Flexible Motion Control of a Linear Synchronous Actuator with an Artificial Stiffness and Damping Factor for a Humanoid Robot

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1. Introduction

The mechanisms of many of the conventional robots are quite different from natural biomechanics. Studies for emulating the natural biomechanics are active, the purpose of which is to realize kinetic performance of a humanoid robot with the redundancies that natural animals own. Let us think of a robot with two joints operated in a two-dimensional plane. All quadrupled and biped animals have bi-articular muscles. A group has studied the reason for and the role of bi-articular muscles, intensively[1][2].

Conventional humanoid robots have no parts like artificial bi-articular muscles. They have only rotary motors, hydraulic or pneumatic actuator and so on at their cubital and shoulder joints, which play the roles of mono-articular muscles. With such hardware configuration, one absolutely needs to calculate complicated inverse kinematics. However, natural life forms never execute such complicated calculations in reality. For example, results of bionic measurements[1] have shown that the motion of our natural arm are controlled by changing the ratio of force divided among mono-articular muscles at cubital and shoulder joints, and a pair of bi-articular muscles linearly. Consequently, a humanoid robot with actuators as bi-articular muscles may be able to move as quickly and flexibly as a natural human.

This idea has been already realized by using bulky mechanical linear actuators which are combinations of mechanical elements, *e.g.*, wires, springs, dampers, stroke sensors and hydraulic or pneumatic mechanisms. Especially, we have proposed to use a linear synchronous actuator for an artificial bi-articular muscle. Several reasons have been advanced for this:

1. It can make the actuator compact by the direct drive of a linear actuator. We can make it without several of the parts in a mechanical system and the total system can be much simpler and lighter.
2. Flux density using Permanent magnet is high, we can get high thrust with compact composition.
3. High position controllability can be realized using a linear encoder. That is why, a linear synchronous motor is used in a precision machine.

For these reasons, the authors have made a coreless type linear synchronous actuator using Nd-Fe-B magnets and Halbach array technique[2]. In this paper, the authors have described a control system of a linear synchronous actuator for an artificial muscle with arbitrary stiffness and damping factor like human.

2. Fundamental Algorithm of Thrust Control Type Mechanical Impedance Control System

Muscle of life generates power after it receives a signal from their brain. The brain sends a thrust reference signal to the muscle. In the same way, an input signal of the proposed control system is a thrust signal.

A block diagram of the proposed control system is shown in Fig. 1. Fundamentally, an actuator generates a thrust F_m depending on an input signal of thrust $F_{m0}{}^*$. When one assumes an AC motor, a vector control has been mainly used. Different to a rotary motor, the transfer function of a linear actuator is described as follows;

$$\frac{1}{F_m(s) - F_L(s)} X(s) = \frac{1}{Ms^2} \tag{1}$$

x : Position of the mover (m), F_m : Thrust of the actuator (N), F_L : Disturbance and load thrust (N)

To include flexibility, a virtual spring and damping factor have been proposed in Fig. 1. In this paper, virtual spring and damping factor have been simulated by a one-inertia spring-mass-damper system. Parameters of the virtual spring and damping factor can be changed by software. Consequently, a thrust that has flexibility can be generated from a linear synchronous actuator and can be changed easily by software.

In fact, a humanoid robot using a linear actuator must assume that it is used for two-inertia system. However, a one-inertia system has been assumed in this paper because a test machine moves a one inertia condition. The transfer function is described as follows;

$$s^2 MX(s) = -kX(s) - CsX(s) - F_L(s) \tag{2}$$

k : Spring factor (N/m), C: Damping factor (Nsec/m)

Also, the characteristic equation of second order system which has spring and damping factor is shown as follows;

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \tag{3}$$

ω_n : Natural angular frequency(rad/sec), ζ : Attenuation factor

Consequently, the transfer function $G(s)$ in Fig. 1 is calculated as follows;

$$\therefore G(s) = \frac{F_m(s)}{F_m^*(s)} = \frac{1}{1 + \dfrac{R + K_p K_t}{K_t K_i} s + \dfrac{L_q}{K_t K_i} s^2} \tag{4}$$

