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Teleoperation System of Industrial Articulated Robot Arms by Using Forcefree Control

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1. Introduction

Recently, network robotics attracts many researchers' attention and a lot of software and hardware on communication technologies are developed for network robotics (Chong et al., 2003; Rogers, 2001; Sanfeliu et al., 2008; Sheridan, 1995; Stassen, 1997). Teleoperation techniques of robot have been developed for many purposes such as ball catching task (Smith et al., 2008), remote handling of dangerous materials in a nuclear environment (Geeter et al., 1999), undersea operation, explosive material disposals, robot-assisted surgery (Challacombe, 2003; Marohn, 2004; Park, 2006) and manipulation systems for planetary exploration (Nickels et al., 2001). Performance of a variety of elements and factors for the telemanipulation system have been investigated by an experimental study (Mora, 2007) and the Internet based teleoperation systems are also eagerly developed (Bambang, 2008; Slawiński et al., 2007; You et al., 2001). For a point of view of control, control techniques of teleoperation system have been investigated such as bilateral control (Aziminejad et al., 2001; Hokayem et al., 2001; Slawiński et al., 2007) and nonlinear adaptive control (Hung, 2003). Explosively grown network technology and robot technology are inextricable relation and expectation on the network robotics becomes large.

In usual teleoperation systems, the operational side and the working side are determined definitely in advance, and the robot in the working side moves according to the command from the operational side. Moreover, in order to operate the robot in the working side, special skill for the operation of the equipment in the operational side is usually required. On the other hand, many kinds of the industrial robot arms have been operated in factories. If these robot arms can be applied both to the operational side and the working side of the teleoperation system, the handleability of the teleoperation system will be remarkably improved. For example, similar mechanism between the operational side and the working side is preferable for intuitive operation of the teleoperation system.

In order to realize passive motion of the industrial robot arms, the forcefree control had been proposed (Goto, 2007). The forcefree control realises the passive motion of the robot arm according to the external force under the zero friction and zero gravity condition. Moreover, the forcefree control was expanded to the forcefree control with independent compensation (Goto et al., 2007). With the forcefree control with independent compensation, the robot arm moves passively according to the external force as in the circumstance of the assigned friction,

the assigned gravity and the assigned inertia. The forcefree control can be applied to the direct teaching (Kushida et al., 2001) and pull-put work of the industrial robot arms (Kushida et al., 2003).

In this research, the teleoperation system is proposed by applying the forcefree control to the robot in the operational side and the position control to the robot in the working side. The method can realize alternation of the roles in the operational side and the working side only by changing the control techniques. The effectiveness of the proposed teleoperation system is confirmed by the experimental results using actual robot arms.

2. Teleoperation System by Using Forcefree Control and Position Control

2.1 Handleability of Teleoperation

Figure 1 shows the concept of the proposed teleoperation system. Both of the operational side and of the working side, any types of industrial robot arms can be used. In the operational side, the forcefree control technique is adopted in order to realize the passive motion due to the influence of external force. When an operator impresses a force upon the robot arm in the operational side by his hand, the robot move according to the applied force. The information of the motion of the robot in the operational side is transmitted to the working side through network. In the working side, the position control is adopted for realization of the same motion of the robot arm in the operational side.

In order to realize the teleoperation system, the dedicated equipment especially for the operational side is usually adopted, and the specific transmission line is usually used. Various equipment is required for various purpose of the teleoperation system, however, the development of the dedicated equipment is costly. If various robot arms can be used both for the operational side and the working side, the development of the dedicated equipment is not required.

The main advantage of the proposed teleoperation system is the usage of the existing equipment and technology. Both for the operational side and for the working side, any kind of robot arms are utilizable. Moreover, the Internet technology is used for the data transmission between the operational side and the working side. Thereby, the most preferable mechanism of the robot arms both for the operational side and for the working side can be selected and the teleoperation system can be constructed freely if the Internet is available.

In addition, the operational side and the working side can be replaced freely by putting both the operational program and the working program in the computer that controls the robot arms. The operational role can be replaced with the working role only by executing the working program, and the working role can be replaced with the operational role only by executing the operational program.

2.2 Configuration Procedure of Teleoperation System

The block diagram of the proposed teleoperation system is shown in Fig. 2. The left side of the Fig. 2 shows the block diagram of the operational side and the hand side shows that of the working side. The operational side and the working side are connected by the network.

A servo controller of industrial robot arm includes a position loop and a velocity loop (Kyura, 1996; Nakamura et al., 2004). Input to the industrial robot arm is usually the joint position of each link. Hence, the industrial robot arms should be considered as the combination of the mechanism of the robot arm and the servo controller. The control loop of the servo controller is shown both on the left side and on the right side of Fig. 2. In the operational side, the

