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# Loosely Coupled Joint Driven by SMA Coil Actuators

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*Abstract*— **We introduce a robotic prototype of an arm with a *loosely coupled joint*, modeled on the human joint. A viscoelastic object functions as cartilage and soft actuators as muscles. First, we show that although viscoelastic object affords smooth movement owing to shift in the center of rotation, the repeat accuracy of the joint is poor under open-loop control. The repeat accuracy was much improved by visual feedback. Under P control, the prototype was shown to be highly robust against mechanical disturbance owing to its good mechanical compliance.**

## I. INTRODUCTION

The creation of arms that are as smooth and compliant as human arms is an aim in the field of robotics. Joints in humans are not as simple as most people think. Importantly, the center of rotation in the shoulder shifts as the joint moves, and the muscles, tendons and ligaments allow the joints to be compliant, dampening vibrations for example. Such features are thought to be necessary for robotic arms, if they are to be able to behave like human limbs, as pointed out by Okada et al., who developed a cybernetic shoulder that imitates the motion of a human shoulder mechanically [1], [2]. Their cybernetic shoulder consists of rigid links connected by joints with three degrees of freedom (3-DOF) and under closed-loop control. In contrast, though the bones in human joints are rigid, the muscles, tendons and ligaments, and even the cartilage between the bones, are soft. Robotic joints with viscoelastic material have also been built, however. Mizuuchi et al. developed a robot that had a flexible spine [3], [4], a series of ball-and-socket joints covered by rubber. By controlling the length, tension and elasticity of the spine's tendons, the robot can twist its upper body. They focus on the control of spine mechanisms rather than the effect of a soft cartilage to smooth motion. The joints, however, are unlike human joints in that human joints contain a fluid which is known to play an important role, changing the properties of the porous cartilage and tissue by moving in and out of them, and altering the pressure within the joint [5]. This suggests that the motion and the compliance of a human shoulder joint may be realized by a mechanism with soft material, and some studies have taken this into account, modeling the human arm including cartilage, and simulating the motion. Vaz et al. formulated a dynamic equation of the human arm with cartilage whose elasticity was assumed to have a nonlinear spring component and a linear damper component, and used a bond graph model to simulate the motion of the arm [6]. As stated above, several studies have been conducted on prototyping and simulating of human-like joints, however, they are not taken effects of soft components into account in the control. We propose a novel link mechanism to investigate effects of soft component in control of a human-like joint. Here, we introduce a robotic prototype of an arm with a loosely coupled joint modeled on the human arm, with viscoelastic material and soft actuators functioning as the cartilage and muscles of a *loosely coupled joint*. First, we explain the concept of the loosely coupled joint. Next, we describe the prototype, and, under open-loop control, tests on verification that the center of rotation is not fixed, repeat accuracy of the motion of the joint, and its mechanical compliance. Finally, we experimentally study angle control of the link with visual feedback.

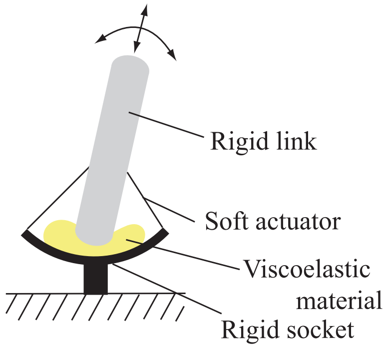

Fig. 1. Concept of loosely coupled joint

## II. CONCEPT OF LOOSELY COUPLED JOINT

The loosely coupled joint is shown in Figure 1. It is a revolute joint with soft actuators driving a rigid link in a rigid socket containing a viscoelastic object, corresponding, respectively, to the muscles, bone and socket of the human joint, and cartilage. The soft actuators and viscoelastic object make the joint compliant. Like the muscles, the actuators expand and contract unidirectionally and work antagonistically as a pair to rotate the link. Importantly, because of the viscoelastic object, the center of rotation of the link is not fixed. The simplicity of the joint mechanism enables it to miniaturize in comparison with one driven by a motor. This prototype moves in a two-dimensional plane.

