Bilateral Teleoperator System of Robot with Force Reflection using Functional Electrical Stimulation

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Abstract

In this paper, we propose a new method in which the functional electrical stimulation technique of muscles is used to present the reaction forces to the operator. Three small electrodes and two position / orientation sensors are attached on the skin of the upper limb of the operator. Force reflection from the slave to the operator is achieved by functional electric stimulation through the surface electrodes. In this method there is no mechanical part in the master subsystem because the upper limb of the operator itself works as the master arm. In this paper the proposed man-machine interface is described and the effectiveness of the proposed method is illustrated by experiments using a seven axes manipulator.

1 Introduction

The two typical manipulator control problems are tracking a desired trajectory in free cartesian space and controlling constrained motion when the end effector contacts a rigid surface in the environment. Several control methods of manipulators have been proposed and implemented to follow a desired path in three-dimensional free space. However, these methods are not directly applicable when the manipulator end-effectors are required to make contact with the environment. Practical examples of such tasks are grinding, assembly related tasks in production factories, opening doors, lifting bodies in rescue missions, etc. In all these applications, contact forces between the manipulator end-effector and the environment are generated. Those forces are frequently unpredictable and likely to be nonlinear. Phase transition from free motion to constrained motion is a difficult control problem and is a typical example of hybrid systems.
Resolved motion force control can be applied to the problem of tracking a desired trajectory maintaining the desired forces and impedance control is also applicable in case of constrained motion. However, those methods are sometime too sensitive to changing factors during the contact. Also, jump or chattering phenomena may occur during phase transition between free motion and constrained motion, if a simple switching strategy is taken for the phase transition. Our approach to cope with this problem is based on

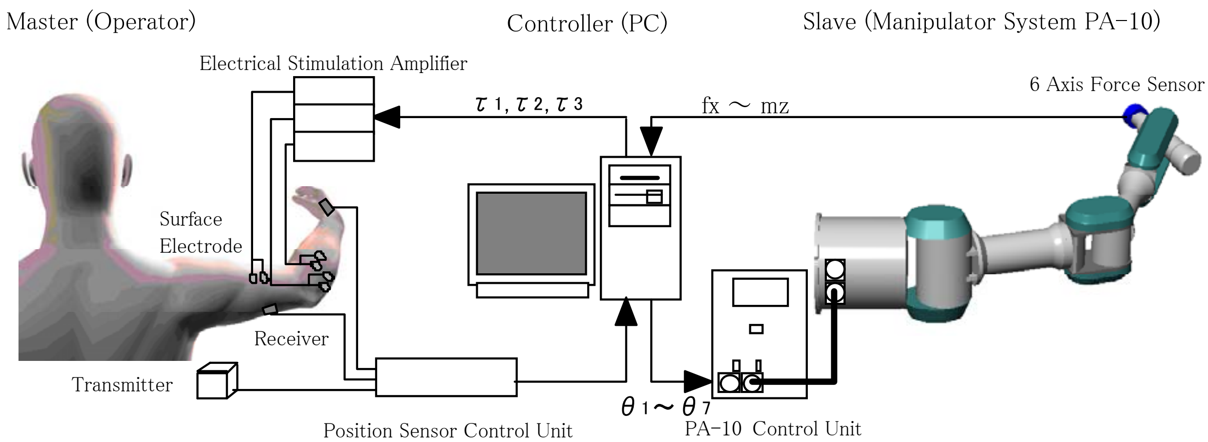


Fig.1 Master and Slave Subsystems

the following three ideas: First, remote operation by a human with a teleoperator is a promising and practical solution under unpredictable changing environment factors. Second, a switching free control can be achieved for phase transition from free motion to constrained motion.

Third, a human operator can learn to perform a skilled motion for completing a given task, if mental loads to the human operator are kept at a pleasant level. The keypoint of the newly proposed teleoperator is in providing force reflection to the operator by using functional electric stimulation (FES).

