The Sixteenth International Symposium on Artificial Life and Robotics 2011 (AROB 16th '11),
B-Con Plaza, Beppu,Oita, Japan, January 27-29, 2011

# Basic Position/Force Control of Single-Axis Arm Designed with an Ultrasonic Motor

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### Abstract

Recently, many studies on assist robots are being conducted, in which the development of a unique system is required to support aged persons, physically handicapped persons and/or caretakers. One of the representative systems is called the assist suit and is partly practiced. The assist suit is a mechatronics device which can assist physical human actions. However, the current assist suit has a few problems with respect to cost, size, weight, long-time run and so on. In this article, a fundamental study concerning a compact assist device is conducted. Where the assist device supports is one spot on the body such as a knee, an elbow and a shoulder. First of all, a simple single-axis arm is designed by using an ultrasonic motor which can generate high torque from a low velocity range. Then, a servo system, a torque control system and a passive torque control system are applied and their characteristics are evaluated. Here, the passive torque control includes a sti ness control and a compliance control.

## 1 Introduction

Recently, many studies on assist robots are being conducted, in which the development of a unique system is required to support aged persons, physically handicapped persons and/or caretakers [1]. One of the representative systems is called the assist suit and is partly practiced. The assist suit is a mechatronics device which can assist physical human actions. However, the current assist suit has a few problems with respect to cost, size, weight, long-time run and so on.

In this article, a fundamental study concerning a compact assist device is conducted [2]. Where the assist device supports is one spot on the body such as a knee, an elbow and a shoulder. First of all, a simple single-axis arm is designed by using an ultrasonic motor which can generate high torque from a low velocity range. Figure 1 shows the experimental setup. Then, a servo system, a joint torque control system and a passive torque control system are applied and their characteristics are evaluated. The passive torque control includes a sti ness control and a compliance control. Finally, a promising application as an assist device is considered. It is assumed that the single-axis

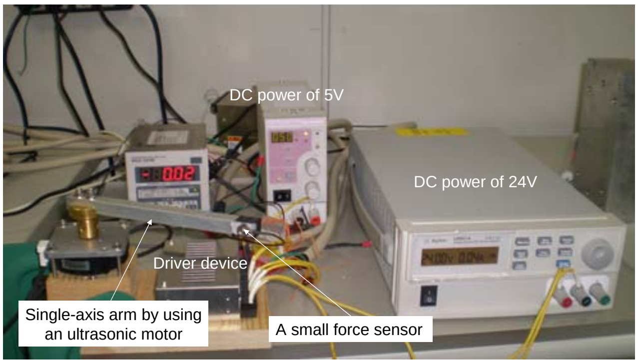


Figure 1: Single-axis arm designed with an ultrasonic motor.

arm is equipped to a damaged joint of a human. The operator can adjust the desired torque, e.g. more sti or more compliant, while feeling the behavior and the e ectiveness of the assist device.

## 2 A Single-Axis Arm Designed with an Ultrasonic Motor

The ultrasonic motor has two features. One is that it can generate high torque from the low velocity range. The other is that it has a large holding torque when no voltage is given. That is the reason why no brake system is needed and consequently the weight reduction can be realized. Also, the responsiveness of the ultrasonic motor is generally superior to the one of conventional electromagnetic motors, so that the energy consumption can be suppressed. Considering the above points, the simple arm is designed based on an ultrasonic motor. Figure 2 shows the hardware block diagram. The ultrasonic motor used in experiments is the model of USR60-E3T provided by Shinsei Corporation. A DA board(CONTEC DA12-8) is used to control the motor velocity. A digital IO board(CONTEC PIO-48D) is also used to switch the direction of motor rotation, i.e., clockwise or counterclockwise. Further, a counter board(CONTEC CNT32-8M) is incorporated to sense the rotation angle. These cards are connected to the ultrasonic motor via a driver device(Shinsei