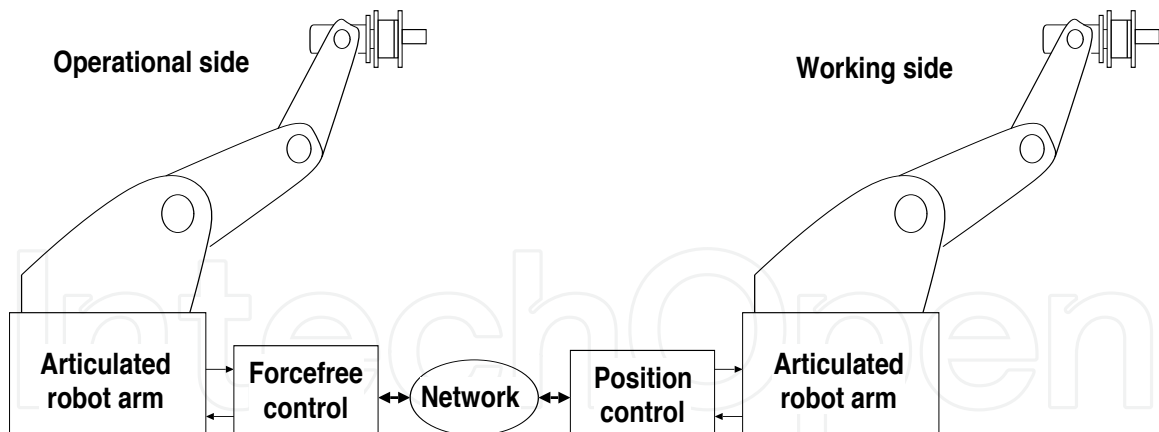


Fig. 1. Schematic diagram of teleoperation system

forcefree control is added to the robot arm and the passive motion according to the external force can be realized.

The tip position of the robot arm in the working side must coincide with that of the robot arm in the operational side. If the robot arm mechanisms between the operational side and the working side are exactly the same, the position output of the robot arm in the operational side can be directly used for the reference input of the robot arm in the working side. However, the robot arm mechanism in the working side is generally different from that in the operational side. Hence, the compensation of mechanism difference is required. The compensated reference input is transmitted to the robot arm in the working side through the network. Then, the robot arm in the working side moves according to the robot arm in the operational side.

2.2.1 Operational Side Control (Forcefree Control)

In the operational side control, the forcefree control is adopted in order to realize the passive motion of the robot arm. Figure 3 shows the concept of the forcefree control. In industrial robot arms, the servo controller is adapted to control the motion of the robot arm, and the robot arm moves according to the position reference of each joint. The external force impressed upon the robot arm is treated as disturbance and the servo controller compensates such disturbance. Hence, the external force never move the industrial robot arm. The forcefree control can achieve the passive motion of the industrial robot arms under virtual circumstances of zero gravity and zero friction without any change of the built-in controller. By use of the forcefree control, the robot arm moves passively according to the external force directly as if it were under the circumstances of zero friction and zero gravity.

The entire dynamics of the industrial robot arms controlled by the forcefree control is described as

$$H^o(\mathbf{q}^o)\ddot{\mathbf{q}}^o + \mathbf{h}^o(\mathbf{q}^o, \dot{\mathbf{q}}^o) = \boldsymbol{\tau}_f^o \quad (1)$$

where $H^o(\mathbf{q}^o)$ is the inertia matrix, $\mathbf{h}^o(\mathbf{q}^o, \dot{\mathbf{q}}^o)$ is the coupling nonlinear term, $\boldsymbol{\tau}_f^o$ is the joint torque corresponding to the external force \mathbf{f} on the tip of robot arm.

Dynamics of an articulated robot arm is expressed by

$$H^o(\mathbf{q}^o)\ddot{\mathbf{q}}^o + D^o\dot{\mathbf{q}}^o + N_{\mu}^o f_s^o(\dot{\mathbf{q}}^o) + \mathbf{h}^o(\mathbf{q}^o, \dot{\mathbf{q}}^o) + \mathbf{g}(\mathbf{q}^o) = \boldsymbol{\tau}_s^o + \boldsymbol{\tau}_f^o \quad (2)$$

where $D^o\dot{\mathbf{q}}^o + N_{\mu}^o f_s^o(\dot{\mathbf{q}}^o)$ is the friction term, $\mathbf{g}(\mathbf{q}^o)$ is the gravity term, \mathbf{q}^o is the position of joint angle, $\boldsymbol{\tau}_s^o$ is the torque input to the robot arm. The dynamic equation of an industrial

