在宅医療支援に向けての電磁ブレーキを用いた ハプティックフィードバックとデッドバンド制御による 遠隔リハビリロボットシステム*

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Telerehabilitation Robot System with Haptic Feedback by Means of Brake and Deadband Control Towards Home Medical Welfare Support*

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In this paper, a master-slave robot system involving haptic feedback and teleoperation for rehabilitation is presented. A teleoperation mechanism capable of force feedback by means of brake is proposed. The stability of the teleoperation system with haptic feedback via a time-delay communication environment is mathematically proved. Moreover, in order to reduce the packet transfer rate for data transmission, a deadband control approach is used. A new data reconstruction algorithm is proposed to improve the system's performance while maintaining the system's stability. This system allows passive assisted movement utilizing teleoperation for the rehabilitation of upper limb function.

1. Historical Background and Problem Statements

Currently, the number of elderly people is increasing, especially in the developed countries, and with this increase comes an increase in the number of people who need some type of medical care. At the same time, people of all ages continue to require assistance in recovering from accidents, congenital problems, chronic illness, etc. However, the number of physicians and nurses is not increasing in step with the increasing number of patients. Therefore, in order to fill this need, it is necessary to develop automated systems for patient care. One alternative that is attracting much interest is the use of welfare or life-supporting robots.

In recent years, many studies have focused on the rehabilitation of upper limb function. Among the proposed systems is a haptic interface arm[11], which patients move in order to interact with a virtual environment. In this system, a spring-damper model is used to help the patient follow the programmed exercises. This system collects and analyzes data regarding the patient's position, velocity and force of move-

ment. Another system that uses speed, time or EMG (Electromyography) threshold to initiate robot assistance for maximizing the patient's recovery has been proposed[10]. During the patient's physical activity, speed of movement, time, or EMG signals are measured and evaluated in order to determine a threshold value. Patients perform an exercise without any assistance until they reach their particular thresholds; the assistant robot is then engaged.

Other rehabilitation systems have also been developed[4,9]. Such systems allow exercises that assist the patient in his or her daily life activities. Depending on the patient's condition and the exercise, the system will assist or guide the patient using the difference between the real position and desired position. In all of the above systems, the exercises are programmed into the computer beforehand and the patients practice the exercises as if they were playing a simple computer game. The disadvantage of these systems is that they all have static characteristics. That is, the movements are set before the systems start their work, and the settings can only be changed when the task finished. As a result, either the physician must spend much time adjusting these machines individually for each patient, or the exercises must be simple enough to accommodate all patients.

Teleoperation systems based on haptic feedback combined with audio-visual communication support are applied in a wide range of areas including telemanufacturing, telemaintenance, telesurgery and rescue applications. In the case of rehabilitation, telere-

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habilitation is an effective solution to solve the problems regarding the distance between the patient and physician, a lack of expertise, the high cost of delivery in rural areas, and so on.

However, a problem concerning the teleoperation system using force feedback is that the communication time delay causes system instability. By using a passivity concept, it has been shown that the non-passivity of the communication environment causes this instability[1,13]. Subsequently, a control method (scattering[1] or the equivalent wave variable transformation[13]) to solve the instability problem has been proposed. The resulting control method stabilizes the system for arbitrarily large constant delays. In the case of time varying delay, it became clear that time varying delay threatened the system stability, and a solution to ensure stability in a variable time-delay environment was proposed[12]. Further improvements of[12] were made, such as improving position tracking[5] and discrete-time implementation of the control law[3]. The limit of this solution is that the derivative of time delay must be known in order to choose the appropriate gain that stabilizes the system. Another method has used a four-channel data transmission structure to guarantee the stability and transparency of a master-slave system[16], but in this system it is assumed that the operator and the environment's model are completely known.

Another problem regarding teleoperation through packet switched networks such as the Internet is high packet transfer rate. High packet rates are difficult to maintain over long distance networks. In addition, the probability of congestion is increased leading to higher transmission delay and packet loss. To reduce the packet transfer rate, one solution is to use deadband control, which has been applied in networked control systems[14]. Deadband control was first applied to the field of teleoperation involving haptic feedback in[8]. It has been shown that by using the passivity approach, the data reconstruction algorithm of the deadband control approach may cause non-passivity in a teleoperation system with haptic feedback. Thus, a control approach utilizing the specified reconstruction algorithm based on a HLS (Hold Last Sample) algorithm was proposed as a way to maintain the system's passivity. The limitations of this control approach are that the specified reconstruction algorithm causes a significant difference between the original signal and the reconstructed signal (in order to guarantee the passivity of the system), and also only a constant time delay environment is taken into consideration.

