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Paper

Development of a power-assisted head-coupled display system using a direct-drive motor

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Abstract—This paper describes a head-coupled display system for remote operation. The system compensates for inertia of the CRT display by internal feedback and helps the operator to manipulate the display by his head motion. By considering elasticity, it can compensate for about 50% of the inertia of the CRT.

1. INTRODUCTION

For increased operating efficiency in the remote control of a robot, it is important to communicate exactly the condition of the task environment to the operator. As a means of providing the operator with visual information of a sufficiently wide field of view and with a sensation of presence, we have proposed an approach [1] to measure the head motion of the operator in real time and to expose the operator steadily to the views acquired from a TV camera that tracks the detected position and orientation of the head. By this approach, the operator sees the same image as that which would be visible to him if he were at the location of the camera in the task environment.

As an essential element of the proposed system, equipment is required which not only measures the operator's head motion but also supports the display in front of his face at all times. In the prototype equipment, a goniometer was included in a link mechanism which supported the display. The operator moved it by the muscular force of his neck. Here, all the moments of inertia exercised on the display had to be applied by the operator. Owing to the significant weight of the display (6 kg for monochrome and 10 kg for colour), considerable physical strength was required to swing the display around or to stop it, which meant that no swift motion of the display was possible.

Next we attempted an approach [2] which involved isolating the display-supporting manipulator from the goniometer and controlling the position of the display by a master–slave system. However, by this approach it was difficult for the operator to attain the full fitness of the head and display.

After that, we developed a control system for orienting the display with the operator's physical strength again, but in this system the moments of inertia were compensated by a direct drive (DD) motor, thereby lowering the apparent mass of the display. This paper reports on the system's configurations and control of the power-assisted head-coupled display.

2. DISPLAY UNIT

Two 1.5-in. colour CRTs were built into the main display unit, enabling stereo-vision. The weight of the display was 4.6 kg, including an optical system and a convergence control mechanism. The display had one degree-of-freedom (horizontal rotation). It was mounted at the tip of an arm and arranged so that it was positioned directly in front of the operator's face even when he moved his head sideways. The arm was driven by a DD motor. The distance between the centre of rotation and display's centre of gravity was 0.24 m (Fig. 1). Its face contact area was formed to a facial contour and finished with sponge cushions. A belt was used as shown in Fig. 2 to fasten the display to the operator's head.

3. ACTIVE POWER ASSISTANCE

A conceivable method for augmenting the operator's physical strength would be first to provide a strain gauge or some other external force sensor between the display and the head, to detect the operating force and assist the operator's physical strength. While this approach gives good sensitivity, it has drawbacks such as the need for an add-on force sensor system in addition to the motor control system, and the infeasibility of detecting collisions at the middle of the arm. In this system, a method [3] of power assistance combining a DD motor with a joint rotation sensor was employed, and no special force sensors were used.

The use of a DD motor precludes the intervention of such factors as backlash, elasticity, friction, etc., due to the reduction gear between the arm and the rotary sensor, so that arm rotation is transmitted directly to the rotary sensor, providing accurate data on the arm's angular velocity, angular acceleration, etc. Besides, since the torque applied on the arm may be controlled precisely with the motor current, inertial, frictional, and other forces may be compensated by feedback for the operator's physical strength assistance.

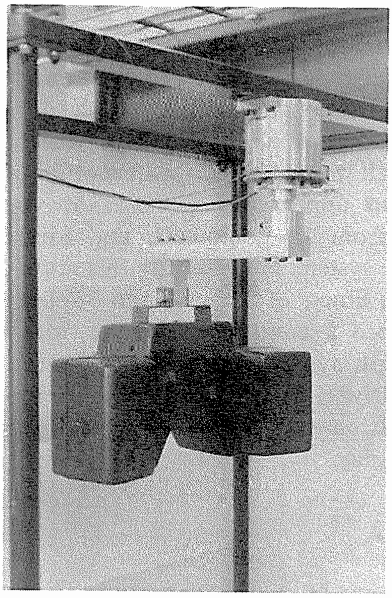

Figure 1. Power-assisted head-coupled display.