2 Methods

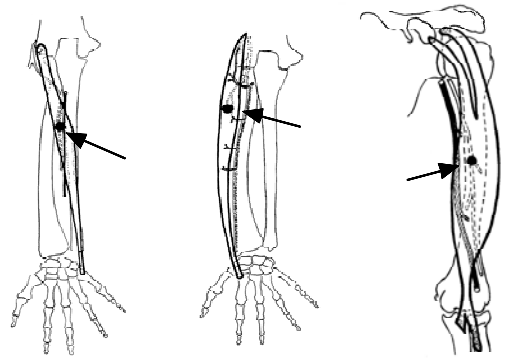
2.1 The new teleoperator

We have developed a new teleoperator to investigate the effectiveness of the proposed method[1]. The master and slave subsystems are shown in Fig.1. There are several remarkable features in the proposed teleoperator. First, there is no mechanical part in the master subsystem. Three small electrodes and two position / orientation sensors are attached on the skin of the upper limb. The upper limb works by itself as the master arm. Second, force reflection from the slave to the master is achieved by FES through the surface electrodes. Third, the structure of slave manipulator is kinematically similar to the master arm and this makes it easy for the operator to command the slave.

Two magnetic position sensors on the operator arm measure the position and orientation in the master coordinate frame. The master arm can be modeled by a seven degree-of-freedom rigid link mechanism. So, we can calculate in real time the corresponding angles of the arm joints from the measurements, and then the calculated angles are sent as position commands to the robot controller of the slave. The force sensor which is placed at the wrist of the slave manipulator measures the generated force and moments. Those are converted to the corresponding torques of the joints, which are reflected to the master for increasing the sense of telepresence of the operator. The force reflection is conducted by stimulating the corresponding muscles. The operator feels the artificially generated forces as a reaction force with visual information in the virtual world. In comparison with conventional joysticks or exoskeletal devices, operator with this new master subsystem manipulates the slave more freely because there is no physical constraint on his arm and hand.

2.2 Force reflection by FES

The external force information is detected by a tendon as a muscle tension, and, if there is a difference in the tension of the antagonist muscles, a human senses it as an external force. Thus, we can artificially transmit force information with the stimulation to the antagonist muscle of the operator's upper limb. If the bend muscle is stimulated by the FES, the operator



(a) Extensor carpi ulnaris (b)Extensor carpi radialis longus (c) Bicps brachii

Fig.2 Stimulated muscles and Motor points

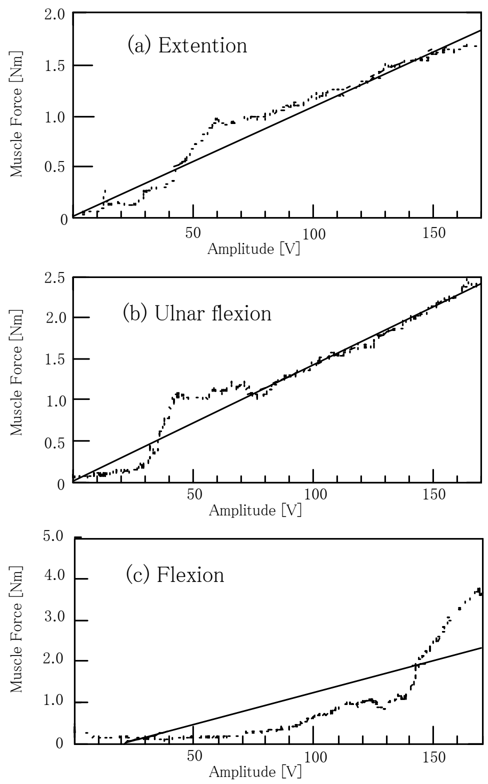


Fig.3 Muscle Force of Arm Joint Longus by Electrical Stimulation

increases the muscle force of the extension muscle in order to maintain the attitude. In this case, the tension of bend muscle and extension muscle becomes equal. Therefore, it would not be sensed that an external force was received from information from the tendon. However, as a result of the experiment, many subjects felt this the stimulation was felt like an external force. The brain probably interpreted it like this. Because the brain must send stronger activation for the extension muscle in order to maintain the attitude. As a result of this illusion, it is possible to transmit the force reflection to the arm of the operator by using FES. In the experiment, each muscles of dorsiflexion direction and ulnar flexion direction and elbow joint are stimulated as shown in Fig.2. The force reflection of these joints are necessary in order to know the direction of the force which the slave end-effector received. Also the motor point of these muscles is easy to stimulate using surface electrode, since they are near the skin.