2. Introduction of This Research

In the present paper, in order to build a total tele-control system for home medical welfare support as shown in Fig. 1, a telerehabilitation system for upper limb function, one part of the complete system, is proposed. The proposed system includes a two-

Fig. 1 Tele-control system for home medical welfare support

degrees of freedom (2-DOF) master robot arm and a 2-DOF slave robot arm with haptic feedback and teleoperation. The rehabilitation field common uses rehabilitation techniques: passive and active assisted movement. The physician will move the limb as the patient remains either passive (the passive technique), or actively attempts to contribute to the movement (the active assisted technique). In the first step of developing a new rehabilitation system, the proposed system in this paper focuses on the passive movement technique (passive rehabilitation). The physician uses the master arm and the patient uses the slave arm. The slave robot arm is designed to match a human arm, and the master robot arm is built upon a similar structure but on a smaller scale than the slave arm. This allows the physician to more easily perform the exercise at lower energy, compared to performing the exercise by holding the patient's arm directly. The patient's conditions can be transmitted to the physician using force feedback. Using a haptic feedback signal, the physician can adjust the exercise for the patient in real-time. In addition, because the physician and the patient interact with each other indirectly via the master-slave system, telerehabilitation (rehabilitation by teleoperation) can be implemented in which the master site and the slave site are connected via communication environment with arbitrary time delay. To overcome the instability problem associated with teleoperation using force feedback via communication environment having time delay, our system employs a new teleoperation mechanism. Instead of using actuators in both master and slave sites such as those used in other master-slave systems, electromagnetic brakes are used at the master site. Brakes can communicate a patient's resistance to the master arm's movement as well as stabilize the system in a communication environment having time delay. In addition, a deadband control utilizing a new data reconstruction algorithm is newly proposed for the teleoperation mechanism. This deadband control can

reduce the network transfer rate while maintaining an acceptable system performance and guaranteeing the system's stability.

This paper is organized as follows. Section 3 presents the structure and the operation of the master-slave system. In section 4, the electromagnetic brakes which are used to present feedback force, are introduced. The stability of the proposed teleoperation system is proved in section 5, and the experimental results are shown. The problem of a communication environment, especially a packet switched network such as Internet, is not only time delay, but also high packet transfer rate. Section 6 provides a discussion of deadband control using the new data reconstruction algorithm to reduce network traffic. Furthermore, evaluation of the new deadband control and the comparison with conventional deadband control are also presented in this section.

3. System Structure and Operation

The master-slave system built in this study includes a 2-DOF master robot arm and a 2-DOF slave robot arm. They share similar structures, but the master arm's size is smaller than that of the slave arm, as shown in Table 1. The master arm uses encoders to give its position to the slave arm. Instead of actuators, the master arm has brakes for the implementation of feedback force. Force feedback can be realized by attaching the force strain gauges to the handle part of the slave arm. The slave arm has two DC motors equipped with encoders and reduction gears with a 1:50 ratio. Two ball reducers with a 1:20 ratio are used in two joints of the slave arm. A controller is designed for the slave arm to allow the slave arm to track the master arm's movement. The master and slave arms are connected through a communication environment specified by more or less time delay. A schematic diagram and the specification of the system are shown in Fig. 2 and Table 1, respectively.

Fig. 2 Experimental apparatus and operation of master-slave telerehabilitation system built in this research

Table 1 Specifications of the master arm and the slave arm

Elements	Master arm	Slave arm
Size(W:D:H)[mm]	195:195:210	165:215:300
Arm1 length[mm]	120	200
Arm2 length[mm]	115	300
Weight[kg]	2.0	30.0
Actuator	Brake	DC Motor
Encoder[ppr]	2000	500
Material	Alloy	Alloy

The system operates as follows. The operator (physician) moves the master arm, and the master arm's joint angles are measured. The position information is then sent to the slave site. At the slave site, the slave arm is controlled in order to track the master arm's movement. The patient holds the handle attached to the tip of the slave arm, and in so doing follows the master arm's movement. If the exercise results in pain in the patient, he or she will resist the slave motion. The force sensor attached to the handle measures the force when the patient pulls or pushes the handle. Force information is then sent back to the master site. The master site receives the force signal and the brake at each joint of master arm is applied. These brakes then actively resist the movement of the master arm performed by the physician. By feeling the resistance, the physician will adjust the exercise to be appropriate to the patient in real-time.

