Parallel controller construction for a multi-DOF hand rehabilitation equipment

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ABSTRACT

This paper describes the development of a hand rehabilitation system for stroke patients. Our aim is to provide fine motion exercise for a hand and fingers. Thus, a hand rehabilitation device that assists patients' finger movements was developed. Because this device has 18 degrees of freedom of motion, it is difficult for disabled patients to use it by themselves. Therefore, an appropriate control strategy and control system are required to allow its safe and effective use. In light of this requirement, a control system was constructed which is comprised of four separated controllers. This paper presents the structure of the control system and introduces the control protocols used in our hand rehabilitation system.

Keywords: Hand rehabilitation, Multi-DOFs equipment, Parallel controller, Control protocol, Multi-control mode

1. INTRODUCTION

The number of elderly persons in Japan is increasing as we move into the 21st century. An elderly person has a high probability of suffering from a physical disability due to disease or an accident, and such persons will need to undergo rehabilitation in order to regain an original body function. As part of a rehabilitation program, doctors and therapists often repeatedly flex or extend a patients' disordered joints. In our present project, we are developing a hand rehabilitation system that allows the patient to perform rehabilitation by him- or herself without having to rely on doctors or therapists as part of the rehabilitation program.

Some arm rehabilitation equipments are employed in actual physical exercise.[1–3] However, few rehabilitation systems provide fine motion assistance for each finger due to the finger's structural complexity, consisting of small finger links. Some haptic devices have been proposed as mechanisms intended for hand rehabilitation.[4,5] However, these devices cannot provide bilateral motion assistance, e.g., extension and flexion, for each joint. Though some hand rehabilitation devices have attempted as much,[6–8] separate motion assistance for each finger, especially for the thumb with its oppositional movement, are difficult to achieve. Thus, we are developing an original hand rehabilitation device which simultaneously realizes the following functions:

- bilateral motion assistance in the flexion/extension of each finger and thumb
- bilateral motion assistance in the abduction/adduction of each finger and thumb
- assintance in the opposing motion in the thumb

Ours is the first to allow all of these motions in a single device.

The developed hand rehabilitation device[9,10] has 18 DoFs of motion: 4 DoFs for the thumb motion assistance mechanism, 3 DoFs for each finger motion assistance mechanism, and 2 DoFs for the wrist joint. A photo of the device is shown in Fig. 1(a). In this paper, the control scheme of the hand rehabilitation device is considered to operate in such multi-DoF systems safely and effectively during rehabilitation exercise.

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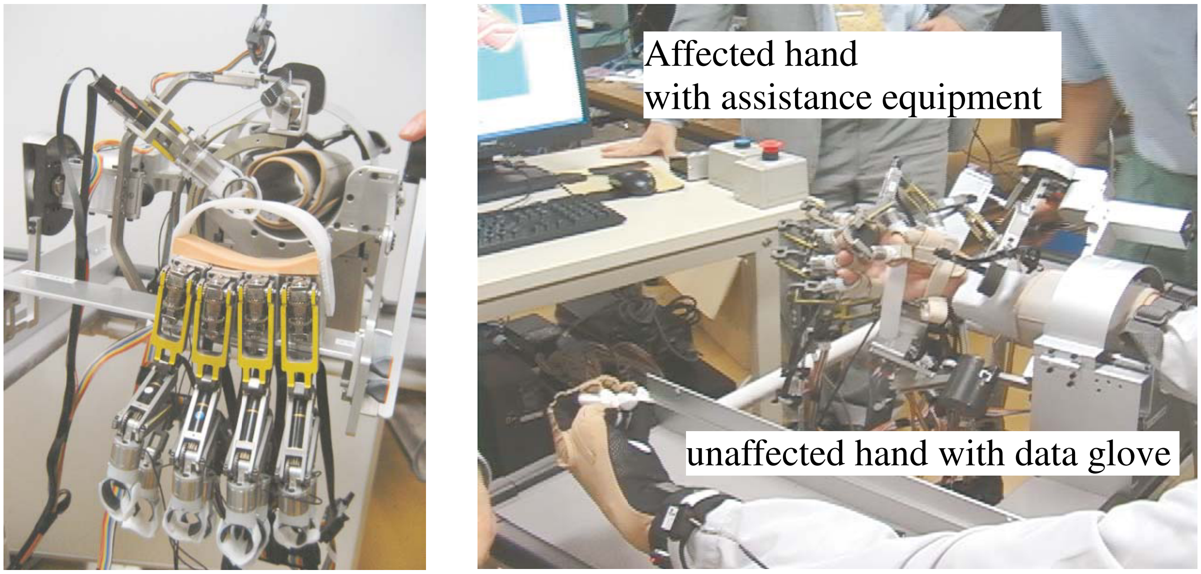


(a) Overview. (b) Operation by a self-motion control.

