A Teleoperation System with an Exoskeleton Interface

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Abstract—In this paper, a teleoperation system with an exoskeleton interface is proposed. An upper-limb exoskeleton worn by a user acts as an interface between the user and a robot in a remote place by exchanging position and force information via the Internet. The robot performs a dexterous task by following the upper-limb motion. The applied external force to the robot is transmitted to the exoskeleton worn by the user. To deliver and apply the position and force information accurately, a rotary series elastic mechanism controlled by a proportional and derivative (PD) controller whose gain is tuned by a linear quadratic (LQ) method is applied as an actuator module. A robust control algorithm, disturbance observer, is added to improve the robustness against the modeling uncertainties. A transmission control protocol (TCP) with a packet buffer is used for telecommunications. The performance of the proposed system and control algorithms was verified by experiments with an elbow-actuated upper-limb exoskeleton and a one degrees of freedom (DOF) robotic arm.

I. INTRODUCTION

With the increasing number of natural disasters and dangerous accidents around the world, there is also increasing demand for work in extreme environments. The Fukushima nuclear disaster and BP oil spill are representative examples. Unmanned robots with artificial intelligence have been tested for extreme environment work [1]; however, due to limited intelligence, sensing abilities, and unpredictable environments, many of these attempts have not been successful. Teleoperation systems may provide a promising alternative for the work in extreme environments.

Teleoperation systems have been used for many applications, including remote surgery, tasks in dangerous environments, education, and training [2]–[6]. In a teleoperation system, a human user sends an input command to a robot in a remote place for complicated manipulation, based on transmitted information from the robot. Previous systems have used a joystick or keyboard for the input interface, and a vision system for the sensing interface [7]. However, due to the lack of interface technologies, the interaction between the human user and the motion of the working robot has not been sufficiently natural. Conventional teleoperation systems have only operated in a master-slave mode, in which the working robot follows the given command without feedback to the human. The information about the robot’s surroundings is synthesized by the operator, using the information from other sensors such as a vision sensor. If there is no change in the working environment, simple tasks such as “pick and place” can be easily achieved by position tracking. However, dexterous tasks that require force information are not possible without detailed interactions between the user and the robot.

In this paper, we describe an upper-limb exoskeleton to be used as an interface for a teleoperation system. An exoskeleton is a wearable system for the human user; thus, it can follow human motions, and appropriate force feedback can be applied to the user. Exoskeleton systems have been researched actively for rehabilitation or power augmentation purposes [8]–[11]; however, such a system has not been devised for the interface of a teleoperation system. In this paper, an upper-limb exoskeleton system, equipped with an actuator module for the elbow joint and a one degrees of freedom (DOF) robotic arm, was used for verification of the proposed concept.

The remainder of this paper is organized as follows. Section II details the configuration of the teleoperation system with an exoskeleton interface by presenting its concept, actuator mechanism, and the teleoperation algorithms. Implementation of the proposed system is discussed in Section III. Section IV presents the experimental results. Conclusions and future work are presented in Section V.

II. CONFIGURATION OF THE TELEOPERATION SYSTEM WITH AN EXOSKELETON INTERFACE

A. Concept of the Teleoperation System with an Exoskeleton Interface

Figure 1 shows the concept of the teleoperation system with an exoskeleton interface. The human user sends an input command to the robot by moving himself/herself with the exoskeleton system. The joint angles are measured and transmitted to the robot. The robot follows the transmitted human joint angle. The external force applied to the robot is delivered to the user by the exoskeleton system. The

Fig. 1: Concept of the teleoperation system with an exoskeleton interface

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Exoskeleton/Robot Joint

\[ k \]

Torsional spring \((k)\)

Actuator (Motor)

\[ \theta_H \]

\[ \theta_A \]

Fig. 2: Schematic diagram of the rotary series elastic mechanism

Exoskeleton/Robot Joint

\[ \theta_H \]

Torsional spring \((k)\)

Actuator (Motor)

\[ \theta_A \]

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Fig. 2: Schematic diagram of the rotary series elastic mechanism

By delivering the external force from the environment to the user, the user is better able to interact with the environment intelligently. Impedance control, which is one of the more widely used algorithms in human-robot interactions, is also based on force control [12]. However, previously developed interfaces for a teleoperation system, such as the joystick or keyboard, cannot transmit force information to the user [7]. Haptic interfaces using vibration or simple force feedback systems have been tried, but the force feedback is limited and the interface is not intuitive [6], [13]. In the proposed system, an exoskeleton was used as an interface for a teleoperation system. The position of the user was measured by the exoskeleton interface and transmitted to the robot remotely; the applied force to the robot was then delivered to the user via the exoskeleton interface.

