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Design of Programmable Passive Compliance Shoulder Mechanism

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Abstract

Design of mechanical compliance would be one of the most important technical foci in making humanoid robots really interactive with the humans. For safety insurance the mechanical compliance should be developed to humanoid robots. The introduction of the passive compliance to humanoid robots has large possibility to achieve the human skill by using the dynamical energy stored in the compliant members. The programmable passive compliance plays an important role to cope with the changing environments and task execution. In this paper, we evaluate the effectiveness of the passive compliance for the realization of the human skill and design a programmable passive compliance mechanism 'PPC cybernetic shoulder' which is the four degree of freedom shoulder mechanism for humanoid robots using a closed kinematic chain. The programmability of the PPC cybernetic shoulder is evaluated by experiments.

Key Words : *Skill of compliance, Prgrammable passive compliance, The cybernetic shoulder, Humanoid robot*

1 Introduction

Humanoid robots that share the space and environments with human should have compliance for human friendliness, safety issue and relief of impacts. 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 or some special joint mechanisms. This compliance works effectively in all frequency (both fast and slow responses) but its programmability is low. For the safety issue, the passive compliance is important because there are many humans in the environments of the humanoid robots.

Our research focuses on the 'Skill of Compliance', which means (1) tuning of passive compliance, (2) planning of swing pattern and (3) design of the control law. In the casting of fishing, for example, the potential energy is accumulated in the rod by taking the swing and the large kinetic energy is obtained by discharging the potential energy in the instant to throw the prickle farer. In this motion, the passive compliance of the rod is tuned, the swing pattern of the rod and the force control of our arm are well designed.

So far, we have developed the cybernetic shoulder[7] that is the three degree-of-freedom mechanism for humanoid robots. It has human-like motion and passive compliance using the closed kinematic chain. In this paper, we design the programmable passive compliance mechanism for the cybernetic shoulder (Programmable Passive Compliance Cybernetic Shoulder) that is useful to filling up the low programmability of the passive compliance, and obtain the compliance ellipsoid[4] of this mechanism that is helpful to design the swing up pattern. The programmability of the designed mechanism is evaluated by experiments.

2 Passive Compliance

2.1 Compliance, control law and swing pattern

In this section, we show the skill of the passive compliance. Consider the two links manipulator in the horizontal plane shown in Fig.1. One joint is actuated and another is free joint that has passive compliance. ℓ_i are the length of links (we set $\ell_1 = 0.3$ [m], $\ell_2 = 0.5$ [m]), s_i are the positions of the center of gravity of

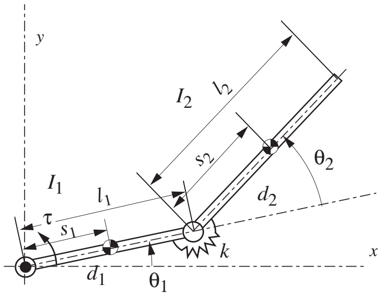

Figure 1: Two links manipulator in the horizontal plane

links ($= \ell_i/2$), I_i are the inertias of links, d_i are the coefficients of the viscosity of joints ($d_1 = 0.3$ [Nms/rad], $d_2 = 1.0$ [Nms/rad]), θ_i are the rotation angles of the links, 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.

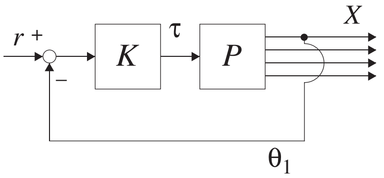

Figure 2: Control system of the two links manipulator

$$X = \left[\begin{array}{cccc} \theta_1 & \dot\theta_1 & \theta_2 & \dot\theta_2 \end{array}\right]^T \tag{1}$$

The dynamics of the two links manipulator is as fallows.

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

$$\Theta = \left[\begin{array}{cc} \theta_1 & \theta_2 \end{array}\right]^T \tag{3}$$

$$M = \left[\begin{array}{cc} a + 2b\cos\theta_2 + c & b\cos\theta_2 + c \\ b\cos\theta_2 + c & c \end{array}\right] \tag{4}$$

$$C = \left[\begin{array}{cc} -b\cos\theta_2(2\dot\theta_1^2 + \dot\theta_2^2)\dot\theta_2 & b\sin\theta_2 \cdot \dot\theta_1^2 \end{array}\right]^T \tag{5}$$

$$U = \left[\begin{array}{cc} \tau - d_1\dot\theta_1 & -k\theta_2 - d_2\dot\theta_2 \end{array}\right]^T \tag{6}$$

$$a = m_1 s_1^2 + m_2 \ell_1^2 + I_1 \tag{7}$$

$$b = m_2 s_2 \ell_1 \tag{8}$$

$$c = m_2 s_2^2 + I_2 \tag{9}$$

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 fastball. Though the optimized spring constant depends on the motor controller (control law) and reference signal in equation (10) (swing pattern), we optimize only the spring constant (compliance) in one situation that fixes control law and swing pattern. 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

