Proc. of International Symposium on Experimental Robotics pp.509-518, 2000

Design of Programmable Passive Compliance (PPC) Mechanism using Closed Kinematic Chain – PPC Cybernetic Shoulder for Humanoid Robots –

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Abstract: We have developed the 3-DOF humanoid's shoulder mechanism 'Cybernetic Shoulder'. Whose advantages are human-like motion, introduction of the passive compliance, large mobile area and singularity free. In this paper, we develop the second prototype of the cybernetic shoulder which has the programmable passive compliance mechanism using a redundant actuator, which is an essential function for humanoid robots to realize the human skill. The programmability of this mechanism is evaluated by an experiment.

1. Introduction

Humanoid robots that share the space and environments with human should have compliance for task execution and safety issue. There are two strategies to develop the robot compliance. One is active compliance on which many researches have been reported [1]∼[6], the other is passive compliance. The active compliance is realized by actuators. The compliance of robot joints is developed using control theories such as impedance matching method. It has high programmability of compliance, however cannot cope with fast responses because of the low resolution of sensors, a long sampling time of control and noises of sensors. The passive compliance means mechanical compliance of members of robot arm. This compliance works effectively in all frequency (both fast and slow responses) but its programmability is low. Because there are many humans in the environments of the humanoid robots, the passive compliance is important for the safety issue.

The mechanical compliance can store the dynamical energy. By using this energy, the human skill can be realized. On the casting of fishing, the rod deforms much and stores the dynamical energy on itself. By radiating that energy in one moment, we can cast the prickle farer by small power. On the sports, the faster motion needs the higher compliance and the harder hit needs the lower compliance. By the introduction of the passive compliance to humanoid robots, it can move more powerful and faster by small actuators. Moreover, because the optimal compliance to the specific task depends on the weight of arms and speed of the motion, the compliance characteristics should be changed adaptively, which means the programmable passive compliance plays an important role for the realization of the human skill.

In this paper, we show the effectiveness of the passive compliance and design the PPC cybernetic shoulder that is the second prototype of the humanoid shoulder mechanism 'Cybernetic Shoulder'[7]. The programmability of the PPC cybernetic shoulder is evaluated by experiments.

2. Passive compliance

2.1. Effectiveness of the passive compliance

In this section, we show the effectiveness of the passive compliance developed to the robot joint. By storing the dynamical energy to the compliant mechanism and radiating the energy in one moment, the robot can throw a ball faster with a small actuator. Consider the two links manipulator in the horizontal plane shown in Fig.1. One joint is actuated and another joint has passive compliance.

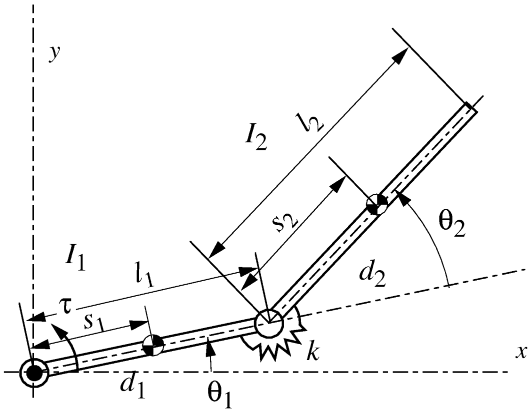

Figure 1. Two links manipulator in the horizontal plane

ℓ_i is the length of link (we set $\ell_1 = 0.3$ [m], $\ell_2 = 0.5$ [m]), s_i is the position of the center of gravity of link ($= \ell_i/2$), I_i is the inertia of link, d_i is the coefficient of the viscosity of rotation ($d_1 = 0.3$ [Nms/rad], $d_2 = 1.0$ [Nms/rad]), θ_i is the rotation angle of the link, k is the spring constant of the passive joint and τ is the torque of the motor. θ_1 is controlled by PD controller K as shown in Fig.2. P is the two links manipulator, r is the reference signal for θ_1 and X is as follows.

$$X = \begin{bmatrix} \theta_1 & \dot{\theta}_1 & \theta_2 & \dot{\theta}_2 \end{bmatrix}^T \tag{1}$$

The dynamics of the two links manipulator is the output vector Fas fallows.