Fig. 1. A hand rehabilitation equipment with 18 DoFs.

2. CONSTRUCTION OF CONTROL SYSTEM

2.1 Self-motion control: A new control strategy for hand rehabilitation

Due to their large number, stroke patients were selected as the main target of our developed hand rehabilitation system. The features of stroke patients include (i) a disruption of only the nerve system, and thus the musculo-skeletal system is intact, (ii) immobile body parts are limited to the 'affected side' and thus patient can move and control his or her 'unaffected' side. Based on these features, we have proposed a self-motion control strategy[11]in which the unaffected hand controls the motion of the affected hand by master-slave control so that both sides behave symmetrically. The merits of this control strategy are as follows: (i) usually, hands on both sides possess the same range of motion, as an expression of physical symmetry. Thus, the range of motion in an exercise is limited by that of the one's own hand. (ii) the patients can stop the motion assistance by themselves whenever they experience pain during the exercise. (iii) the patients can perform the exercise by imaging the affected hand's motions based on the motion of the unaffected hand, which would increase the effect of the exercise. This operation achieved by using self-motion control is shown in Fig. 1 (b)

2.2 Structure of control system

In order to realize the self-motion control strategy, 4 controllers are prepared: A personal computer for measuring unaffected hand motion, a controller for the motion assistance mechanisms of fingers, one of the wrist, and the safety supervisor. The structure of the control system is illustrated in Fig. 2

2.2.1 A personal computer

A personal computer is connected with a device called 'data glove' that can measure the finger joint angles and the '3D motion sensor' that can measure the posture of the hand. Using the data glove, the following finger joint angles are obtained: extention/flexion of the proximal interphalangeal (PIP) and the metacarpophalangeal (MP) joint and the abduction/adduction of the MP joint for each fingers, the extention/flextion of the interphalangeal (IP), MP and carpometacarpal (CM) joint and the abduction/adduction of the CM joint for the thumb, and procurvation/dorsiflexion of the wrist joint. From the 3D motion sensor, on the other hand, the pronosupination angle of the wrist is obtined. The data from the data glove is sent using serial communication with 115,200 bps. The data form the 3D motion sensor comes through the USB interface.

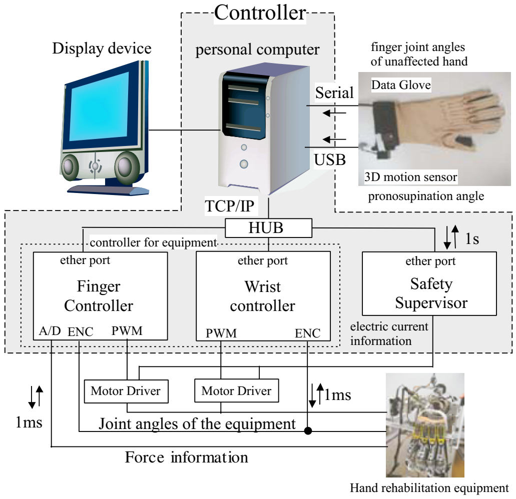


Fig. 2. Controller structure.

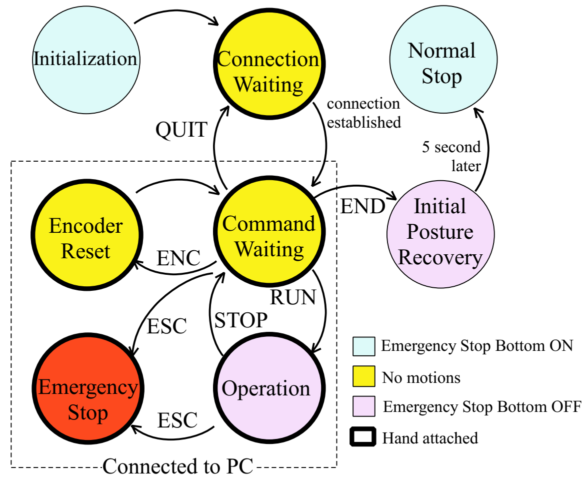


Fig. 3. State tranisition diagram.