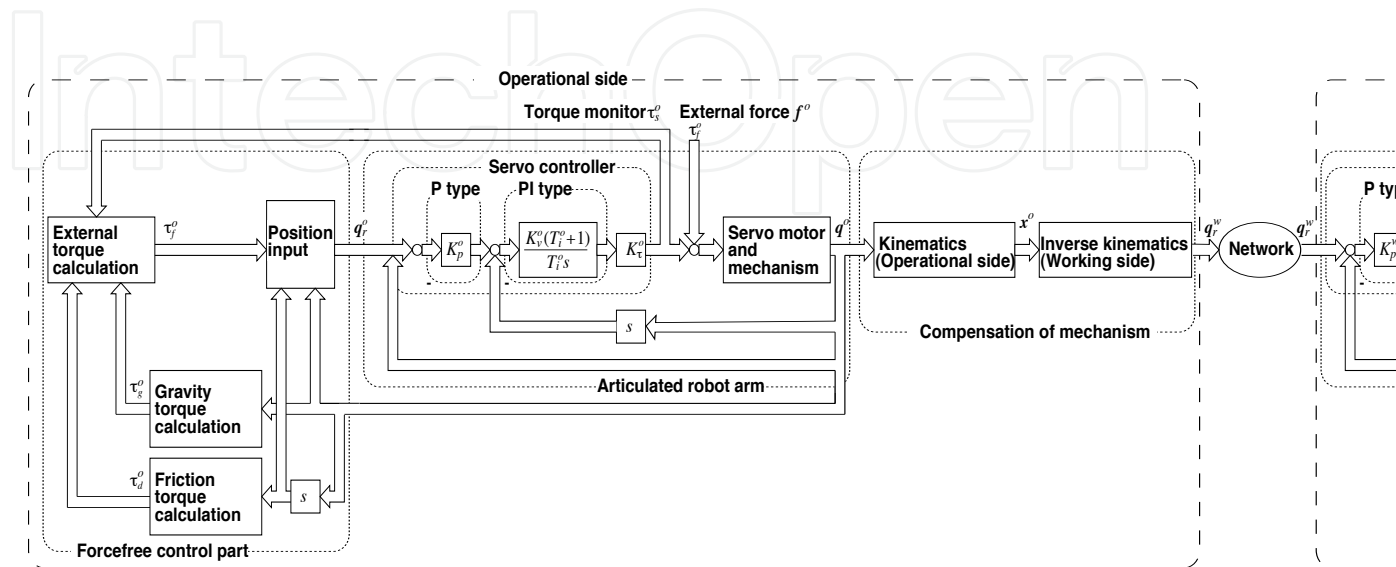


Fig. 2. Block diagram of the teleoperation system

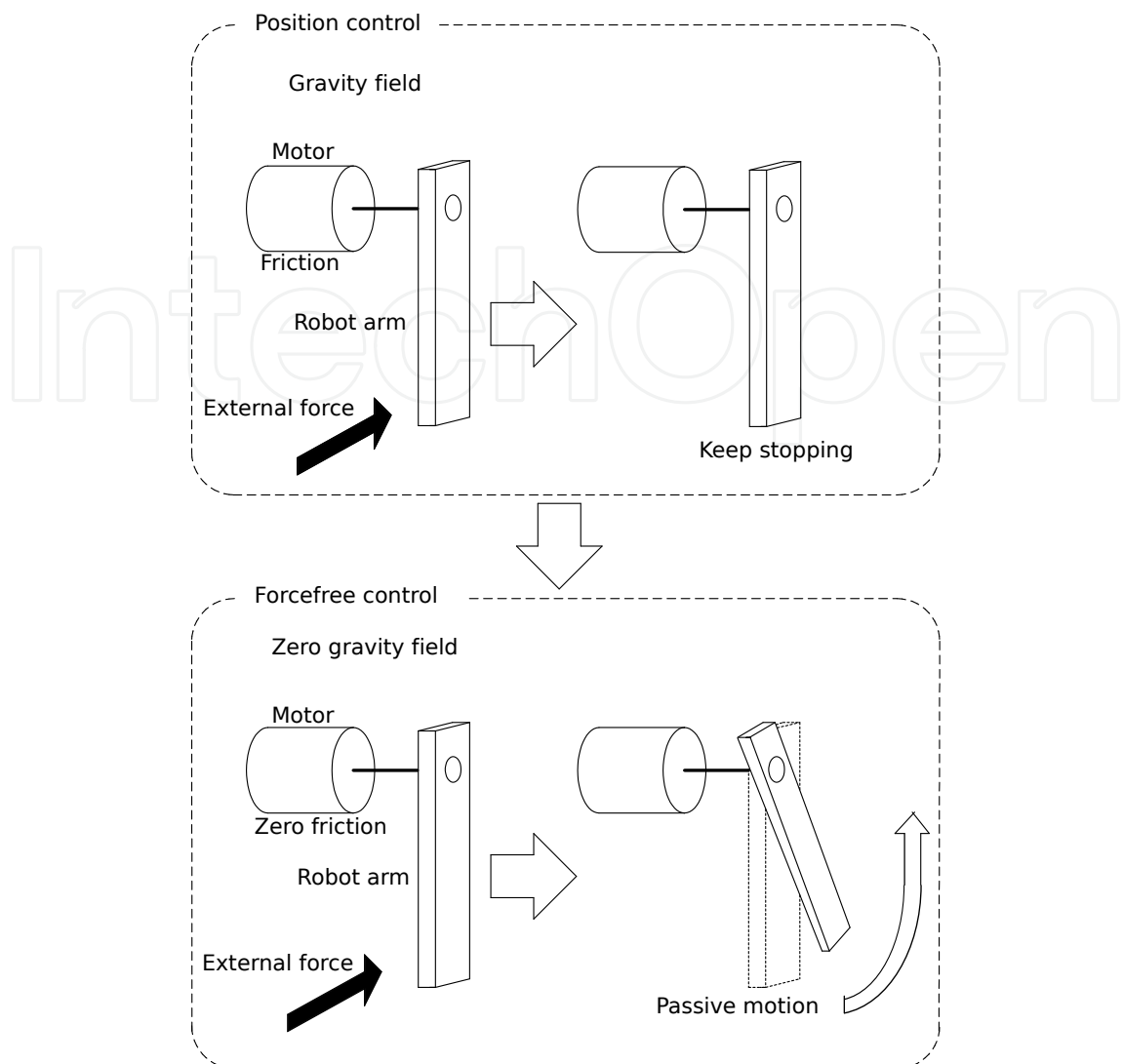


Fig. 3. Concept of the forcefree control

articulated robot arm in the operational side including the servo controller is given by