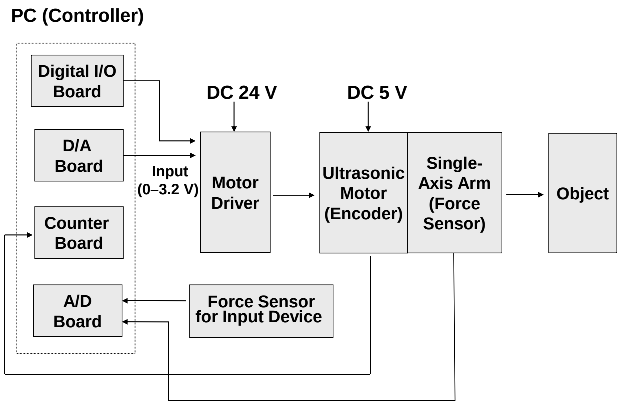


Figure 2: Hardware block diagram of the experimental system.

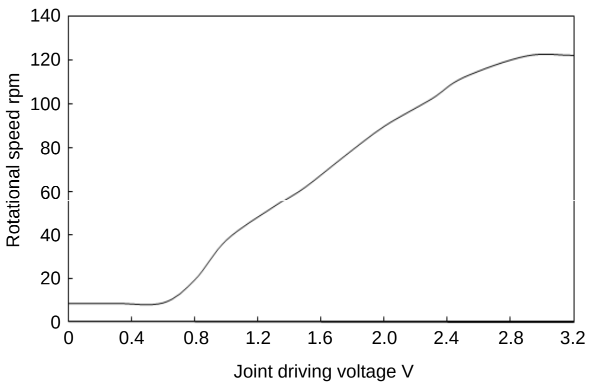


Figure 3: Relation between joint driving torque and rotational speed in steady state.

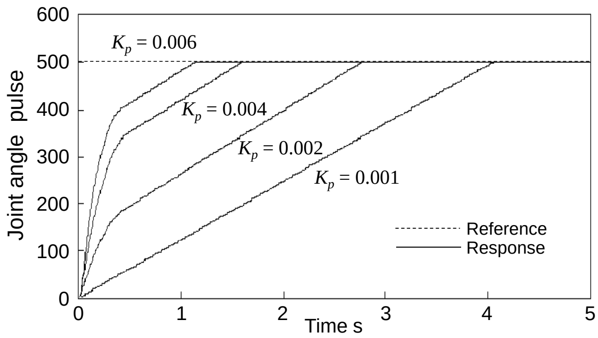


Figure 4: Step responses obtained by using Eq. (1), in which 500 pulses mean $\pi$ rad.

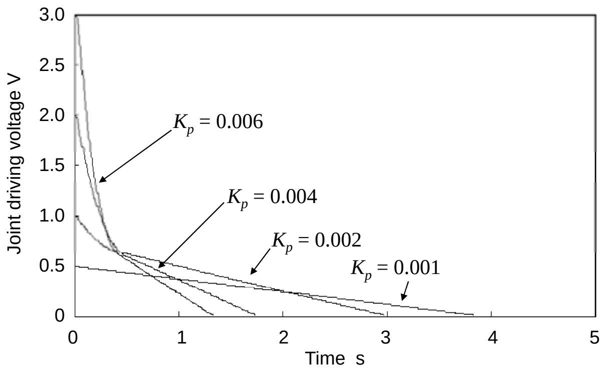


Figure 5: Joint driving voltage calculated from Eq. (1).

Corp. D6060 24V). A small force sensor is  xed at the tip of the single-axis arm to estimate the joint torque.

# 3 Control System

Basic functions were  rst developed on Microsoft Visual C++ to give the commands such as the direction of rotation and the rotational velocity and to obtain the rotational angle from the encoder. Then, it was measured on how the relation between the voltage and its given time in uenced the dynamic response of the motor. Figure 3 shows the characteristics, in which it is con rmed that the velocity tends to be constant under 0.6 V. The dynamic characteristics were used to design a position feedforward controller.