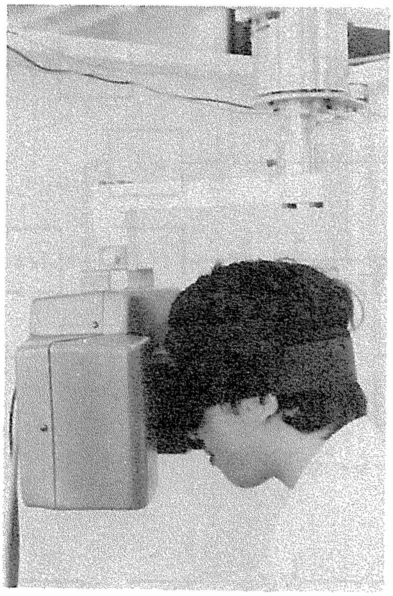

Figure 2. Operator and display.

The dynamic equation of the system can be expressed as follows:

$$k_t I + T_0 = J\theta s^2 + F_b \theta s + F_c, \tag{1}$$

where θ is the motor rotary angle, I is the motor current, k_t is the sensitivity of the motor torque, T_0 is the operating torque, J is the moment of inertia, F_b is the viscous frictional coefficient and F_c is Coulomb's frictional torque.

By substituting

$$I = (\alpha J\theta s^2 + \beta F_b \theta s + \gamma F_c)/k_t \qquad (0 < \alpha,\ \beta,\ \gamma < 1) \tag{2}$$

into equation (1), we find that

$$\begin{aligned} T_0 = (1-\alpha)J\theta s^2 + (1-\beta)F_b\theta s \\ + (1-\gamma)F_c, \end{aligned} \tag{3}$$

which exhibits the effects attainable by multiplying the inertial force, viscous frictional coefficient and Coulomb's frictional coefficient $(1-\alpha)$, $(1-\beta)$ and $(1-\gamma)$ times as high respectively. Figure 3 shows a block diagram of the system.

However, because the inertial forces are much greater than the frictional ones, we assumed that $\beta = \gamma = 0$ and compensated for inertial forces only.

4. SYSTEM CONFIGURATIONS

The hardware configurations of this system are shown in Fig. 4. To detect the joint angle, a rotary pulse encoder with 1800 pulses per revolution was used. A frequency multiplier was employed to obtain 7200 pulses per revolution. The value of the angle at the 16-bit up/down counter was converted into a position signal voltage through a D/A converter, connected to the camera servo system. To acquire angular velocity

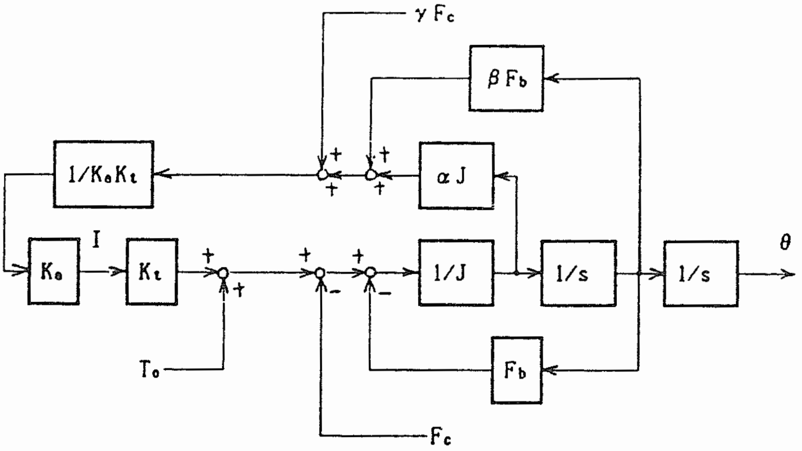

Figure 3. Active power assistance system.

