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Skill of Compliance with Controlled Charging/Discharging of Kinetic Energy

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Abstract

Use of compliance in muscle is the inherent skill of a human. By using the potential energy charged in the compliant members, we can skillfully equalize the characteristics of muscles and body. Integrating the skill of compliance will provide robots with higher mobility, dexterity and safety and extends the fields of applications. The main research issues of the skill of compliance are tuning passive compliance, planning compliant motion and designing control law. To achieve the skill, we focus on the planning compliant motion considering the kinetic energy. In this paper, we propose to design a compliant motion through iterative model identification and motion design. A humanoid robot with passive compliance is used to integrate the skill of compliance and shows fast swing charging and discharging the kinetic energy.

Keywords: Skill of compliance, Passive compliance, Cybernetic shoulder, Humanoid , Iterative method

1 Introduction

Motion design and control considering a robot dynamics realize a fundamental skill of the robot body. In this paper, we discuss the integration of 'skill of compliance'[1]. The skill of compliance implies attainability of higher mobility, dexterity and safety by efficiently using the compliant members. Typically, faster motion would become possible with smaller actuator power. There are two strategies to integrate compliance into robots. One is an active compliance[2]~[7], the other is a passive compliance[8][9]. The active compliance is realized by actuators and their control. The passive compliance means mechanical compliance of robot arm. For the skill of compliance, the passive compliance and its control under dynamical constraints play important rolls.

We previously developed the cybernetic shoulder[10], a three-degree-of-freedom shoulder mechanism for humanoid robots. It showed human-like motion and passive compliance using the closed kinematic chain. Thanks to the closed kinematic chain using designed elastic links, the cybernetic shoulder has integrated mechanical compliance. Fig.1 shows the humanoid robot with the cybernetic shoulder. In this paper, we study the skill of compliance specifically on its mechanism.

The main research issues of the skill of compliance are (1) tuning passive compliance, (2) planning compliant motion and (3) designing control law. We focus on planning compliant swing motion like swinging a ping-pong racket. Although the dynamics model of the robot is necessary for the motion planning, the dynamics of the cybernetic shoulder is highly complex. In this paper, we take an experimental iterative method to find the swing motion that maximizes the hand velocity. Based on the swing motion, a model of the shoulder is updated using the experimental results of the previous motion. The swing motion is updated based on the new model and the motion is tried iteratively. By the iterative method, we realize the skill of compliance and obtain the appropriate dynamic model for the skill.

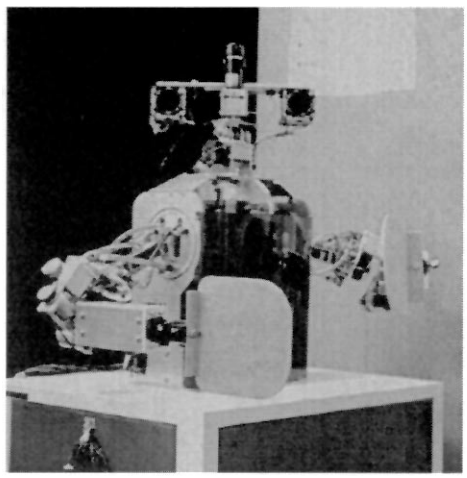

Figure 1: The humanoid robot with the cybernetic shoulder

2 Iteration of model identification and motion design

The swing motion should be designed based on the dynamics of the humanoid robot. However, because of the high complexity of the cybernetic shoulder, it is difficult to obtain the dynamical model of the humanoid robot. Therefore, we iterate the model identification, the motion design and the experiment with the humanoid robot. The algorithm is shown in Fig.2 and as follows.

step.1 Assume that the initial model of the humanoid robot is given. Based on this model, we design the swing motion that realizes the skill of compliance.

step.2 Based on the experimental data of the swing motion, we re-identify the model of the robot.

step.3 Based on the new model, we re-design the swing motion.

step.4 We iterate step.2 and 3.

