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Haptics for Medical Applications

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***Abstract*— Robots and intelligent machines in future should adapt themselves autonomously to the open environment in order to realize physical support for human activities. In addition, the physical support by them must be based on the individual's "action" and "sensation" in order that the physical support becomes really human-friendly. Then, the robots must actively recognize the unknown environment according to the individual's action. They also have to transmit the obtained environmental information to the individual in harmony with his or her sensation. Since haptic information is so important as well as visual information and auditory information, development of real-world haptics is one of the important key issues for the purpose.**

Haptic information is inherently bilateral, since an action is always accompanied by a reaction. That means the bilateral control with high transparency is necessary to transmit real-world haptic information artificially. The acceleration-based bilateral controller is one of the solutions for the acquirement of high transparency.

There remain many issues to solve for the application of haptics to the physical support for the actual human activities. Haptic system with high transparency should obtain the flexibility in order to extend its function. This paper presents flexible actuation techniques that have high force transferability and flexibility of actuators arrangement. Furthermore, in order to support for human activities in remote environment, bilateral tele-haptics over network is also described.

In summary, this paper introduces the fundamental techniques in haptics including several examples of medical applications, since they are the first target of the real-world haptics.

I. INTRODUCTION

Robots and intelligent machines in future should support human physically. Additionally, the physical support by them must be based on individual's "action" and "sensation". For such a physical support, it is necessary to realize "action-based" recognition in the real environment rather than "model-based" recognition. They should communicate the environmental information in harmony with the individual's "sensation" to him or her. This relationship among human, robots, and the real environment is able to be represented as Fig. 1. In other words, robots and intelligent machines should act as an interface and/or an agent between human and the real environment.

From this point of view, real-world haptics will be one of the key-technologies for the realization of physical support for human. This is because that haptic sensation is important for human activities as well as auditory sensation and visual sensation. However, auditory and visual sensations are unilateral information whereas haptic information is bilateral information of action and reaction. Thus, to obtain and transmit the haptic information artificially, a bilateral control with high transparency is necessary. Then, the acceleration-based bilateral controller is one of the solutions for the acquirement of high transparency. The acceleration-based haptic system has realized the artificial transmission of real-world haptic information from DC up to 300 Hz [1].

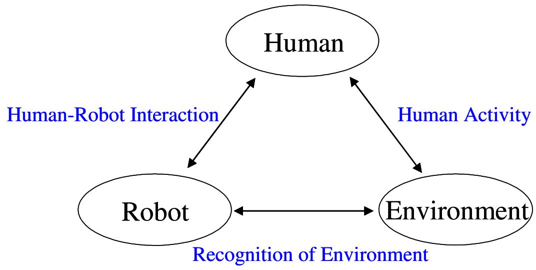


Fig. 1. Relationship among human, robot, and real environment

However, there remain many issues to solve for the application of haptics to the physical support for the actual human activities. For the extension of the functions of haptic system, it is important to acquire the flexibility. Especially, in the multi-degree-of-freedom haptic system, flexible actuation techniques that have high force transferability and flexibility of motor arrangement are necessary. This is because the functions of telehaptic system should be concentered at the end-effecter in small range for the improvement. Additionally, in order to expand the bilateral control to remote support for human activities, haptics over network is also one of the important issues. However, the communication delay must be a serious problem for the purpose.

From the point of view, this paper introduces some ideas to deal with these important issues for realization of bilateral haptics in physical support for human activities. Later, the examples of haptics for medical application are shown. This paper is organized as follows. In the following section, bilateral motion control based on acceleration control is described. In section III, flexible actuation techniques for the natural extension of human sensation are introduced. Section IV shows haptics over network for the realization of tele-haptics. In section V, the possibility of haptics for medical application is shown. At the last section, some concluded remarks are described.