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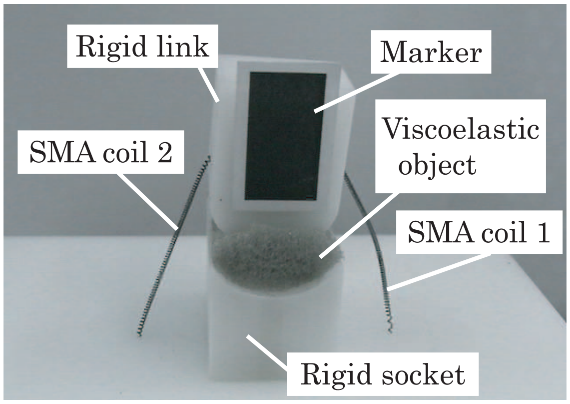


Fig. 2. Prototype of loosely coupled joint

## III. PROTOTYPE OF LOOSELY COUPLED JOINT

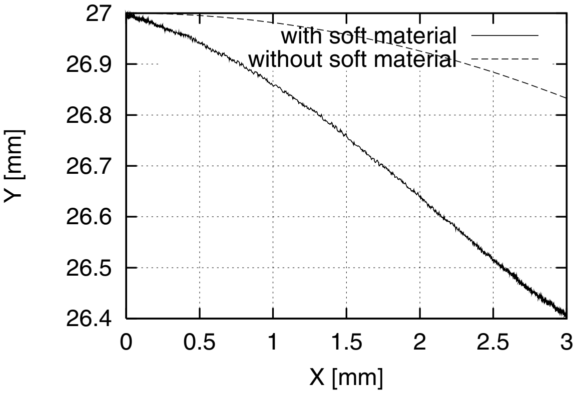
In this section, we describe the prototype and how we measure the motion of the link using open loop control to verify the movement of the center of rotation.

### A. Specifications and system

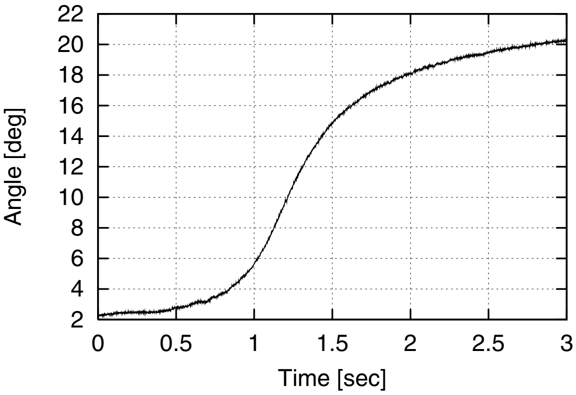
The prototype is shown in Figure 2. The actuators are made from BMX200 shape memory alloy (SMA) coil (TOKI Corporation, Japan), the link and socket are made from polyoxymethylene, and the viscoelastic object is an off-the-shelf sponge, 10 mm in thickness, 0.08 g in weight, and with a Young's modulus of about 20 kPa. To prevent slip, the sponge is fixed to the link and socket. The rigid link and the socket have a combined weight of 21.7 g, and the link end and origin of the joint are separated by a distance of 27 mm. The size of the complete joint mechanism is about that of a human fingertip. The actuators are powered through a ULN2003AN driver (Texas Instruments, USA). With a rectangular piece of black paper (9.5 x 19.5 mm$^2$) on the bottom of the link as a marker, the position and orientation of the link were calculated from the moments of the first and second orders, respectively, of images captured using a 1,000 Hz high-speed camera [7].

### B. Shift in center of rotation under open-loop control

When the voltage $v_{inp}^1$ applied to the driver for one of the actuators was set to 5 V while the voltage $v_{inp}^2$ to the other actuator was 0 V, X, the position of end of the link in horizontal direction, moved relative to Y, the position of end of the link in vertical direction, as indicated by the solid line in Figure 3-(a). In contrast, when a solid object replaced the viscoelastic object the end of the link moved as indicated by the broken line, which is an arc of a circle centered at the origin of the joint. Clearly, the center of rotation of the link is not fixed, similarly to the human joint, particularly in the presence of the viscoelastic object. Additionally, Figure 3-(b) shows that the link angle increases monotonously as time advances. Therefore, the link can move smoothly, like a human joint.