In this method, the model formulation of the humanoid robot is fixed and parameters of the model are modified, which means that the appropriate model for the swing motion is obtained in the fixed model formulation.

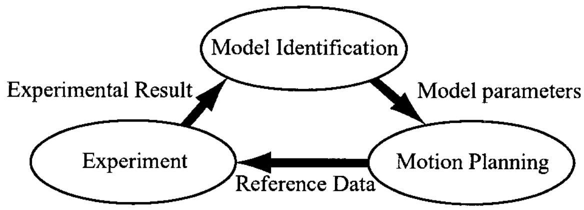

Figure 2: The iterative model identification and motion design

3 Model identification

3.1 The formulation of the model

For the motion design, it needs the dynamic model of the robot. In this paper, we consider the swing motion on the horizontal plane for simplicity and obtain the dynamic model based on the experimental data. Fig.3 shows the model of the humanoid robot. u is the joint angle of the roll axis of the shoulder, and x is the strain angle of the compliant members.

We regard the dynamics of the cybernetic shoulder as a spring-mass damper system, and set the dynamic model as ARX model [11] like the following formulation.

$$x[k] = \frac{b_2 q^2 + b_1 q + b_0}{q^2 + a_1 q + a_0} u[k] \qquad (1)$$

Here, k means a data number, and q is the sift-operator which is defined as follows.

$$qu[k] = u[k+1] \qquad (2)$$

The model parameters a_i and b_i are assumed to be the function of the angle u as follows.

$$a_i = a_i(u[k]) \quad , \quad b_i = b_i(u[k]) \qquad (3)$$

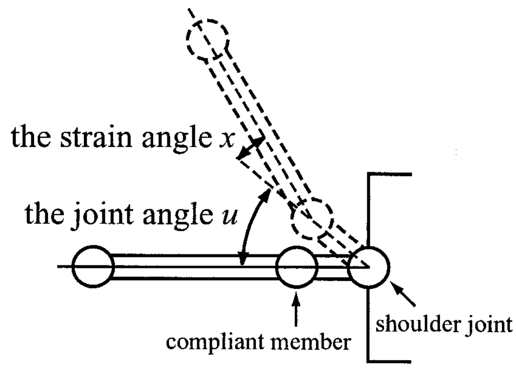

Figure 3: The model of the humanoid robot

Because the compliance characteristic of the cybernetic shoulder depends on the configuration of the shoulder angle, which is shown in [1] based on the compliance ellipsoid[5].

3.2 Model identification

Because the humanoid model is assumed to be the u-dependent ARX model, we identify the model parameters as follows.

1. The model parameters are assumed to be constants at small range about the angle $u[k]$. We classify the experimental data $x[k](k = 1, 2, \cdots)$ into nine groups according to $u[k]$ in each 5[deg] from -22.5[deg] to 22.5[degree].
2. In each class, we identify the humanoid model as an ARX model.
3. The parameter set is approximated by fourth-order polynomials of the angle u.

We obtain the initial model for the iterative method. In each classified range of the angle u, we identify the ARX model using random inputs, and approximate the parameter set by the polynomials of the angle u. Fig.4 shows the obtained model parameter of the initial model. Each line shows the approximated polynomial.

4 Swing motion design

4.1 Swing motion

The joint is controlled by a PD controller, and the motion is given as the reference position of the joint angle u. Considering a human motion, winding up and swinging of arm, we design the trajectory of the angle u as follows and shown in Fig.5.

- $0 \leq u \leq 20$ [deg]
- The angular velocity $|\dot{u}|$ has the upper bound.