II. ACCELERATION-BASED BILATERAL CONTROL

In bilateral control, the goal of force for artificial realization of the "law of action and reaction" between master system and slave system is represented as (1);

$$F_m + F_s = 0. \tag{1}$$

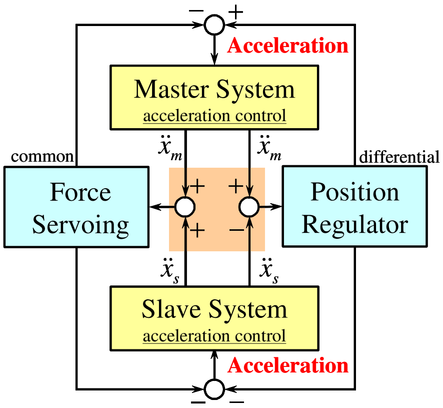


Fig. 2. Robust bilateral control system

On the other hand, the goal of position for tracking between master system and slave system is represented as (2);

$$x_m - x_s = 0. \tag{2}$$

In bilateral control, the coinstantaneous achievements of force control and position control are required. However, force control and position control are not able to be realized at the same time in one real axis.

In order to attain the robustness of the system, (1) and (2) are transformed into the common dimension of acceleration;

$$\ddot{x}_m + \ddot{x}_s = 0 \tag{3}$$

$$\ddot{x}_m - \ddot{x}_s \rightarrow 0. \tag{4}$$

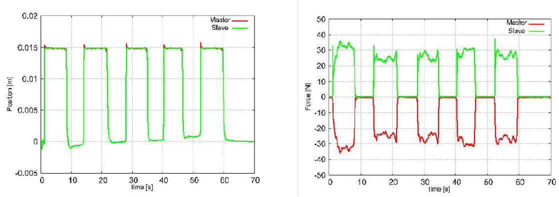
Acceleration control is the best solution to achieve a robust motion control [2], [3], [4]. The block diagram of the robust bilateral control system is shown in Fig. 2. As a result, high reproducibility and high operationality are achieved in acceleration based controller.

Fig. 3 shows the experimental results on bilateral control with two linear actuators. The slave system has contact with the environment made of aluminum. Even though the haptic system contact with very hard environment, the stable contact motion is realized. It also turns out that trasmission of inpactive force sensation is achieved as well from the spikes at the moment of contact in Fig. 3, since the haptic system acquires wide bandwidth.

Through the robust bilateral control with high transparency, not only environmental information, but also the individual's motion or skill as a personal history is able to be preserved into the bilateral haptic database [5], [6]. Then, it may achieve a lot of kinds of physical support for human activities, such as the haptic e-learning, the individual's skill acquisition, the skill training, the skill transfer to the robots, the haptic broadcasting, and so on. Fig. 4 shows the example of the applications of bilateral haptic database.

III. Flexible Actuation

This section describes flexible actuation techniques for flexible implementation of haptics technologies. In



(a) Position responses (b) Force responses

Fig. 3. Experimental results on acceleration-based bilateral control

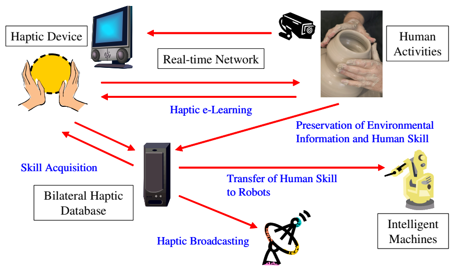


Fig. 4. Applications of Bilateral Haptic Database

robotics systems, end-effectors and actuators are usually connected using hard or high-stiffness materials for realization of accurate position tracking and sufficient force transmission. However, the configuration with hard materials makes it difficult to assign end-effectors and actuators flexibly. In the case that the number of end-effectors and actuators increases, it becomes difficult to assign the elements flexibly and the whole system needs extra spaces for implementation. On the other hand, the flexible actuation technique uses flexible thrust wires for connecting end-effectors and actuators. Fig. 5 shows a schematic diagram of flexible actuation system [7]. Although the thrust wires are thin and flexible, they

