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A basic study of a pillow-shaped haptic device using a pneumatic actuator

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ABSTRACT

As a new haptic device for daily use, a pillow-shaped haptic device using a pneumatic actuator, the Air-pillow telephone, is proposed. The Air-pillow telephone allows an intimate couple at a distance to mutually share the partner's sense of touch and presence, which cannot be easily conveyed by conventional communication media: text, voice, still image and video. We have developed a prototype system with an air bag driven by a piston-cylinder mechanism. The user's head motion affects the air pressure of the air bag and then its signal is bilaterally transmitted in real time via internet to actuate the partner's air pillow. Inside the pillow's subtle motion, the user can find the existence of the partner's haptic language. This paper describes the Air-pillow telephone concept and application as well as implementation of the prototype system, modeling and control design. For the user's sense of touch control method, we propose two control modes: the seesaw mode and the synchronous mode. The validity of the proposed idea was confirmed with successful simulation and experimental results under the TCP/IP network environment.

1. INTRODUCTION

In recent years there have been many studies about new communication styles employing daily commodities, such as a pillow, cushion, stuffed doll, and jacket. Unlike existing communication devices, such as the telephone, fax, or PC, the aim of these daily commodities is completely natural communication in which the user is not aware of the communication function inside the device. An important common point among the commodities is that the user's skin touches the device. The devices attempt to haptically transmit the intimate feeling and/or presence, which cannot be easily conveyed by conventional media: text, voice, still image and video. As one such haptic device for communication, we propose a pillow-shaped haptic device using a pneumatic actuator: the Air-pillow telephone.

Here we introduce several devices proposed in relevant work in this research field. The PillO'Mate [1] is an electrical cushion composed of a proximity-sensor, a galvanic skin resistance sensor, a vibration motor, a heating pad, and a speaker. HUG over a distance [2] is an air-inflatable vest that can be remotely triggered to create a sensation resembling a hug. Hapticat [3] is a cat-like cushion device including moving ears, a breathing mechanism, a purring mechanism and a warming element. The bed [4] is a remote collaboration system where one person can feel his/her partner's presence by a heated pillow or hearing a heart beat. RobotPhone [5] is an animal type robot with multiple motors in its arms and head where motions are bilaterally controlled via internet using master-slave control technology.

These devices and our Air-pillow telephone share a similar concept of the haptics in daily life. These conventional devices, however, have no function that can measure and control a user's head motion on a pillow. Therefore, with conventional technology, it is impossible to mutually transmit subtle head motion when lying down.

In this paper, first we describe the concept and applications of our Air-pillow telephone. Then we discuss the implementation of the prototype system and its dynamic modeling and control method for communication via internet. Finally we provide some successful simulation and experimental results as well as the direction for future work.

2. CONCEPT AND APPLICATION IMAGE

Figure 1 presents a conceptual image of a communication system where an intimate couple at a distance from each other can mutually share a partner's sense of touch and presence through the pillow. The user's head motion or pillow hugging motion affects the form of the pillow and the signal is bilaterally transmitted in real time via internet. Based on the signal, the

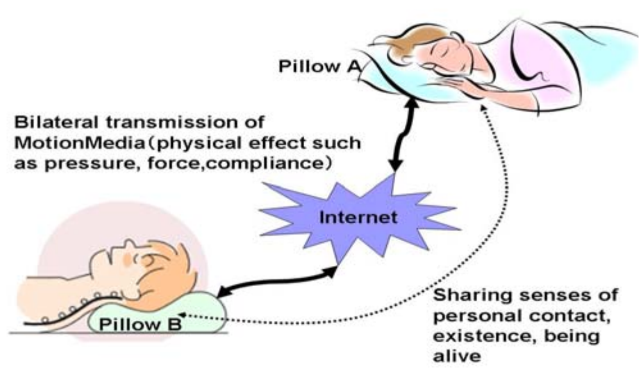

Figure 1. *Conceptual idea of pillow communication*

pillow is physically affected by a certain actuator. Inside the pillow's subtle effect, the user can find the existence of the partner's haptic language, which cannot be easily conveyed by conventional media. This is one of the communication services using MotionMedia [6,7], which has been advocated by the authors for some years.