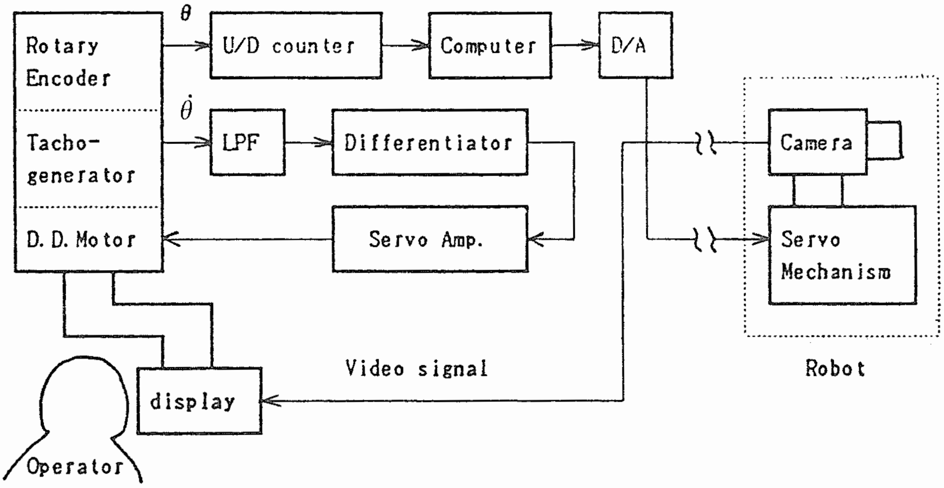

Figure 4. Control system of power-assisted display.

signals, we employed a tacho-generator. An analogue differentiator was used to obtain angular acceleration signals. Signals were passed through a low pass filter for noise rejection and then on to the servo amplifier. The servo amplifier was used to control the motor current. The parameters of the DD motor employed for power assistance are given in Table 1.

5. EXPERIMENTS

When we initially employed the control system discussed in Section 3, as is, and raised the inertial force compensating gain α to about 0.1, oscillation occurred. The part required to mount the display on the arm had a low rigidity and acted as an elastic factor. Actually, the oscillation was observed around the part.

Table 1.
Specifications of the DD motor

Motor diameter	9.48×10^{-2} m
Motor weight	9.07×10^{-1} kg
Peak torque T_p	3.4 N m
Peak current I_p	5.6 A
Torque sensitivity k_t	6.1×10^{-1} N m/A

We therefore used a model [4] which took into consideration the elastic factor between the motor with the rotary sensor and the inertial load (Fig. 5).

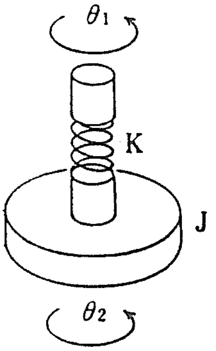

Figure 5. Model of elastic coupling.

Denoting the motor rotary angle by θ_1, the inertial load rotary angle by θ_2, the motor torque by T_m, and the operating torque applied on the load by T_0, this model behaves as follows:

$$\left.\begin{aligned} T_m &= K(\theta_1 - \theta_2) \\ T_m + T_0 &= J\theta_2 s^2, \end{aligned}\right\} \tag{4}$$

where J is the moment of inertia and K is the elastic constant of the coupling.

By employing a similar approach to equation (2) and substituting $T_m = J\theta_1 s^2$ in the above, we find

$$\ddot{\theta}_2 = \frac{\alpha J s^2 - K}{\alpha J^2 s^2 - (1-\alpha) JK} T_0. \tag{5}$$

As $0 < \alpha < 1$, one of the characteristic roots of the transfer function has a positive real component and the system is unstable.

Accordingly, by changing the torque feedback to

$$T_m = \alpha JK\theta_1 s^2 / (J' s^2 + Bs + K'), \tag{6}$$

the second-order transfer function is

$$\ddot{\theta}_2 = \frac{(J' - \alpha J)s^2 + Bs + K'}{J\{(J' - \alpha J)s^2 + Bs + (K' - \alpha K)\}} T_0. \tag{7}$$

This system may be stabilized under the following conditions:

$$J' - \alpha J > 0, \quad K' - \alpha K > 0, \quad B > 0. \tag{8}$$

If the step input is given as T_0 under these conditions, θ_2 will converge to $K'T_0/J(K' - \alpha K)$. In other words, the apparent inertial moment of the load will be made $(K' - \alpha K)/K'$ times as high. The natural frequency ω_n and attenuation factor ζ are given by

$$\left.\begin{aligned} \omega_n &= \sqrt{(K' - \alpha K)/(J' - \alpha J)} \\ \zeta &= B/\{2\sqrt{(J' - \alpha J)(K' - \alpha K)}\}. \end{aligned}\right\} \tag{9}$$

For a non-oscillatory response, $\zeta > 1$ and therefore

$$B > 2\sqrt{(J' - \alpha J)(K' - \alpha K)} \tag{10}$$

will suffice.

