3 DOF Upper Limb Rehabilitation Robot-Assisted Training System

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Abstract—Hemiplegia is the most common performance of stroke. In order to assist the recovery of upper limb hemiplegia patients, the author developed a 3-DOF upper limb rehabilitation robot system based on the technology of Virtual Reality. The system can help patients to complete the shoulder movements of abduction/adduction, flexion/ extension and the elbow movement of flexion/extension. The paper expounded the structure of the robot and conducted the kinematics analysis of the robot mechanism. A computer and a digital signal processor (DSP) constitute the control center of the system. Absolute encoders collect the information of robot motion and magnetic powder brakes complete the braking and loading processes. We have exploited Windows GDI and OpenGL to construct a virtual reality environment on the platform of Visual C++. Experiments show that the system can achieve both linear and compound motions easily, and reach the requirements of design. The introduction of the technology of Robot and Virtual Reality into the field of rehabilitation has provided a scientific and effective recovery mode for patients.

Keywords-hemiplegia; rehabilitation; robot; VR; DSP;

I. INTRODUCTION

Stroke is a disease with high incidence and disability rate[1]. Investigations show a tendency that the incidence of stroke increased year by year in china[2]. The patients suffered great inconvenience in their life with the disability. One of the research results in the field of neural rehabilitation is that the highly plasticity of the central nervous system. Experiments showed that specific functional training is essential during the rehabilitation process[3]. The introduction of the robot technology into the field of rehabilitation has become a research focus in the countries. Massachusetts institute of technology developed the MIT-Manus[4] which can achieve rapid smooth motion, and 6 DOF upper limb rehabilitation device[5] was developed by Furusho Junji and others at Osaka University. In china, the development of rehabilitation robot started late relatively, but there are still some progress has been made at Tsinghua University, Harbin Institute of technology and other schools in this field.

Motor relearning method[6] put forward by the Australian scholar Carr has provided a new guidance for medical rehabilitation, and the Patient's initiative is considered as an important factor in the rehabilitation process[7]. Compared to traditional rehabilitation therapies, the introduction of the Virtual Reality (Virtual Reality, VR) technology[8] into the field of rehabilitation can greatly improve interest and immersion of patients during rehabilitation process, and patients are more likely to carry out a long-term training. The multi-sensory stimulation virtual environment established through VR technology can improve initiative of patient, also provide real feedback and provide a basis for evaluating during the late rehabilitation.

II. MECHANICAL STRUCTURE DESIGN

In the field of rehabilitation robot research, the most common form of upper limb rehabilitation robot mainly includes the exoskeleton wearable rehabilitation robot and end traction type rehabilitation training robot by now.

Exoskeleton wearable rehabilitation training robot has more degrees of freedom. Its institution is similar to human body joint that it can be attached to the body and produce body tight mechanical coupling. It is worn in patient to support and protect the upper limb. But this kind of robot structure is relatively complex, poor operability, and easy to bring patients with psychological fear that it is not conducive to rehabilitation training.

End traction type rehabilitation robot can draw limb movements in space, so that they can achieve the joints rehabilitation training. It has characteristics like: simple structure, easy control, low cost, large working space and many other features that can meet the needs of recovery. Typically structure system consists of two or three degrees of freedom is the first selection of end traction rehabilitation robot.

This paper chooses end traction type rehabilitation robot. It completes three-dimensional movements of space by series connecting rod structure. The overall system structure has many advantages: simple, compact, easy to operate, able to complete space motion, not interfere each other, and can ensure the orderly conduct of rehabilitation training.

Human's upper limb can perform more than one degree of freedom movements[9]. From a practical point of view, patients can just complete the simple composite motion and complex daily functional resume movement training during rehabilitation, and taking into account design complexity and cost of the robot's structure, The author has designed a 3-DOF robot system which can complete linear or compound motions: up and down (shoulder abduction\adduction), left and right (elbow flexion\ extension), forward and backward (shoulder flexion\extension). The system is simple, flexible, easy to manipulate for patient, and able to meet the requirements of the average patient's rehabilitation. The robot system structure shows in Fig .1 and Fig .2.