## 3.1 Basic servo system

The servo system of an ultrasonic motor is easily constructed due to the high holding torque and the responsiveness. Here, a simple proportional control has only to be applied as

$$\tau(k) = K_p \{\theta_d \quad \theta(k)\} \tag{1}$$

where $\tau(k)$ is the joint driving voltage at the discrete time $k$, $K_p$ is the $p$-gain; $\theta(k)$ and $\theta_d$ are the joint angle and desired one, respectively. In order to conduct high accuracy positioning, when $\theta_d = \theta(k)$ is detected in the sampling loop, the excitation power to the motor has only to be o  at the same time. Figure 4 shows examples of step response with several $K_p$, in which 500 pulses mean $\pi$ rad. Note that a linear characteristic suddenly appears from a point, for example, in case of $K_p$=0.006. To examine the matter a bit more detail, the relation between the time and the torque obtained by Eq. (1) is measured as shown in Fig. 5. It is observed from Figs. 3, 4 and 5 that the joint velocity tends to show a constant value about 8.5 rpm under the point of 0.6 V. So, in order to cope with the characteristic, Eq. (1) is improved as

$$\tau(k) = K_p \{\theta_d \quad \theta(k)\} + 0.6 \tag{2}$$

Figure 6 shows the step response when Eq. (2) is employed. As can be seen, a desirable response without an overshoot and delay is observed only by using a $p$-action. This is the attractive characteristics of the ultrasonic motor used in the experiment.

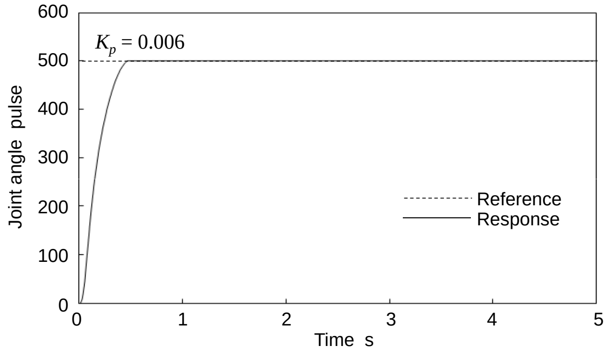


Figure 6: Step responses obtained by using Eq. (2).

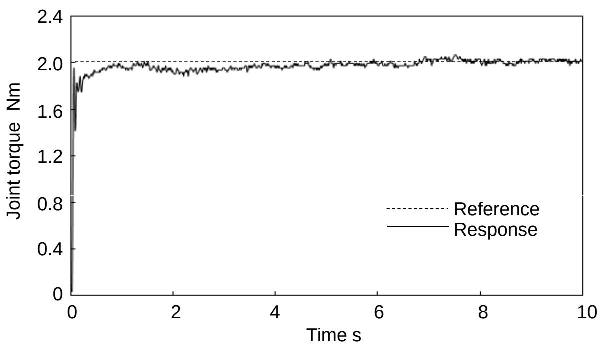


Figure 7: Joint torque control reslut in using Eq. (3).

### 3.2 Joint torque control

In the joint torque control mode, the torque acting at the joint is actively controlled by a PI controller written by

$$\tau(k) = K_{fp}\{\tau_d \quad \tau_s(k)\} + K_{fi}\sum_{n=0}^{k}\{\tau_d \quad \tau_s(n)\} + 0.6 \qquad (3)$$

where $K_{fp}$ and $K_{fi}$ are the $p$-gain and $i$-gain, respectively. $\tau_d$ is the desired joint torque, $\tau_s(k)$ is the estimated joint torque which is calculated from the force value sensed by a small force sensor attached to the arm tip. Figure 7 shows a torque control result, in which the response desirably follows the reference 2 Nm by setting $K_{fp}$, $K_{fi}$ to 3 and 0.001, respectively.