$$M(\theta_2)\ddot{\Theta} + C(\Theta, \dot{\Theta}) = U \tag{2}$$

$$\Theta = \begin{bmatrix} \theta_1 & \theta_2 \end{bmatrix}^T \tag{3}$$

$$M = \begin{bmatrix} a + 2b\cos\theta_2 + c & b\cos\theta_2 + c \\ b\cos\theta_2 + c & c \end{bmatrix} \tag{4}$$

$$C = \begin{bmatrix} -b\cos\theta_2(2\dot{\theta}_1^2 + \dot{\theta}_2^2)\dot{\theta}_2 & b\sin\theta_2 \cdot \dot{\theta}_1^2 \end{bmatrix}^T \tag{5}$$

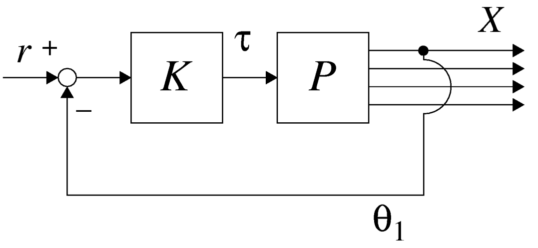

Figure 2. Control system of the two links manipulator

$$U = \begin{bmatrix} \tau - d_1\dot{\theta}_1 & -k\theta_2 - d_2\dot{\theta}_2 \end{bmatrix}^T \tag{6}$$
$$a = m_1 s_1^2 + m_2 \ell_1^2 + I_1 \tag{7}$$
$$b = m_2 s_2 \ell_1 \tag{8}$$
$$c = m_2 s_2^2 + I_2 \tag{9}$$

Setting the reference signal as

$$r(t) = -\sin(2\pi t), \quad 0 \le t \le 1 \tag{10}$$

we get the optimal spring constant k_{opt} which minimizes the following cost function J.

$$J = \sum_{i=1}^{2} w_i J_i \tag{11}$$
$$J_1 = \max_t (\dot{\theta}_1(t)\tau(t)) \tag{12}$$
$$J_2 = \frac{1}{\max_t (v_y(t)} \tag{13}$$
$$v_y(t) = \dot{\theta}_1 \ell_1 \cos\theta_1 + (\dot{\theta}_1 + \dot{\theta}_2)\ell_2 \cos(\theta_1 + \theta_2) \tag{14}$$
$$w_1 = 1, \quad w_2 = 500 \tag{15}$$

J_1 aims at reduction of the actuator power. J_2 aims at maximizing the velocity of the end of the arm along with y axis. Maximization of the velocity means that the two links manipulator can throw fast ball. The values of J and J_1, J_2 due to the spring constant k are shown in Fig.3, 4 respectively, which are given from the numerical simulations. These figures show that the optimal spring constant k_{opt} is given as

$$k_{opt} = 2.15 \tag{16}$$

and the maximum velocity is 6.19 [m/s]. These results show that by using the passive compliance, the two links manipulator can throw the faster ball by small consumption of the motor energy.

2.2. PPC Mechanism

Because the optimal spring constant given in the previous section depends on the weight of links and trajectory of the reference signal, the spring constant should be changed adaptively, which is achieved by the programmable passive compliance. Fig.5 shows the PPC mechanism using a closed kinematic chain. There are two redundant actuators. When the members A and B have a nonlinear relationship between the strain stress, the compliance of the position C can be changed by giving tension to members A and B. These types of PPC mechanisms have been developed [6, 8, 9]. The drawbacks of these mechanisms are as follows.

Development of the multi-DOF mechanism Development of the multi-degree of freedom mechanism assembling the single degree of freedom mechanism, it gets heavy weight and large volume.

Control of redundant actuators The programmable passive compliance is realized by two redundant actuators whose outputs should be exactly same. Otherwise the joint may rotate or has an oscillation.

To overcome these problems, we develop the PPC mechanism using a closed kinematic chain.

3. PPC Cybernetic Shoulder

3.1. Design and mechanism

We have designed the cybernetic shoulder[7] that is the three DOF shoulder mechanism for humanoid robots. The passive compliance mechanisms using closed kinematic chain have been developed. The model of the cybernetic shoulder is shown in Fig.6. β and δ are two degree of freedom gimbal mechanisms, d is a three degree of freedom ball joint, b is a two degree of freedom universal joint, a is a four degree of freedom joint of spherical and prismatic motion, and e is a prismatic joint. Moving point A within vertical plane alters the pointing direction of the main shaft G, which determines, along with the constraints due to the free curved links E between points b and d, the direction of the normal vector of D. The rotation about the normal of D is mainly

