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Architectural Design of a Cloud Robotic System for Upper-Limb Rehabilitation with Multimodal Interaction

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Abstract The rise in the cases of motor impairing illnesses demands the research for improvements in rehabilitation therapy. Due to the current situation that the service of the professional therapists cannot meet the need of the motor-impaired subjects, a cloud robotic system is proposed to provide an Internet-based process for upper-limb rehabilitation with multimodal interaction. In this system, therapists and subjects are connected through the Internet using client/server architecture. At the client site, gradual virtual games are introduced so that the subjects can control and interact with virtual objects through the interaction devices such as robot arms. Computer graphics show the geometric results and interaction haptic/force is fed back during exercising. Both video/audio information and kinematical/physiological data are transferred to the therapist for monitoring and analysis. In this way, patients can be diagnosed and directed and therapists can manage therapy sessions remotely. The rehabilitation process can be monitored through the Internet. Expert libraries on the central server can serve as a supervisor and give advice based on the training data and the physiological data. The proposed solution is a convenient application that has several features taking advantage of the extensive technological utilization in the area of physical rehabilitation and multimodal interaction.

Keywords cloud robot, multimodal interaction, motor rehabilitation, haptic/force feedback

1 Introduction

Stroke is one of the leading causes for disability worldwide. Motor function deficits due to stroke affect the patients' mobility, limit their daily life activities and participation in society, and lead to their odds of returning to professional activities. All of these factors contribute to a low overall quality of life. Rehabilitation training is the most effective way to reduce motor impairments in stroke patients[1-2]. Though the efficacy of some interventions for motor skill learning may be under debate, some new technological approaches give promising outcome prognosis in stroke motor rehabilitation.

First, an increasing number of robotic devices have become available for post-stroke rehabilitation[3-5]. Not only is the robot a good substitute of a therapist for performing suitable exercises on the injured person but also it can perform repetitive and case-oriented exercises that are hard for the therapist to carry out. Repetitive and task-oriented exercises can improve muscular strength and movement coordination in patients with impairments due to neurological or orthopedic problems[6]. Researchers have developed several robot-assisted rehabilitation therapy systems, such as MIME[7], ARM Guide[8], MIT-MANUS[9], UECM[10], the Bi-Manu-Track[11], the In-motion Shoulder-Elbow robot[12] and Barret Arm Based Rehabilitation robot[13-14]. The main advantages of using robot-assisted therapy are to deliver high-dosage and high-intensity training and to acquire precise training data[15]. In order to assist the stroke pa-

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tients during rehabilitation therapy, robotic aids can provide programmable levels of assistance, and automatically modify their output based on sensor data using control frameworks[16-17]. Carpinella *et al.* evaluated the feasibility of a robot-based rehabilitation protocol for the improvement of upper limb motor coordination[18].

Second, the Internet and cloud computing play an important role in motor rehabilitation. Improvement in joint mobility may not be long-term and patients cannot receive professional supervision and well-controlled schemes when they do various exercises themselves. For both patients and therapists, there is a need for a system that can stretch and mobilize the joints accurately, reliably, and effectively. As the results of the increasing cost of healthcare for stroke patients, the idea of home-based or community-based therapy is gaining popularity. The invention of the Internet and cloud computing provided convenient and cost-effective platforms for performing tele-treatment and tele-assessment for the impaired limbs of stroke patients and is rapidly changing traditional robot-assistive rehabilitation infrastructures. In recent tele-rehabilitation structures, there are a variety of architectures proposed[19]. Huijgen *et al.* investigated the feasibility of a tele-rehabilitation intervention for arm/hand function (H-CAD training) in a home setting[20]. Researchers have developed some Internet-based tele-rehabilitation robot systems to bridge the patients at home and the therapists at rehabilitation service, and to provide distance support, assessment, and intervention to individuals with disabilities[21-24].

Despite the great potential of new therapy models enabled by the integration of robots and the Internet, there is little concern to construct an operating tele-rehabilitation system that allows the multimodal interaction between the patients and the therapists, and individuation settings by taking advantage of cloud computing. In this paper, a novel architecture of a cloud robotic system for upper-limb rehabilitation with multimodal interaction is designed. In this system, the therapist can direct and monitor impaired patients to do rehabilitation exercises assisted by remote controlled rehabilitation robots. This system consists of a web-based server computer for therapists at hospital, one or more telerehabilitation robots respectively connected to their own different client computers for patients at home or in nursing home, and computer networks as bilateral information transmission line between the server computer and each of the client computers.