4. Brake Characteristics

In our system, electromagnetic brakes are used at the master site to implement the feedback force from the slave site so that the physician can feel the patient's resistance. The brake torque is set to be proportional to the resistance force and therefore proportional to the magnitude of the strain gauge signal. The brake torque can be controlled by input voltage. However, as shown in Fig. 3, the relation between input voltage and brake torque in the case of increasing or decreasing voltage (shown in the figure by circles and triangles, respectively), are neither similar nor nonlinear. In those circumstances, the brakes cannot be controlled directly by the input voltage proportional to the strain gauge signal.

In order to improve the brake characteristics, the PWM (Pulse Width Modulation) method was used. Instead of generating the voltage with a magnitude proportional to the desired value, a pulse of constant magnitude and width proportional to the desired value is generated in each PWM cycle. The magnitude is chosen so that the brake torque in the case of increasing voltage is similar to that in the case of decreasing voltage. The brake torque is controlled by adjusting the width of the pulse (the duty cycle). The input voltage of the brake can only be zero or equal to the magnitude of the pulse. Therefore, the same input

Fig. 3 Relation between input voltage and brake torque

Fig. 4 Relation between PWM duty cycle and brake torque

pulse, the same output torque of brake. As shown in Fig. 4, the relation between duty cycle and brake torque is the same in both an increasing and decreasing duty cycle (shown in the figure as dashed lines and circles, respectively). The characteristic line is still nonlinear, but it can be divided into four linear parts (the solid line in Fig. 4).

5. Stability of the System

5.1 System Dynamics

In this paper, we consider the case of the general n -DOF master and n -DOF slave robot system. The n -DOF master and n -DOF slave robot system can be described as:

$$M_m(q_m)\ddot{q}_m(t) + C_m(q_m, \dot{q}_m)\dot{q}_m = T_m \quad (1)$$

and

$$M_s(q_s)\ddot{q}_s(t) + C_s(q_s, \dot{q}_s)\dot{q}_s = T_s, \quad (2)$$

where q_i are the master and the slave arm angular position vectors, T_m is the total torque at the master site, and T_s is the slave control. $M_i(q_i)$ and $C_i(q_i, \dot{q}_i)$ are the symmetric and positive definite inertia matrices and Coriolis matrices, respectively. $\dot{M}_i(q_i) - 2C_i(q_i, \dot{q}_i)$ are skew-symmetric matrices ($i = m, s$).

The total torque T_m includes the human torque T_h and the brake torque T_b : $T_m = T_h + T_b$. Because the brake only resists the movement, the electromagnetic brake torque depends on not only its input value, but also on the movement's direction and human torque. Therefore,

- $\dot{q}_{mj} \neq 0$:

$$T_{bj} = -\text{sign}(\dot{q}_{mj})|T_{fj}| \quad (3)$$

- $\dot{q}_{mj} = 0$

$$T_{bj} = \begin{cases} -\text{sign}(T_{hj})|T_{fj}| & \text{if } |T_{hj}| > |T_{fj}| \\ -T_{hj} & \text{if } |T_{hj}| \leq |T_{fj}|, \end{cases} \quad (4)$$

where T_{fj} is the desired brake output, T_{bj} is the brake torque, T_{hj} is the human torque, and $\dot{q}_{mj}$ is the joint's velocity at the j^{th} joint of the master arm ($j = 1, \dots, n$).

5.2 System Stability

Fig. 5 Block diagram of the master-slave robot system

Consider the teleoperation of the system as shown in Fig. 5. The desired communication response between the master site and the slave site is

$$q_{sd}(t) = q_m(t - T_1); \quad T_f(t) = T_g(t - T_2), \quad (5)$$

where q_{sd} is the reference slave position, T_g is the feedback torque from the slave site to the master site, and T_1 and T_2 are the communication time delay from the master site to the slave site and vice versa. In the slave site, a PD (Proportional-Derivative) controller is used to control the slave arm to track the master arm's movement:

$$T_s = K_P(q_{sd} - q_s) - K_D\dot{q}_s, \quad (6)$$

where K_P and K_D are coefficients of the PD controller. For our slave robot arm, $K_P = \text{diag}[20 \ 20]$; $K_D = \text{diag}[1280 \ 1280]$. They are determined by trial and error to get minimize steady state error. The system has an equilibrium point at $\dot{q}_m = \dot{q}_s = 0$. The proof of the stability is as follows:

Initially, the system is proved to be stable at $\dot{q}_m = 0$. Consider the system such that the input is human torque T_h and the output is master velocity $\dot{q}_m$. Other parts of the system are in the feedback path. The Lyapunov candidate function V is

$$V = \frac{1}{2}\dot{q}_m^T M_m \dot{q}_m. \quad (7)$$

V is a positive definite function, $V > 0$ except $\dot{q}_m = 0$. Then, $\dot{V}$ is calculated as follows (suppose that $T_h = 0$):

$$\begin{aligned}
\dot{V} &= \dot{q}_m^T M_m \ddot{q}_m + \frac{1}{2} \dot{q}_m^T \dot{M}_m \dot{q}_m \\
&= \dot{q}_m^T (T_b - C_m \dot{q}_m) + \frac{1}{2} \dot{q}_m^T \dot{M}_m \dot{q}_m \\
&= \dot{q}_m^T T_b + \frac{1}{2} \dot{q}_m^T (\dot{M}_m - 2C_m) \dot{q}_m.
\end{aligned}$$

Because $\dot{M}_m - 2C_m$ is skew-symmetric matrix, $\dot{q}_m^T (\dot{M}_m - 2C_m) \dot{q}_m = 0$. Moreover, from eqs. (3) and (4), we have

$$\dot{q}_{mj} T_{bj} = \begin{cases} -\text{sign}(\dot{q}_{mj}) \dot{q}_{mj} |T_{fj}| < 0 & , \text{ if } \dot{q}_{mj} \neq 0 \\ 0 & , \text{ if } \dot{q}_{mj} = 0 \end{cases} \quad (8)$$

$\dot{q}_{mj} T_{bj} \leq 0$ with any value of T_{fj} . Therefore

$$\dot{V} = \dot{q}_m^T T_b \leq 0. \quad (9)$$

The system is asymptotically stable at the equilibrium point $\dot{q}_m = 0$ with any time delay and feedback torque values.

Secondly, the system is proved to be stable at $\dot{q}_s = 0$. As shown above, the system is asymptotically stable at the equilibrium point $\dot{q}_m = 0$; therefore, $\dot{q}_m \rightarrow 0$ when $t \rightarrow \infty$. Using eq. (5), then $\dot{q}_{sd}(t) = \dot{q}_m(t - T_1) \rightarrow 0$ when $t \rightarrow \infty$, with any value of time delay T_1 and T_2 . Because the slave robot uses a PD controller and q_s is the vector of angular positions, the slave robot system is Input-to-State stable[2]. Using the interconnection property of Input-to-State Stability[15], the system is also stable at the equilibrium point $\dot{q}_s = 0$. The PD controller at the slave site guarantees the stability of the slave system.

In conclusion, the system is stable at the equilibrium point $\dot{q}_m = \dot{q}_s = 0$ with any value of time delay T_1, T_2 , and feedback torque. When the input is zero, the brakes dissipate the energy, and the robot system then settles down at $\dot{q}_m = \dot{q}_s = 0$, despite the non-passivity of the communication environment.

5.3 Experimental Setup and Results

To perform the experiment regarding teleoperation, a network simulator (a Berkeley Network Simulator (ns2)[7]) is used as the communication environment. The live traffic generated by the master and slave site is passed through the virtual network defined by the user. A private network is established for communication among the master PC, the network simulator PC, and the slave PC.

5.3.1 Experimental Setup

The experimental setup was as follows:

- The round trip time delay is set randomly using a virtual network as shown in the first part of Fig. 6
- In the experiments, a person held the handle of the slave arm and suddenly resisted the slave arm's motion in imitation of a situation in which the patient felt pain and wanted to reduce or stop the movement.
- The brake torque is also proportional to the measured force at the strain gauge attached to the handle of the slave arm.

5.3.2 Experimental Results

The experimental results regarding the system's teleoperation with constant time delay can be seen in[6]. The experimental results involving time varying delay is shown in Fig. 6.

Fig. 6 Experimental result of teleoperation of the system

The experimental results demonstrated the system's stability and its effective tracking, despite the time delay. When the patient pushes or pulls the handle of the slave arm using strong force, it becomes difficult for the physician to move the master arm (the position is also constant) due to the activation of the electromagnetic brakes. The brakes consistently obstruct the physician's movement in order to both ensure the patient's safety and also present the patient's state.

6. Network Traffic Reduction

In a teleoperation system, data transmitted over the communication channel is usually sampled at a rate equal to the sampling rate of the local control loops at the sending site. That makes the packet transfer rate high. A high packet transfer rate may cause an increase in time delay and packet loss. Therefore, the packet transfer rate must be decreased. One approach is then to use deadband control[8,14]. However, the algorithms in[8,14] cause a significant difference between the original signal and the reconstructed signal while reducing the network traffic. That may not be appropriate in the rehabilitation field, in which the system's performance must be precise enough to convey the exact exercises created by the physician to the patient. In the next section of this paper, the deadband control combined with a new data reconstruction algorithm is introduced to reduce the network traffic as a way to ensure greater system performance. At first, the definition of the deadband control and the new data reconstruction algorithm is presented. Moreover, effects of communication environment such as time delay and packet loss are dis-

cussed. Finally, the comparison between the new data reconstruction algorithm and conventional algorithm is presented. The overall system architecture including the proposed deadband control and the data reconstruction is presented in Fig. 7. The proposed deadband control and data reconstruction algorithm are used in transmission for both position and force feedback.