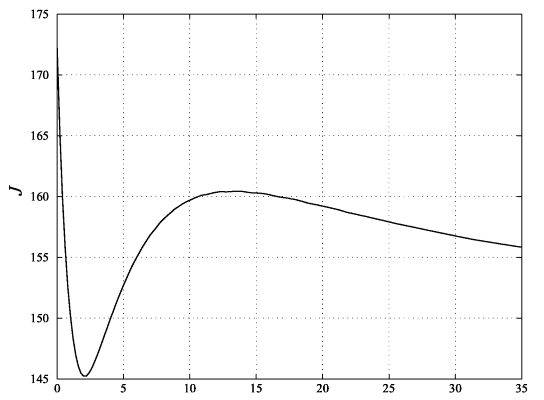

Figure 3. Value of J versus spring constant k

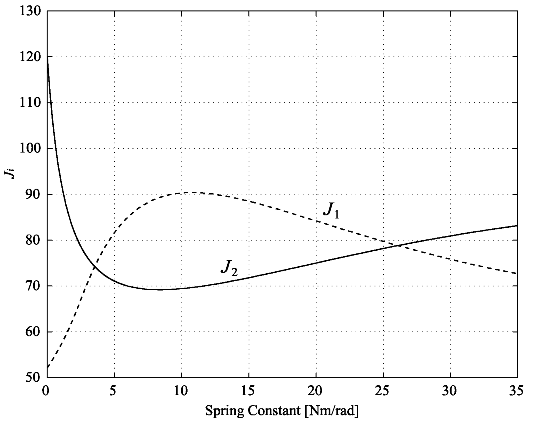

Figure 4. Value of J_i versus spring constant k

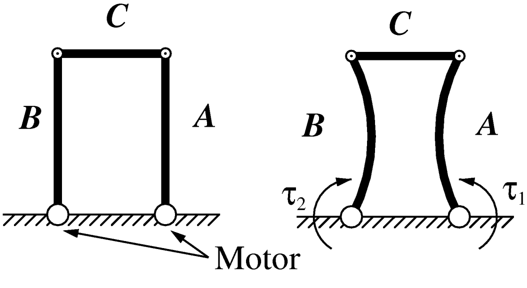

Figure 5. Programmable passive compliance mechanism

determined by the rotation of C through B and G. Note that the rotation of C is coupled with the pointing direction of D when B and D are not parallel.

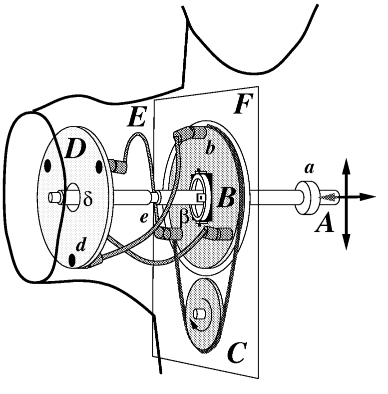

Figure 6. The cybernetic shoulder

Based on this mechanism, we design the PPC cybernetic shoulder shown in Fig.7. The advantages of this mechanism are as follows.

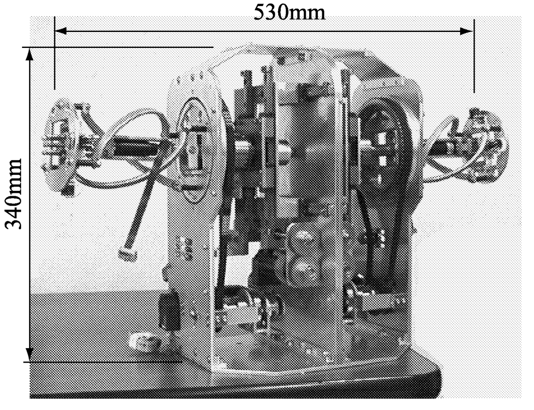

Figure 7. The PPC cybernetic shoulder

PPC mechanism We replace the prismatic joint e in Fig.6 with a linear actuator (4.5[W] DC motor and ball screw) as shown in Fig.8. By changing the

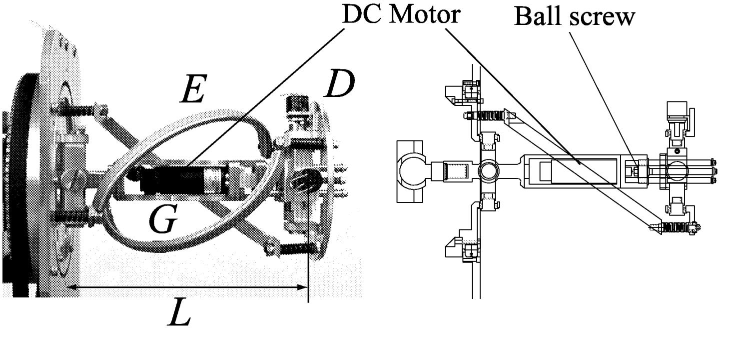

Figure 8. PPC mechanism

length of L in ΔL, the internal force is applied to members E, which causes the programmable passive compliance when E have nonlinear relationship between strain and stress.