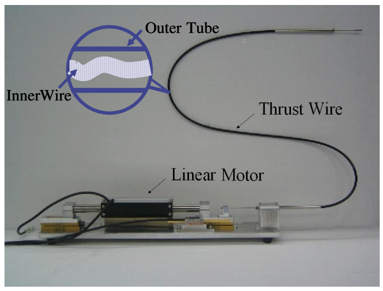


Fig. 5. Schematic diagram of flexible actuation system

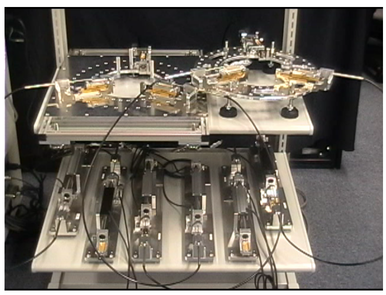


Fig. 6. Telehand system

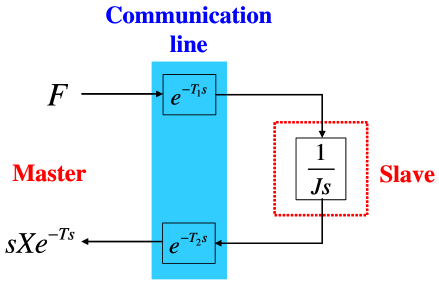


Fig. 7. Example of time delayed telehaptics system

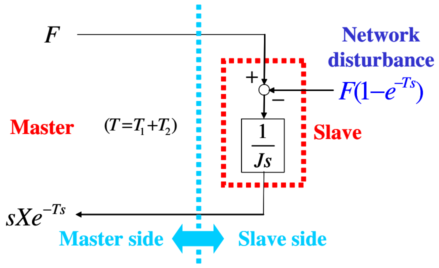


Fig. 8. Concept of network disturbance (ND)

have high position response performance and sufficient force transmission characteristic. Therefore, the flexible actuation system makes it possible to realize flexible assignment and actuation without deterioration of position tracking performance and force transmission performance.

Fig. 6 is an example of the flexible actuation applications. The system is called telehand. In Fig. 6, three end-effectors and three actuators are implemented in both master and slave side. The telehand system demonstrates the possibility of the realization of multi-degree-of-freedom flexible implementation of haptics technique. Therefore, the flexible actuation technique is one of the key elements for future development of haptics.

IV. Haptics over Network

A. Concept of Network Disturbance (ND)

In this subsection, concept of network disturbance (ND) [8], [9] is introduced using a simple example of time delayed bilateral tele-haptics system shown in Fig. 7. In Fig. 7, F means a control input for slave in force (or torque) dimension and sX is a slave output in velocity (or angular velocity) dimension. T_1, T_2 and $T(= T_1+T_2)$ are a time delay from master to slave, a time delay from slave to master and a round-trip delay, respectively. A feedback signal to master side sXe^{-Ts} is delayed T relative to F because of time delays over network T_1, T_2. Here, if we consider only the relationship between F and sXe^{-Ts}, the system can be regarded as shown in Fig. 8. In Fig. 8, the feedback signal to master side sXe^{-Ts} is again delayed T relative to F. However, there is no time delay in Fig. 8. There exists an ND instead of time delays. That is to say, considering only the relationship between F and sXe^{-Ts}, we can regard that sXe^{-Ts} is delayed

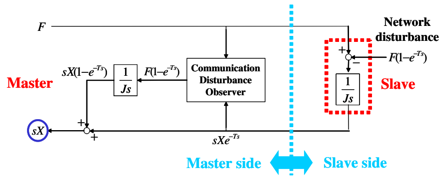


Fig. 9. Schematic diagram of time delay compensation

by not time delay but ND described as follows.

$$D_{net}(s) = F(1 - e^{-Ts}) \tag{5}$$

This is the concept of ND.

B. Time Delay Compensation

ND is estimated by communication disturbance observer (CDOB) [8], [9] and the estimated ND is utilized for time delay compensation. A schematic diagram of time delay compensation using CDOB is shown in Fig. 9. Fig. 9 shows that the feedback signal to master side is not delayed anymore. It turns out that time delay compensation is accomplished by using CDOB. Furthermore, the time delay compensation method has a significant feature for Internet-based applications, in which time delay is usually time-varying. The compensation method does not need delay time model for implementation. Therefore, the compensation method works even in the case of time-varying delay.