$$H^o(\mathbf{q}^o)\ddot{\mathbf{q}}^o + \mathbf{h}^o(\mathbf{q}^o, \dot{\mathbf{q}}^o) = K_\tau^o [K_v^o \{K_p^o(\mathbf{q}_r^o - \mathbf{q}^o) - \dot{\mathbf{q}}^o\}] \quad (3)$$

where \mathbf{q}_r^o is the position reference of joint angle, K_p^o , K_v^o and K_τ^o are position loop gain, velocity loop gain and torque constant for the robot in the operational side, respectively

In order to realize the entire dynamics of the industrial robot arms (1), the inputs of joint angle (\mathbf{q}_r^o) for the forcefree control is given by

$$\mathbf{q}_r^o = (K_p^o)^{-1} \{ (K_v^o)^{-1} (K_\tau^o)^{-1} \boldsymbol{\tau}_f^o + \dot{\mathbf{q}}^o \} + \mathbf{q}^o \quad (4)$$

where $\boldsymbol{\tau}_f^o$ is the joint torque corresponding to the external force \mathbf{f} on the tip of robot arm as

$$\boldsymbol{\tau}_f^o = -(\boldsymbol{\tau}_s^o - \boldsymbol{\tau}_d^o - \boldsymbol{\tau}_g^o) \quad (5)$$

where $\boldsymbol{\tau}_d^o$ is the friction torque described by

$$\boldsymbol{\tau}_d^o = D^o \dot{\mathbf{q}}^o + N_\mu^o f_s^o(\dot{\mathbf{q}}^o) \quad (6)$$

and τ_g^o is the gravity torque described by

$$\tau_g^o = g(q^o). \quad (7)$$

2.2.2 Compensation of Mechanism

In order to coincide with the tip position of the robot arm in the working side to that in the operational side, the compensation of the mechanism difference between the operational side and the working side is required. The tip position of the robot arm in the operational side (x^o) is calculated from the position output (q^o) by using the kinematics of the robot arm in the operational side as

$$x^o = f^o(q^o) \quad (8)$$

where f^o means the kinematics of the robot arm in the operational side. The inputs of joint angle (q_d^w) for the robot arm in the working side is given by using the inverse kinematics of the robot arm in the working side as

$$q_r^w = (f^w)^{-1}(x^o) \quad (9)$$

where $(f^w)^{-1}$ means the inverse kinematics of the robot arm in the working side. Thereby, the tip position of the robot arm in the working side coincides with that in the operational side.

2.2.3 Working Side Control (Position Control)

In the working side control, the usual servo controller for industrial robot arms is adopted as a position control. The position control can realize the following motion of the position reference of the robot arm.

The dynamic equation of an industrial articulated robot arm in the working side including the servo controller is given by

$$H^w(q^w)\ddot{q}^w + h^w(q^w, \dot{q}^w) = K_\tau^w [K_v^w \{K_p^w(q_r^w - q^w) - \dot{q}^w\}] \quad (10)$$

where $H^w(q^w)$ is the inertia matrix, $h^w(q^w, \dot{q}^w)$ is the coupling nonlinear term, q^w is the position of joint angle, K_p^w , K_v^w and K_τ^w are position loop gain, velocity loop gain and torque constant for the robot in the working side, respectively.

2.3 Communication Procedure

The Internet technology is used for the communication of the teleoperation because the main advantage of the proposed teleoperation is the usage of the existing technology and the Internet is easily available for the communication channel of the teleoperation system. Concretely, the Socket communication via TCP/IP is applied for communication technique of the teleoperation system. Table 1 shows the data format of the communication. The transmit data from the operational side to the working side are the position reference of the robot arm in the working side and the received data of the operational side from the working side are the position output of the robot arm in the working side.

Figure 4 shows the time chart of the teleoperation system. The robot arms both of the operational side and of the working side are controlled by the real time tasks at the constant sampling interval. On the other hand, the real time property can not be fulfilled by the Socket communication via TCP/IP, then the communication must be operated by using the non real time task.

Transmit data	Time[s]	Position reference q_{r1}^{sw} [rad]	Position reference q_{r2}^w [rad]
Received data	Time[s]	Position output q_1^o [rad]	Position output q_2^o [rad]

Table 1. Data format of the communication between the operational side and the working side

	MK.3	SCARA
Resolution	8192	8000
Link2 gear ratio	160	1
Link3 gear ratio	160	1
Link2 Length[m]	0.25	0.3
Link3 Length[m]	0.215	0.3

Table 2. Schematic parameters of Performer MK3 and SCARA

Concerning about the communication, the position reference generated in the operational side is transmitted to the working side. After receiving of the position reference, the position reference is sent to the real time task of the robot arm control in the working side. Then, the robot arm in the working side is moved according to the received position reference. As a result, even if the time intervals between the successively received position references in the working side are varying, the teleoperation system works well.