This paper is organized as follows. In Section 2, we present a framework of the cloud robotic system for upper-limb rehabilitation. Then we describe the hardware and software design of the tele-rehabilitation robot system in Section 3. In Section 4, we discuss the preliminary experimental results. Finally this paper is concluded in Section 5.

2 Framework of Cloud Robot System for Rehabilitation

The rehabilitation robotic system consists of a cloud central server, several therapists as the server and one or more patients as clients that may be distributed in towns and villages, in the community, at home and so on, as shown in Fig.1. All the patients and the therapists are connected to the central server through cloud so that the therapist can monitor and direct the rehabilitation progress remotely. Each client rehabilitation station may be different but includes a computer, a web camera and a microphone, a robotic arm attached with position and force/torque sensors, and the controller of the robotic arm. The client rehabilitation station receives the commands from the server, and detects the dynamic and physiological information as well as videos and audios. Then the client computer sends the information to the server during exercising. There is a PC at the server site to control/monitor the clients, to analyze data and assess the status of the patients, and further to adjust the training parameters or to optimize therapy scheme. The therapists can also monitor the training by the mobile terminal. Patients log on the remote server from the local client computers using the web or executable program, while therapists receive the requirements from the patients and dialogue with the patients in video communication. According to the history records of the rehabilitation performance in database and the current status the patients submitted, the central server can give advice by the expert libraries. Consulting diagnostic advising of central server, the therapists can remotely set the treatment plan and control parameters of each rehabilitation robot for each patient according to comprehensive dialogue results and history records. Then the rehabilitation robot receives the commands from the therapists, and automatically guides the movement of the impaired upper limb in different modes, such as active training with damping force, passive training with drag force. In this way, the patients can receive professional treatment comfortably and economically.

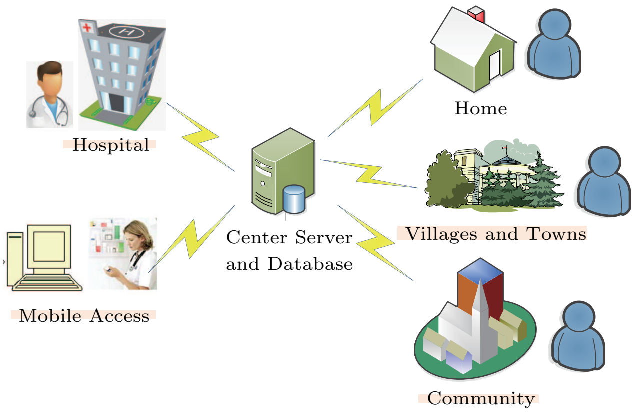


Fig.1. Framework of cloud robot for rehabilitation.

3 System Architecture

Fig.2 depicts the system architecture of the proposed system for the upper-limb motor rehabilitation, which consists of a server computer in the therapist service, three rehabilitation robots distributed at different client sites, three client computers for robot control, and computer networks which connect the central server, the client computers and the server computer or the mobile terminal. At each patient site, the upper-impaired subject can do excises with the assistance of a robot. Users log on to the system, perform a customized program of the therapeutic activities, and receive the quantitative feedback of their rehabilitation progress. A webcam and a microphone are connected to the client computer, which acquires video and audio information during the training process and sends them to the server computer in the therapist service through the Internet. Both kinematic information such as displacement and interaction force between the subject and the robot and physiological information related to training such as respiratory, oxygen saturation (SpO2) and blood pressure are detected and sent to the therapists. On the other hand, the therapists can monitor and control the robot by either the computer or the mobile terminal. All information is received and recorded by the computer at the server site, including not only the video/audio but also the kinematics and dynamics information of the patient arm such as movement speed, velocity peaks, and the interaction force between the arm and the robot feedback from the client computer. A database is built in the server computer to record the history and current data of each patient performance and rehabilitation training effects, which is important for the therapist when he/she remotely initializes the training mode and control parameters or the rehabilitation training of each patient. The video is displayed on the screen and the kinematic and physiological information is illustrated in curves so that the therapist can understand and assess the current status of every subject. But when the therapist monitors by the mobile terminal, he/she should switch to one subject at one time and only audio and sententious parameters are received from the server computer. According to the