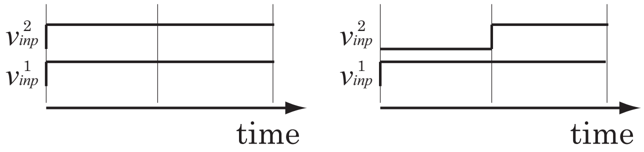


(a) End-point position



(b) Link angle

Fig. 3. Experimental results under open-loop control

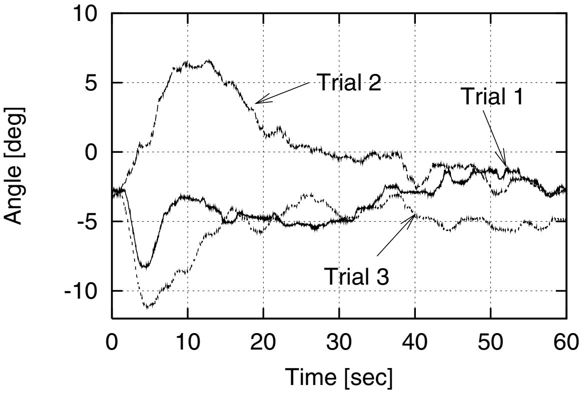


(a) pattern1 (b) pattern2

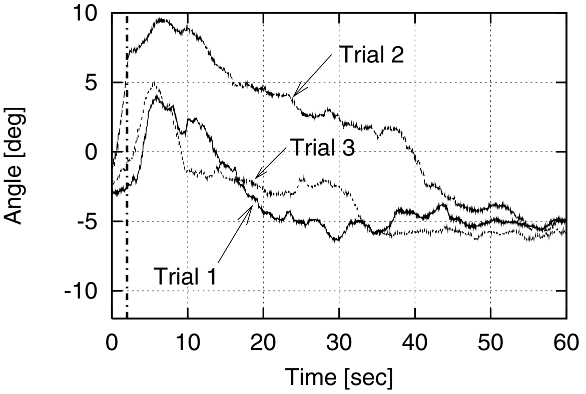
Fig. 4. Voltage patterns for repeat accuracy

### C. Repeat accuracy of link's motion under open-loop control

In general, the properties of SMA actuators, even when they are the same type, vary widely. Therefore, we experimentally verified the repeat accuracy of the link's motion under open-loop control. When we set $v_{inp}^1$ to 2.3 V and $v_{inp}^2$ to 2.1 V for 60 s in three trials as shown in 4-(a), the angle of the joint changed with time as shown in Figure 5-(a). Clearly, the repeat accuracy is poor. When we set $v_{inp}^1$ to 2.3 V for 60 s and $v_{inp}^2$ to 2.1 V, starting from 2 s as shown in 4-(b), the angle changed as in Figure 4-(b). In this case, the angle in the three trials eventually converged. The results tells us that there is hysteresis of the actuator, and that the repeat accuracy varies with the pattern of the voltages.



(a) pattern1



(b) pattern2

Fig. 5. Test results for repeat accuracy of link's motion under open-loop control