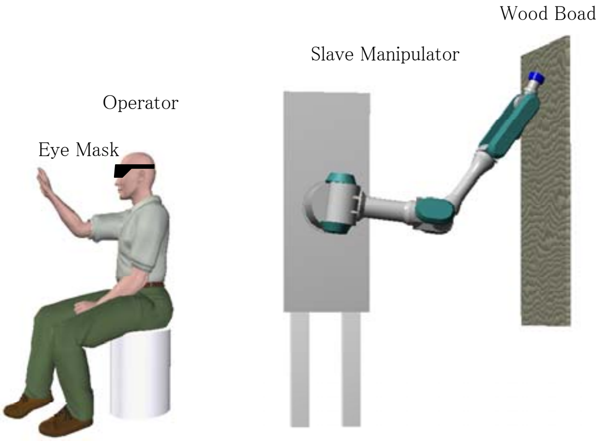


Fig.4 Experimental Setup

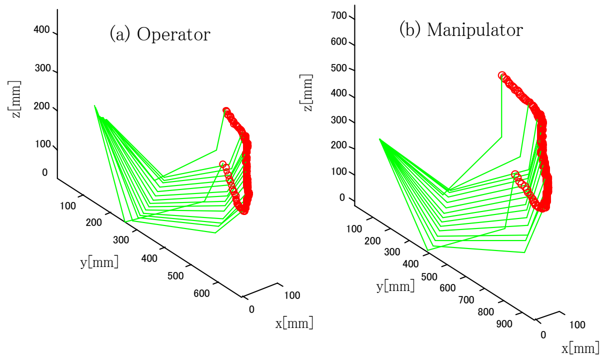


Fig.5 Experimental result of Wall touching

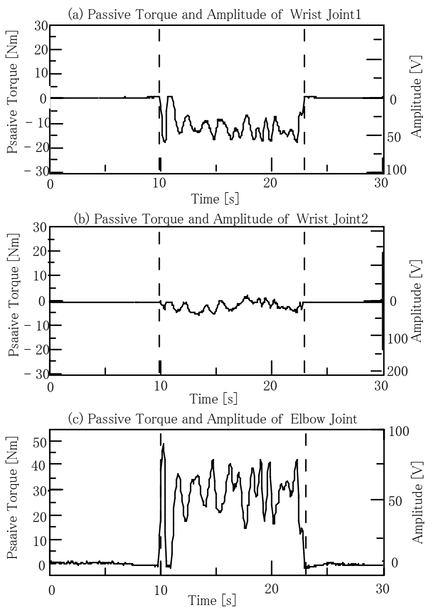


Fig.6 The Passive Torques of Manipulator Joints and Stimulation Amplitudes

We chose 100[Hz] as the frequency and 400[μs] as the pulse width of stimulation in the experiment. The muscle forces are controlled by the amplitude of the stimulated voltage. The relationship between amplitude voltage and the resultant torque of the joints are shown in Fig.3.

2.3 The perception of the direction

The next experiment is a trajectory tracking task on a contact surface. In this experiment, the muscles of dorsiflexion of the wrist joint, ulnar flexion of the wrist joint and flexion of the elbow joint are stimulated. The operator can feel the amplitude and direction of the generated force at the slave end-effector by this force reflection. The experimental setup is shown in Fig.4. An opaque mask was put on the operator's face so that he could not observe the movement of the slave and his own arm. Thus, the information to the operator is limited to the force reflection using FES. The slave end-effector tracked a line on the wall surface by his operation. The movements of the operator arm and the slave manipulator in this experiment are shown in the stick pictures of Fig.5. Circles in the figure show the positions of the end-effector and the operator's hand respectively. It seems from Fig.6(a) that the operator's hand moves along an unreal wall which is imaged by the operator. In other words, nearly perfect tracking has been observed in this experiment although there is no wall on the master side. The experimental result proved that the direction of the generated force at the end-effector can be detected by force feedback using FES. The reflected forces and the amplitude voltages of the electric stimulation are also shown in Fig.6. The dotted lines in the figures indicate the beginning and the ending of the wall contact phase. Chattering phenomena in generated forces at the slave end-effector is observed during contacting the wall. It is not clear at this moment where the phenomena come from. There are several possibilities for such phenomena, for example, a delay in the communication lines, near the unstable poles of the overall closed-loop system, and psychological problem of the operator.

3 Concluding remarks

We have developed a new teleoperator with FES force reflection so as to solve control problems of teleoperation. The controller is designed to achieve a smooth phase transition during contact and a better sense of telepresence for the operator. It is proved by the experimental results that the developed teleoperator with the designed controller is more effective to cope with the phase transition problem and to increase sense of telepresence in comparison with conventional teleoperation systems.

4 Literature

(1) Robert J. Anderson and Mark W. Spong,: "Bilateral Control of Teleoperators with Time Delay" IEEE Transactions on Automatic Control, Vol.34, No.5, pp.494～501, 1989.