the 3D path length and the linear distance between the original position and the background, and the statistics about the pushing time.

7. CONCLUSIONS AND FUTURE WORKS

We have presented a solution based on an innovative HCI to deploy services of remote monitoring and tele-rehabilitation for PD patients.

At the beginning of each tele-rehabilitation session the status of the patient is evaluated by means of the remote monitoring features and the game's difficulty level is set according. The exergames have been designed by neurologists, by adapting exergames commonly used by physical therapists to make them suitable for the unassisted execution at home. These new games are intended both to train cognitive and motor functions and to investigate their relationship.

The paper describes the overall solution, focusing on the most innovative part that is the HCI of the Patient Subsystem which is particularly user friendly, suitable for elders and motor impaired patients. The HCI has been proved to be able to precisely track hands and fingers movements in the 3D space.

This first phase of the work was focused on the automatic evaluation of the motor functions (UPDRS scores), the exergame design, the logic to be used to automatically set their difficulty level according to the current patient condition and the parameters to be used to evaluate the patient performance.

In order to make the exergames more enjoyable and increase the patient compliance, the graphical aspects should be improved and the games should be implemented in a full 3D graphic environment.

Then an extensive validation of the exergames and their self-adapting mechanism should be done with respect to standard clinical scales used to assess motor/cognitive deficits.

Samples of subjects which are statistically representative of patients with differentiated levels of motor and cognitive impairments will be involved in the validation experiments. Furthermore, other types of classifier (e.g. Support Vector Machine) will be considered.

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