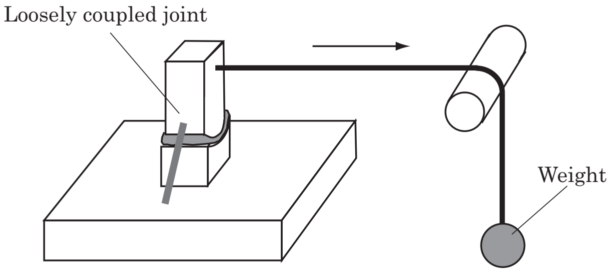


Fig. 6. Experimental setup for measuring compliance

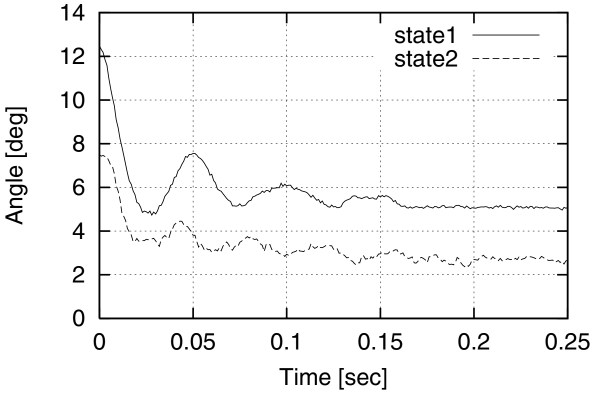


Fig. 7. Test results for compliance

### D. Variable compliance

The compliance of the link mechanism was tested experimentally using the setup shown in Figure 6. The 50 g weight caused the link to move 12 deg when no voltage was applied to the actuators at any time. The combination of the weight and $v^1_{inp}$ set to 3.0 V and $v^2_{inp}$ to 2.0 V simultaneously, caused the link to move 7.5 deg. When the thread connecting the weight to the link was severed by burning without changing the voltage applied to the actuators, the angle of the joint, monitored using a 1,000 Hz CMOS camera, changed as shown in Figure 7. The results show that the compliance is higher when a voltage is applied to the actuators and that in this state, as expected, the actuators and the cartilage are stiffer. Additionally, the viscous properties of the link mechanism are little changed when the voltage is applied to the actuators.

## IV. ANGLE CONTROL USING VISUAL FEEDBACK

As found above, the repeat accuracy of the link's motion is poor, making the joint difficult to control when it is an open-loop system. A potentiometer would not be much help because the center of rotation is not fixed. Therefore, we adopted visual feedback to control the angle of the joint. We used proportion laws that do not depend on knowledge of the physical properties of the joint because, in the case of soft materials, the physical properties, especially the viscosity, are not accurately known. We did not attempt to control the velocity of the joint because it would be more data intense.

### A. Experimental setup

Figure IV shows the visual feedback system. Two personal computers (PCs) were connected using a 1 Gbps optic fiber (AVAL DATA, Japan). The time lag between the PCs was negligible. One PC was used to generate control inputs to the actuators at a frequency of 10 $\mu$s and the other was used to store and process the visual information captured by the CCD camera operating at the standard NTSC frame rate of 30 per second. The sampling rate of the sensor was adequate because SMA actuators have slow responses.

### B. P control

We used the following simple proportional (P) control law for the link:

$$\begin{cases} v^1_{inp} = -K_P(\theta(t) - \theta_d) + v_{offset}, \\ v^2_{inp} = 0, \end{cases} \tag{1}$$

where $\theta_d$ is the desired angle, to be held constant, $t$ is the length of time that the control input voltages $v^1_{inp}$ and $v^2_{inp}$ for actuators 1 and 2 are applied to the drivers, $K_P$ is the proportional gain which is a positive constant, and $v_{offset}$ is the minimum voltage required for the drivers, which was 1.7

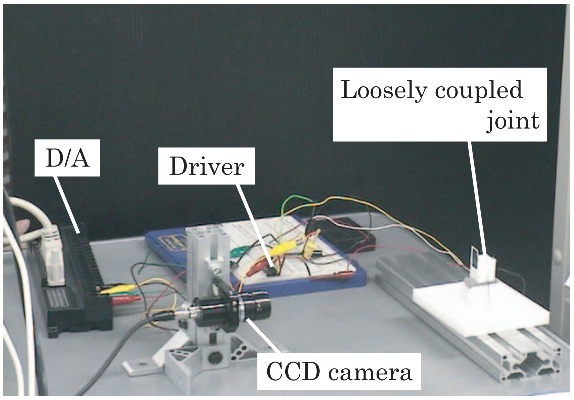


Fig. 8. Control system

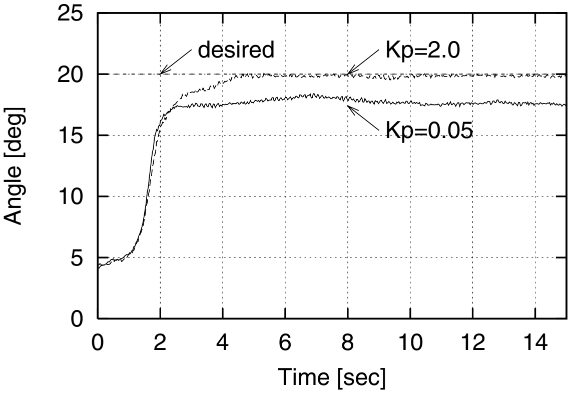


Fig. 9. Experimental results under P control

V for our drivers. The load on the actuator complicates the relationship between input voltage and the actuator's driving force, hence use of the input voltage to the driver IC as the control input in Eq.1. Figure 9 shows how the angle changes with time when the desired angle $\theta_d$ was 20 deg and $K_p$ was 0.05 or 2.0. The angle reaches a steady value, albeit there is some fluctuation. This steady-state error depends on the value of $K_P$, increasing with gain. However, even when the gain $K_p$ to 2.0, the steady-state error is acceptable, being less than 0.15 deg.