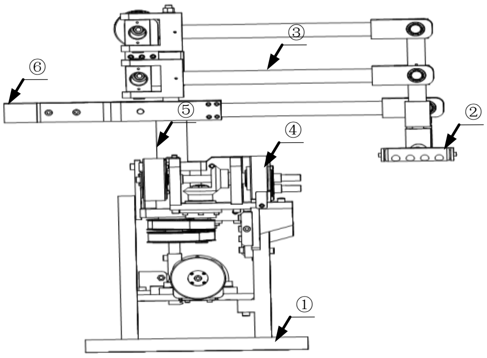

Figure 1. Robot mechanism assembly drawing

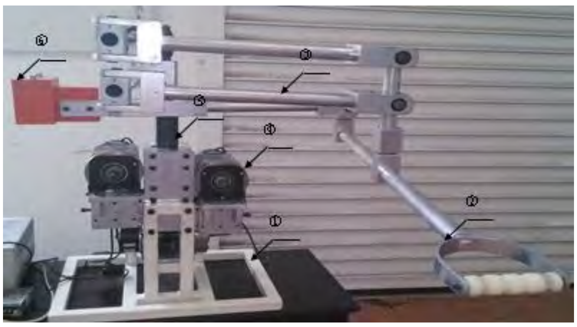

Figure 2. Robot system structure

①Pedestal；②Handle；③Link；④controller；⑤Triple shaft；⑥Balance block；

This paper presents a four-bar linkage as a moving part of the system. The entire linkage mechanism is made of aluminum, and the dual-link is used to connect the medial part which can slow its instability generated by the impact during the movement. Through the inner shaft, the intermediate shaft and the outer shaft transmit the three directions of movement. The three-fold axis is connected by gears and belts, and there is no interference with each other, it can operate independently with the three-axis. One end of the shaft is installed with absolute encoder to collect the output information of shaft and the detection accuracy is 0.1° , and the other end of the shaft is installed with magnetic brakes which can achieve the brake of motion and force feedback during exercise.

Transmission structure is the core of the robot, which controls its space movement with three degrees of freedom. In this system, the movement of the inner shaft, intermediate shaft and the outer shaft through the triple-axis mechanism operate orderly. Free movements of non-interference between each other ensure the smooth progress of upper limb movement in the complex process.

1) Outer shaft transmission system structure design

Outer shaft transmission structure fixed to the base rack by a joint panel. The structure consists of an outer shaft and outer shaft pulley, belt, small pulleys, bevel gears, encoders, magnetic brakes, gear shafts and bearings. Encoders and magnetic brakes connected to base rack through the corresponding fixed panel which has two fixed bushing bracket that inside bearing are respectively mounted to hold the horizontal state of the gear shaft. Encoders, bevel gears, magnetic brakes connect through the pin joints, to maintain consistency of coaxial rotation. Using a pair of bevel gears meshing with each other structures to ensure the accuracy of the motion is passed in two different directions during the movement. Furthermore, the system uses a pair of pulley which gear ratio is 1:2 to facilitate the conversion of information. For ease of installation pulley structure, we designed a long hole structure in fixed plate, which can adjust the installation distance between the outer shaft, so the synchronous belt is installed smoothly.

2) Intermediate shaft transmission system structure design

Intermediate shaft transmission structure has a composition substantially same with the outer shaft. Its mainly constituted by the intermediate shaft, intermediate shaft pulley, Synchronous belt and small pulleys, bevel gears, encoders, magnetic brakes, gear shafts and bearings. It is distributed at both ends of the base with the outer shaft transmission structure, which primarily responsible for the completion of the patient's left/ right direction movement during rehabilitation training mission.

The intermediate shaft transmission system is also a hollow shaft and it is longer than the outer shaft. On one hand, facilitating the installation of a pulley; on the other hand, there is non-interference between each other with the process of moving, and the rehabilitation can be successfully achieved.

3) Inner shaft transmission system structure design

The inner shaft transmission system includes: sector gear, cylinder rack, inner shaft, straight rack, spur gears, encoders, magnetic brakes, pulleys and gears shaft.

In this system, the entire control section installed on the lowest end of the base bracket. There are two bearings fixed on base bracket, holding the gear shaft horizontally. Encoders and magnetic brakes are connected at both ends of the shaft through the fixed plate, and the middle part connected with spur gear through the key. The other side of the spur gear fixed straight rack through the pulley structure to ensure that it does not swing in motion, moving up and down along a straight line which improves the accuracy of movement. Using gear and rack structure to translate linear motion into rotary motion, and symmetrical joint plate in pulley frame structure to conducive to the pulley assembly. Elongated hole in the plate can adjust structure easily, so the structure can be fixed in the right position.

In order to obtain the trajectory of the end handle of robot, we have made kinematics analysis of the entire system that each axis is analyzed and calculated according to the D-H analysis method[10]. The outer shaft is an example to explain it, and the schematic diagram of the mechanism is shown in Fig .3.

