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A Novel VR-based Upper Limb Rehabilitation Robot System

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***Abstract* - This paper presents a novel upper limb rehabilitation robot system based on virtual reality as many benefits of robots involved in upper limb rehabilitation for stroke are found out. The system has advantages of small size, less weight and interaction in rehabilitation. This system mainly consists of a haptic device called PHANTOM Premium, the upper limb exoskeleton rehabilitation device (ULERD) and a virtual reality environment. The impaired hand wears the ULERD, so the therapist can control and move the injured hand by PHANTOM Premium in tele-operation. With description of the system, the realization of virtual reality environment is implemented, which can potentially motivate patients to exercise for longer periods of time. Not only virtual images but also position and force information are sent to the doctors. This system aims to develop a light and interactive upper limb rehabilitation robot system which allows rehabilitation stations to be placed in a patient's home. And some exercise parameters evaluate the performance of patients. Experiment has been conducted to prove that it is accurate and convenient in the rehabilitation process. The development of this system can be a promising approach for further research in the field of tele-rehablitation science.**

Key words: Upper limb rehabilitation robot, Virtual reality, Tele-rehabilitation

I. INTRODUCTION

Stroke and cerebrovascular accident are the leading cause of illness in particular affecting older people. In present-day Chinese society, stroke is a serious threat to the health of the elder, because its incidence increases year after year. From 2020, aging populations in China is expected to increase with the average staying above 6.2 million a year and jump to almost 400 million until 2050, which means the incidence of stroke in the country will rank first in international comparison. It is good for employing robots in upper limb rehabilitation process for their efficacy and economy.

MIT-Manus, the first one of famous upper limb rehabilitation robots, was developed by Hogan and Krebs in 1991, which offering a highly back-drivable mechanism with a soft and stable feel for the user [1]. In 1999, Reinkensmeyer and his team members designed a robot named ARM-Guide. As a diagnostic tool the robot could provide a basis for evaluation of several key motor impairments, as a therapeutic one it could also provide a means to implement and evaluate active assist therapy for the arm [2]. MIME was implemented by Stanford University. Chronic stroke patients had significant improvements in isometric strength, free reaching extent, and clinical evaluations of function after training with MIME [3]. Gentle/s was a project under the Quality of Life initiative of the framework five of the European Community with aim to improve quality of treatment and reduce costs. Different with robots mentioned above, Gentle/s had made satisfactory effect in clinical application due to a virtual reality environment where subjects can be manipulated [4], [5]. In 2007, a new semi-exoskeleton robot called ARMin for arm rehabilitation has been developed and tested by Nef in university Zurich. ARMin had a semiexoskeletal structure with six degrees of freedom (DoFs), and it was equipped with position and force sensors [6], [7].

The rehabilitation robot research in China has also attracted scientific and technological workers. Yuchuan Hu and Linhong Ji developed an upper limb compound training rehabilitation robot for hemiplegic patients in Tsinghua University [8]. A rehabilitation robot with force-position hybrid fuzzy controller was designed in National Cheng Kung University in Taiwan. The robot was able to guide patient’s wrist to move along planned linear or circular trajectories [9]. A novel Internet based tele-rehabilitation exercise manipulator was presented in Southeast University. The doctor could remotely control the manipulator to help the upper limb injured [10].

Although these systems have some advantages and are contributive to the restore of upper limbs of patients, but the bodies of robotic devices are so large that it is not convenient to rehabilitate at home. Furthermore, rehabilitation process with these robots seems tedious and boring to patients if training time is so long. So it is necessary to design a light and interactive upper limb rehabilitation robot system which allows rehabilitation stations to be placed in a patient's home.

In this paper, an upper limb rehabilitation robot system based on virtual reality has been designed in our lab to make attempt to solve some existing problem mentioned above.

II. EXPERIMENTAL SYSTEM

In this unit, the experimental system used in this study is presented. The system includes PHANTOM Premium 1.5, ULERD, and allowing patient’s interaction with a virtual reality environment.