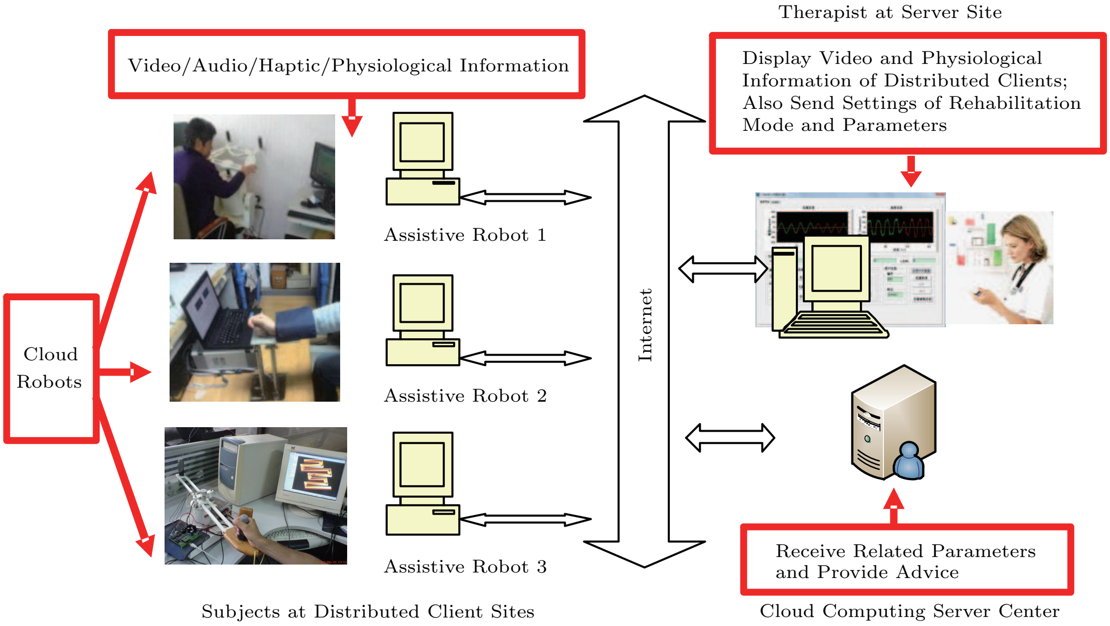


Fig.2. Diagram of the proposed system.

personalized information, a remote therapist can simultaneously monitor subjects' rehabilitation progresses, evaluate each patient's performance, make changes to each exercise program, and provide information and encouragement to each patient. Individual training mode and control parameters are remotely set or modified by the therapist through the server computer over the Internet.

The multimodal interactive information flow of the proposed system is demonstrated in Fig.3. The client station controls the robot, acquires videos and audio, collects the kinematic and physiological information, visualizes and shows data curves and connects with the servers through the Internet. The patients can view the VR-based rehabilitation, feel the interaction force between the avatar and the virtual object, and listen to the sound feedback from the therapist and the game. The therapist server sends treatment plans and controls parameters, receives videos and audio to display, receives data and sends them to the cloud center server. The cloud center server receives data, saves, computes and compares the indication, and sends advising of the expert library to the therapist server.

3.1 Client Station

3.1.1 Assistive Robots

In our tele-rehabilitation robotic system, the assistive robot is usually used at home or in nursing home, thereby it should be safe, inexpensive, and convenient to use. We develop a double parallel-linked, back-drivable robot for upper-limb rehabilitation system, which consists of DC torque motors, encoders, a force/torque sensor, a robot arm, a support tray, a handle, etc. Fig.4 shows the upper-limb rehabilitation robot prototype.

During the passive rehabilitation training, the patient's upper limb holds the handle and puts his/her wrist on the support tray at the end of the robot arm. The robot drives the human upper limb to do the repetitive movement circularly under the control of client PC. An optical encoder with the resolution of 500 pulses per revolution, manufactured by Agilent Technologies Incorporation, is used as the position sensor to measure the movement of the rehabilitation robot arm, and a 4-dimensional force/torque sensor developed in [25] with the measurement precision of 1.5% F.S. is installed between the motor shaft and the rotation axis of the robot arm to measure the interactive force between the rehabilitation robot arm and the patient arm during the training process of the post-stroke patient. In this way, the therapist can monitor the movement and interaction force, assess the status of the subject and can adjust the training mode and parameters in time. Fig.5 shows the multimodal interaction at the patient client. The rehabilitation robot assists the patient to exercise and training-related information is acquired and sends to the therapist server through the Internet. In the other hand, the client controller receives the setting from the therapist and controls the robot to work.