The data of the finger joint angles are used to calculate the reference angles of the hand rehabilitation device. When the patient attaches his or her unaffected hand to the device, the link mechanisms construct a closed loop with the finger because of the device's exoskeletal structure. In the closed loop, there are two passive joints and one active joint driven by the DC motor. Based on the kinematic relation of the closed loop structure, the reference angles of the active joint in the motion assistance mechanism are solely determined.[11] These reference angles bring the affected hand into symmetry with the unaffected hand by means of the motion assistance of the device.

A personal computer provides the users a graphical user interface drawn by Open GL. Through this interface the users can give commands to the device's controller. The controller's state transition is represented in Fig. 3. Each control mode will be explained in section 3 The joint angle data are used to draw the affected hand's posture using computer graphics. The operating system of the personal computer is Windows XP.

2.2.2 Controller of the hand rehabilitation device

A "HRP-3P-CN" controller board with an I/O module for multi-channel link node (General Robotics Inc.) is used as the device's controller. This controller contains a SH-4 CPU working at 240 [MHz], and 2 ethernet ports for TCP communication. Combined with the I/O module, 16ch analog input ports, a 16ch pulse counter, and 16ch PWM output ports are prepared as an extended function. This board is operated by ART-Linux.

The controller of the motion assistance device is divided into two parts due to the shortness of the channel for analog and digital interfaces. All the DC motors used in the device have magnetic rotator encoders, the output of which is connected to the controller's pulse counter port. The output of the force sensors is connected to the controller's AD converter. The force information will be used to limit the output torque.

2.2.3 The safety supervisor

The above three controllers send a signal to the safety supervisor every 1s in order to notify the normal operation of the program. The safety supervisor determines an obstacle in the controller by receiving no signal from each controller. The safety supervisor observes the electric current of the DC motor as well as the emergency stop bottoms.

2.3 Control protocol

2.3.1 Initialization

One of the important problems involved in the parallel control system is the establishment of communication among them. Basically, the finger and wrist controller as well as the safety supervisor do not have a user interface.

On the other hand, the personal computer usually has a keyboard and mouse which users can utilize in giving commands, and thus can trigger a time when communication should be established. From this point of view, the personal computer is treated as a client of TCP/IP communication. The time chart of the communication initialization is depicted in Fig. 4 (a).

First, communication between the finger and the wrist controller is established. Then, the finger controller is selected as a server. The two ports are prepared for communication; one is for commands while the other is for data.

After that, the finger controller waits for a connection to be established with the personal computer. The two ports are also prepared for communication between them, while there is no direct communication between the personal computer and the wrist controller. A few bits of data should be sent to or from the wrist controller, e.g., position and force information regarding wrist motion. Therefore, we designed the protocol so that all the data are sent at once to or from the finger controller together, and a few bits of position and force information regarding wrist motion are then sent between the finger and the wrist controller.

Finally, three direct lines of communication are established between the safety supervisor and the others. The safety supervisor then works as a server. When all the communication lines have been established, the controller moves to the waiting command mode.

2.3.2 Control and communication on operation mode

As shown in Fig. 3, the RUN command from the user makes the controller mode transit from the waiting command mode to the operation mode. The time chart in the operation mode is depicted in Fig. 4(b).

Unaffected hand motion data are measured by the Data Glove and the 3D motion sensor connected to the personal computer. These data are translated to the reference position of the joint angles in the device based on the inverse kinematics of the link structure. All the data regarding the reference position are sent to the finger controller, and part of these data are then transferred to the wrist controller. Due to the limit of the communication speed, the reference data are transferred every 15[ms].

The finger and wrist controller controls the joint angles of the exoskeletal link in relation to the reference position. In the control process, joint angle detection, force information measurement, control law computation, and PWM output are performed in this order. Proportional position control is adopted as a control law. A series of these processes is executed as a real-time process in 1[ms].

The data describing the joint angles as well as force information are inversely sent back to the personal computer. These data are also transferred every 15[ms].