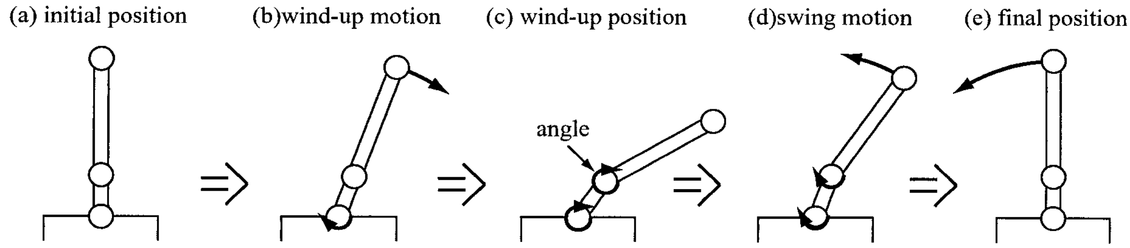

Figure 5: The humanoid swing motion

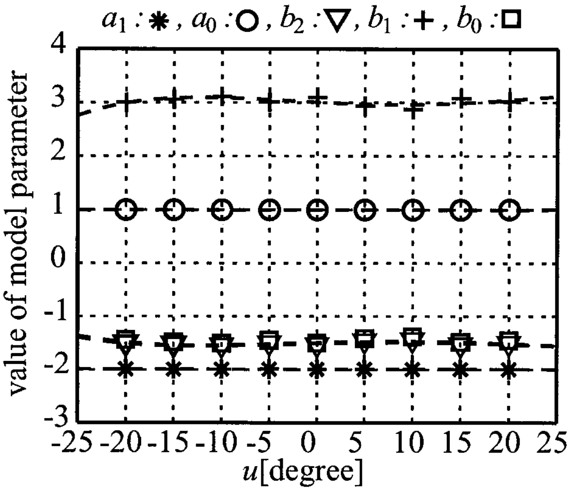

Figure 4: The result of the initial model identification

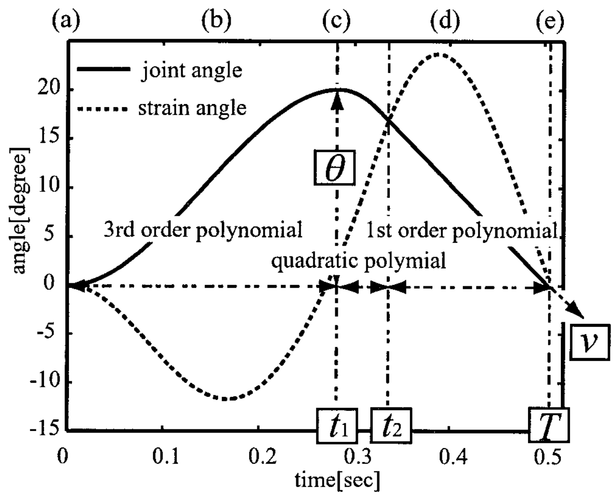

Figure 6: The motion design and simulation

- (a) in Fig.5, Initial position :
  $t = 0$, $u = 0$, $x = 0$, $\dot{u} = 0$, $\dot{x} = 0$
- (b) in Fig.5, Wind-up motion :
  The angle u monotonously increases until it takes the maximum value.
- (c) in Fig.5, Wind-up position :
  The angle u takes the maximum value.
- (d) in Fig.5, Swing motion :
  The angle u monotonously decreases after it takes the maximum value.
- (e) in Fig.5, Final position :
  $t = T$, $u = 0$

4.2 Motion design and simulation

Fig.6 shows the designed swing motion. The solid line is the motion of the angle u, and the dashed line is the strain angle x. They are obtained by the following algorithm. Since the motion pattern and its second-order derivative should be continuous, we divide the motion into three sections as follows.

- $0 \leq t \leq t_1$: the wind-up motion
  The angle u should be a third order polynomial.
- $t_1 \leq t \leq t_2$: the swing motion 1
  The angle u should be a quadratic polynomial.
- $t_2 \leq t \leq T$: the swing motion 2
  The angle u should be a first order polynomial.
- The second-order derivative of the angle u is continuous at $t = t_1$ and t_2.

In the third section ($t_2 \leq t \leq T$), the angle u is not accelerated so that the potential energy is discharged into the kinetic energy. We aim to change the almost all potential energy into the kinetic energy, and realize the fast motion of the hand in this section.

For the design of the swing motion, we approximate the polynomials as follows. We set design parameters as follows which are shown in Fig.6.