3.1.2 Training Modes

There are four training modes provided by this system for post-stroke patient rehabilitation, including passive mode, active mode, assistive mode and resistive mode. Under the passive training mode, the thera-

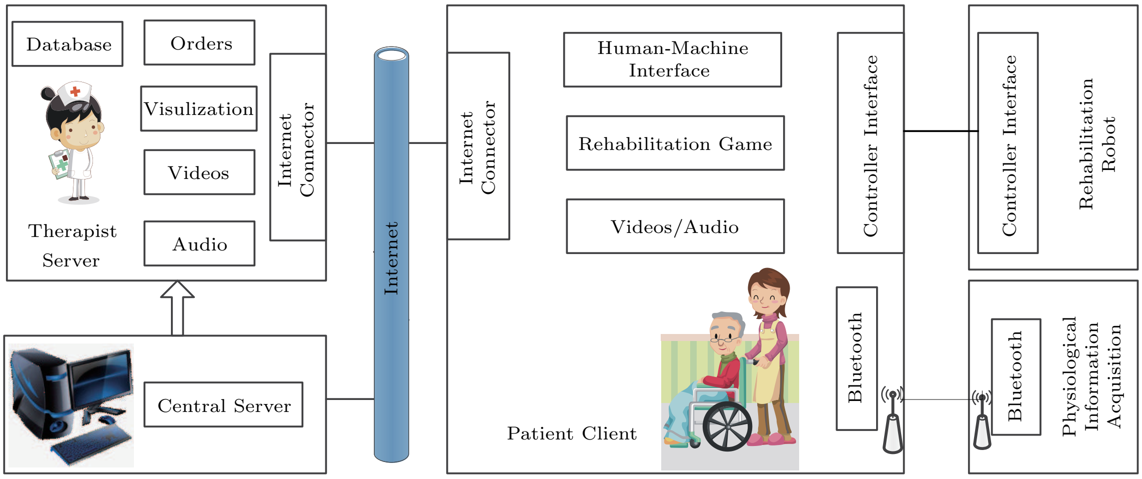


Fig.3. Multimodal interactive information flow of the proposed system.

pists set the velocity and the maximum output of the motor to avoid the injury of the impaired upper limb. The commands are sent to the robotic device control PC through the Internet. The patients are guided by the robotic device in its working space according to the preset velocity and trajectory of the therapists. This mode is designed mainly to the patients without muscle motor. Under the assistive mode, the patients accomplish the preset trajectory with the assistance of the robotic device. This is desirable because it will allow each patient to achieve a movement objective, but with the least amount of or "just enough" assistance. The output of the motor depends on the errors between the current position and the preset goal position. In our system, a PD controller is used to get the output of the motor. Under the active training mode, the subject can exercise actively by moving the robotic device freely. The robotic system acts as a tool to measure the trajectory and the interaction force between the impaired upper limb and the robotic arm, which is used to analyze the rehabilitation status of the patients. This mode is used to test and assess the muscle motor function of the patients. In this system, a virtual-reality (VR) based game is built to provide visual and haptic feedback. When the subject exercises with the robot, the position information is detected and used to control an avatar in virtual rehabilitation game. If the avatar in the VR contacts with virtual objects, virtual interaction force is calculated and sent to the controller of the robot and the torque motor produces a proportionate force so that the subject can observe the effects of his/her motion and feel the interaction between the avatar and the virtual objects just as his/her arm interacts with the actual object. Under the resistive mode, the patients try to achieve the goal position by overcoming the resistance generated by the motor. The resistance varies with the status of the patients in order to realize effective therapy. This mode is mostly used by the patients who want to improve the muscle motor function.

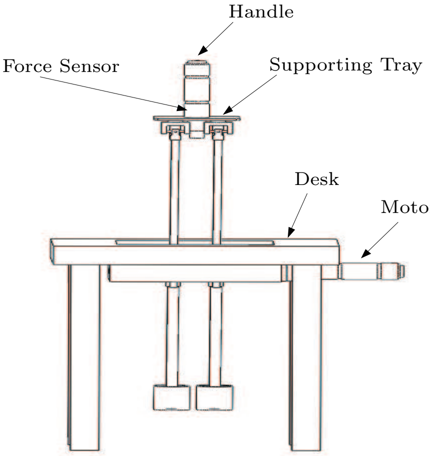


Fig.4. Upper-limb rehabilitation robot prototype.

3.1.3 *Interface of Client Computer*

Rehabilitation medicine research shows that the active training mode is most conducive to improve the central nervous system tension. Active mode of rehabilitation training is a gradual and perseverance process so that stroke patients with lower limb function