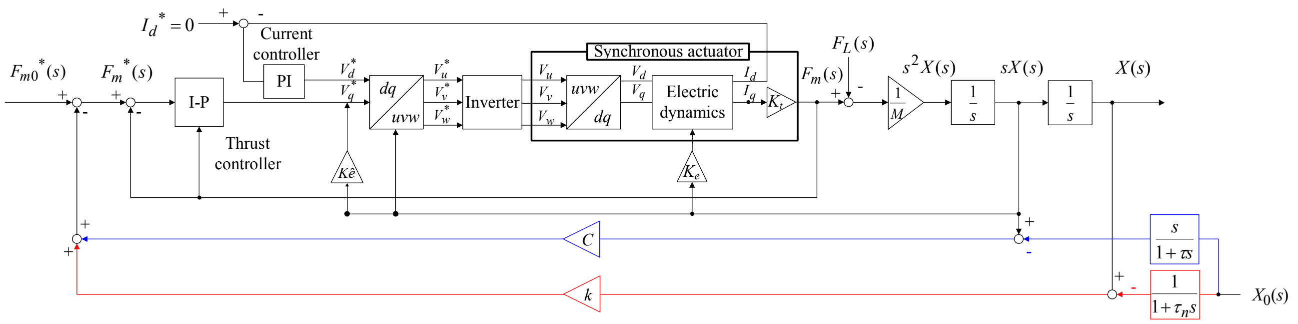


Figure 1: Block Diagram of Thrust Control Type Mechanical Impedance System.

And the pole location is calculated in the following simple form.

$$G(s) = \frac{1}{1+2T_2 s+2T_2^2 s^2} \cong \frac{1}{1+2T_2 s} \tag{5}$$

From Kessler method,

$$T_1 = \frac{R+K_pK_t}{K_tK_i}, T_2 = \frac{L_q}{R+K_pK_t}, \frac{T_1}{T_2} = 2.0 \tag{6}$$

Parameters of the intended model are shown in Table 1. The thrust controller is composed by the I-P controller to prevent an overshoot of the actuator[3][4].

The parameters of the thrust controller: K_p and K_i have been calculated from Table 1. Under the condition of K_p= 1.0, T_1 and T_2 are set to 3.2 msec and 1.6 msec respectively. Also, K_i is set to 325.8.

Table 1: Parameters of the Test Machine.

R	0.675 (Ω)
L_d	15.5 (mH)
L_q	18.65 (mH)
M	6.0 (kg)
K_e	18.0 (N/A)
K_t	18.0 (V/[m/sec])

The position function $X(s)$ have been calculated in Fig. 1 using these relations. $X_0(s)$ means position reference. The proposed system can be used not only the thrust reference but also the position reference. However, the position reference is not considered in this paper. Also, the position of the actuator $X(s)$ is using followed equation (7) and (8);

$$D_1(s) = \frac{1}{G(s)} \cong 1+2T_2 s, D_{2(s)} = 1+\tau s \tag{7}$$

$$\therefore X(s) = \frac{1}{k}\frac{1}{1+\frac{C}{k}s+\frac{M}{k}s^2D_1(s)}F_{m0}^*(s) + \frac{1}{D_2(s)}\frac{1+\frac{C}{k}s}{1+\frac{C}{k}s+\frac{M}{k}s^2D_1(s)}X_0(s) - \frac{1}{k}\frac{D_1(s)}{1+\frac{C}{k}s+\frac{M}{k}s^2D_1(s)}F_L(s) \tag{8}$$

It is found that the position of the actuator depends on thrust and position reference and disturbance and load thrust from equation (8). In addition, under the condition that $2\pi/\omega_n$ is sufficiently larger than $2T_1$ and τ, $D_1(s)$ and $D_2(s)$ can be set to 1.0. Consequently, the characteristic of the actuator can be adjusted by parameters ω_n and ζ.

Also, one must think of the two-inertia system as a robot actuator. However, the position function can be $X(s)$ calculated the input functions F_{m0}^*, X_0 and F_L same as one-inertia system. The proposed system can be extended easily.