- T : the final time
- θ : the maximum value of the angle u
- t_1 : the time when the angle u takes the maximum value
- v : the value of $\dot{u}(T)$

The parameter t_2 is determined dependently. If design parameters are given, we uniquely obtain the swing motion of the angle u as the solid line in Fig.6. The trajectory of the angle x is obtained by the model simulation as the dashed line shown in Fig.6. At the model simulation, the trajectory of u is inputted into Eq. (1), and the trajectory of x is outputted. We search the appropriate design parameters by changing parameters and based on the cost function as the section 4.4.

4.3 Control of charging and discharging the kinetic energy

In a dynamic motion, there is an appropriate rhythm based on the body dynamics for the skill of compliance. The parameter T is the most important for the swing motion. We optimize the design parameters θ, t_1 and v in the case of $T = 0.2$, 0.5 and 1.0.

1. T=0.2 is so short that the humanoid robot cannot discharge the kinetic energy charged in the elastic members. In Fig.7, the strain angle x is large at $t = T$, which means the compliant members have large potential energy.
2. T=0.5 is appropriate for this robot dynamics. In Fig.8, the humanoid robot charge large potential energy to the compliant links, and discharge all potential energy at $t = T$ efficiently.
3. When T is 1.0, the swing motion is so slow that the humanoid robot cannot charge the potential energy to the mechanical compliance mechanism. In Fig.9, the maximum value of the angle x is small, which means the charged energy is small.

Fig.10 shows the angular velocity of the hand of these motions. The motion 2 obtains the fastest velocity by the skill of compliance. These considerations means not only swing pattern but also appropriate time control is important.

4.4 Evaluation of the swing motion

The trajectory of the strain angle x shown in Fig.6 by the dashed line is important for the swing motion. An appropriate trajectory of the angle x should meet following conditions so that the hand moves fast at $t = T$ and that the energy efficiency of the actuator becomes high.

- $0 \leq t \leq T$, the angle x has only one local maximum value so that the energy consumption of the damping becomes small.
- The maximum value of the angle x is large so that the high energy is charged in the compliant members.
- The angle $x(T)$ should be zero so that all potential energy changes to the kinetic energy.
- The direction of $\dot{x}(T)$ should be same as that of $\dot{u}(T)$.

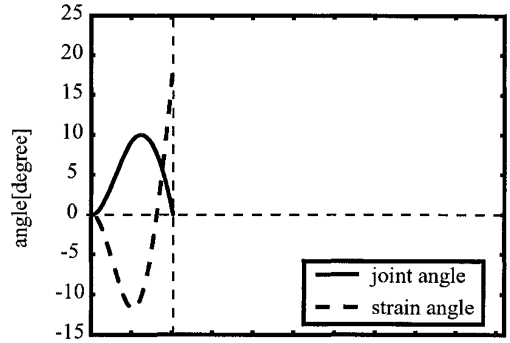

Figure 7: The motion 1 : $T = 0.2$ (fast)

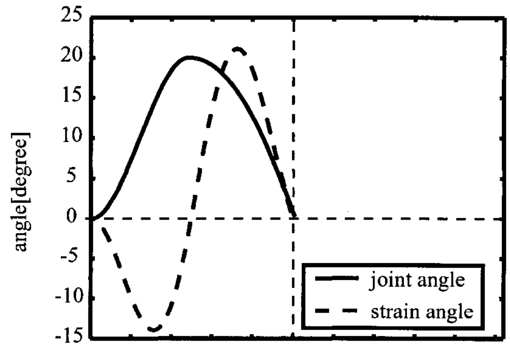

Figure 8: The motion 2 : $T = 0.5$ (appropriate)