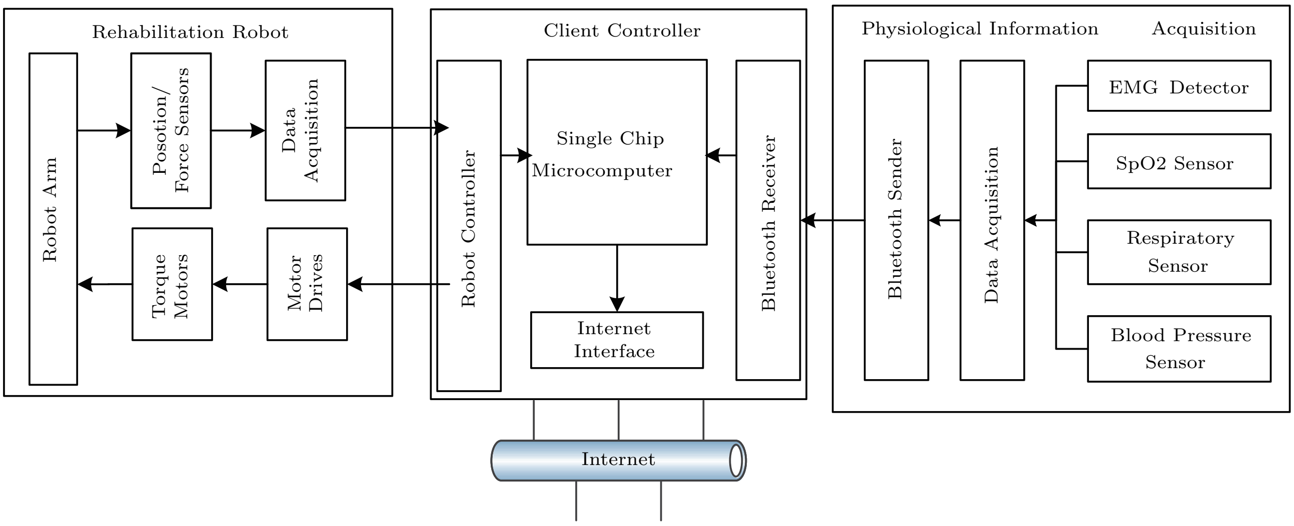


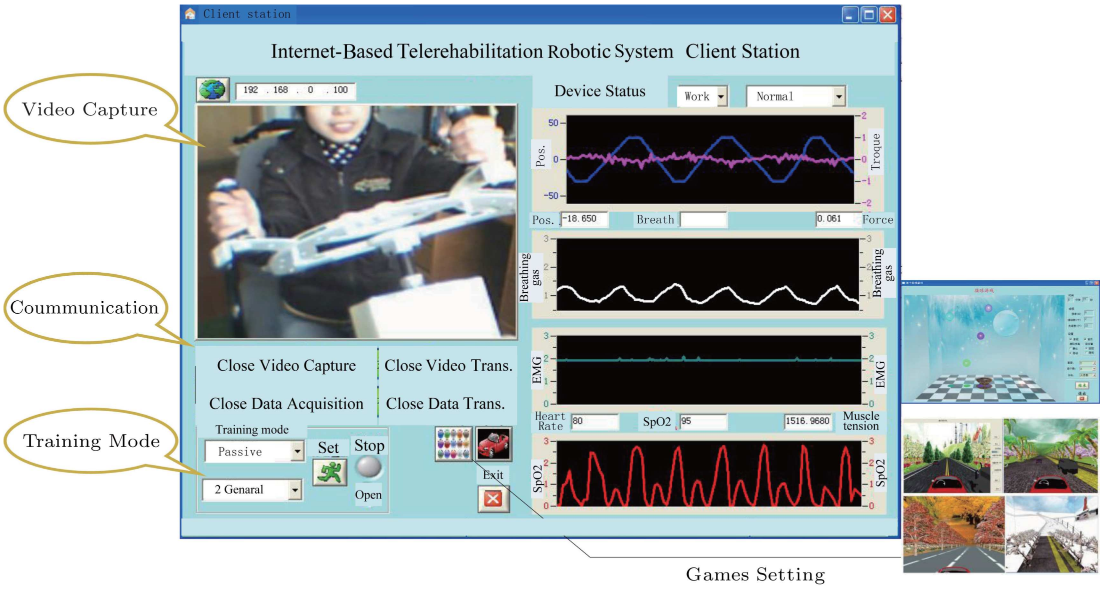
Fig.5. Functional diagram of multimodal interaction.

would be tired of long-term training. Here we design a VR-based interactive rehabilitation game for active training using openGL to attract the patients to exercise. Game parameters can be personalized according to the specific status of patients and different stages of rehabilitation training settings. Patients can choose different difficulties of the game according to their own appropriate rehabilitation training status. During the course of the rehabilitation training, the position information of the patient is collected as an input parameter of the game by the encoder to control the movement of the target object in VR. At the same time, the force of the virtual avatar is calculated and fed back so that the patient can feel his/her motion better. Also, rehabilitation game score can be used as one of the parameters to evaluate the rehabilitation training.