3. Evaluation of the Proposed Control System with Stiffness and Damping Factor

3.1. Condition of Simulation and Experiment

Change of the mover position and thrust alternation of the actuator have calculated using MATLAB Simulink on the follow condition. The tunnel actuator is one of the linear synchronous motor. The primary side of the tunnel actuator consists of two or more magnetic poles with an armature winding. This actuator has various merits due to its unique structure, such as large thrust, small magnetic attraction and small detent force. The tunnel actuator which has the characteristics as Table 1 have used both simulation and experiment.

Actual control diagram for the experiment was different from in Fig. 1, and it was assumed that the motor thrust F_m is always almost same numerical value of input thrust F_{m0} because of the control program is operated by a computing process unit in the servo amplifier.

The change of the mover position and thrust alternation have been measured and been compared to the simulation results in the follow condition. The mover was pulled from the position of 100 mm to original point 0mm. This condition means that the actuator which has virtual spring and damping is pulled by the load F_{m0}^* and balanced out with the load thrust on the original position. And, if the load thrust becomes 0 N, the mover goes back to the stable point 100 mm. The Characteristics are changed by parameters ω_n and ζ. It has been simulated the condition of ω_n = 10.0 rad/sec and ζ = 0.1, 0.5, 0.7 and 0.9 in this paper. For instance, the spring factor k = 600.0 N/m and spring factor C = 12.0 Nsec/m when the condition of ω_n = 10.0 and ζ = 0.1 and k = 600.0 N/m and C = 108.0 Nsec/m when the condition of ω_n = 10.0 and ζ = 0.9.

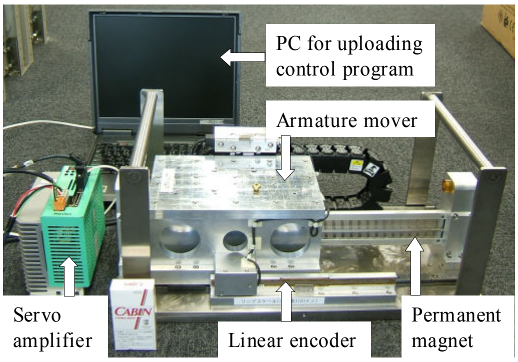


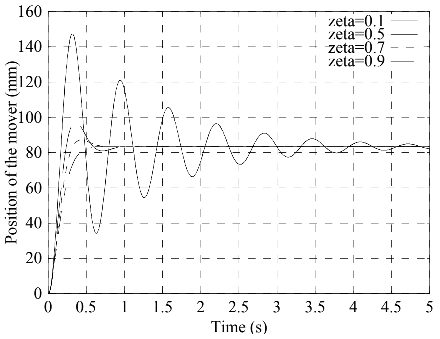
Figure 2: Overview of the Linear Synchronous Actuator Control System.

3.2. Effects of the Proposed Control System

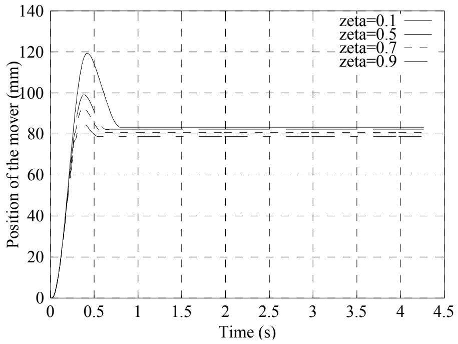
Simulation result of a change of mover position when ω_n = 10.0 is shown in Fig. 3 (a). For comparison, an experimental result of a change of mover position when also ω_n = 10.0 is shown in Fig. 3 (b).

Results of Fig. 3(a) and Fig. 3(b) were almost the same. The mover position was oscillatory in Fig. 3(a). An attenuation factor ζ being too small is the main reason. It was found that one must drive in conditions of high attenuation factor when a linear synchronous actuator is used for a humanoid robot. Otherwise, the actuator generates an overshoot and the humanoid robot cannot operate normally.