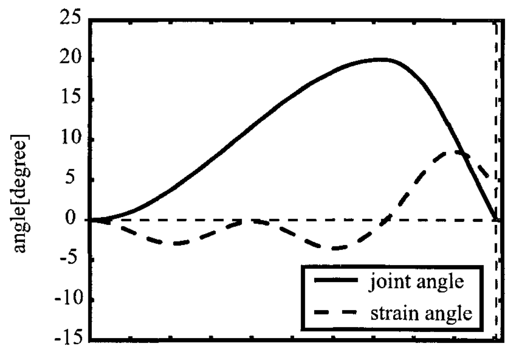

Figure 9: The motion 3 : $T = 1.0$ (slow)

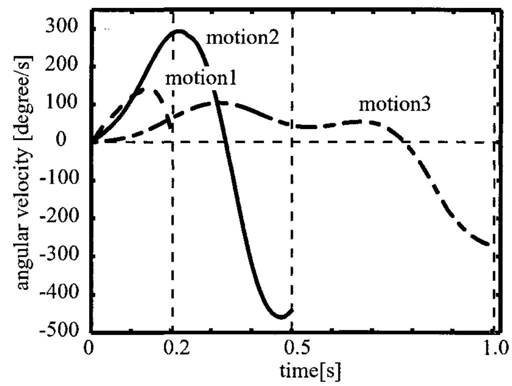

Figure 10: The angular velocity of the hand

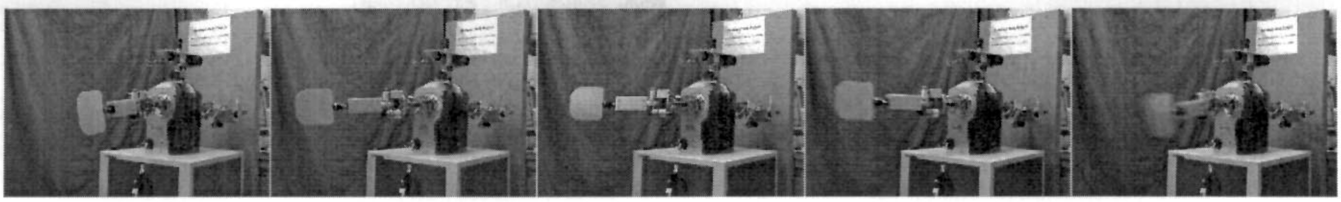

Figure 11: The swing motion with the humanoid robot

To realize the appropriate motion, we set the cost function J as follows.

$$J = w_1 x(T)^2 + \frac{w_2}{(w_3 u(T) + x(T))^2} \quad (4)$$

Here w_i $(i = 1, 2, 3)$ are weight constants, and $(w_3 u + x)$ equals the velocity of the hand. Each term of in Eq.(4) means as follows.

- The first term aims at making the angle x become zero at $t = T$.
- The second term aims at making the hand move fast at $t = T$.

Based on the cost function in Eq.(4), we search the appropriate design parameters. Table.1 shows the obtained parameters. As the dynamics model changes through the iteration method, the appropriate design parameters change.

Table 1: The design parameters

	initial model	2nd model	3rd model
T	0.5[s]	0.5[s]	0.46[s]
θ	20[deg]	20[deg]	20[deg]
t_1	0.28[s]	0.236[s]	0.2[s]
v	-150[deg/s]	-150[deg/s]	-140[deg/s]

5 Experimental results

Based on the proposed algorithm, we design the swing motion and identify the dynamic model for the skill of compliance. Fig.11 shows the realized swing motion. From the initial position, the humanoid robot winds up and swings. We iterate the proposed method three times. From experimental results, we make the following considerations.

- Fig.12 shows the experimental result. The solid line shows the joint angle u, and the dashed line shows the strain angle x. The strain angle becomes large during the swing motion and becomes zero at $t = T$, which means that the kinetic energy is charged in the elastic links as the potential energy, and all potential energy is changed to the kinetic energy at $t = T$.
- The experimental result shown in Fig.12 is same as the simulation result in Fig.6, which means that we obtain the appropriate dynamic model of the humanoid robot.
- Table.2 shows the value of the cost function and the velocity of the hand at $t = T$ on each iteration. Each value is the average of 10 times experiments. Fig.13 shows the re-identified humanoid model. By iterative model identification and motion design, the cost function gets small, and the velocity of the hand becomes large, which means that by iterating the proposed algorithm, more appropriate model is obtained.
- Fig.14 shows the velocity of the hand with the elastic links and rigid links with the same input signal of the angle u. By using the compliant links the humanoid robot obtains faster velocity, which shows the effectiveness of the skill of compliance.