The client operation window contains functional areas such as data monitoring, server connection, control parameters, game interface and status bar, shown in Fig.6. On the client interface, video and data monitoring function areas display video and data, respectively. The displayed data contains force data and position data shown as curve graphs. Server connection area can set server IP and port number. When the server computer is running, a message box for signing in will pop up on the client computer screen. After a user inputs his/her account and password for login, the server confirms the data and establishes a connection to the client computer, and then establishes video and audio connection.

After the server remotely sets the rehabilitation training mode and control parameters for clients, the control parameters area displays the parameters of training mode. In the game interface, a virtual basket on the virtual ground is controlled to catch the falling balls by the patient arm through the rehabilitation robot. The therapist can remotely change the dropping speed of balls and the damping force of baskets according to the patients' current performance. The status bar at the bottom displays video, data and voice connection status in real time.

While the subjects exercise with virtual games assisted by robots, the interaction includes the following three channels. 1) *Visual Interaction*. The movement of avatar in the virtual game reflects the movement state of the limb and its interaction with the objects in the virtual environment, and displays them graphically to the patient. 2) *Haptic/Force Interaction*. The robot manipulator is used to control the movement of the avatar in the virtual environment. The position is updated real-time to show the actual movement of the patient visually. According to the motion of the limb and the interaction between the avatar and the virtual environment, virtual forces are calculated and feedback to the subjects through the robot arm. The virtual force feedback can be designed to help the subjects feel the interaction between the avatar and the virtual environment or to help them move in the right way. 3) *Audio Feedback*. At each patient site, a webcam and a microphone are connected to the client computer, which


Internet-Based Telerehabilitation Robotic System Client Station

192 . 168 . 0 . 100

Device Status Work Normal

Pos. -18.650 Breath 0.061 Force

Heart Rate 80 SpO2 95 1516.9680 Muscle tension

Training mode Passive

2 Genaral

Fig.6. Client operation interface.

acquires video and audio information of the patient during tele-rehabilitation training process and sends them to the server computer in the therapist service through the Internet. On the other hand, if audio feedback is introduced in the virtual games, the subject can hear the sound of the avatar or the virtual objects. Also, he/she can talk with the therapist via the Internet.

3.2 Interface of Server Computer

At the server site, a visual C++ program is developed to provide several services which include the ability to send commands to the tele-rehabilitation robotic system through the Internet, receive information during therapy progress, and display and save received signals. There is a client list to choose which client is observed and modified, but the information from all clients is accepted and saved in the database. The position and the force reflection from the chosen client are visualized in curves. From these curves in combination with visual aids, the therapists will control/monitor the program of the treatment and assess the outcome by the received data in the clinic, to further optimize the therapy plan according to the status of each patient. When the therapists consider it necessary to modify someone's treatment scheme, they stop the robotic device and send new parameters to the particular clients. A knob control is used to choose different training modes by the therapists according to different status of the patient. Program interface at server site exercising with 1 DOF (degree of freedom) robot in passive mode is shown in Fig.7.

3.3 Network Transmission

Data transmission over computer networks is realized based on TCP/IP protocol, which uses wsassyncselect socket model for therapist-side server computers to receive data from three patient-side client computers at the same time, and vice versa for client computers to receive the commands from the server computer. Network communication connects the central server, the therapist and the distributed patients at the same time for information exchange, including mainly control settings, acquired data, videos and audio. The Internet protocol for command communication is TCP, while the protocol for other data is UDP. The force and position signals of the clients are sampled at a rate of 100 HZ. The signals are buffered and transmitted to the server and videos are acquired and transmitted at 15 f/s (frame per second).

3.3.1 *Communication of Control Command*

Rehabilitation control commands include a training mode and a difficulty level. The training mode consists of stop, active mode and passive mode. The difficulty level is divided into four degrees that are simple, general, a little difficult, and very difficult. When the program is implemented, two kinds of integer variables are used to represent different training modes and levels, and their corresponding relationship is shown in Table 1 and Table 2, respectively.