The flow of the teleoperation system is explained as follows;

1. The start command is transmitted from the operational side to the working side through the Socket communication via TCP/IP.
2. In the operational side, the robot arm is controlled by the forcefree control at the constant sampling time interval.
3. In the operational side, the position request is sent to the real time task, then the position response of the robot arm in the operational side is received.
4. In the operational side, the position reference of the working side is calculated from the position response of the robot arm in the operational side.
5. The position reference of the working side is transmitted from the operational side to the working side through the Socket communication via TCP/IP.
6. The position output of the working side is transmitted from the working side to the operational side through the Socket communication via TCP/IP.
7. In the working side, the received position reference is sent to the real time task of the robot arm control and the robot arm is controlled at the constant sampling time interval, then the position response of the robot arm in the operational side is received.

3. Validation of the Proposed Teleoperation System

3.1 Experimental Condition

In order to assure the effectiveness of the proposed teleoperation system, an experimental study was carried out using actual robot arms connected with LAN. Figure 5 shows the experimental setup. In order to conform that the proposed teleoperation system is applicable to various types of the robot arms, two different types of the articulated robot arms were used for experiments. One was a vertical articulated robot arm, Performer MK3 (Yahata Electric Machinery Mfg. Co. Ltd.) and another was a SCARA (Selective Compliant Articulated Robot