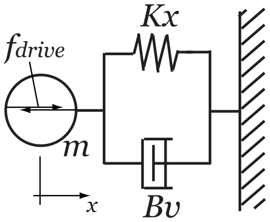
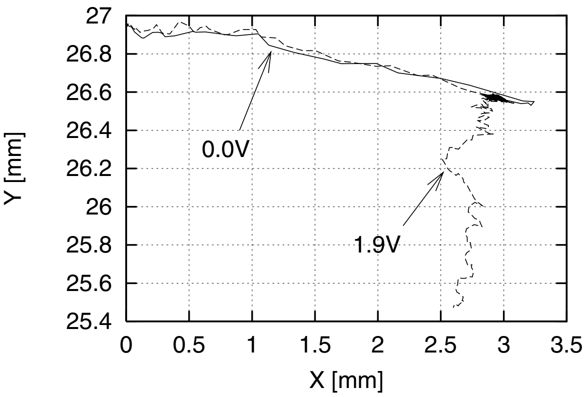
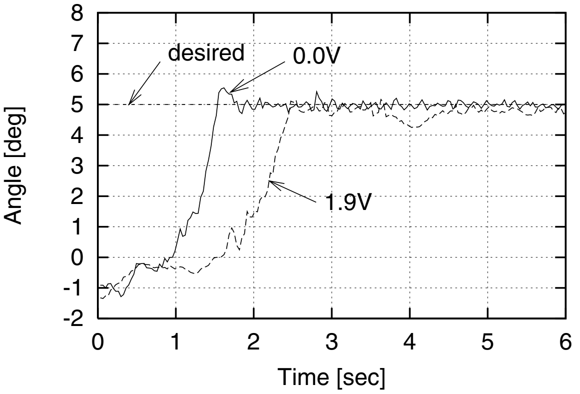


Fig. 10. Viscoelastic object fixed to a wall



(a) End-point position



(b) Link angle

Fig. 11. Test results for variable compliance under P control

Therefore, we can control the angle of the link, within a positive range, by one actuator. We can explain these results by examining position control of the viscoelastic object fixed on a wall as shown in Figure 10. Let $x$ and $f_{drive}$ be the position of a mass point and the driving force acting on the mass point, respectively. Here, the dynamic equation of the mass point can be expression as $m\ddot{x} = -Kx - B\dot{x} + f_{drive}$, where $m$, $K$, and $B$ are the mass, stiffness and viscous coefficients of the mass point, respectively. Let $x_d$ represent the desired position. Applying driving force $f_{drive} = -K_P(x(t) - x_d)$, the mass converges to a certain position with a steady-state error as the gain increases. This matches the experimental results obtained above. The viscosity of a soft material contributes to the stability. Hence, the joint can be controlled by feedback control without damping. Now, let $K_I$ be an Integral gain and be a positive constant. Using Integral (I) control law, that is, applying the driving force $f_{drive} = -K_I \int_0^t (x(t) - x_d)\ \mathrm{d}t$, the mass converges to the desired position correctly. Hence, we think that the joint will converge to a desired location correctly under I control only. However, we have not verified it experimentally because the actuators have a slow response, but we aim so study it in the future work.

When we used two actuators to control the angle of the link, we obtained the results in Figure 11. For $v_{inp}^1$, we applied the proportional control law of Eq.1, and $v_{inp}^2$ was a step voltage. In Figure 11, $v_{inp}^2$ is set at 0.0 V and at