3. A PROTOTYPE SYSTEM

3.1. Merits of the actuation method

Considering the concept and the application mentioned above, we have developed a prototype system with an air bag driven by a piston-cylinder mechanism. The merits of this prototype include:

(1) This is a very simple mechanism which can precisely control the air pressure inside the air bag. No bulky air compressor is needed.

(2) An air bag, in direct contact with human skin, is low noise, safe, lightweight and inexpensive. This is because it is possible to distantly separate the noisy piston-cylinder mechanism and the air bag by using just a long air tube.

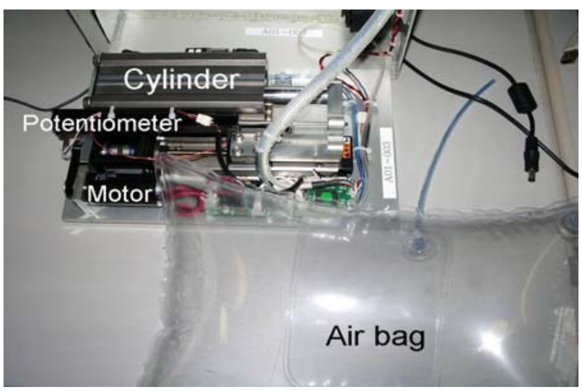

Figure 2. *Prototype for Air-pillow telephone*

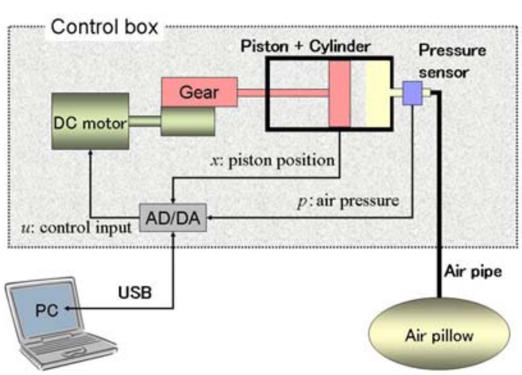

Figure 3. *Schematic drawing of the prototype system*

(3) It is easy to make any form of a vinyl air bag with a laminate molding method, enabling customizing the shape for many purposes.

These three merits are available only for our method, not for the method of a built-in actuator.

3.2. Design of the hardware components

We have implemented the prototype by means of steps as follows:

(1) Air bag

By testing the size and compliance of many commercially available pillows, we have determined the appropriate form and size of the air bag. For a material that will be in contact with the skin, considering the simplicity of customization and cost, vinyl was chosen.

(2) Piston and cylinder

By using the above mentioned air bag and several pairs of a piston-cylinder, we have manually examined the sensitivity and sensation for users. Thus an appropriate volume of a cylinder and the required speed of a piston were determined.

(3) Actuator and transmission

Taking into account the compactness of the control box involving the actuator and transmission, to satisfy the required speed and stroke of the piston, an appropriate pair for a DC motor and a transmission system (a ball bearing, a belt and a pulley) has been selected. The final prototype system and its block diagram are shown in Fig. 2 and 3.

4. DYNAMIC MODELING OF THE PROTOTYPE SYSTEM

In this section we derive a dynamic equation of the prototype system. Strictly speaking, the behavior of this air bag should be treated as a nonlinear and distributed parameter system. In this paper, however, we adopt a very simple linearly approximated model shown in Fig. 4, because high speed and accurate control will not be needed for our application.

The major differences, which we expect can be solved by some control techniques, between the real prototype and the approximated model are as follows:

(1) The elasticity of the vinyl skin of the air bag is nonlinear.

(2) The area of the piston (cylinder) differs from the contact area between the user's head and the air bag.

(3) The air spring constant of the air bag will inherently change depending on the shape and pressure.

From Fig. 4, the following dynamic equation can be derived:

$$p = p_0 + k_s(x - h) \tag{1}$$

$$m_h\ddot{h} + d_h\dot{h} + k_p(h - x) + k_h h = q \tag{2}$$

$$m_p\ddot{x} + d_p\dot{x} + k_p\left(x - h\right) = f \tag{3}$$

$$f = k_m u \tag{4}$$

where

p : air pressure inside the air bag
p_0 : initial air pressure when the head is on the air bag
k_s : gain from the displacement to the air presure
x : piston displacement
h : head displacement
m_h : head weight
k_p : air spring constant between the head and the piston
k_h : spring constant by elasticity of the air bag
u : Input for a driver of the motor
f : force to the piston from the motor
q : force to the head from the user' neck
k_m : gain from u to f
d_p : damping factor of the piston
d_h : damping factor of the head

As it is difficult to calculate the air spring constant from the physical parameters, we have estimated it by simple weighting experiments. For simplicity, the friction factor except viscous friction is neglected in this equation.