### 3.3 Passive joint torque control

In the passive joint torque control mode, an external force given to the arm can be absorbed smoothly. Here, a sti ness control and a compliance control are considered. The sti ness control law is given by

$$\tau_s(k) = K_d\{\theta(k) \quad \theta_d\} \qquad (4)$$

where $K_d$ is the desired sti ness [Nm/rad]. Note that in the sti ness control mode, the initial position is set

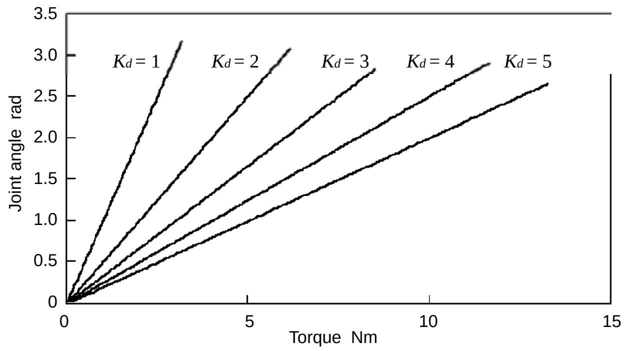


Figure 8: Sti ness control result in using Eq. (4).

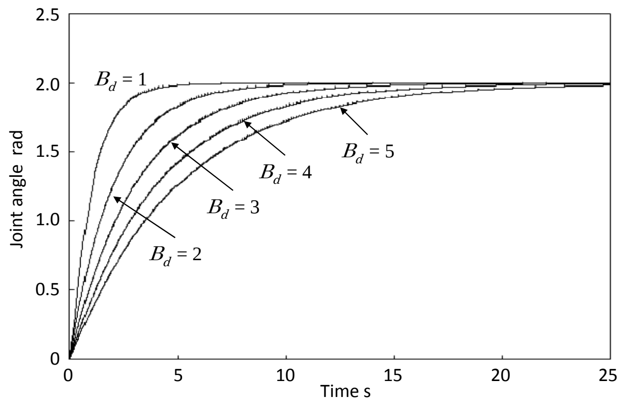


Figure 9: Compliance control result in using Eq. (5).

to the desired position $\theta_d$, and also $\theta(k)$ obtained from Eq. (4) is given to $\theta_d$ in Eq. (2). Figure 8 shows an example of the sti ness control result.

Next, the compliance control law is written as

$$\tau_s(k) = B_d\left\{\dot{\theta}(k) \quad \dot{\theta}_d\right\} + K_d\{\theta(k) \quad \theta_d\} \qquad (5)$$

where $B_d$ is the desired viscosity [Nm s/rad]. In the compliance control mode, the transient behavior to an equilibrium position can be controlled. Of course, the equilibrium position depends on $K_d$. If it is assumed that both $\dot{\theta}_d$ and $\theta_d$ are 0, and $\tau_s(k) = \tau_{step}$(constant), then $\theta(k)$ is obtained by

$$\theta(k) = \frac{\tau_{step}}{K_d}(1 \quad e^{\ \frac{K_d}{B_d}\Delta t k}) \qquad (6)$$

where $\Delta t$ is the sampling width. Compliance control can be easily realized by giving $\theta(k)$ obtained from Eq. (6) into $\theta_d$ in Eq. (2). Figure 9 shows an example of compliance control result, in which the transient behaviors are changed with $B_d$. In the experiment, $K_d$ and $\tau_{step}(k)$ are set to 1 and 2, respectively.

## 4 Example of Application

In this section, a promising application called an assist device is considered. It is assumed that the single-

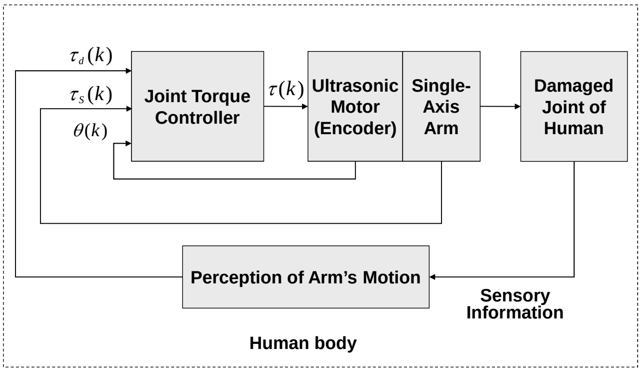


Figure 10: Block diagram of an application called the assist device for assisting a damaged or weakened joint.