B. Rotary Series Elastic Mechanism

In the proposed exoskeleton interface, a rotary series elastic mechanism, shown in Fig. 2, was applied as an actuator module. The rotary series elastic mechanism originated from the series elastic mechanism [14]–[16], but uses a torsional spring instead of a linear one. The installed spring acts as a torque sensor by measuring the spring deflection. The transmitted torque, \( \tau \), is measured as follows:

\[
\tau = k(\theta_A - \theta_H)
\]  

(1)

where \( k \) is the spring constant, \( \theta_H \) and \( \theta_A \) are the human joint and actuator angles, respectively. Using the rotary series elastic mechanism, the joint angles and force can be measured and applied (see [17]–[19] for more details on the rotary series elastic mechanism). In this research, the actuator module with the rotary series elastic mechanism is applied for both the exoskeleton interface and the working robot.

C. Teleoperation Algorithms

In the proposed teleoperation system, the robot in a remote place follows the user’s motion for dexterous manipulation. When the external force is applied to the robot, the applied force is measured and transmitted to the user via the exoskeleton interface. Thus, the human joint angle, \( \theta_H \), is sent to the robot, and the applied torque from the environment, \( \tau_E \), is transmitted to the human user, as shown in Fig. 3.

If \( \tau_E = 0 \), i.e., no external force is applied to the robot, then the desired motor angle of the robot, \( \theta_{MRd} \), is set using the transmitted human joint angle, \( \theta_H \), as follow:

\[
\theta_{MRd} = N(\theta_H + \theta_{MC})
\]  

(2)

where \( N \) is the gear ratio of the actuator, and \( \theta_{MC} \) is the required angle to compensate the robot link inertia as shown in Eq. (2). \( \theta_{MC} \) is determined by the robot link inertia and the joint angle as follows:

\[
\theta_{MC} = \frac{mgl}{k_R}
\]  

(3)

where \( k_R \) is the spring constant of the robot joint, \( m \) is the robot frame mass, and \( l \) is the length to the center of the robot frame. By setting the desired motor angle of the robot joint as (2), the motor follows the human joint angle such that the remotely operated working robot simulates the actual motion of the human arm.

If an external torque, \( \tau_E \), is applied from the environment to the robot, then \( \tau_E \) is measured by the spring deflection as

\[
\tau_E = k_R(\theta_{MR} - \theta_R)
\]  

(4)

where \( \theta_{MR} \) is the motor angle, and \( \theta_R \) is the robot frame joint angle. The measured torque is transmitted to the human user via the exoskeleton interface. Considering safety and the required sensitivity of the task, the transmitted torque is scaled as follows:

\[
\tau_{Hd} = \frac{\tau_E}{k_{scaling}}
\]  

(5)

where \( \tau_{Hd} \) is the desired torque for the human joint and \( k_{scaling} \) is the scaling factor. If the task performed by the robot requires large force, then \( k_{scaling} \) is set greater than one, i.e., the transmitted torque to the human user is smaller than the actual applied torque to the robot. This scaling factor protects the user from excessive forces. If the task needs sensitive reaction of the human user, then \( k_{scaling} \) is set less
B. Control Algorithms

Precise tracking control of the motor plays a key role in the proposed exoskeleton interface system. The control algorithm shown in Fig. 6 was used for the actuator module. The desired torque, $\tau_d$, was converted to the desired motor angle, $\theta_{Md}$, in the ‘Torque Conversion’ of the block diagram by the relationship in (1) as follows:

$$\theta_{Md} = \frac{\tau_d}{k} + \theta_H$$  \hfill (6)

A proportional and derivative (PD) controller was applied to the basic controller (‘C’ in the block diagram), and the controller gains were optimally tuned by the linear quadratic (LQ) method. The quadratic performance is given by

$$J = \int_{0}^{\infty} [x^T Q x + u^T R u] dt$$  \hfill (7)

where $Q$ and $R$ are the weighting factors that determine the relative importance between the state and the control input. The state, $x$, is the angle and angular velocity of the motor. The control input $u$ to minimize (7) is given by

$$u = -K x$$  \hfill (8)

where $K = -R^{-1}BP$, and $P$ is the positive definite solution of the Riccati equation

$$A^T P + PA - PBR^{-1}B^T P + C^T C = 0$$  \hfill (9)

The state space equation of the DC motor was identified by sweeping sine signals to the system. The PD controller with LQ tuned gains showed good tracking performance; however, the tracking performance deteriorated as the modeling uncertainties increased, due to the interaction with the human user. To deal with the increased modeling uncertainties, a robust control algorithm or disturbance observer (DOB) was applied, as shown in Fig. 6. In general, the DOB was used to:

1) estimate and cancel external disturbances
2) compensate for the variation of plant dynamics by treating the variation as an equivalent disturbance.