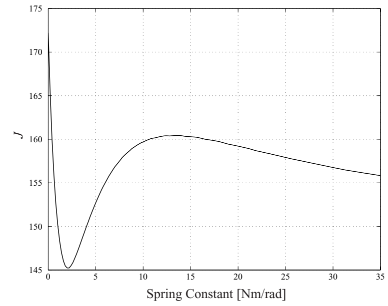

Figure 3: Value of J versus spring constant k

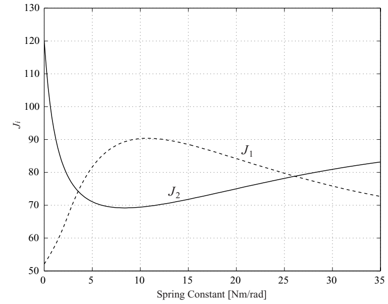

Figure 4: Value of J_i versus spring constant k

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 Programmable passive compliance 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. Figure 5 shows the example of the programmable passive compliance mechanism using a closed kinematic chain. There are two redundant actuators. When the members A and B have a nonlinear relationship between the strain and 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.

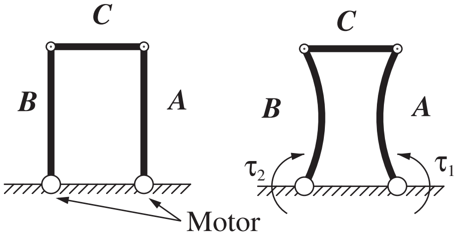

Figure 5: Programmable passive compliance mechanism

Development of the multi-DOF mechanism If we develop 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 programmable passive compliance mechanism using a closed kinematic chain.

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

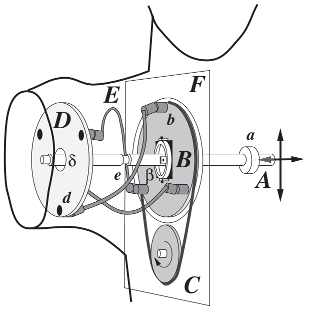

Figure 6: The cybernetic shoulder

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 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

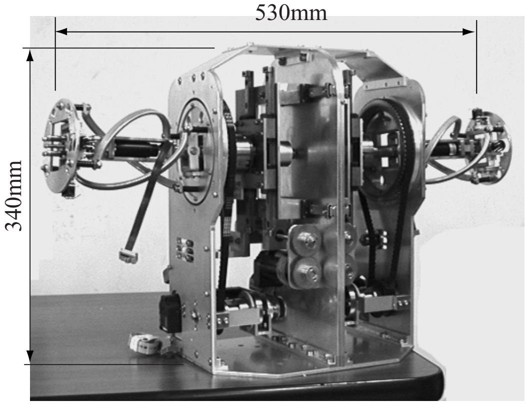

Figure 7: The PPC cybernetic shoulder

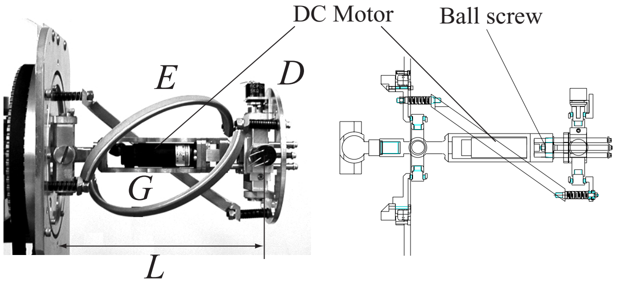

Figure 8: PPC mechanism

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 gimble mechanism on its center, the PPC cybernetic shoulder has two degree of freedom compliance around the rotation axis of the gimble 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 Compliance ellipsoid of the cybernetic shoulder

The compliance ellipsoid [4] is helpful for the foundation of the swing pattern and motor control law.