Fig. 7 System architecture with proposed deadband control

6.1 Definition of Deadband Control

The deadband control in [8, 14] is defined that the data is sent via the communication network only if the signal value changes more than a given threshold. Fig. 8 illustrates the deadband control with the time instants of packet transmission for the example signal presented by squares in the standard case and by diamonds in the deadband case. This shows the resulting reduction in the packet transfer rate. Because not all the data in deadband control, as shown in Fig. 8, is sent, in the receiving site it is necessary to have a scheme to reconstruct the signal from received data; this is called the data reconstruction algorithm. In [8], the threshold is a constant value or proportional one to the magnitude of the sent data according to Weber's law, such that the size of the just noticeable difference is a constant proportion of the original stimulus value. In addition, the data reconstruction algorithm is modified from the algorithm that holds the last sample until the newer one arrives. In [14], the threshold is determined considering the reduction of the packet transfer rate and system error. System error can be considered as the difference between the reference signal and the received signal that is constructed from received data using the data reconstruction algorithm.

In the proposed deadband control of the present paper, a signal called "predictive signal" is introduced. The predictive signal is generated in the sending site from sent data values by using the same data reconstruction algorithm with the receiving site. Therefore, the predictive signal is the representation in the sending site of the received signal which is constructed from received data in the receiving site. Deadband control is that the reference signal is sent via the communication network only if

(i) The difference between the reference signal value

Fig. 8 Visualization of the normal deadband control approach in comparison with the standard approach

and the predictive signal value is greater than Δ , a given threshold value, or

(ii) The reference signal value changes more than Δ_s , another given threshold, where Δ and Δ_s are different values and these values are determined in section 6.3.

With the first condition, the system error can be easily observed by the given threshold Δ . This threshold is mainly used to decide the system's performance with deadband control. The second condition restricts the difference between two consecutively sent data. Therefore, the reconstructed signal between two consecutively received data must also be restricted. The second condition is necessary to restrict the reconstructed data in case of time varying delay or packet loss. Because the reconstruction process only resets when a new data comes, the reconstruction data depends on time delay and received data packet, which is unknown in advance. Therefore, the reconstructed data must be restricted. Fig. 9 shows the proposed deadband control; the time instants of the packet transmission for the example signal are presented by squares in the standard case and by diamonds in the proposed deadband case. When the predictive signal (dashed line) is beyond the limited area between the lower restriction line and the upper restriction line, the data is sent (the first condition). The distance between the reference line and the lower and the upper restriction lines is Δ . The data is also sent when the reference signal value changes more than Δ_s , even if the difference between the predictive signal and the reference signal is smaller than Δ (the second condition).

6.2 Data Reconstruction Algorithm

When using the deadband control to send a reference signal, a series of data from the reference signal is collected in the sending site and the collected data is sent to the receiving site. Therefore, the receiving site also receives a series of data. A series of data in the sending site is used to generate the predictive signal, while a series of data in the receiving site is used to construct the received signal.

Suppose a series of the obtained data $\{x_s(t_k)\}, k =$

Fig. 9 Visualization of the proposed deadband control approach in comparison with the standard approach

0, 1, 2, ... The data reconstruction algorithm constructs the data $x(t)$ with $t_k < t \leq t_{k+1}$ from $x_s(t_i)$ ($i \leq k$), where in the sending site, $x(t)$ is the predictive signal, and in the receiving site, $x(t)$ is the received signal. The algorithm is as follows:

$$x(t) = \begin{cases} x_s(t_k) + \alpha_k(t - t_k) & , \text{ if } |\alpha_k(t - t_k)| \leq \Delta_s \\ x_s(t_k) + \text{sign}(\alpha_k)\Delta_s & , \text{ otherwise} \end{cases} \quad (10)$$

where α_k is the linear reconstruction coefficient calculated as follows:

$$\alpha_k = \begin{cases} 0 & , \text{ if } k = 0 \\ \frac{x(t_k) - x(t_{k-1})}{t_k - t_{k-1}} & , \text{ if } k \geq 1 \end{cases} \quad (11)$$

The signal $x(t)$ is constructed using first-order interpolation (the first case) until $t = t_{k+1}$. During this period, if $|x(t) - x(t_k)| \geq \Delta_s$, the first-order interpolation stops, and the last value is kept (the second case) until this period finishes. This is to match the second condition in deadband control, in order to restrict the reconstructed signal in case of time varying delay and packet loss where the construction time is unknown in advance.

