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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 objective is to provide fine motion assistance in exercises for a hand and fingers. Thus, a hand rehabilitation device that assists patient's finger movements was developed. Because this device has 18 degrees of freedom, it is difficult for disabled patients to use it by themselves. Therefore, an appropriate control strategy and a control system are required to allow it to be used safely and effectively. In light of this requirement, a control system was developed that comprises four separate controllers. This paper presents the structure of the control system and introduces the control protocols used in the 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 in the 21st century. An elderly person has a high probability of suffering from a physical disability caused by a disease or an accident, and such a person needs to undergo rehabilitation to regain his or her normal body function. As part of a rehabilitation program, doctors and therapists often assist the patient to repeatedly flex or extend his/her impaired joints. In our study, we developed a hand rehabilitation system that allows patients to perform exercises as part of the rehabilitation program by themselves without having to rely on doctors or therapists.

Some arm rehabilitation equipment has been employed in actual physical exercise [1–3]. However, few rehabilitation systems provide fine motion assistance for each finger because of the structural complexity of a finger, which consists 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 for each joint, e.g., assistance in extension and flexion of finger. Although several hand rehabilitation devices have been developed [6–8], separate motion assistance for each finger, especially for the thumb with its oppositional movement, has been difficult to achieve. Thus, we developed an original hand rehabilitation device that realizes the following functions simultaneously:

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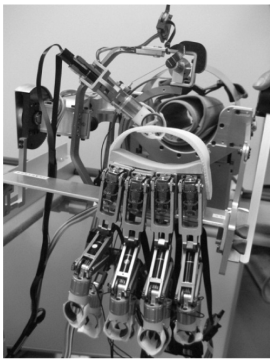
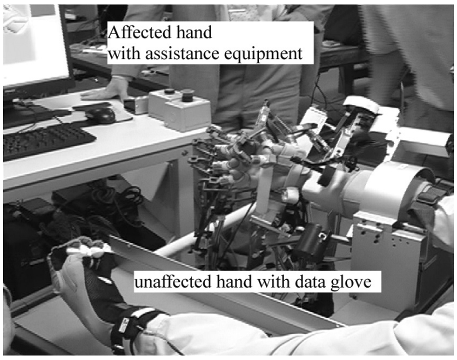


(a) Hand rehabilitation device



(b) Operation by a self-motion control

Fig. 1. Hand rehabilitation equipment with 18 DoFs.

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

Our device is the first of the kind that allows all of these motions in a single device.

The developed hand rehabilitation device [9,10] has 18 degrees of freedom (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 designed to operate in such multi-DoF systems safely and effectively during rehabilitation exercise.

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 group to assist with our developed hand rehabilitation system. The features of stroke patients include (i) a disruption of only the nervous system, and thus, the musculo-skeletal system is intact; and (ii) immobile body parts are limited to the "affected side," and thus, the patient can move and control his or her "unaffected side." On the basis of these features, we have proposed a self-motion control strategy [11] in which the unaffected hand controls the motion of the affected hand using a master-slave paradigm 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 person'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; this would increase the effectiveness of the exercise. A photograph of a patient engaging in self-motion control is shown in Fig. 1(b).

2.2. Configuration of the control system

To realize self-motion control, the following four controllers are prepared: A personal computer for measuring unaffected hand's motion, a controller for the motion assistance mechanisms of the fingers and one for the wrist, and a safety supervisor. The structure of the control system is illustrated in Fig. 2.

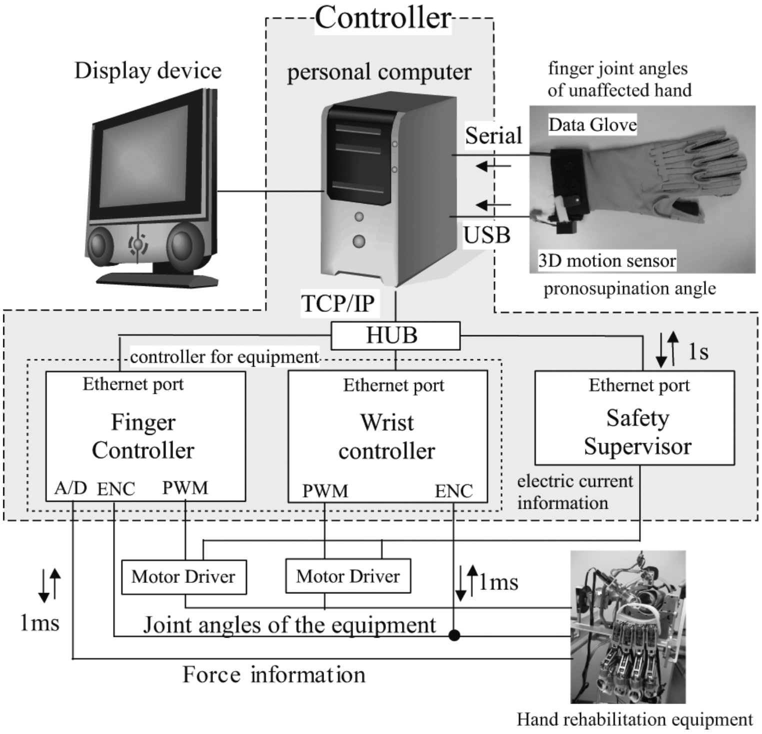


Fig. 2. Controller structure.