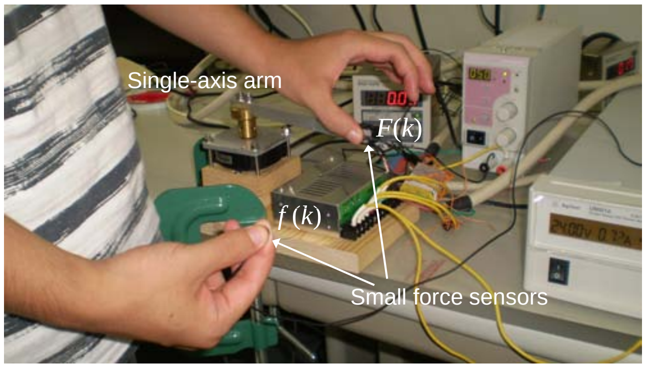


Figure 11: Experimental scene assumed to be the assist device.

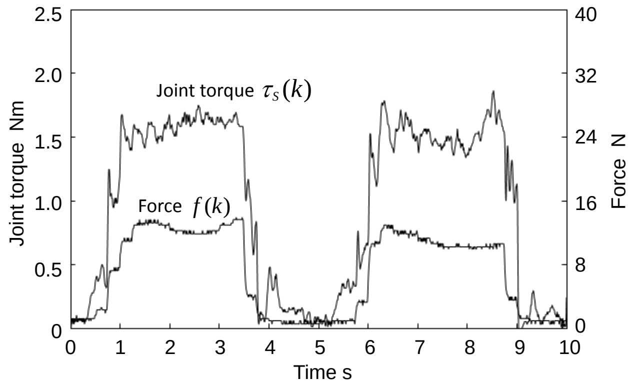


Figure 12: Joint torque manually controlled by an operator. Force is given by the operator's fingers.

axis arm is equipped to a damaged joint of a human. A small and light weight force sensor is used so that the desired torque can be directly given by the fingers of the operator. The operator can adjust the desired torque, e.g. more stiff or more compliant, while feeling the behavior and the effectiveness of the assist device, i.e., the single-axis arm.

The block diagram of the controller is shown in Fig. 10, in which the desired torque $\tau_d(k)$ is manually given by an operator. The control law is derived from Eq. (3) by varying the desired joint torque as

$$\tau(k) = K_{fp}\{\tau_d(k) - \tau_s(k)\} + K_{fi}\sum_{n=0}^{k}\{\tau_d(k) - \tau_s(n)\} + 0.6 \quad (7)$$

$$\tau_d(k) = \alpha f(k) \quad (8)$$

$$\tau_s(k) = LF(k) \quad (9)$$

where $f(k)$ is the small force generated by an operator's fingers, $\alpha$ is the gain which transmits the force to the time-varying desired joint torque. $F(k)$ is the force acting between the arm tip and the object, $L$ is the length of the single-axis arm. In the experiment, $\tau_s(k)$ is regarded as the joint torque.

Figure 11 shows the experimental scene assumed to be the assist device. The control result of $\tau_s(k)$ is shown in Fig. 12, in which the response $\tau_s(k)$ is desirably amplified according to $f(k)$ by giving 1 and 0.15 to $\alpha$ and $L$, respectively.

## 5 Conclusions

In this article, a fundamental study concerning a compact assist device is conducted. Where the assist device supports is one spot on the body such as a knee, an elbow and a shoulder. First of all, a simple single-axis arm has been designed by using an ultrasonic motor which can generate high torque from a low velocity range. Then, a servo system, a joint torque control system and a passive torque control system have been applied and their characteristics are evaluated. The passive torque control includes a stiffness control and a compliance control. Finally, a promising application as an assist device has been considered. It is assumed that the single-axis arm is equipped to a damaged joint of a human. The operator can adjust the desired torque, e.g. more stiff or more compliant, while feeling the behavior and the effectiveness of the assist device.

## References

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[2] K. Ogiwara and F. Nagata, "Basic Position/Force Control of a Single-Axis Arm Designed with an Ultrasonic Motor," in *Procs. of the 12th IEEE Hiroshima Section Hiroshima Student Symposium*, (F)–11, 2 pages, 2010 (in Japanese).