Fig. 10 demonstrates the above data reconstruction algorithm. However, at the fixed point t_{k+2} , a sudden change appears (dashed line). In the period from t_{k+1} to t_{k+2} the reconstruction data value increases ($\alpha_{k+1} > 0$), the same as in the period from t_{k+2} to t_{k+3} ($\alpha_{k+2} > 0$). However, at the switching point t_{k+2} of these periods, the reconstruction value $x(t_{k+2})$ is larger than fixed data value $x_s(t_{k+2})$. Then, at that point, the reconstructed data value decreases from $x(t_{k+2})$ to $x_s(t_{k+2})$. In order to avoid this discontinuous motion, the data reconstruction algorithm is added as follows ($t_k < t \leq t_{k+1}$):

- At first, the reconstruction data is calculated using (10).
- If $(x(t) - x(t_k))\alpha_k < 0$, then

$$x(t) = x(t_k). \quad (12)$$

As seen in Fig. 10, at the period $t > t_{k+2}$ ($t \leq t_{k+3}$), $x(t) = x(t_{k+2})$ until the first-order interpolation value $x(t) = x_s(t_{k+2}) + \alpha_{k+2}(t - t_{k+2}) \geq x(t_{k+2})$ (solid line).

Fig. 10 The principle of the data reconstruction algorithm

6.3 Finding of Thresholds for Deadband Control

Deadband control is used to reduce packet transfer rate. However, it also reduces the system's performance. Two thresholds, Δ and Δ_s , exist in the proposed deadband control corresponding to the two conditions in the definition of the deadband control. They are determined to satisfy a specified requirement of system's performance. As mentioned in section 6.1, in the proposed deadband control, the Δ threshold is the most important, it decides two performance indexes of the system, the packet transfer rate and the difference between the reference signal and the predictive signal. The threshold Δ_s is only for restriction of reconstructed signal in case of time varying delay or packet loss. In simulation analysis, it becomes clear that Δ_s does not affect much to the performance indexes under a fixed Δ . Hence, since sensitivity of Δ on two performance indexes which is explored later is high, we assume that $\Delta_s = \eta\Delta$ with $1 < \eta = \text{const}$. We suitably have to choose only the threshold value of Δ .

The threshold value Δ is determined by evaluating the packet transfer rate and the difference between the reference signal and the predictive signal. The packet transfer rate is evaluated using network index δ_n defined by

Network index:

$$\delta_n = \frac{\text{number of sending times using deadband}}{\text{number of sending times without deadband}}. \quad (13)$$

The difference between the reference signal and the predictive signal is evaluated using system error index δ_e defined by

System error index:

$$\delta_e = \frac{\text{total absolute value of the difference}}{\text{total absolute value of the reference signal}} \quad (14)$$

Here, the difference between the reference signal and the predictive signal, not the reconstructed signal at receiving site is considered because the reconstructed signal depends on the communication environment that is unknown in advance. In the later section, the effect of communication environment such as time delay, or packet loss to the difference between the predictive signal and the received signal is evaluated.

The thresholds Δ may be determined by using specific reference signals. Rehabilitation exercises for the human arm usually involve slow and repeated movements. Therefore, the reference signal should be a low frequency sinusoidal signal. In this research, the reference signal is given by $q_m = \sin(2\pi ft)$ with $0.1[\text{Hz}] \leq f \leq 1[\text{Hz}]$. The relation between Δ and the network index δ_n , and the system error index δ_e are shown in Fig. 11. In this case, the frequency of the reference signal is 1[Hz].

Fig. 11 Relation between network index, system error index and the threshold value ($f=1\text{Hz}$)

It is found that when Δ increases, the network index decreases, but the system error index increases. By using these relations, Δ can be appropriately determined by the specified conditions such as system error or network transfer rate.

The determined threshold value also depends on the frequency of the reference signal. Fig. 12 shows the relation between the network index and the system error index at different frequencies. It is found that under the same network index requirement, the system error index is smaller if the frequency is smaller. Therefore, Δ should be determined by using a reference signal of sufficiently high frequency to keep robustness due to the frequency variation. Then, the requirements at lower frequencies are always satisfied.