Also, the test machine has a considerable viscosity itself. It was found that the test machine has a big viscosity of about 100 Nsec/m. However, very soft damping for example about ζ = 0.1 almost is not needed for an actuator of a humanoid robot and this is not a big problem.



(a) Calculation by MATLAB Simulink



(b) Experiment on the test machine

Figure 3: Change of the Mover Position to Change Attenuation Factor ζ (Natural angular frequency ω_n = 10.0).

In addition, an overshoot was generated in Fig. 3(b) but not in Fig. 3(a). It can be thought that composition of the proposed control system by the servo amplifier and the controller on Simulink was different.

An I-P controller[3][4] as a thrust controller is considered to prevent the overshoot of an actuator in simulation. On the contrary, the controller of the test machine control has not been considered because of the control process has been operated by the servo amplifier. That is why, the leading edge of the thrust of the test machine is higher than the simulation.

Also, results was different in condition of C = 0.9. The reason is thought that friction, viscosity of the actual machine and low speed control process of the servo amplifier.

In fact, the authors have to consider about the control to prevent the overshoot. The compensation controller has been considered based on the disturbance observer therefore.

4. Compensation of the Disturbance and the Another Driving Method

4.1. Compensation of the Disturbance in the Actual Machine

Compensation controller to restrain the disturbance of the actuator for example the friction and the viscosity is composed of the observer and the arbitrary transfer function in Fig. 4. The transfer function $\hat{G}(s)$ is described as follows;

$$\hat{G}(s) = \frac{\omega_n^2}{1 + 2\zeta\omega_n s + \omega_n^2} \tag{9}$$

In condition of $\hat{G}(s) = 1$, the compensation controller means a same effect to the conventional disturbance observer. An input signal is assumed not thrust reference $F_{m0}{}^*$ but disturbance reference F_L in this case. If the input reference is the $F_{m0}{}^*$, the actuator operates the same motion in chapter 3.

The authors have calculated and evaluated the effect of the compensation controller using MATLAB Simulink. The disturbance reference F_L is applied to the actuator in state that the mover is in resting state on original point. Force of the disturbance is 30 N and it is applied for 4 seconds from 3 sec to 7 sec.

Change of the mover position and thrust alternation have been calculated.

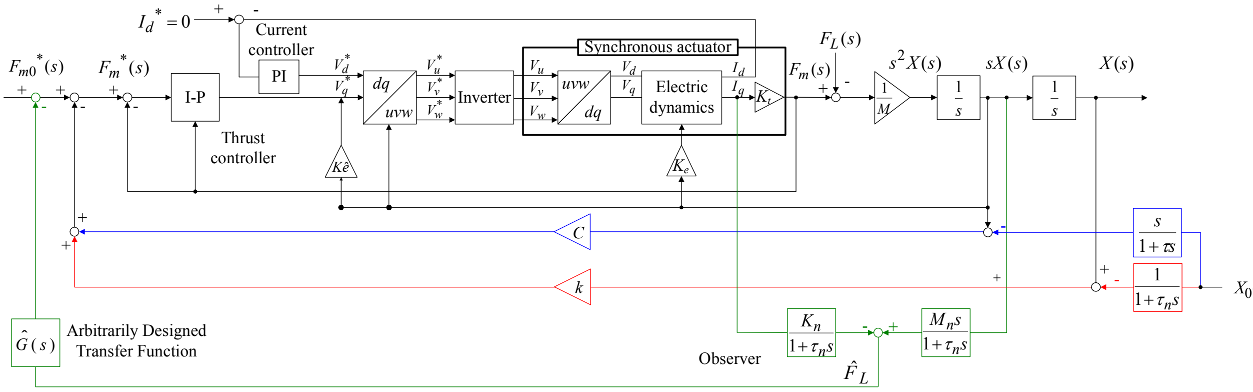


Figure 4: Compensation of the Disturbance and the Another Driving Method.