A. Haptic Device (PHANTOM Premium 1.5)

The PHANTOM Premium 1.5 (SensAble Technologies) has been widely recognized as the finest 3 DoFs force-feedback device available. As a master part manipulated by doctor, PHANTOM Premium 1.5 is chosen and applied in the system successfully provide force feedback to the stylus (Fig. 1). The large workspace of the product (19.5x27x37.5cm) is a guarantee of moving upper limb in a big space.

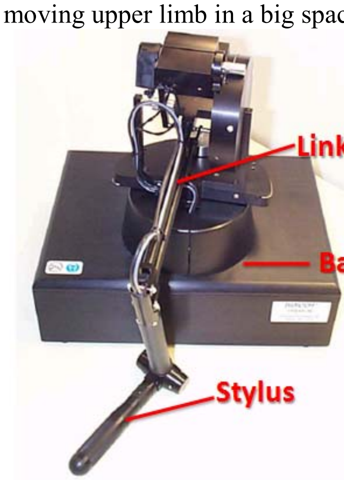

Fig. 1 PHANTOM Premium1.5 haptic device（SensAble Technologies）

B. The Upper Limb Exoskeleton Rehabilitation Device (ULERD)

The motivation of design the ULERD is to provide effective training to the patients with motor dysfunction to recover the motor function of upper limb including elbow and wrist joints. The ULERD is ergonomically comfortable. Meanwhile, it is the aim to design such a wearable and portable device. Design process of ULERD can be obtained in detail from reference [11]. The structure of the ULERD from upper view is showed in Fig. 2. ULERD has three active DoFs including the elbow flexion/extension, forearm pronation/supination and wrist flexion/extension in elbow and wrist joint. Furthermore, an additional four passive DoFs are added to the elbow and wrist joints to correct any misalignment between the human and device joints.

Due to comfortable and suitable for home-rehabilitation to patients, it is necessary to decrease the mass of such device as light as possible. BLDC motor (Maxon Technology) which is used for the ULERD for its high power density to decrease the mass of the device. Meanwhile, main frames of this device are made of aluminum board. The total weight is 1.3kg.

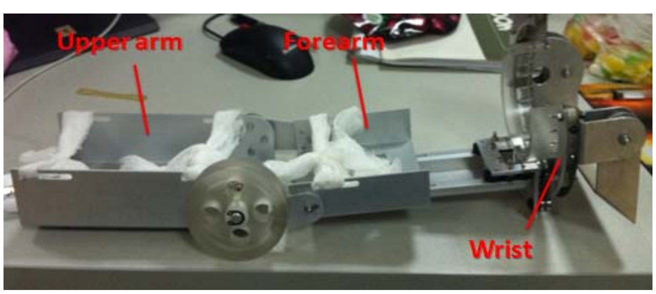

Fig. 2 The prototype of the upper limb exoskeleton rehabilitation device

C. Operation Principle of The Robot System

The upper limb rehabilitation robot system proposed in the paper is a tele-rehabilitation system where the Internet can be used for data transfer, allowing a therapist to remotely monitor progress and to change the patient's movement [12]. Composition of the system is shown in Fig. 3. The system mainly consists of a master part and a slave part. The master part is a haptic device PHANTOM Premium and the slave part is ULERD [13]. The slave part coordinates with the master part with a PC-based virtual reality system (Fig. 4). The impaired hand is hard bolted to the ULERD, so the rehabilitation therapist can move the stylus of PHAMTOM Premium and guide the injured hand to move along certain of predefined training track in tele-operation.

In order to keep safe and assess the experimental results, a force sensor is fitted to the forearm plate by which can detect the general contact force. The MTx sensor is chosen to get the accurate pose information of patient's impaired hand.

In the system, the hand of doctor can be used to assist the injured hand of patient in the rehabilitation. When the injured hand has recovered gradually, the assistance from doctor can be decreased slowly, until there is no assistance.