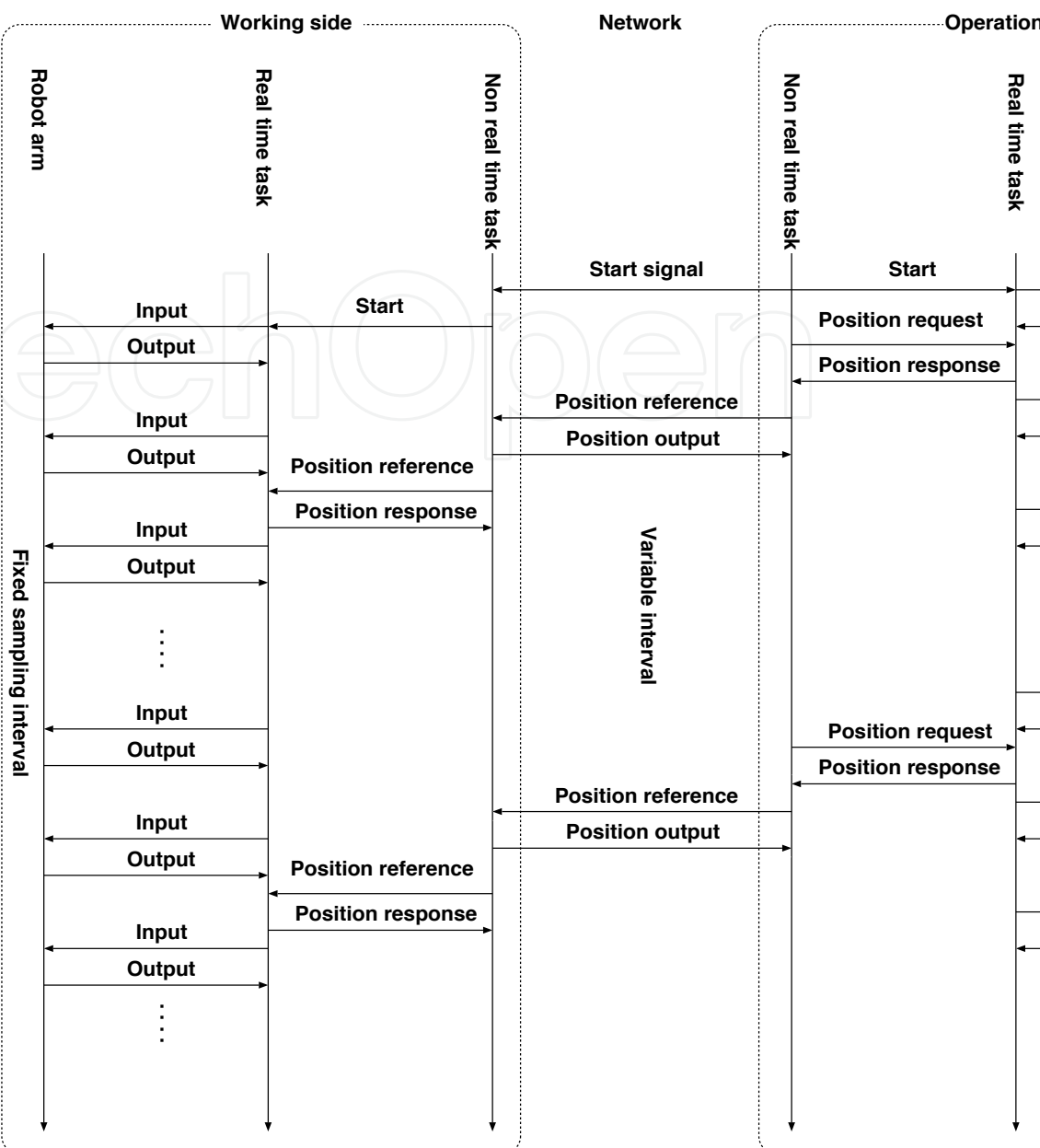


Fig. 4. Time chart of the teleoperation system

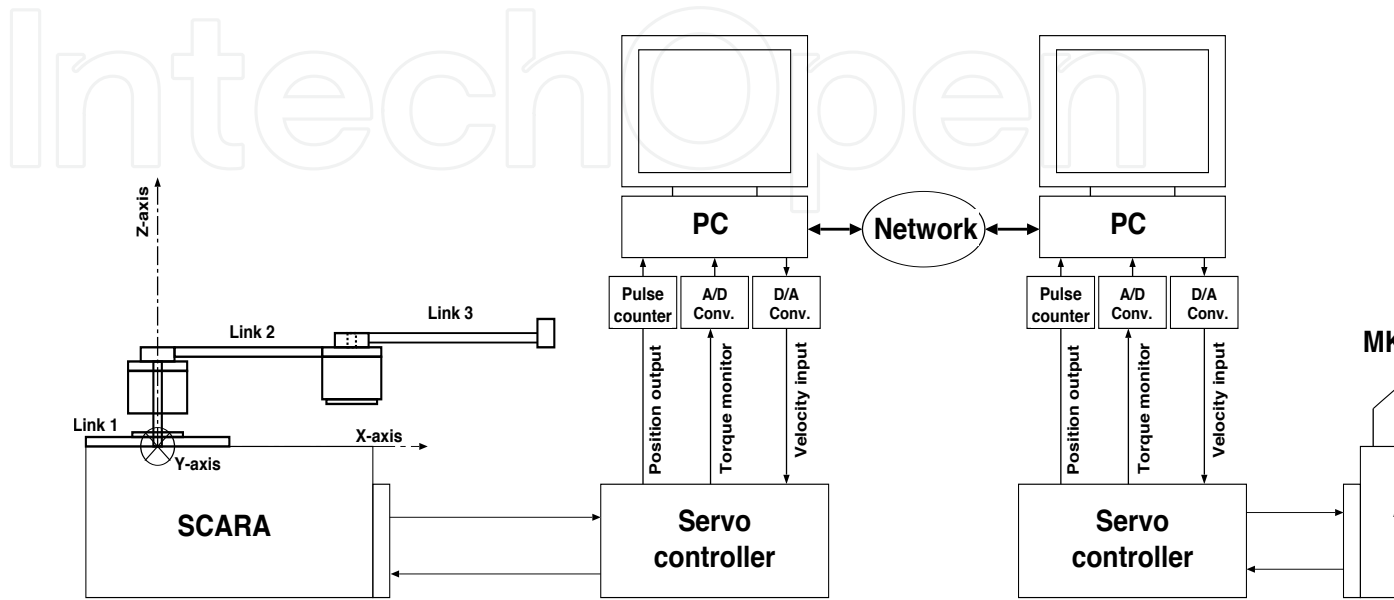


Fig. 5. Experimental setup

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Arm). The schematic parameters of these robots are shown in Table 2. The position loop gain was given as $K_p = 25$ [1/s] and the velocity loop gain was given as $K_v = 150$ [1/s] for Performer MK3 and the position loop gain was given as $K_p = 2$ [1/s] and the velocity loop gain was given as $K_v = 120$ [1/s] for SCARA. The sampling interval of the real time task for the robot arm control was 4 [ms], and the time interval of the position reference generation in the non real time task of the operational side was approximately 50 [ms]. Two links of the link2 and the link3 were used both for Performer MK2 and for SCARA. The robot arm in the operational side was moved passively according to the external force applied by a human hand.