2.2.1. *Personal computer configuration*

A personal computer is connected with a device called "data glove" that can measure the finger joint angles and a "3D motion sensor" that can measure the posture of the hand. Using the data glove, angles for the following finger joint motions are obtained: extension/flexion of the proximal interphalangeal (PIP) and the metacarpophalangeal (MP) joints and abduction/adduction of the MP joint for each finger; extension/flexion of the interphalangeal (IP), MP and carpometacarpal (CM) joints and 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 obtained. Data from the data glove is transmitted using serial communication with 115,200 bps, whereas that from the 3D motion sensor is transmitted through a USB interface.

Finger joint angle data are used to calculate reference angles for 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 a DC motor. The reference angles of the active joint in the motion assistance mechanism are determined solely on the basis of the kinematic relationships of the closed loop structure [11]. These reference angles bring the affected hand into symmetry with the unaffected hand using the motion assistance provided by the device.

A personal computer with Windows XP operating system provides the user with a graphical user interface (GUI) using OpenGL. Through this interface the user can give commands to the device's controller. The controller's state transition is illustrated in Fig. Fig. 3. Each control mode is explained in detail in Section 3. The joint angle data are used to draw the affected hand's posture using computer graphics.

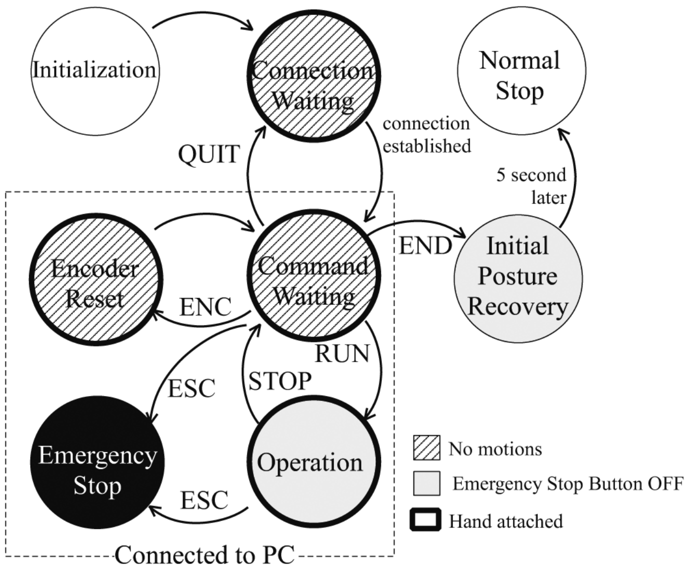


Fig. 3. Controllers' state transition diagram.

2.2.2. Hand rehabilitation device controller

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

The motion assistance device controller is divided into two parts because of the limited number of analog and digital channels available. All the DC motors used in the device have magnetic rotator encoders; their output is connected to the controller's pulse counter port. The output of the force sensors is connected to the controller's AD converter. Force information is used to limit the output torque.

2.2.3. Safety supervisor

The above mentioned three controllers send a signal to the safety supervisor at an interval of 1 s in order to notify the safety supervisor about the current operating state of the device. The safety supervisor determines that there is a problem in the controller when no signal is received from each controller. The safety supervisor checks the electric current of the DC motor as well as the emergency stop button in the GUI provided in the personal computer.

2.3. Control protocol

2.3.1. Initialization

One of the important problems involved in the parallel control system is the establishment of communication between the controllers. The finger and wrist controllers as well as the safety supervisor do not have user interfaces themselves. The personal computer, on the other hand, usually has a keyboard and a mouse using which the user can give commands, and thus can initiate communication when required. From this point of view, the personal computer is treated as a client in terms TCP/IP communication. A sequential chart showing how communication is initialized is shown in Fig. 4 (a).