Compactness and small backlash The universal joints on the point b and d are replaced with elastic universal joints as shown in Fig.9. It has the same structure as a flexible coupling. This is for the compactness and the small backlash.

Multi-DOF compliance Because the end disk D has a gimbal mechanism on its center, the PPC cybernetic shoulder has two degree of freedom

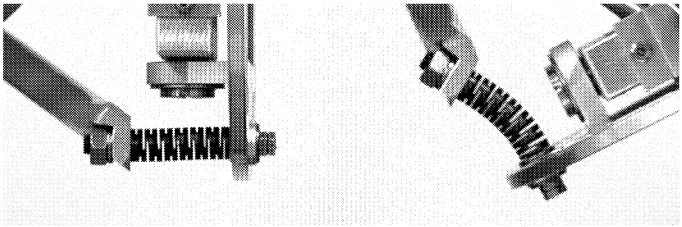

Figure 9. Elastic universal joint

compliance around the rotation axis of the gimbal mechanism. Because the center rod G is rigid, the PPC cybernetic shoulder has high stiffness for any other degree of freedom of compliance.

3.2. Evaluation of the programmability

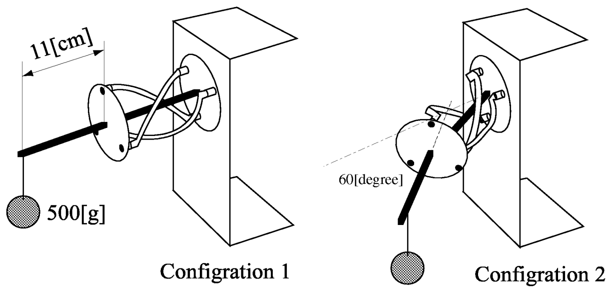

Figure 10. Configurations of the PPC cybernetic shoulder

In this section, we evaluate the programmability of the passive compliance on PPC cybernetic shoulder. We set two configurations of the PPC cybernetic shoulder as shown in Fig.10. By cutting the 500[g] weight hung from the end of the arm, the external force is applied. The torque of the external force becomes 0.539 [Nm]. Two cases are adopted on each configuration, in one case ΔL = 0 [mm], in another case ΔL = -3 [mm]. Each occasion is defined as Table 1. The responses of each case are shown in Fig.11 and 12. In this prototype, the members E are rigid but joints (elastic joints) have compliance. The passive compliance of this mechanism is caused by the joint compliance. The compliance on each case are as follows which is calculated from the rotation

Table 1. Definition of the experimental set

	ΔL = 0 [mm]	ΔL = -3 [mm]
Configuration 1	Case 1	Case 2
Configuration 2	Case 3	Case 4

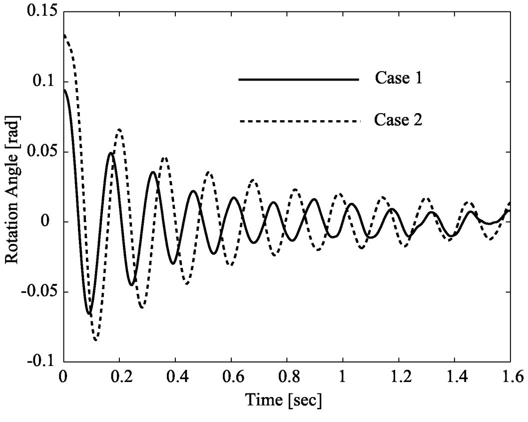

Figure 11. Responses on configuration 1

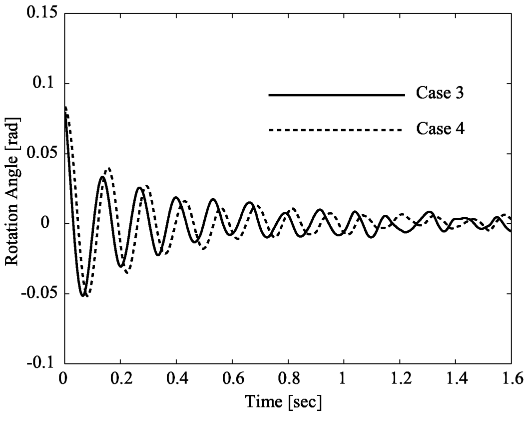

Figure 12. Responses on configuration 2

angle in time zero.