3.2 Experimental Result by Using Actual Industrial Robot Arms

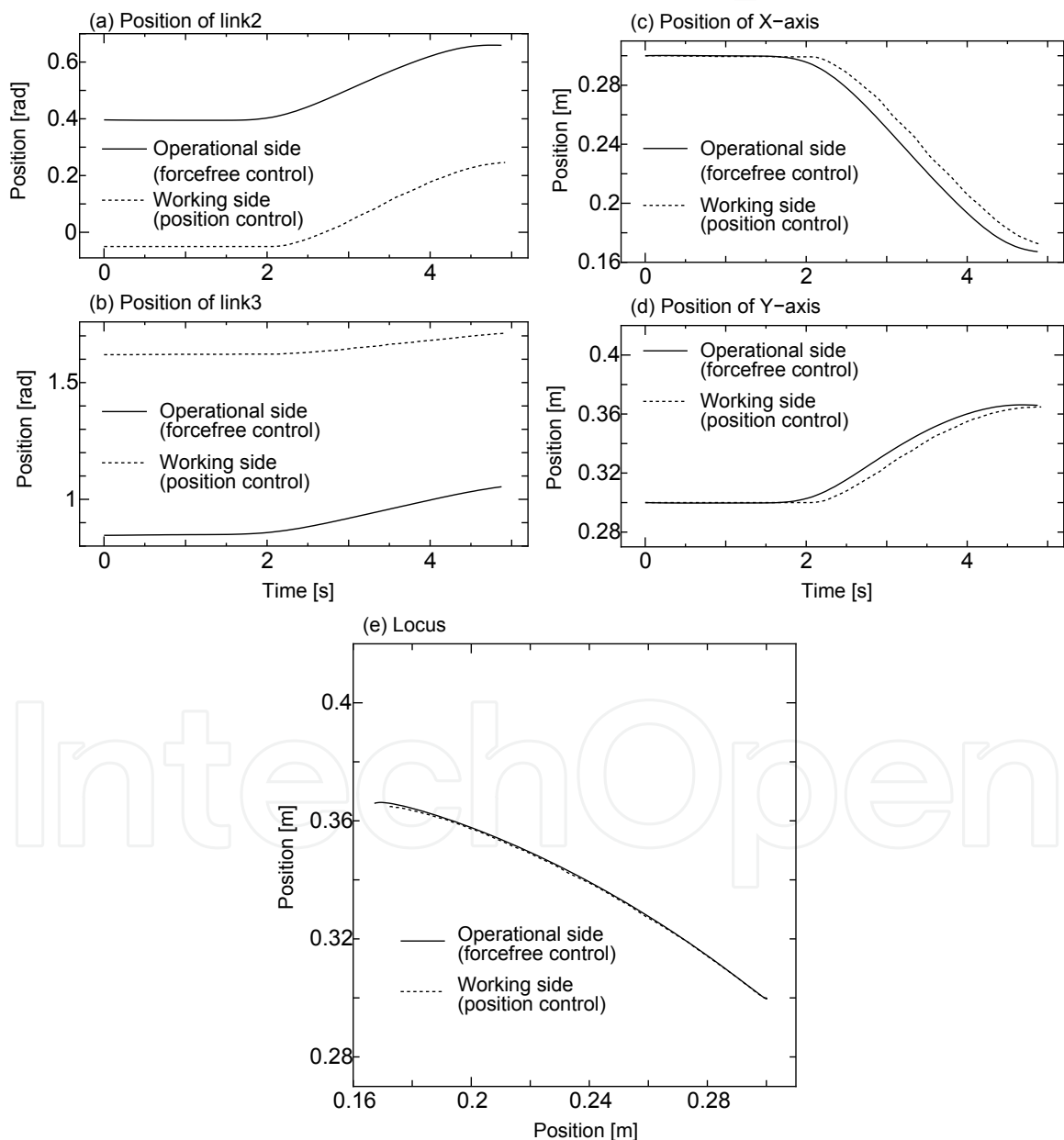


Fig. 6. Experimental result of the teleoperation when the robot arm in the operational side was Performer MK3 and that in the working side was SCARA

First, Performer MK3 was used as the robot arm in the operational side and SCARA was used as the robot arm in the working side. Experimental result is shown in Fig. 6 (a) the time trajectory of the joint position of link2, (b) the time trajectory of the joint position of link3, (c) the time trajectory of the tip position of X-axis, (d) the time trajectory of the tip position of Y-axis and (e) the tip position locus. As shown in Fig. 6 (a) and (b), the joint position in the working side is different from that in the operational side. This is caused by the difference of the mechanism between the working side and the operational side. The tip position in the working side, however, is almost the same as that in the operational side as shown in Fig. 6 (c) and (d) because of the appropriate mechanism compensation. The communication delay was negligible small because LAN was used for the communication channel. The delay about 200[ms] of the working side from the operational side was caused by the dynamics of the robot arm in the working side. As shown in Fig. 6, the robot arm in the working side follows the motion of that of the operational side. The result shows that the teleoperation system by using the forcefree control can be achieved.

3.3 Experimental Result of Alternation of Operational Side and Working Side

Next, the roles of the two robot arms were alternated. SCARA was used as the robot arm in the operational side and Performer MK3 was used as the robot arm in the working side. Experimental result is shown in Fig. 7 (a) the time trajectory of the joint position of link2, (b) the time trajectory of the joint position of link3, (c) the time trajectory of the tip position of X-axis, (d) the time trajectory of the tip position of Y-axis and (e) the tip position locus. As shown in Fig. 7, the robot arm in the working side followed the motion of that of the operational side. The delay about 16[ms] of the working side from the operational side was caused by the dynamics of the robot arm in the working side. The result shows that the teleoperation system by using the forcefree control can be achieved when the operational side and the working side are alternated.

4. Discussion

4.1 Handleability

The proposed teleoperation system can realize the teleoperation as if the operator were in the working side. In the proposed teleoperation system, any types of the industrial robot arms are applicable both for the operational side and for the working side. The experimental study showed that both of the vertical articulated robot arm and SCARA can be applied to both of the operational side and of the working side in the proposed teleoperation system. The servo controller of the industrial robot arm is without change and the additional software of the forcefree control and communication program is enough for the realization of the teleoperation system. The advantage brings flexible teleoperation system construction by use of the appropriate mechanism selection both for the operational side and for the working side.