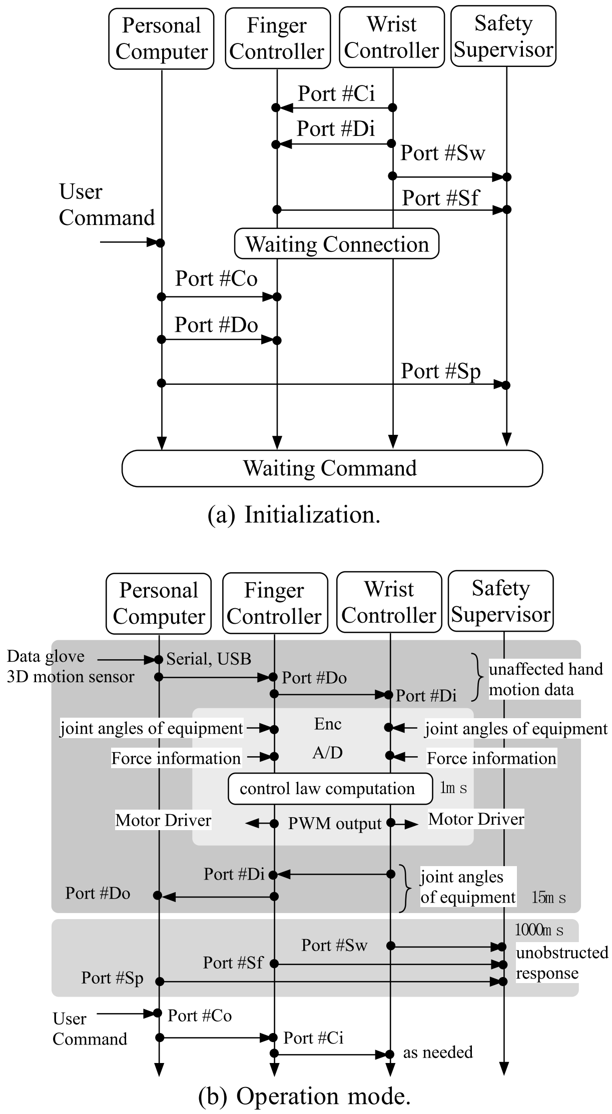


Fig. 4. Time chart of controllers.

First, communication between each finger controller and the wrist controller is established. Then, the finger controller is selected as a server. Two ports are then 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 (called the connection waiting mode). The two ports are also prepared for communication, while there is no direct communication between the personal computer and the wrist controller. A few bytes 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 data regarding both fingers and wrist are sent at first between the personal computer and the finger controller, and a few bytes of data on position and force information regarding wrist motion are then sent between the finger and the wrist controllers.

Finally, three direct lines of communication are established between the safety supervisor and the other controllers. The safety supervisor then works as a server. When all the communication lines have been established, the controller moves to the mode where it waits for commands (command waiting mode).

2.3.2. Control and communication in operating mode

As shown in Fig. 3, the RUN command from the user makes the controller mode change from the command waiting mode to the operating mode. A sequential chart depicting the operating mode is shown 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 data regarding the reference position are sent to the finger controller, and some of these data are then transferred to the wrist controller. Due to the limited communication speed, the reference data are transferred every 15 ms.

The finger and wrist controllers control 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.

Data describing the joint angles as well as force information are transferred back to the personal computer every 15 ms.

Each controller sends an unobstructed response that notifies the safety supervisor that each 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 determines that the controller is obstructed. Then the safety supervisor cuts the power supply to the motors.

A command that changes the control mode is accepted at any time. Such a command is usually generated by the user at the personal computer, and transferred to the finger controller and next to the wrist controller. When the STOP command is issued, the operation stops and the control mode changes to the command waiting mode, as shown in Fig. 3.

3. Various control modes

3.1. Overview

To utilize a multi-DoF hand rehabilitation device safely and efficiently, we prepared various control modes as shown in Fig. 3. The emergency stop mode, shown in the black circle, halts the electric power supply to the motors. In the dark circle, the device is shown in motion, and thus, the emergency stop button must be off. In the hatched circle, the device is not in motion. Each circle with a bold outline indicates a state in which the patient's hand is attached to the device.

A transition occurs when a command is issued from the personal computer interface. A button click with the mouse in GUI generates specific commands.

The connection waiting, command waiting, and operating modes were explained above in Section 2.3. In the following sections, the remaining control modes are discussed.

3.2. Emergency stop mode

The device stops with an ESC command. This command is usable in the operating mode as well as in the command waiting mode, and makes the control mode change to the emergency stop mode. In the device's final version, a physical button for the emergency stop will be introduced because of its ease of use.

3.3. Encoder reset mode

The encoder counters are set to zero when the controller starts up. At that time, the device must be set back to the initial posture, but we sometimes forget it when we start using this device. 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 on the basis of information describing the unaffected hand's posture using inverse kinematics. Thus, these angles are sent to the encoder counter by this command. When the encoder counter is reset, the control mode automatically changes 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. This function to recover the initial posture occurs when the END command is sent in the command waiting mode. The control program in the finger and wrist controllers then stops in 5 s, which is sufficient time for the device to recover its initial posture. This function is available only at a normal stop.

4. Concluding remarks

In this paper, we described a control system based on a self-motion control strategy for a hand rehabilitation device that has 18 DoF of motion. The control system has a parallel structure consisting of four controllers. The control protocols as well as the various control modes used in the control system are explained. Although the stability of the system as a whole is not discussed, it will be ensured because the master-slave communication is unilateral from unaffected to affected hand from the control point of view. We are currently adjusting the prototype system for practical application in some hospitals. The results of clinical experiments will be presented in forthcoming papers.

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