V. Haptics for Medical Applications

In this section, the medical experimental results are shown as the examples of haptics for medical applications [10]. In the experiments, the surgeon manipulated master system, and slave system contacted with the organs of a rat through micro/macro bilateral control with high transparency. Then, the stiffness of each organ is abstracted. The experimental forceps robot is shown in Fig. 10.

Firstly, the comparison results on the abstracted impedance of the ileum in four different situations are shown in Fig. 11. The ileum is ligated at low temperature or body temperature. In Fig. 11, the difference among four situations is able to be distinguished clearly. Secondly, the comparison results on the abstracted impedance of five different organs are shown in Fig. 12. In Fig. 12, the difference of organs is able to be classified obviously. Thirdly, Fig. 13 shows results of the contraction experiment with chemical on the posterior stomach of the rat. With the special chemical, the organs of the rat constrict and become tight. From the result, it turns out that the dynamical change of the stiffness is abstracted.

Finally, the break test through micro/macro bilateral haptic system was conducted on some samples as shown in Fig. 14 and the organs of the rat. The experimental situation is shown in Fig. 15.

These experimentations are just the first trial. However, these results showed the potential of haptics to contribute a great variety of progression for realization of human support. Additionally, the haptic forceps robot was able to present the difference of haptic information as the

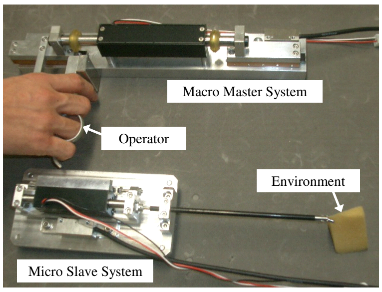


Fig. 10. Haptic forceps robot

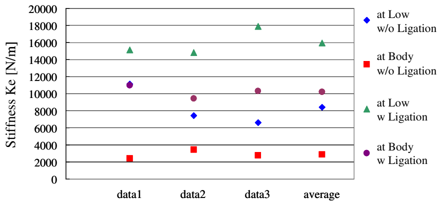


Fig. 11. Ligation experiment

numerical data, even when human operator could not feel it.

VI. Concluded Remarks

- Real-world haptics will be one of the key technologies for the physical support for human activities.
- Human, robot and environment have unilateral and bilateral relation corresponding model-based and action-based recognition respectively.
- Transmission of vivid tactile and/or force sensation is realized by bilateral motion control based on acceleration control. Experimental robot realizes wide frequency response for good force reproducibility.
- Flexible actuation techniques are important for the extension of the functions of haptic system. Flexible actuators achieve both high force transferability and flexibility of motor arrangement.
- The information of environment in real-world haptics is hard real-time. The haptic system with communication disturbance observer works even in the case of time-varying delay over network.
- Haptics will help medical activities such as robotic surgery, tele-palpation as well. The examples of medical experimentation demonstrate great potential of that.

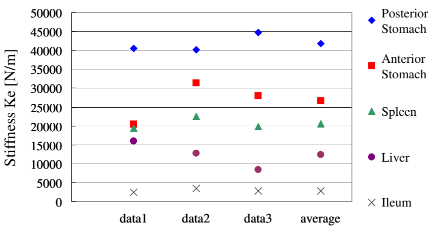


Fig. 12. Classification experiment

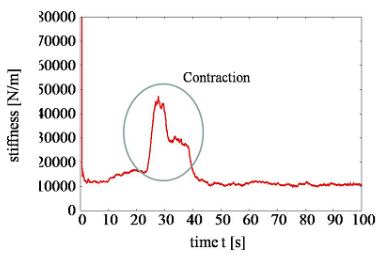


Fig. 13. Contraction experiment (Posterior stomach)

(a) Samples before break test (b) Samples after break test

Fig. 14. Experimental samples in break test

Fig. 15. Situation of break test (Salmon caviar)

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