Table 2: The result of the iterative method

model	the cost function	the velocity [m/s]
1st	70.6	2.42
2nd	37.4	2.44
3rd	31.4	2.48

6 Conclusions

We discussed the skill of compliance from the motion planning point of view, and proposed iterative motion design and model identification. The conclusions of this paper are as follows:

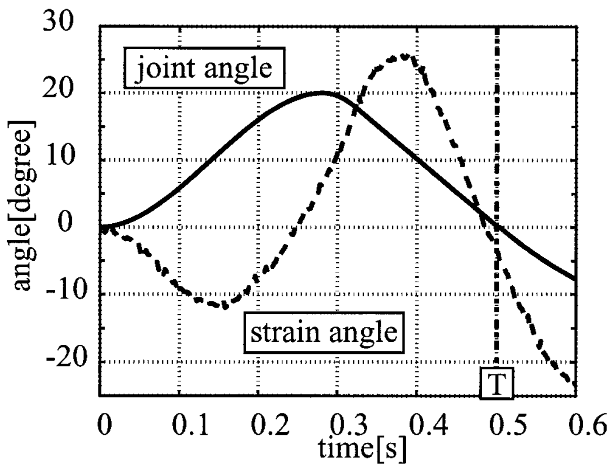

Figure 12: The experimental result

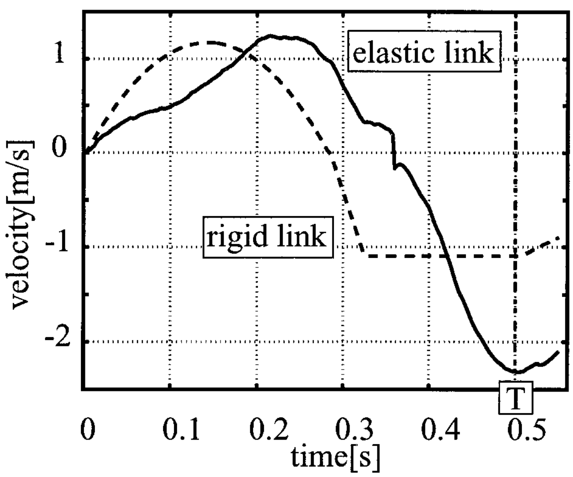

Figure 14: The velocity of the hand

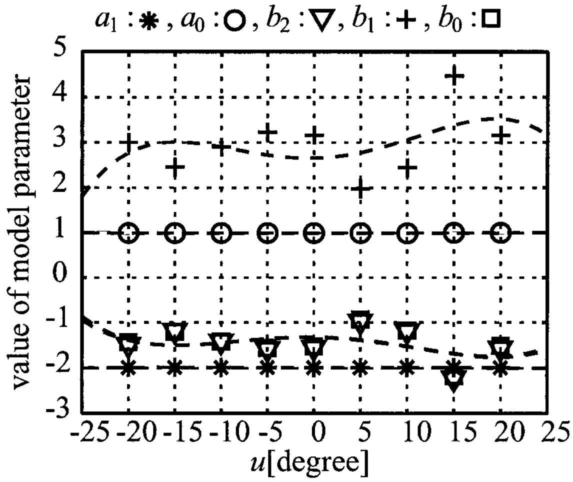

Figure 13: The results of the model re-identification

1. By the iteration of the motion design, the experiment with the humanoid robot and the model identification, we realize the skill of compliance and obtain the appropriate dynamic model for the skill.

2. By the motion planning considering the kinetic energy, we realize the skill of compliance with charging and discharging the kinetic energy.

3. Through the experiment with the robot, we evaluate the effectiveness of the proposed strategy.

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