4.2 Effects on Communication Delay and Data Loss

The Internet technology is used for the proposed teleoperation system. The Socket communication via TCP/IP may include communication delay and data losses. With respect to the communication delay, the influence may appear as the delay of the robot arm motion in the working side from the motion in the operational side because the position reference generated in the operational side is transmitted to the working side, and the robot arm in the work side is moved according to the received position reference with communication delay. With respect to the data loss, the influence may appear as an awkward robot arm motion in the working

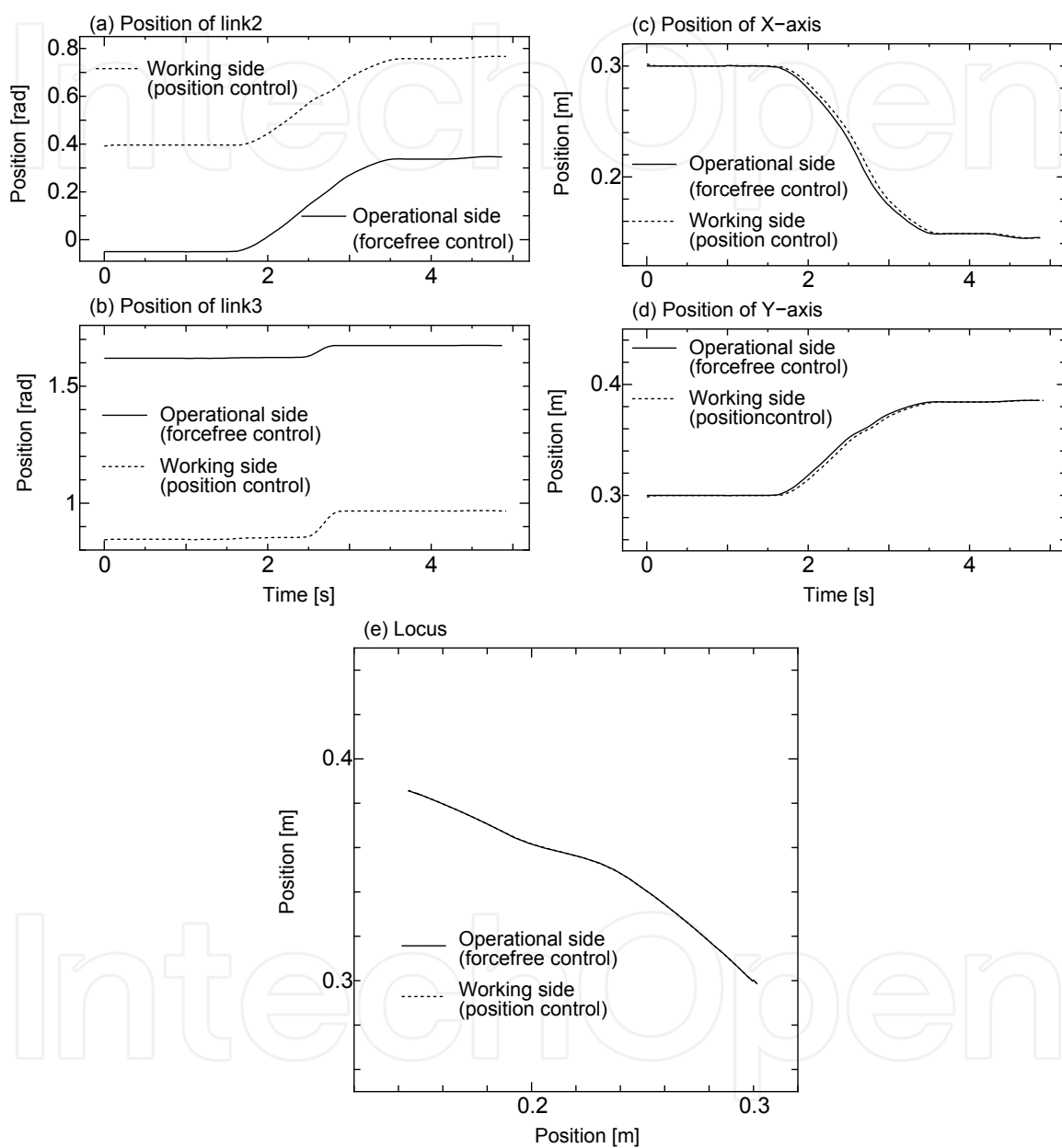


Fig. 7. Experimental result of the teleoperation when the robot arm in the operational side was SCARA and that in the working side was Performer MK3

side because the reference position corresponding to the lost data is vanished. However, the teleoperation system will not become unstable caused by the communication delay or the data loss because the information from the working side is fed back to the operational side.

5. Conclusion

The teleoperation system of the robot arm by using the forcefree control and the position control was proposed. The Internet technology was applied to the communication channel of the teleoperation system. In the proposed teleoperation system, the existing robot arms can be used both for the operational side and for the working side. The experimental results show the effectiveness of the proposed teleoperation system. In the future, further teleoperation system for industrial robot arms considering position, force and visual feedback will be investigated.

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This book presents the most recent research advances in robot manipulators. It offers a complete survey to the kinematic and dynamic modelling, simulation, computer vision, software engineering, optimization and design of control algorithms applied for robotic systems. It is devoted for a large scale of applications, such as manufacturing, manipulation, medicine and automation. Several control methods are included such as optimal, adaptive, robust, force, fuzzy and neural network control strategies. The trajectory planning is discussed in details for point-to-point and path motions control. The results in obtained in this book are expected to be of great interest for researchers, engineers, scientists and students, in engineering studies and industrial sectors related to robot modelling, design, control, and application. The book also details theoretical, mathematical and practical requirements for mathematicians and control engineers. It surveys recent techniques in modelling, computer simulation and implementation of advanced and intelligent controllers.

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