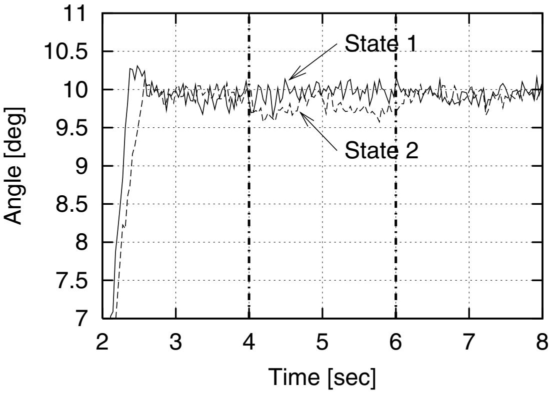


Fig. 12. Test results for robustness against disturbance

1.9 V. Setting $v_{inp}^2$ to 0.0 V, only one actuator moves the link. Gain $K_p$ was set to 2.0 and the desired angle $\theta_d$ was 5.0 deg. The link angles converged and could be controlled successfully, shown in Figure 11-(b). When both actuator were used, link end moved as indicated in Figure 11-(a). The link goes down into the cartilaginous area, that is, the viscoelastic object, when $v_{inp}^2$ = 1.9 V is applied. The force generated by actuator 2 and deformation of the cartilaginous area when two actuators are used are greater than ones when one actuator is used. These results imply that the compliance when one actuator is used is different from that when two actuators are used under visual feedback control.

### C. Robustness under P control

We experimentally investigate the robustness of the joint for disturbances. We used one SMA actuator as a disturbance, and compare two states. In state 1, we continuously applied the $v_{inp}^1$ and $v_{inp}^2$ as in Eq. 1. In state 2, we set $v_{inp}^2 = 5.0$ V from 4.0 s to 6.0 s, making actuator 2 a disturbance for SMA actuator 1. Figure 12 shows how the angles changed in the two states, with $K_p$ = 2.0 and $\theta_d$ 5.0 deg. The angle converges to a stable location after $v_{inp}^2$ breaks contact. We experimentally confirm that the disturbance by SMA actuator 2 is about 150 g weights. The weights generate a momentum for the rigid link as much as the momentum applied by actuator 1, and it is a large disturbance for the joint. These results imply that P control of the joint is robust.

## V. ANGLE CONTROL USING LENGTH SENSOR

As described in the previous section, we confirmed that under visual feedback, the motion of the joint is highly robust. Human muscles have muscle spindles to measure the current length of the muscles. Hence, human can use not only visual information of an object but also length information of muscles to move their arms. In this section, we realize angle control of the joint using length information. The motion of the joint is lowly robust when occlusion occurs in visual feedback. The length information for angle control improves the robustness. Figure 13 shows the experimental setup with a length sensor. We use a pulse coder (LEVEX, Japan) as a length sensor. This sensor can measure the length of insert distance of a SUS 304 wire into the sensor tube. Figure 14 shows angle identification for the length sensor. We experiment P control using the identification results as input angles instead of angle data captured from a CCD camera. Figure 15 shows how the angle changes with time when the desired angle $\theta_d$ was 15 deg and $K_p$ was 2.0. The angle reaches a steady value with estimation error. In future, we will apply plural sensors to reduce the error.

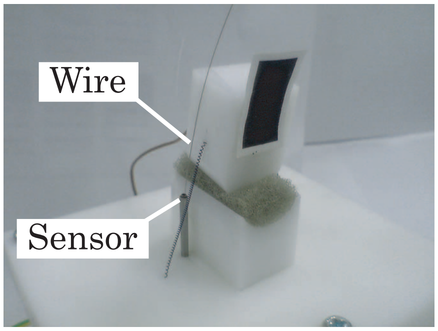


Fig. 13. Experimental setup using length sensor

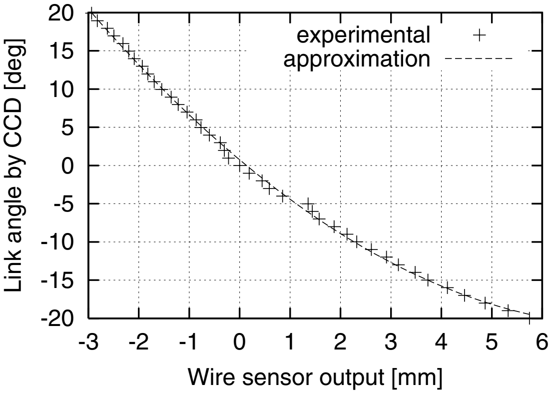


Fig. 14. Angle identification for length sensor

## VI. DISCUSSION

In this paper, we made a link mechanism with a cartilaginous area. We investigate the availability of the link mechanism. Figure 16 shows the link mechanism without a cartilaginous area. The link mechanism has a rotational joint with a bearing. In addition, the trajectory of the rigid link describes an arc since the center of rotation is fixed. We arrange a pair of SMA actuators to rotate the rigid link. The size of the link mechanism is the almost same as the size of the link with loosely coupled joint shown in Figure 2. Figure 17 shows an experimental result of P control in Eq.1. In this control, the actuator 2 does work instead of a bias spring which generates a restoring force for shrinkage of a SMA actuator since the SMA actuators are arranged antagonistically. By comparing of Figures 11 and 17, it is