5. CONTROL SYSTEM DESIGN

In this section, based on equations (1)-(4), we discuss how to mutually transmit the sense of touch via internet. There are many studies about teleoperation or master-slave robot technique via internet. Their final purpose is to precisely and rapidly control the slave's position following the master operation. Therefore they are mainly focusing the control technology to ensure the robust stability and the tracking ability under an uncertain time delay due to the IP network traffic condition. In this study, however, our aim is to establish the control scheme to appropriately and mutually transmit the sense of touch for the human head. That is, the machine control is an essential mean but not our final goal. Namely our basic problem is how we can capture the human's sense and transmit it via internet and output it by means of the air bag motion. Hence we face the following problems:

(1) What is a control system structure to ensure stability under an uncertain time delay?

(2) How can we transmit head motion?

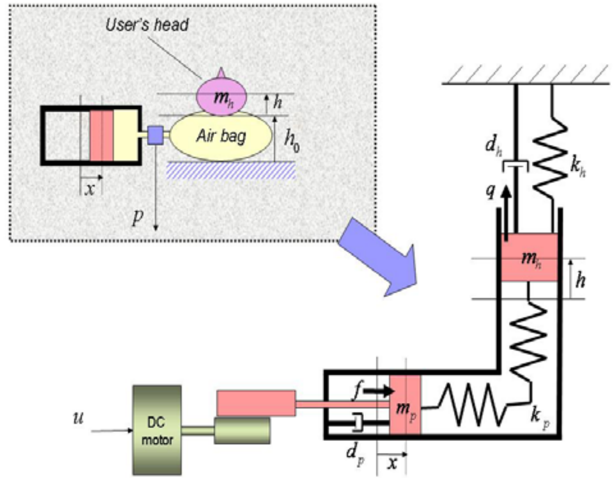

Figure 4. *Lineally approximation of the prototype*

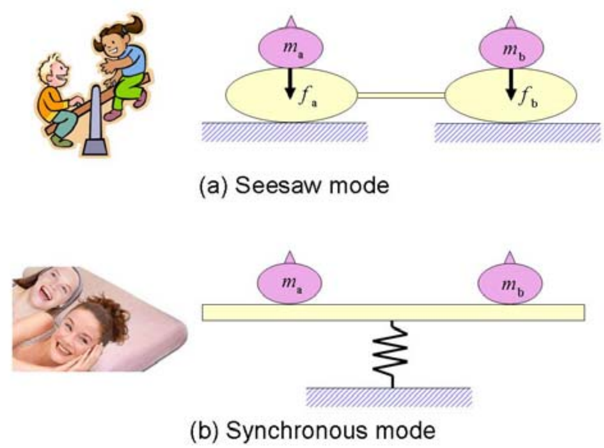

Figure 5. *Two control modes and the intuitive images*

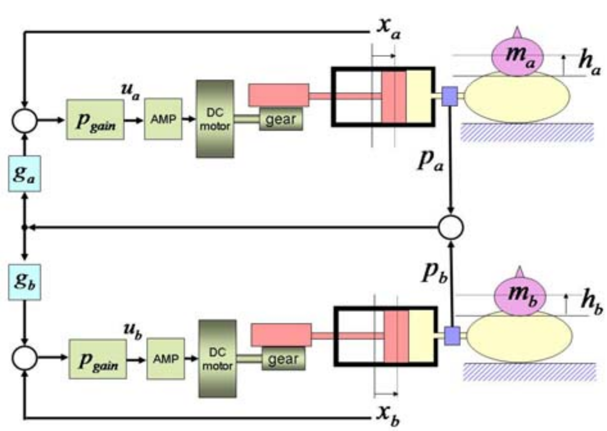

Figure 6. *Bilateral touch sense communication control*

For question (1), here we propose a basic control structure such that each air pressure is exchanged via internet, while the local systems are closed by the piston position feedback to ensure the local stability regardless of the uncertainty of the internet bandwidth.