In its application to a rehabilitation system, the frequency of the reference signal indicating position

Fig. 12 Relation between network index and system error index in different frequencies

should be 1Hz. With a system error requirement of $\delta_e = 0.01$, Fig. 11 shows that the deadband value is $\Delta = 0.025$ (2.5% of the magnitude of the reference signal), and the corresponding network index is $\delta_n = 0.047$ (47 times/ 1 seconds). Fig. 13 shows the reference signal and the predicted signal corresponding to this deadband value. In this case, it is assumed that $\eta = 4$ ($\Delta_s = 4\Delta$). The experiments shows that the motion is smooth and people may not recognize the difference between reference motion and reconstructed motion.

Fig. 13 The reference signal and the predictive signal in the case of $\Delta = 0.025$, $\Delta_s = 4\Delta$

6.4 Effects of Time Delay and Packet Loss

The threshold value is determined based on the difference between the reference signal and the predictive signal. The reconstructed signal at the receiving site is desired to be the same as the predictive signal. However, time delay and packet loss during data transmission cause the difference between these signals. This section discusses the effects of time delay and packet loss on the difference between the predic-

tive signal and the reconstructed signal at the receiving site.

6.4.1 Effect of Time Delay

The predictive signal is constructed from series $\{x_p(t_k)\}$, while the received signal is constructed from series $\{x_c(t_k^*)\}$. They use the same data reconstruction algorithm. Moreover, the relation between the series $\{x_p(t_k)\}$ and the series $\{x_c(t_k^*)\}$ is:

$$x_p(t_k) = x_c(t_k^*); \quad t_k = t_k^* - T_k,$$

where t_k is the time that $x_p(t_k)$ is sent, t_k^* is the time that $x_p(t_k)$ is received, and T_k is the communication time delay.

In order to compare the reconstructed parts of two signals, the linear reconstruction coefficient is firstly considered. From eq. (11), the linear reconstruction coefficient α_k^p of the predictive signal and α_k^c of the reconstructed signal at the slave site are

$$\alpha_k^p = \frac{x_p(t_k) - x_p(t_{k-1})}{t_k - t_{k-1}}; \quad \alpha_k^c = \frac{x_c(t_k^*) - x_c(t_{k-1}^*)}{t_k^* - t_{k-1}^*}.$$

Then,

$$\begin{aligned} \alpha_k^p &= \frac{x_p(t_k) - x_p(t_{k-1})}{t_k - t_{k-1}} \\ &= \frac{x_c(t_k^*) - x_c(t_{k-1}^*)}{t_k^* - t_{k-1}^*} \times \frac{t_k^* - t_{k-1}^*}{t_k - t_{k-1}} \\ &= \alpha_k^c \frac{(t_k + T_k) - (t_{k-1} + T_{k-1})}{t_k - t_{k-1}} \\ &= \alpha_k^c \left(1 + \frac{T_k - T_{k-1}}{t_k - t_{k-1}}\right). \end{aligned}$$

Hence, it follows that

$$\alpha_k^p = \alpha_k^c \left(1 + \frac{T_k - T_{k-1}}{t_k - t_{k-1}}\right) = \alpha_k^c (1 + \tau_k), \quad (15)$$

where $\tau_k = \frac{T_k - T_{k-1}}{t_k - t_{k-1}}$ is the variation rate of time delay.

The difference between the predictive signal $x_p(t)$ with $t_k < t < t_{k+1}$ and the corresponding reconstructed signal $x_c(t^*)$ is evaluated by

$$\mu_k = \frac{\sum_{t_k}^{t_{k+1}} x_p(t) - \sum_{t_k + T_k}^{t_{k+1} + T_k} x_c(t)}{\sum_{t_k}^{t_{k+1}} x_p(t)} = \frac{\alpha_k^p - \alpha_k^c}{\alpha_k^p}.$$

Substitute (15) into above equation,

$$\mu_k = \frac{\tau_k}{1 + \tau_k}. \quad (16)$$

Thus, the difference μ_k depends on the variation of communication time delay τ_k . In case of constant time delay or little time varying delay, the difference is very small as shown in Fig. 14. However, it will become significant if the variation is large as shown in Fig. 15.

6.4.2 Effect of Packet Loss

When packet loss occurs, the data for reconstruction is lost; therefore, the system error may increase. Fig. 16 shows the simulation results of the relation

Fig. 14 Reconstructed signal at the receiving site under small variation of time delay

Fig. 15 Reconstructed signal at the receiving site under large variation of time delay

between the rate of packet loss and the system error index in the case of $\Delta = 0.025$, $\Delta_s = 4\Delta$. In this simulation, the rate of packet loss is from 0 to 50%. At each packet loss rate, the simulation is repeated about 10 times and the packet loss is randomly generated. Depending on the time that packet loss happens, the system error is varied as seen in Fig. 16.