By providing a steady amplitude sinusoidal signal to the servo amplifier and examining the tacho-generator signal frequency response, we observed resonances at 16.7 and 530 Hz. This meant that there was another part which acted as an elastic factor and that higher order vibrational modes were present.

Resonances at 530 Hz can be eliminated by using a low pass filter (160 Hz) as shown in Fig. 4. To eliminate the resonance at 16.7 Hz, the differentiator shown in Fig. 4 was replaced by a double pole filter for transfer function $\alpha JKs/(J's^2 + Bs + K')K_t$. The filter parameters J', K', B and α were selected not only to satisfy equations (8) and (10) but also to bring about as high a compensation gain $\alpha K/K'$ as possible. The filter consisted of an analogue circuit to make K'/J', B/J', and α variable by operating potentiometers. Then, while examining actual responses, all the individual parameters were carefully adjusted to provide high stability responses together with intensified inertial compensation effects.

As a result of the above efforts, about 50% of the inertial load caused by the display was successfully compensated for. The motor mounting framework made of iron pipes was not stiff enough; a compensation gain higher than 50% caused deformation of the framework and oscillation. However, since these oscillations can be easily suppressed by fixing the framework by hand, a stiff framework would make a higher gain possible.

Figure 6 shows the rotary angles of the motor when an external force was applied to the display to move it, and the assisting torques generated in the motor in response. It reveals that the motor torque was generated when the operator accelerated or decelerated the display.

When an operator actually wore the display and moved it by neck force, the reactionary forces of inertia appeared to be lighter than with zero compensation. Thus, the burden was reduced. The difference was particularly noticeable when the display was moved swiftly. However, 50% inertial compensation produces an inertial burden of about 2 kg. A higher compensation gain would be preferable to minimize restraints by the display.

6. CONCLUSION

In this paper, a power-assisted head-coupled display for remote operation has been reported. This equipment compensates for inertial effects of the display with a DD

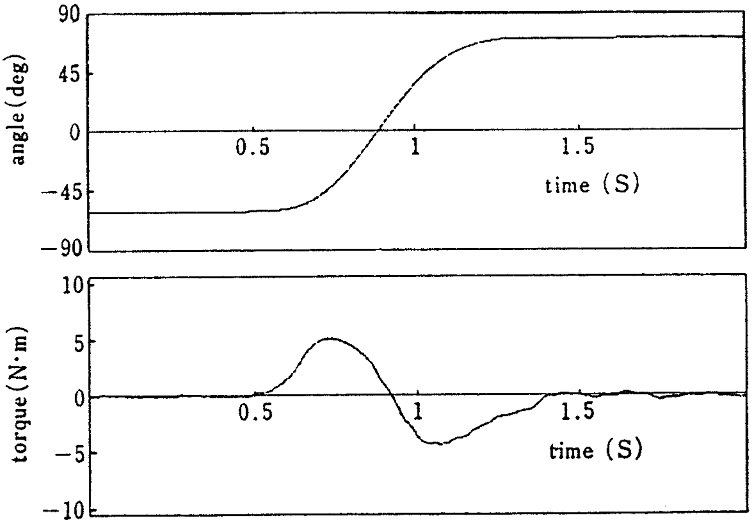

Figure 6. Torque output for power assistance.

motor when the operator controls the display orientation with his physical strength, and alleviates his physical burden. About 50% of the display inertia was successfully compensated by taking elastic coupling fully into consideration.

For future progress, not only will we aim for a higher compensation gain by employing a more rigid motor-mounting framework, but we will also attempt to apply these techniques to a model possessing multiple degrees of freedom of the display orientation.

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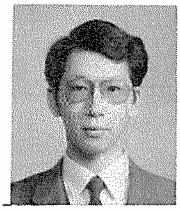
ABOUT THE AUTHORS



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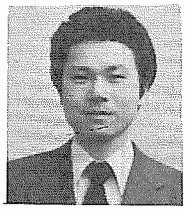

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