For question (2), here we propose two control modes for sense of touch transmission as follows:

5.1. Seesaw mode

In the beginning of this study, for air-pillow communication, we had a very primitive but intuitive idea inspired by the well-known "string telephone". Namely we thought that exchanging each air pressure directly through an air pipe was the simplest and most primitive. (Fig. 5(a)) The seesaw mode is realized by substituting this passive air pipe with the active piston-cylinder mechanism and internet. Based on this primitive idea, and by using the conventional force-feedback type master-slave control technique with the same phase, we design the control system shown in Fig. 6, where,

p_{gain} :a proportional feedback gain for piston position control loop,

g_a, g_b :bilateral proportional feedback gain for air pressure.

In this seesaw control mode, the control law is as follows:

$$u_a = p_{gain}\{g_a(p_a - p_b) - x_a\},\ g_a < 0,$$
$$u_b = p_{gain}\{g_b(p_a - p_b) - x_b\},\ g_b > 0$$

5.2. Synchronous mode

The synchronous mode is the inverse phase of the seesaw mode motion. This is a mode where two people can share the sensation as if together on a bed they were using a big pillow as shown in Fig. 5(b). In this seesaw control mode, the control law is as follows:

$$u_a = p_{gain}\{g_a(p_a + p_b) - x_a\},\ g_a < 0,$$
$$u_b = p_{gain}\{g_b(p_a + p_b) - x_b\},\ g_b < 0$$

6. EXPERIMENT

To confirm the validity of the proposed control scheme, first we conducted several simulations taking into account some nonlinear factors inside the real system and the uncertainty of the IP network. Based on the simulations, we set up experimental system using two air-pillow telephones controlled by two PCs connected via TCP/IP in an intranet environment. On the PCs with VC++ .NET, we implemented a real time control system shown in Fig. 6. An overview of our experimental system is shown in Fig. 9. In Fig.7 and 8, we got system responses when two users were randomly moving their heads. From the figures, we can qualitatively confirm the expected response as follows;

(1) In a seesaw mode (Fig. 7), each piston moves in an opposite phase.

(2) In a synchronous mode (Fig. 8), each piston moves in a same phase.

(3) By the local position feedback loop, when pushing the pillow A, not only pillow B's piston but also pillow A's piston itself moves and vice versa.

From these elementary and qualitatively experimental results, we can confirm the validity of the proposed control scheme and the system design of our air-pillow telephone.

7. CONCLUSION

This paper describes the concept, applications, modeling and control for a pillow-shaped haptic device using a pneumatic

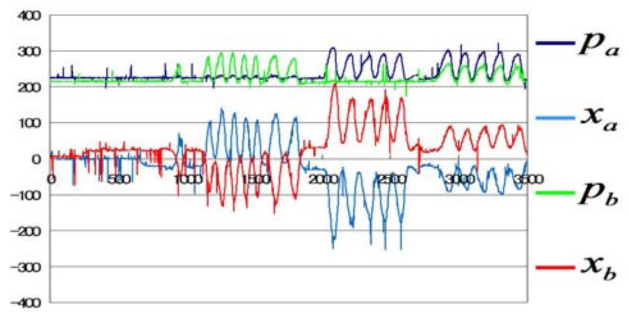

Figure 7. *Experimental results (Seesaw mode)*

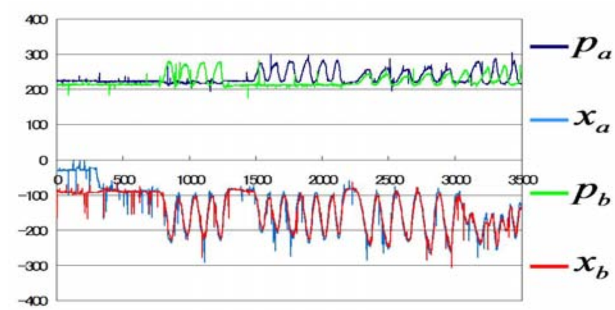

Figure 8. *Experimental results (Synchronous mode)*

Figure 9. *Experimental setup*

actuator: the Air-pillow telephone. To date, we have not yet experimentally or statistically evaluated how the user could feel the sense of touch and presence of the partner. Therefore soon we will conduct the human sensation evaluation test. Additionally, we will look for other applications for more practical use, for example, as an input/output interface between a human and machine in a local area.

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