Consider the compliance matrix C defined as

$$C = JK^{-1}J^T \tag{17}$$

Here, J is the jacobian matrix and K is the spring constant matrix. Using the singular value decomposition

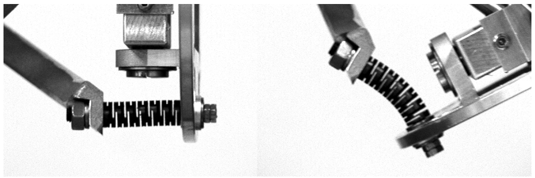

Figure 9: Elastic universal joint

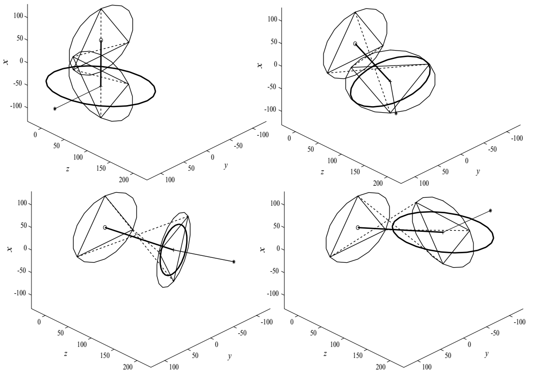

Figure 10: Compliance ellipsoid of the cybernetic shoulder

of C,

$$C = USV^T \tag{18}$$

$$= \begin{bmatrix} U_1 & \cdots & U_n \end{bmatrix} \mathrm{diag}\left\{ \begin{matrix} s_1 & \cdots & s_n \end{matrix} \right\} V^T \tag{19}$$

the compliance ellipsoid is defined in the n dimensional space whose axes are $s_iU_i(i = 1, 2, \cdots n)$. In this paper, we consider the two-dimensional compliance ellipsoid of the cybernetic shoulder. Figure 10 shows the compliance ellipsoid in accordance with the motion of the cybernetic shoulder. These ellipsoids are calculated in each orientation using equation (19).

3.3 Evaluation of the programmability

Each occasion is defined as Table 1. 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.11. 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 $\Delta L = 0$ [mm], in another case $\Delta L = -3$ [mm]. The responses of each case are shown in Fig.12 and 13.

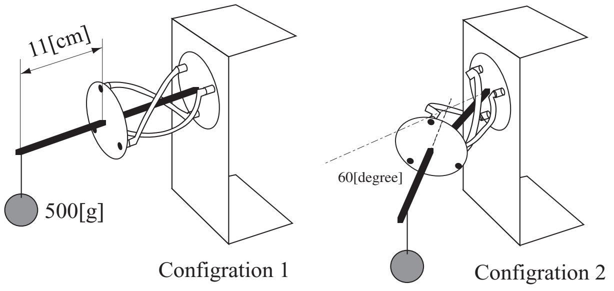

Figure 11: Configurations of the PPC cybernetic shoulder

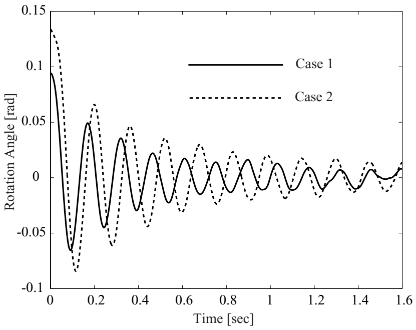

Figure 12: Responses on configuration 1

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 is as follows which is calculated from the rotation 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. In configuration 1, we measure the passive compliance by small resolution of changing ΔL. Figure 14 shows the compliance due to ΔL in the configuration 1. The shorter L yields the higher compliance.

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

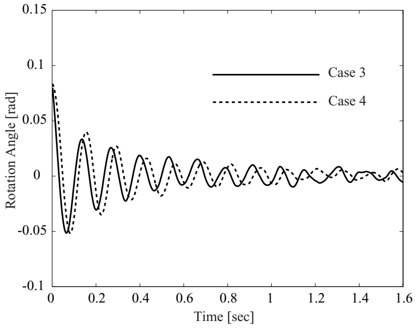

Figure 13: Responses on configuration 2

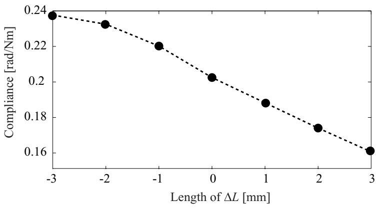

Figure 14: PPC due to ΔL

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.

3.4 Design of elastic members

The programmable passive compliance in the previous section was realized adopting the elastic universal joint in Fig.9. In this section, we design the nonlinear elasticity as a property of link E in Fig.8.