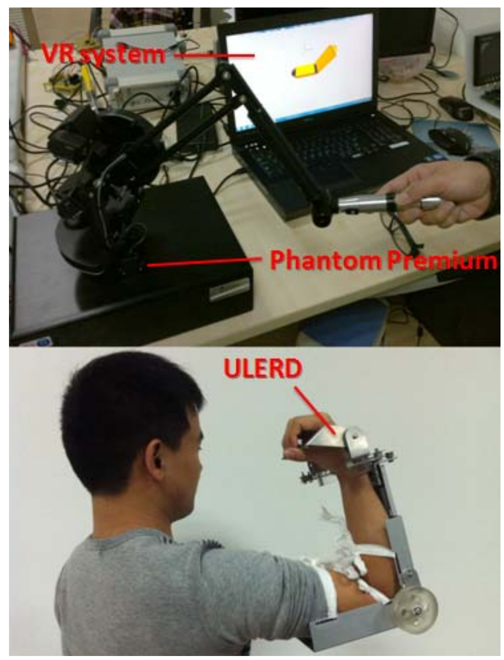

Fig. 3 Composition of the upper limb rehabilitation robot system

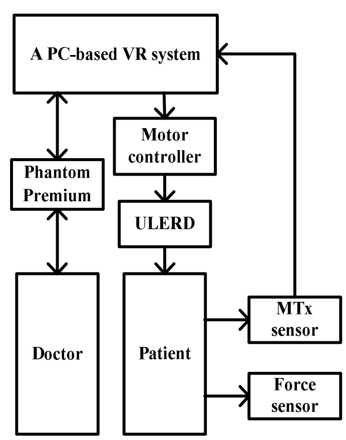

Fig. 4 Block diagram of the upper limb rehabilitation robot system

III. Realization of Virtual Reality

According to the vision feedback and force feedback, the therapist can adjust his operation. Virtual reality technology can provide repeated practice, performance feedback and motivation techniques for rehabilitation training [14]. Patients can learn motor skills in a virtual environment, and then transfer the skills to the real world.

In this unit, the realization of virtual reality for rehabilitation hand function in stroke patients will be concentrated and it is hopeful to achieve satisfactory outcome in the future.

A. Structure of Virtual Reality system

Classical haptic rendering system for virtual reality mainly consists of the haptic device, the human operator and the simulating environment (Fig. 5) [15]. In Fig. 5, X is the position value of end-effector, S is the speed information of end-effector by differential computing the position value X, Fd is the ideal force from calculation, Fr is the force of motor control from the controller. These variables mentioned above are all vectors. As a kind of human interface, haptic device is not similar with the keyboard or mouth that we are familiar with. It sends the information, such as positions or actions of the operator, to virtual environment and feedbacks force to operator, by which operator can feel and manipulate the object successfully in virtual environment. The simulating environment mainly realizes HMI (Human-Machine Interaction), visual rendering, haptic rendering, etc. The scene of virtual environment can be created by OpenGL graphics library or other 3D modeling software (eg.3DSMAX). Virtual environment, as the core of control unit, makes functional modules of the system work harmonize with one another.

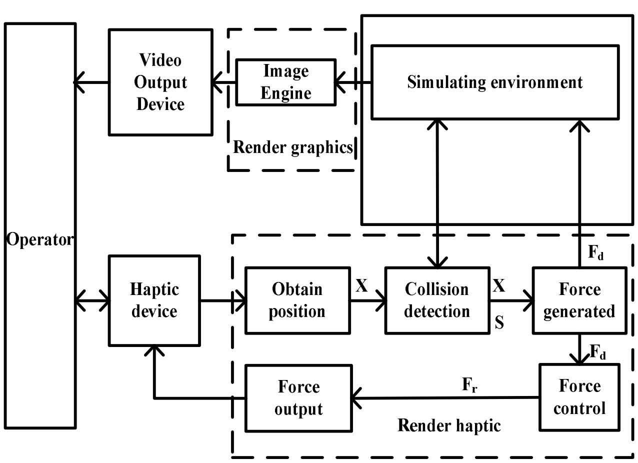

Fig. 5 Block diagram of haptic rendering system for virtual reality

B. Scene of Virtual Simulating Environment

A simple 3D virtual simulating environment which represents an empty room and intends to provide early stroke subjects with awareness of physical space and movement is created. The environment and virtual objects are rendered by using OpenGL and VC++.