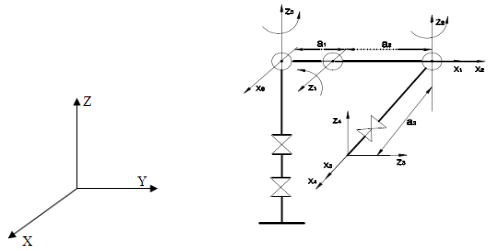

Figure 3. Schematic Diagram of Mechanism

The posture matrix of adjacent link is written in follow:

$$^{n}T_{n+1} = A_{n+1} = Rot(z,\theta_{n+1})\times Tran(0,d_{n+1}) \times Tran(a_{n+1},0)\times Rot(x,\alpha) \quad (1)$$

The characters θ、d、a、α are angle, length, distance between the adjacent joints, and the angle between each joint in the DH parameters. The parameter values show in TABLE I.

TABLE I. D-H PARAMETERS TABLE OF OUTER SHAFT

Joint i	θ (°)	d(mm)	a(mm)	α(°)
1	θ_1	0	55	90
2	0	0	500	-90
3	θ_3	0	865	-90
4	0	0	0	90

Set T as the robot end position transformation matrix, and matrix A got from the above equation can be substituted into it. We can get the equation like follows:

$$T={}^{0}T_n = A_1A_2A_3\Lambda\ A_n = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

The position equations of end actuator :

$$p_x = (c_1c_2c_3 - s_1s_3)a_4c_4 + c_1s_2a_4s_4 + c_1c_2a_3c_3 - s_1a_3s_3 + c_1a_2c_2 + a_1c_1$$

$$p_y = (s_1c_2c_3 + c_1s_3)a_4c_4 + s_1s_2a_4s_4 + s_1c_2a_3c_3 + c_1a_3s_3 + s_1a_2c_2 + a_1s_1$$

$$p_z = s_2c_3a_4c_4 - c_2a_4s_4 + s_2a_3c_3 + a_2s_2 \quad (3)$$

For the convenience of showing, the above formula Sin θ_i、Cos θ_i are replaced with s_i、 c_i .

To verify the results that robot joints meet the motion requirements, we used Robotics Toolbox[11] to establish kinematics simulation for outer shaft. The robot joint displacement curve and the end of the displacement curve as follows.

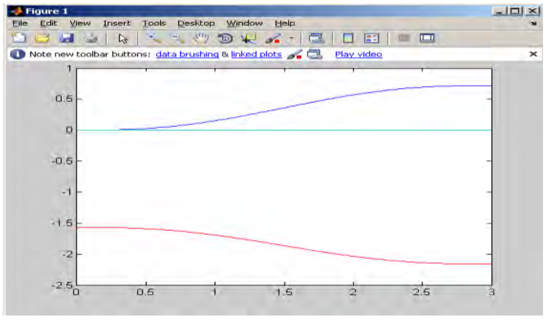

Figure 4. Joint displacement

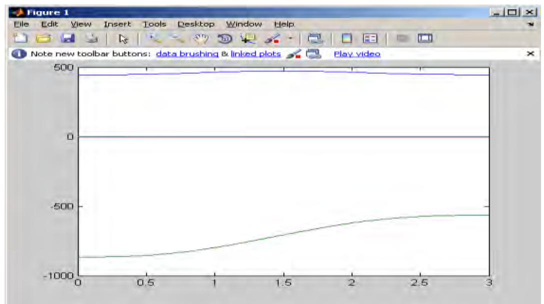

Figure 5. Ends displacement

As can be seen from the figure the joint moves smoothly and stably during the process of motion, and the robot joint can meet the requirements of its movements, and it is verified the reasonableness of design parameters for the link.

III. MOTION CONTROL SYSTEM

In order to facilitate future expansion of the system application, we use the digital signal processor (DSP) TMS320LF2407A which has more powerful processing capacity. Three encoders on the shafts output the position information with three directions when patients do rehabilitation training. The output mode of the encoder is RS485 which is directly connected to the computer by RS485-USB converter. The computer analogs three serial ports to receive data from encoders after installed the driver on the computer. The data is processed to control the object model in virtual environments.

In the rehabilitation process, we expect to get certain degree control of force to protect patients and strengthen the effect of rehabilitation. After the installation of balance block, the system requires only a small force to drive the movement of end handle. In order to achieve a gradual rehabilitation process, we designed different levels of movement patterns by controlling the magnetic brakes to output feedback resistance. The PWM pulse signal generated by the DSP was used to drive and control magnetic brakes, and the driving signal is weak, that amplification circuit composed by IR2110 was designed to amplify signal. The system control process shows in Fig 6.