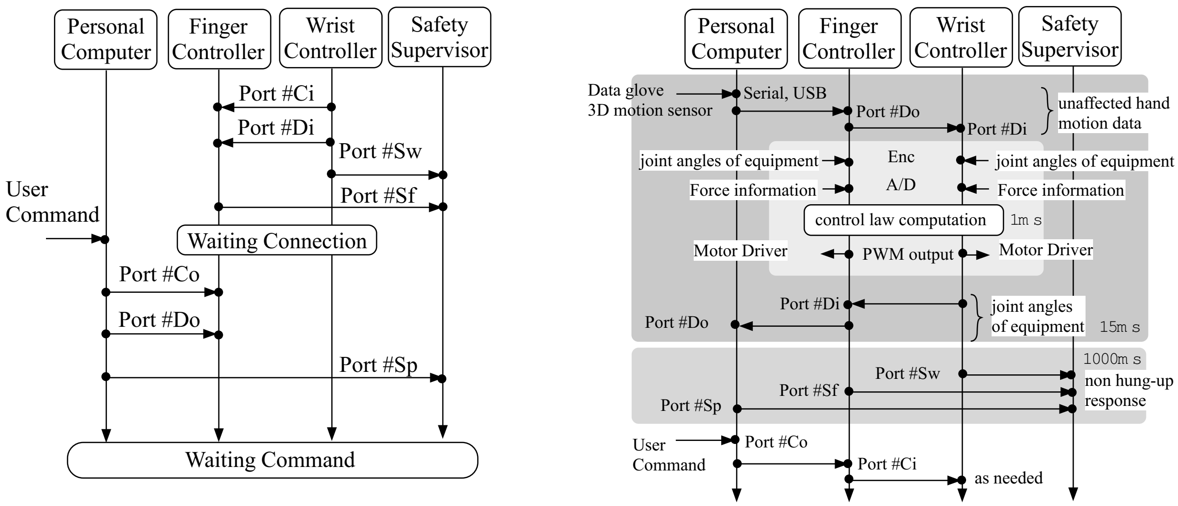
Each controller sends a non-obstructed response which notifies the safety supervisor that this computer process is functioning, i.e., is being executed normally. This response must be sent in every 1[s]. If there are no responses in 3 [s], the safety supervisor judges that this controller is considered obstructed. It then cuts the power supply to the motors.

A command that makes a transition in the control mode is accepted at any time. This command is usually generated by the users at the personal computer, and transferred to the finger controller and next to the wrist controller. When the STOP command is input, the operation stops and the control mode moves to the command waiting mode, as shown in Fig. 3.

3. SEVERAL CONTROL MODES

3.1 Outline

In order to utilize a multi-DoF hand rehabilitation device safely and efficiently, we prepared several control modes as shown in Fig. 3. The emergency stop button, shown in the blue circle, can halt the electric power supply to the motors. In the pink circle, the device is shown in motion and thus the emergency stop button must be off. In the yellow circle, the device is not in motion. The state of the emergency stop button is then not determined. The circle with the bold outline is the state in which the patient's hand is attached to the device.



(a) Initialization. (b) Operation mode.

Fig. 4. Time chart of controllers.

A transition occurs when a command is input from the personal computer interface. This interface is provided as a specific application software including computer graphics, and a button click with the mouse generates these commands.

The connection waiting mode, command waiting mode, and operation mode have been explained in the section 2.3. In the following, the other control mode will be briefly explained.

3.2 Emergency stop mode

The device stops with an ESC command. This command is usable in the operation mode as well as in the command waiting mode. This stops the software from the graphical user interface. In the device's final version, an emergency stop button will be included because of its ease of use.

3.3 Encoder reset mode

Basically, the encoder counters are set to zero when the controller starts up. The device must then be set to the initial posture. However, this initial posture setting is easily forgotten. Therefore, an encoder reset command is prepared. In this process, the patient is asked to assume a posture with his or her unaffected hand symmetrical to the affected hand. In this symmetrical situation, the joint angles that should be set to the motors of the device can be calculated based on the information describing the unaffected hand's posture through the use of inverse kinematics. Thus, these angles are sent to the encoder counter by this command. When the encoder counter is reset, the control mode automatically moves to the command waiting mode.

3.4 Initial posture recovery

It is convenient for the device to recover its initial posture automatically when the user concludes a rehabilitation session. We add this function to ensure recovery of the initial posture. This occurs when the END command is sent from the command waiting mode. The control program in the finger and wrist controller then stops in 5 seconds, which is enough time for the device to reocery its initial posture. This function is available only at the normal stop.

4. CONCLUDING REMARKS

In this paper, we introduced a control system for hand rehabilitation device having 18Dof of motion based on a self-motion control strategy. It has a parallel structure consisting of four controllers. The control protocols as well as several control modes used in the control system are explained. However, the stability of the total system is not discussed. The stability may be ensured with passivity-based analysis because the control law is basically proportional and the mechanical system has high viscosity. We are currently adjusting the developed system for practical use at some hospitals. The results of clinical experiments will be presented in forthcoming papers.

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