One virtual upper limb and a coordinate Axis are created in the virtual environment (Fig. 6). At the beginning of the study, the virtual upper limb mainly consists with one ball and two cubes. The experiment requires operator to manipulate the stylus of PHANTOM Premium to make the motion of virtual arm to follow the device. The patients can train in an elbow joint training mode. In our experiment, performance focusing on the elbow joint is discussed.

Subjects are able to adjust the position of upper arm in a real environment in order to comfortably and efficiently rest the impaired hand of patients to acquire elbow training targets. At the beginning of training, the position of upper arm can be adjusted to match in the virtual environment as well (Fig. 7).

The overall software flow chart for the PC rehabilitation virtual reality system is shown in Fig. 8. The real-time 3D position of point on the stylus can be sampled by the PHANTOM Premium. During the trials, the patient is shown a graphical model of his own hand, which is updated in real time to accurately represent the flexion of his elbow. Flexion angle is calculated by inverse trigonometric function and position of stylus.

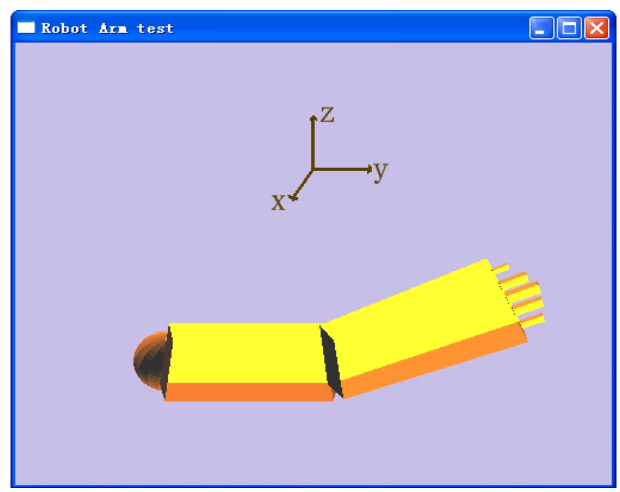

Fig. 6 The virtual environment of experiment 1

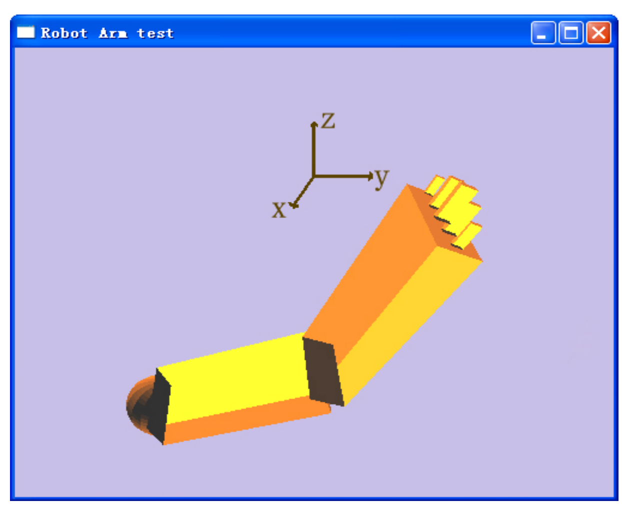

Fig. 7 The virtual environment of experiment 2

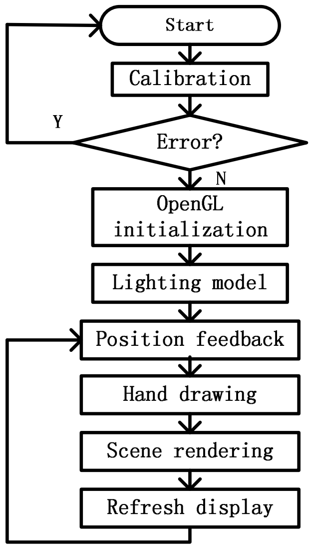

Fig. 8 Software flow chart of VR interface

C. Performance Evaluation

During range trial, the exercise parameters are estimated in order to provide feedback to the patient. After the trial has been completed, data collected on the patient's movements are reevaluated and stored into the database.