The training mode and appropriate level settings can be directly selected by the patient at the local site or be settled by the remote therapists. The settings of the therapists will be delivered to the patient through the network, and a pop-up dialog box will remind the

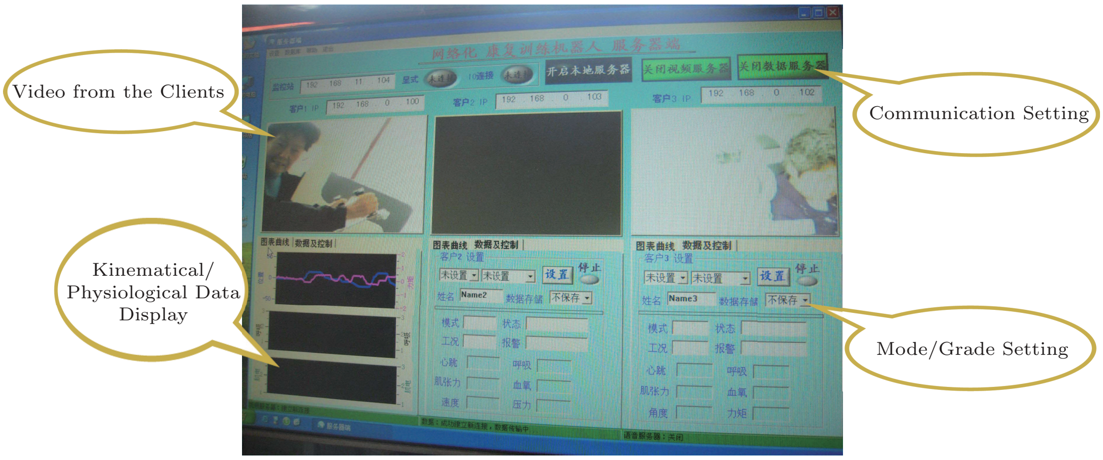


Fig.7. Interface of server computer.

patient to confirm or to cancel the settings from the therapist. The training status of the patient will be sent to the therapist in real time along with other local training-related data to ensure that the therapist can understand the patient's current training status accurately.

Table 1. Training Mode

Mode	Integer
Stop	0
Active mode	1
Passive mode	2

Table 2. Training Level

Level	Integer
Simple	1
General	2
A little difficult	3
Very difficult	4

3.3.2 Communication of Acquired Data

Rehabilitation-related data is displayed at the local computer and transmitted to the therapist's computer through the network. The information includes equipment conditions (standby, work, fault), alarm information (normal, fault not recorded, fault recorded), position, torque, respiration, heart rate, blood oxygen, training mode and grade. According to the needs of each client, the information is sent to the server side while 1~5 groups of position and torque information are collected including the conditions, location, torque and physiological data. Due to the uncertainty of the length of the physiological data, the definition of the data structure of each transmission consists of two parts, and the first 56 bytes constitute a fixed structure, including type, data length, condition and alarm, respiration, blood oxygen, heartbeat and five groups of position and force at most.

3.3.3 Communication of Videos

The client uses direct draw component in direct SDK (software development kit) and gets data through video capture card supporting the WDM (windows driver model) driver model. H.264 video codec standard is used for video compression. It is the latest block-oriented motion compensation based codec standard. H.264 contains a number of new features that allow itself to compress videos much more effectively than older standards and to provide more flexibility for application to a wide variety of network environments. A network abstraction layer (NAL) definition allows the same video syntax to be used in many network environments.

Completion port model is used to transmit videos from the clients to the therapist. The application first creates a thread pool at startup and then the thread pool is utilized to process asynchronous I/O requests. These threads are created for the sole purpose of handling I/O requests. To handle a large number of concurrent asynchronous I/O requests, it is faster and more efficient to use the completion port than to create a thread when an I/O request occurs. In essence, the completion port model requires to create a Win32 completion port object through a specified number of threads to manage the overlapping I/O request in order to provide services for the completed overlapping I/O requests.

3.4 Database Design

There is a large amount of data during cloud robot-assisted tele-rehabilitation process, which is important to access the effect of rehabilitation training and for therapists to revise the treatment plan. Therefore, it must be managed effectively. We select access database to store historical training data and patient performance data on the server computer at the central server location. The database management technology and the SQL server database are used to design the electronic medical records to manage individual basic information and the rehabilitation training related information of each patient. Access database is a type of small database, which has high efficiency to manage a small amount of data on single server computer. An interface for database access includes ODBC, ADO connections. ADO packages C++ oriented complex interface of OLEDB as API functions for high-level application. These are quick and easy ways to manage data in the database such as querying, deleting and adding data. Therefore we utilize the ADO interface for interviewing the access database. The database is in the central server computer and the therapist can read, add, modify, delete, and query operations as needed through the Internet.

4 Preliminary Experiments and Results

In order to test and verify the reliability and efficiency of the cloud robot-assisted tele-rehabilitation robot system, we did a series of experiments. Before experiments, the patient-side computer and wireless physiological receiver module, rehabilitation training robot control box were connected correctly, and the USB camera and the headset were connected to the client computer. Otherwise, the client subject, the therapist server and the center were connected through the Internet.