When data is not received because of packet loss, instead of using linear reconstruction as in the first case of eq. (10), the second case of eq. (10) usually occurs and the error increases. Fig. 17 shows the reconstructed signals without packet loss and with 25% packet loss. The system error index can be 0.05 when packet loss is 25%, although the threshold value $\Delta = 0.025$ is chosen so that the system error index is 0.01 as mentioned in section 5.3. Therefore, the effect of packet loss should be considered when determining the threshold value for deadband control.

Fig. 16 Relation between rate of packet loss and system error index ($\Delta = 0.025$)

Fig. 17 Reconstructed signals without packet loss and with 25% packet loss

6.5 Stability of the System with Deadband Control

The stability of the system with deadband control is demonstrated based on the proof in section 4.2 as follows.

From eq. (8), it is found that the inequality eq. (9) is always true with any value of T_{fj} . Therefore, the deadband control for force feedback transmission does not affect the stability of the system at $\dot{q}_m = 0$.

To prove the system's stability also at the point $\dot{q}_s = 0$, the following condition must be satisfied:

$$\dot{q}_m \rightarrow 0 \Rightarrow \dot{q}_{sd} \rightarrow 0. \quad (17)$$

Then as shown in section 4.2, the PD controller at the slave site can guarantee the stability of the slave system. In the following, we show that the data reconstruction algorithm can satisfy eq. (17).

When $\dot{q}_m \rightarrow 0$, then $\forall \epsilon > 0, \exists t_0 : |\dot{q}_m(t)| < \epsilon, \forall t > t_0$, hence

$$\begin{aligned} \alpha_k^p &= \frac{q_m(t_k) - q_m(t_{k-1})}{t_k - t_{k-1}} = \frac{\int_{t_{k-1}}^{t_k} \dot{q}_m(t) dt}{t_k - t_{k-1}} \\ &< \frac{\int_{t_{k-1}}^{t_k} \epsilon dt}{t_k - t_{k-1}} = \frac{\epsilon(t_k - t_{k-1})}{t_k - t_{k-1}} = \epsilon \end{aligned}$$

$$\Rightarrow \alpha_k^p \rightarrow 0$$

Combine with eq. (15) $\Rightarrow \alpha_k^c \rightarrow 0$. Moreover, from the data reconstruction algorithm, $\dot{q}_{sd} = \alpha_k^c$ or 0, then $\dot{q}_{sd} \rightarrow 0$. The proof is thus completed. This indicates that the data reconstruction algorithm does not affect the stability of the system.

6.6 Comparison with “Hold Last Sample” Algorithm

Fig. 18 Comparison between the proposed algorithm and conventional HLS

In comparison with a reconstruction algorithm such as HLS[8], Fig. 18 shows the relation between network index δ_n and system error index δ_e in two cases: the HLS and the present algorithm. It is found that with the same network index value, the system error index in the HLS algorithm (shown in the figure by a dashed line) is higher than in the present algorithm (shown by a solid line). This indicates that with the same requirement for reducing network traffic, the system's performance achieved when using the present algorithm is better than by obtained by the HLS algorithm. This is because that the present algorithm is based on first-order prediction, which is more precise and smoother than the zero-order prediction used in the HLS algorithm, in the case of varying signals and large sampling times. Therefore, the present algorithm is more appropriate than HLS is in a rehabilitation system whose performance must be high in order to convey the exact exercises created by the physician to the patient.

7. Conclusion

The paper presents a master-slave robot system with haptic feedback and teleoperation for the rehabilitation of upper limb function. The stability of the system is guaranteed by using brakes instead of active

actuators at the master site to provide the feedback force. In addition, deadband control using the specified data reconstruction algorithm employing first-order prediction is proposed as a means to reduce network traffic. The simulation and experimental results show the effectiveness of the proposed approach.

Using the proposed master-slave system, the passive assisted movement technique, a common rehabilitation technique, can be easily and remotely implemented, with the patient and the physician being in different locations. Using feedback force information from the patient site, the physician can adjust the exercise immediately to match with patient's condition. Moreover, the proposed teleoperation mechanism and the deadband control algorithm described in this paper can be applied to other teleoperation systems utilizing force feedback.

Moreover, in order to compete and develop the present system, rehabilitation with bilateral teleoperation for active assistance will also be considered. In the future, human sensing information such as EMG (Electromyography), pain level, heart rate, blood pressure, autonomous nerve functions, etc. will be considered as feedback information in the development of a better rehabilitation robot system.

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