The patient's performance is calculated after several trials. As shown in Fig. 9, θ represents the flexion of elbow which is 0-150° in normal range. The range of stoke patients, however, decreased dramatically.

For the range-of-motion exercises, the flexion angle of the elbow is considered to be the mean of the maximum and minimum joint angles. The performance measure is

$$M = \frac{\sum_{i=1}^{n} (\max\theta_i - \min\theta_i)}{n}$$

where n is the numbers of exercises. To reduce fatigue, n is always less than ten.

Fig. 9 The schematic of elbow range trial

Fig. 10 shows the elbow rotation angle of the left limb in the real environment and in the virtual simulating environment respectively. The vertical axis stands for the angle, and the horizontal axis stands for the time. The green line represents elbow angle of ULERD worn in the hand when manipulating the Phantom Premium, the red line represents rotation angle of Phantom Premium. Form the blue line in Fig. 11 which stands for the error between two angles, we can learn that the rotational angles detected by the Phantom Premium, were close to angle of upper limb in real environment detected by protractor. Therefore, the environment in the experiment can provide patents with the accurate and effective messages.

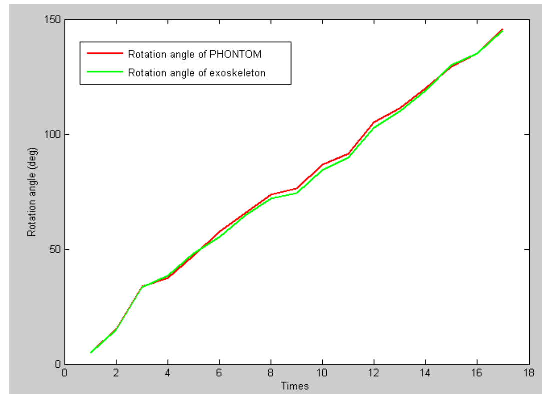

Fig. 10 Line graph of elbow rotation angle

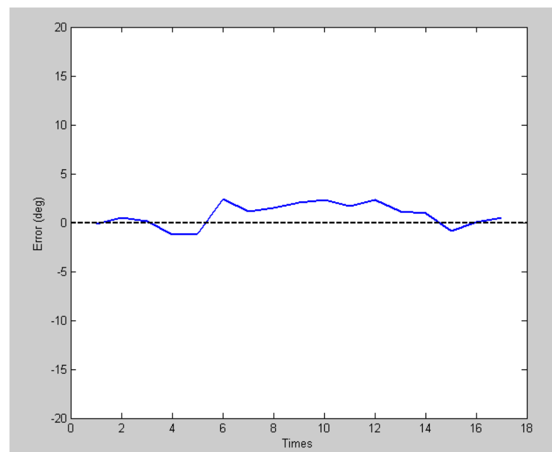

Fig. 11 Line graph of error between elbow rotation angles

IV. Conclusion and Future Work

In this paper, a novel upper limb rehabilitation robot system based on virtual reality is proposed. The system based on virtual reality is so light and interactive that it is suitable for home-rehabilitation. The master part is a haptic device and the slave part includes ULERD. The injured hand wears the ULERD, so the therapist can control and move the hand by PHANTOM Premium in tele-operation anywhere. A preliminary 3D interface is created by using OpenGL and VC++ in experiment. The virtual reality environment makes the training process more visible and interactive. Furthermore, virtual reality environment can potentially motivate patients to exercise for longer periods of time due to the encouraging words and sounds. And some exercise parameters to measure performance of patients is put forward. Experiment has been conducted to prove that the system is accurate and convenient in the rehabilitation process. So, it is effective for this system to apply in the tele-rehabilitation at home.

The proposed system is not fit for severe stroke patients such as the patients with hemiplegia. It is mainly fit for mild stroke patients. And more joint range and force exercise should take into consideration.

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