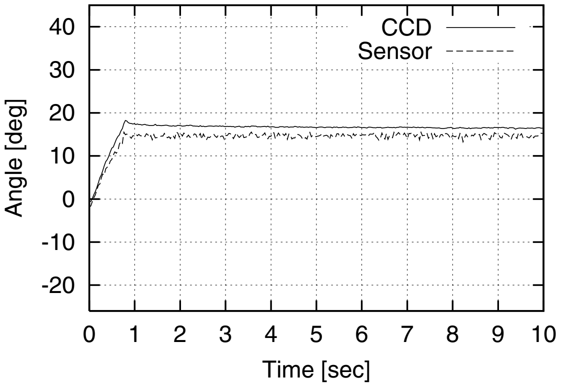


Fig. 15. Experimental result for length control

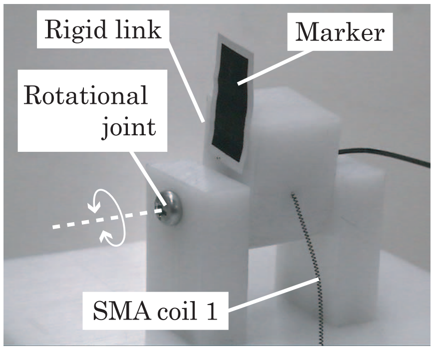


Fig. 16. Joint mechanism without the cartilaginous area

clear that the viscoelastic object reduces the oscillation in the angle.

In this paper, we used a CCD camera to control the link angle. Due to a low response speed of SMA actuators, we do not need to use a high sampling rate sensor to control it. Because in general, external sensors complicate the control system, we hope to develop an internal sensor. Ikuta et al have developed an active endoscope which uses SMA actuators [8]. They proposed using electric resistance feedback to control the lengths of the SMA actuators. They measured the electric resistance of SMA actuators directly through a bridge circuit. If we can measure the full length of SMA coils correctly, we might be able to estimate the position and orientation of the link end.

Whitney has proposed a remote compliance center hand in which an elastic body is arranged between a base and an area in contact with an object being grasped [9]. Using this hand, the compliance absorbs errors in positioning and orientation occurring in insertion tasks of an object. The hand is highly robust for disturbances. The loosely coupled joint mechanism contribute to a realization of a human-like hand with natural compliance.

## VII. SUMMARY

We described a robotic joint, dubbed a *loosely coupled joint*, which has a viscoelastic object and soft actuators that function as the cartilage and muscles, respectively, in human joints. We confirmed that the viscoelastic object causes the center of rotation of the link to shift, allowing the link to move smoothly like a human joint. Next, we experimentally verified that our prototype has good mechanical compliance. We also found that the motion of the link under open-loop control has poor repeat accuracy and is prone to hysteresis. Therefore, we improved the control of the joint by using visual feedback. We confirmed that under P control, the motion of the joint is highly robust against disturbances because it is highly compliant. In the present study, the top surface of the viscoelastic object was fixed to the rigid link and the rigid socket to prevent slip. In future work, we will investigate the effects of slip between the rigid link and the cartilage. We will also make a dynamic model and analyze the stability of the control law.

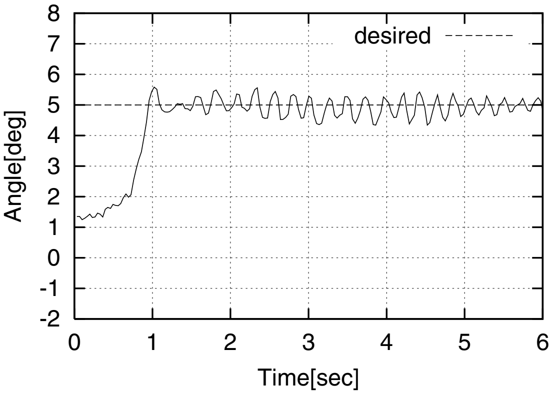


Fig. 17. Experimental result of joint without the cartilaginous area

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