4.2. Effects of the Compensation Controller

Simulation result of a change of mover position is shown in Fig. 5. It was confirmed that the mover was affected from the disturbance moved and but the actuator pushed back to the disturbance quickly. And the actuator returned an initial condition quickly too when the disturbance became nothing. However, the conventional state of G(s) = 1 cannot implement the arbitrary flexibility of muscle. Because, the conventional disturbance observer is used for restraint the disturbance including an intentional load thrust from outside and the system does not have a conception of flexibility. That is why, the proposed compensation system is suitable for the muscle actuator.

However, one cannot discriminate whether the friction and viscosity of the actuator itself or an intentional load thrust to the actuator from the proposed system. Therefore, though the other originality is needed, it can be considered to add the other term for extraction of the friction and viscosity.

It is needed to measure the characteristics of the actuator when the actuator moves normally *i.e.*, without the load thrust. Then, the position information of the actuator can be gotten from an optical position sensor and acceleration information be gotten from the observer. Model identifications can be calculated by using these information.

The conception is shown in Fig. 6. The friction and viscosity of the actuator can be measured in state that only the thrust signal F_{m0}^{*} is applied to the actuator. If the actuator has nonlinearity when the actuator moves, using a neural network method and so on will be able to thought for the identifications.

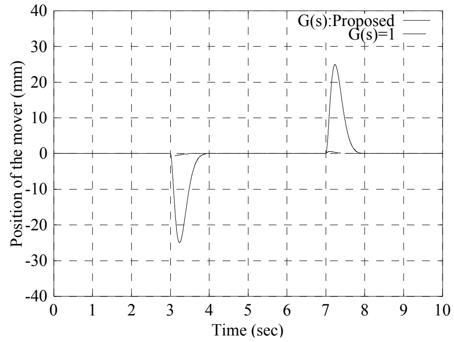


Figure 5: Change of the mover position including the compensation controller

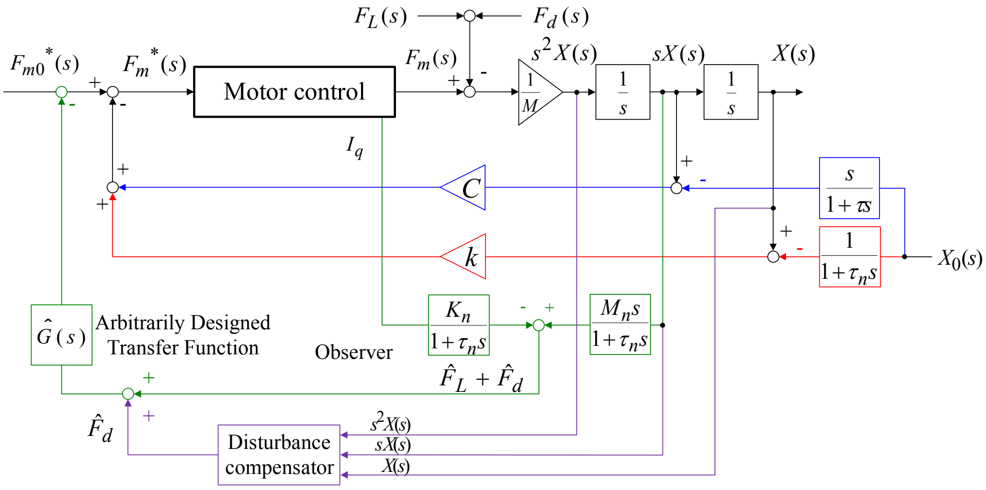


Figure 6: Conception of the friction and viscosity of the actuator.

5. Conclusion

The authors have proposed a linear synchronous actuator for an artificial bi-articular muscle of humanoid robot and designed a control system with arbitrary stiffness and damping factor for the actuator. The proposed control system has implemented that Parameters of arbitrary stiffness and damping factor can be changed easily using software.

The test machine could move flexibly by the proposed system. And it was found that a linear synchronous actuator has a viscosity about 100 Nsec/m and friction or viscosity itself so that result of simulation and experiment was different just that much. The authors have considered the compensation controller and calculated the effect.

As future work, the authors are going to implement the compensation control system. It will need to use a PC processing system to control quick and to implement the compensation controller.

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