Figures 15 and 16 illustrate the idea and design of nonlinear elastic link. Link E has a series of holes with different diameters and small cuts. As seen in Fig.16, the largest hole has the minimum thickness and, therefore, bends first when bending moment is applied until the cut C-shaped hole deforms and becomes closed. If the bending moment exceeds, it further deforms the second largest C-shaped hole and so on. Since the thickness of halls are different, the elastic coefficient of link E changes in a discrete manner. Figure 17 shows the result of measurements of the fabricated link, which clearly shows the nonlinear discrete elasticity. The spring constant in each area is as Table 2. The diameters, thickness, and width of cut would need

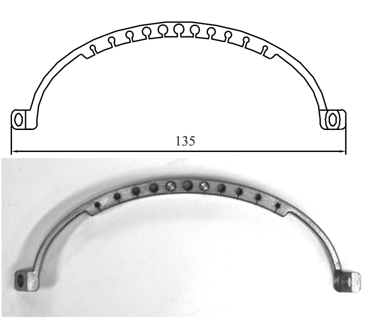

Figure 15: Elastic link

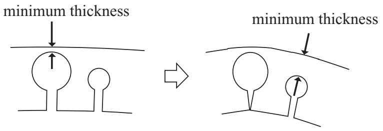

Figure 16: Change of the spring constant

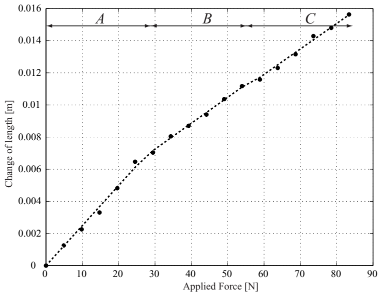

Figure 17: Applied force and change of length

more careful design using FEM numerical analysis if it requires a specific shape of elastic curve.

The redundant actuator of "DC Motor" in Fig.8 determines length L. When it shortens, it is accompanied by the bends of three of link E, which determines the mechanical compliance of the PPC cybernetic shoulder mechanism.

4 Conclusions

In this paper, we discuss on the skill of compliance, which is tuning of the passive compliance, planning of the swing pattern and design of the control law, and design the programmable passove compliance cybernetic shoulder. The results are as follows.

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

Table 2: Tunable spring constant

Area	Spring constant [N/m]
A	4.009×10^3
B	6.203×10^3
C	6.303×10^3

2. We design the programmable passive compliance cybernetic shoulder which is the shoulder mechanism for humanoid robots.
3. The programmable passive compliance cybernetic shoulder has high programmability of the passive compliance by using the elastic joint and elastic link.

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References

[1] R.P.C.Paul and B.Shimano : Compliance and Control, Proc. of the 1976 Joint Automatic Control Conference, pp.694–699, 1976.

[2] H.Hanafusa and H.Asada : Stable Pretension by a Robot Hand with Elastic Fingers, Proc. of the 7th International Symposium on Industrial Robots, pp.361–368, 1977.

[3] N.Hogan : Mechanical Impedance Control in Assistive Devices and Manipulators, Proc. of the 1980 Joint Automatic Control Conference, pp.TA10-B, 1980.

[4] J.K.Salisbury : Active Stiffness Control of a Manipulator in Cartesian Coordinates, Proc. of the IEEE Conference on Decision and Control, 1980.

[5] N.Hogan : Impedance Control: An Approach to Manipulation: Part 1∼3, ASME Journal of Dynamic Systems, Measurement and Control, Vol.107, pp.1–24, 1985.

[6] K.F.L-Kovitz, J.E.Colgate and S.D.R.Carnes: Design of Components for Programmable Passive Impedance, Proc. of IEEE International Conference on Robotics and Automation, pp.1476–1481, 1991.

[7] M.Okada and Y.Nakamura: Development of the Cybernetic Shoulder – A Three DOF Mechanism that Imitates Biological Shoulder-Motion –, Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems , Vol.2, pp.543-548 (1999)

[8] T.Morita and S.Sugano: Design and Development of a new Robot Joint using a Mechanical Impedance Adjuster, Proc. of IEEE International Conference on Robotics and Automation, pp.2469-2475 (1995)

[9] H.Kobayashi, K.Hyodo and D.Ogane: On Tendon-Driven Robotic Mechanism with Redundant Tendons, Int. J. of Robotics Research, Vol.17, No.5, pp.561-571 (1998)