Experiments show that the use of multimodal interactive games which combine exercise therapy and psychological treatment will greatly improve the interest of the patients and improve the effectiveness of rehabilitation training. Fig.8 shows the number of voluntary training sessions and training time per session for patients in the non-game interface, single-game interface, and multi-game interface modes during the rehabilitation exercise respectively. In the absence of the game, the simply movement could only last a few minutes. In the simple game based interface for rehabilitation training, the patient could continue more than half an hour for rehabilitation training, and the number of training also increased. When the multi-game based training interface was induced, the patient could choose different games and can excise for hours, immersing in training. Also the voluntary training number of patients is significantly increased. In Fig.8, the red curve indicates the training duration per time and the blue curve indicates the training times intentioned.

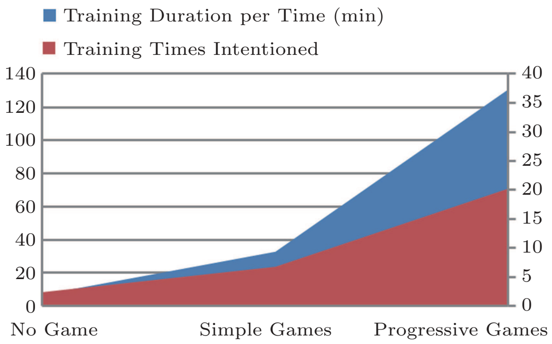


Fig.8. Results of multimodal interaction experiments.

To perform the experiment in active mode, we selected the training mode "active" in the mode selection tab and then the subject moved to the end of the robot with the active motion of the upper limb. Also the rehabilitation training game was introduced in this mode by clicking on the corresponding game selection button to pop up the game interface. Rehabilitation training with fun game obviously aroused the enthusiasm of patients during the process of training, which greatly improves the efficiency of rehabilitation training owing to its combination of the kinesitherapy with the psychotherapy in nature. The experiments indicate the cloud robot assisted rehabilitation system works stable and safe, which is able to assist the subject to do rehabilitation training under the remote monitoring of therapists.

In the experiments, the rehabilitation games were leveled in three grades. In addition to mapping the movement of the arm in a virtual ball, there was a guiding ball in the direction of movement. A healthy woman tracked the leading pellet in the virtual environment through the robot arm and controlled the movement of the avatar. Virtual force feedback and actual interaction force between the upper limb and the robot arm were recorded, as shown in Fig.9. The virtual force and the actual force are consistent, which indicates that the interaction force between the avatar and the virtual game was fed back to the subject and the subject could interact with the rehabilitation game by both watching the graphic display and feeling interaction forces. But due to the influence of inertial force and damping force transmitted by the mechanical impedance (mass, damping, etc.) of the manipulator, there was still an error between them.

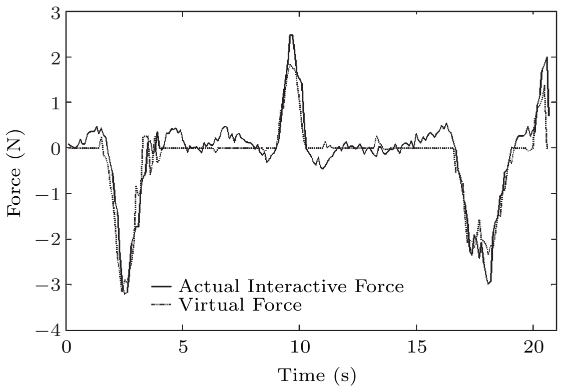


Fig.9. Force feedback and actual interaction force between the upper limb and the robot system.

5 Conclusions

In this study, a cloud robot assisted rehabilitation system with multimodal interaction was developed. In this system, the therapist can remotely supervise the upper-impaired subject to exercise and set/modify the rehabilitation training mode, therapy game level, and control parameters of rehabilitation robot. He/she can also on-line assess the current performance of the post-stroke patients according to the history data in database, the dialogue results and the advising from the central server over networks. Compared with the traditional hospital-based therapy, this system is more cost-efficient and more convenient for both the stroke patients and the clinicians. Preliminary experiments demonstrated that the system had good reliability and efficiency of the rehabilitation training, which can solve the problem of lack of therapists to a certain extent. Further work would involve clinical trials with natural multimodal interaction to determine the efficacy of this system and to improve the cloud-based service.

The highlights of the proposed system are: 1) the developed robotic system can realize tele-rehabilitation via Internet; 2) multimodal interaction and progressive training games are designed to attract the subjects during training and to increase the efficiency of rehabilitation excise.

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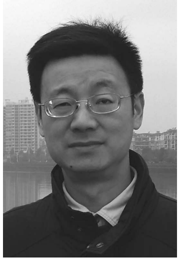

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