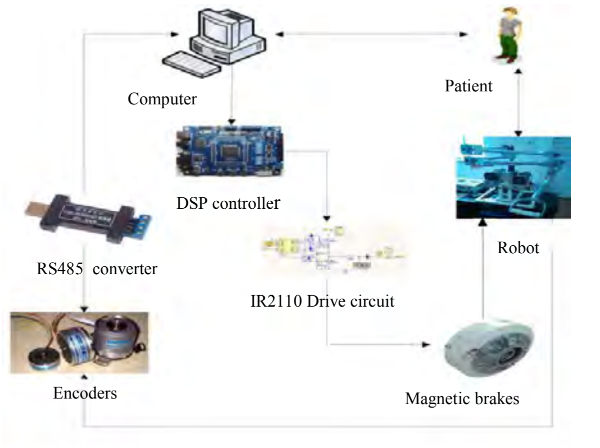

Figure 6. System control flow

IV. HUMAN-COMPUTER INTERACTION ENVIRONMENT

For the movements of 3 dof upper limb rehabilitation robot, the author designed a display objects game by OpenGL (Open Graphic Library). The virtual platform is established with single document of MFC (Microsoft Foundation Classes) in the environment of VC ++ 6.0. The flow chart of creating a virtual environment is as Fig.7 and the virtual environment is shown Fig .8.

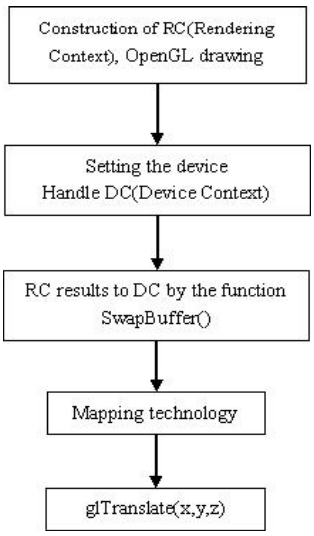

Figure 7. Virtual environment build process

Patients manipulate the robot handle to place various objects on the display rack in turn, and the system will automatically recognize and determine to control magnetic powder which can control force feedback and braking, when it encountered a wall, display rack or other extreme positions in the process of movement.

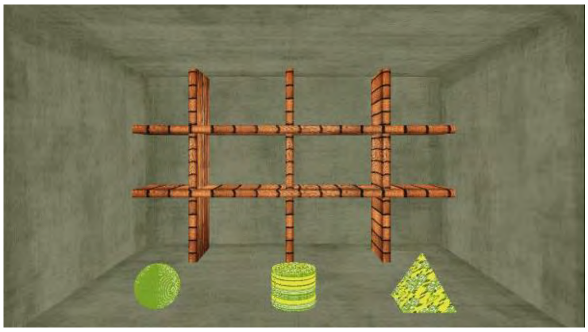

Figure 8. Game Interface

Virtual platform consists of two parts: virtual reality environment and computer serial communication. In order to complete the data monitoring and processing for three analog serial in computer, while enabling computer and DSP serial communication, it is necessary to use multi-threading technology. CSeriaPort class, which is serial communication class written by a third party, package of the API functions, enabling programming efficiency, transformative and scalable better, and its based on multi-threaded which enables serial communication. The work flow is as follows: While receiving data, opening monitoring thread after setting the serial port parameters. When the monitoring thread monitor received data from serial port, flow control events or other events, notifying the main thread by the way of message, then the message functions process data. Data can be sent directly to the serial port.

The real-time data processed change the position of objects in the virtual environment by the function Translatef(). When the object is blocked, the output data from serial port was sent to DSP to control magnetic brake's braking and feedback force by function WriteToPort(). During the construction of a virtual environment, Texture Mapping was applied to make more beautiful and enhance the realism of the virtual environment.

V. CONCLUSION

Experiment results show that the system can achieve 3 DOF space motions with patient's actively control, and real-time movements of the object in virtual environment. The system reached the preliminary expected effect, and laid the foundation for the next step that adding servo motor system to switch active or passive mode freely. For a better rehabilitation, we need to optimize the trajectory planning of rehabilitation exercise process on the basis of the patient's specific situation, and develop a more scientific rehabilitation evaluation system. Due to the advantages of low cost, no affected by environmental constraints, accurate control and effective information storage, robot-assisted rehabilitation has become a new rehabilitation model.

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