In this controller, the DOB was used to compensate the modeling uncertainties in plant dynamics by considering them as equivalent disturbances. For the design of the DOB, the identified nominal model, $P_n$, is used, and the $Q$ filter with a cut-off frequency 10 Hz is applied considering the normal human motion range [20].

Performance of the control algorithm with the PD controller and the DOB was verified by experiments. For the experiments, the proposed control algorithms were implemented by LabVIEW; an NI DAQ board was connected to the DC motor. In the series of experiments, the upper-limb exoskeleton was worn by the user, and the human joint moved arbitrarily. The desired torque was set to a sinusoidal signal, with amplitude 0.2 and a frequency of 0.8 Hz. Figure 7 shows the motor-tracking performance for arbitrary human motions. The desired motor angle was determined from (6), which was amplified for the human joint angle by the 60:1 gear ratio. The desired motor angle and the controlled motor angle are shown in Fig. 7. As a result of precise tracking control, the torque was accurately generated, as shown in Fig. 8. Figure 8a shows the desired and generated torques; the torque error is shown in Fig. 8b.

C. Telecommunication via the Internet

For the proposed teleoperation system, the telecommunication between the exoskeleton interface and the robot in a remote place is achieved by the Internet. In this system, transmission control protocol (TCP) was used for the telecommunication method, as in normal Internet communication. TCP is known as a more reliable data transmission method, as in normal Internet communication. TCP is known as a more reliable data transmission.
protocol than user datagram protocol (UDP), because TCP uses an acknowledgment scheme to verify that the signal is delivered correctly. In TCP, if the sender does not receive acknowledgment before the specified time, then the packet is resent [21]. Because the received signal is used as the reference of the rehabilitation device, a delayed resent signal cannot be used as the reference in the local host controller. In the proposed system, a packet buffer, which is responsible for maintaining the queue of previous values, was utilized in both the local host controller and the second host controller so that a delayed packet could be used. Using the packet buffer, a time delay corresponding to the size of the packet buffer may exist, but the transmitted information can be insulated from unexpected fluctuations in network traffic and/or read/write rates in the programs.

Preliminary experimental results are shown in Fig. 9. In this experimental setup, two computers were connected via the Internet; the Internet communication was implemented by National Instrument (NI) LabVIEW on each computer. The size of the packet buffer could be set in each program. The exoskeleton system was connected to one computer, and the elbow joint angle was measured and transmitted to the second computer. The received joint angle was transmitted again to the original computer, and the received signal was compared with the original signal. Figures 9a and 9b show the two signals without a packet buffer and with a packet buffer of size 50, respectively. Without the packet buffer, the returned signal is not smooth, i.e., a packet loss during the wireless transmission is observed. With the packet buffer of size 50, the returned signal shows a smooth line, which means there is no packet loss even it is a little bit delayed. The time delay during the wireless transmission depends on the wireless communication environments and the size of the packet buffer. By appropriately selecting the size of the packet buffer, the time delay would be the main issue than the packet loss issue. In the actual experiments, and the observed time delay of the measured signals in one computer was 0.1 sec. Since the time delay in transmission between the two computers was assumed to be half of the total delay, the actual time delay can be considered as 0.05 sec.

IV. PERFORMANCE VERIFICATION BY EXPERIMENTS

A. Experimental Setup

The performance of the proposed teleoperation system was verified by experiments. The actuator module in Fig. 2 was installed on the elbow joint for the upper-limb exoskeleton interface and the 1-DOF robotic arm as shown in Fig. 10. Each actuator module was controlled by the control algorithms in Fig. 6, and two systems were connected via the Internet. Both control algorithms and Internet communication were programmed by the NI LabVIEW. In the experiments, the human joint angle was transmitted to the robot and the measured torque of the robot was transmitted to the user via the exoskeleton interface.

B. Experimental Results

The measured human joint angle was transmitted to the robot via the Internet. The desired motor angle of the robot
PD controller with LQ-tuned gains was applied for accurate position control, with the addition of a DOB algorithm for improved robustness. The information between the upper-limb exoskeleton and the robot was transmitted via the TCP. The performance of the proposed teleoperation system and control algorithms was verified by experiments with an upper-limb exoskeleton, equipped with an actuator module for the elbow joint and a 1-DOF robotic arm, with actual Internet communication.

Even though the concept of a teleoperation system with an exoskeleton interface has been demonstrated in this paper, more research is required for practical use of the proposed system. For example, stability issues with time delays due to Internet communication and increased uncertainties from interactions with the user should be carefully studied. Also, the DOF of the exoskeleton interface should be increased to match that of a human arm, so that the user can intuitively, and thus easily, operate the robot remotely.

V. CONCLUSION

In this paper, a teleoperation system with an exoskeleton interface was proposed. The human user operated the robot remotely using an upper-limb exoskeleton. An actuator module utilizing a rotary series elastic mechanism was applied to both the exoskeleton system and the robot. A

REFERENCES