Case 1	:	0.202 [rad/Nm]
Case 2	:	0.237 [rad/Nm]
Case 3	:	0.156 [rad/Nm]
Case 4	:	0.170 [rad/Nm]

In configuration 2, the compliance cannot be changed so much. On configuration 1, we measure the passive compliance by small resolution of changing ΔL. Figure 13 shows the compliance due to ΔL in the configuration 1. The shorter L yields the higher compliance. The elastic universal joints have high compliance for yaw and pitch direction but have low compliance on thrust direction, that yield the passive compliance of the PPC cybernetic shoulder. The more dominant the thrust compliance becomes the lower the passive compliance of the PPC cybernetic shoulder becomes.

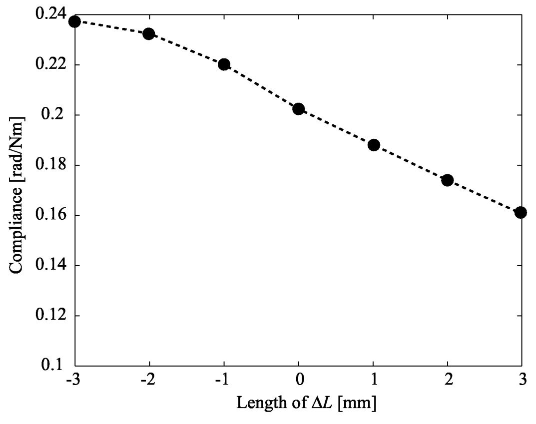

Figure 13. PPC due to ΔL

Consider a humanoid robot with the PPC cybernetic shoulder shown in Fig.14. Suppose that a 200 [g] weight falls from 1 [m] height and collide with an

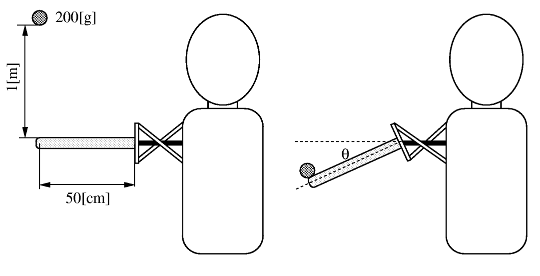

Figure 14. Configuration of the ball hit

arm. The rotation angles θ are shown in Fig.15 on each ΔL. This result shows that by changing L and giving tension to elastic joint on the PPC cybernetic shoulder, we can get large change of the passive compliance, that means the PPC cybernetic shoulder has high programmability of the passive compliance.

4. Conclusions

In this paper, we discuss on the effectiveness of the passive compliance and design the PPC cybernetic shoulder. The results are as follows.

1. By using the passive compliance mechanism, robots can throw a faster ball by small actuators.

2. We design the PPC cybernetic shoulder which is the shoulder mechanism for humanoid robots.

3. The PPC cybernetic shoulder has high programmability of the passive compliance by using the closed kinematic chain.

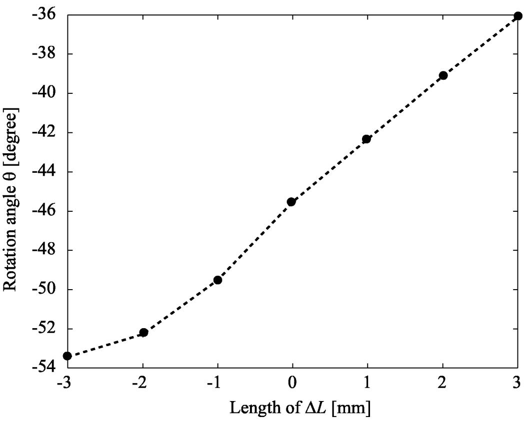

Figure 15. Rotation angle of θ due to ΔL

This research is supported by the Research for the Future Program, the Japan Society for the Promotion of Science (Project No. JSPS-RFTF96P00801).

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