Study on Control Performance with Consideration of the Articulated Manipulators with Pneumatic Cylinders
-Simple Adaptive Control System and its Application to Nonlinear Frictions-

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ABSTRACT
The biggest problem of using a pneumatic system in an actuator is the difficulty of handling caused by the compressibility of air. This is especially true when taking measures for stick-slip phenomenon that occurs when driving cylinders at low speeds. This paper identifies nonlinear friction which is the main cause of stick-slip phenomenon using the LuGre friction model and examines its effect using a simulation model. This paper also examines and reports the improvement of position control using Simple Adaptive Control System.

KEY WORDS
Stick-slip Friction, LuGre friction model, Parallel Feedforward Compensator, Simple Adaptive Control System, Robust control

INTRODUCTION
Our group is involved in the development of various devices using pneumatic cylinders which is a common pneumatic actuator\(^1\),\(^2\),\(^3\). The development of hand-type articulated manipulators with high conformational flexibility that do not cause injury to people or damage to objects is one example. In the previous paper [3], we formulated the relationship between the trajectories of manipulator fingertips and the angle of each joint for both forward kinetics and inverse kinetics based on robotics, created a nominal model for designing control systems by conducting frequency response experiments for the pneumatic cylinder mounted on each joint of the manipulator, and controlled the fingertip trajectories by designing a PID controller. A controller was designed for each model to verify the possibility of controlling the fingertip positions of the manipulator; however, the problem encountered here was the deterioration of the tracking performance caused by the stick-slip phenomenon occurring when driving the cylinder at low speeds.

Although various measures have been proposed regarding the stick-slip phenomenon \(^4\),\(^5\),\(^6\),\(^7\),\(^8\), this research identifies nonlinear friction which is the main cause of stick-slip phenomenon using the LuGre friction model to improve the reliability of control system design by using the model in simulations. Furthermore, this paper reports the results of improving the performance of position control using simple adaptive control.
OVERVIEW OF ARTICULATED MANIPULATORS TO BE DEVELOPED

The articulated manipulator that we designed and manufactured is shown in Figure 1. Each articulated manipulator is composed of a first joint that will be attached to the base, a second joint that will be in the middle, and a third joint that will be the fingertip, and three of these articulated manipulators are combined to enable objects to be gripped.

Small cylinders made by KOGANEI Corporation are embedded in each joint of the manipulator (see Table 1.), and directly convert translational motion to rotational motion using a crank slider mechanism that enables accurate directly driven motion conversion.

Table 1 Specifications of pneumatic cylinders

<table>
<thead>
<tr>
<th></th>
<th>Joint1</th>
<th>Joint2</th>
<th>Joint3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore [mm]</td>
<td>15</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Rod diameter [mm]</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Stroke [mm]</td>
<td>20</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Max. pressure [MPa]</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 2 presents a simplified overview of the experimental device. It is comprised of a controller, manipulator, and power source components, using a controller that is designed on a MATLAB/Simulink and mounted using xPC-Target. The sampling time is set at 2 [ms], it feeds back the angle and force of each joint, and decides how much manipulation is required using the designed controller.

This amount of manipulation will be used as the control voltage for the electro-pneumatic regulator connected to the pneumatic cylinder heads/rods that are embedded in the manipulator. A tank that reduces the pressure to 1.0[MPa] is connected to the electro-pneumatic regulator, and enables the pressure to be directly controlled at the cylinder head and rod by the control voltage.

FRICITION MODEL

Figures 3 and 4 show the result of controlling joint 1 of the manipulator conducted in the previous paper [3]. Figure 1 shows the trajectory of the manipulator fingertip used in the experiment and Figure 4 shows the control result of joint 1. PID was used for the controller. As you can see in the diagram, the target angle is reached at 15[s]; however, stick-slip phenomenon occurs around 5[s] where the cylinder is being driven at low speeds while the fingertip of the manipulator is in motion, causing a major angle error.
The LuGre friction model [9],[10],[11],[12] is used to identify nonlinear friction as the main cause of stick-slip phenomenon.

\[
F_s(v) = \beta \left( F_C + (F_s - F_C) \times e^{\frac{|v|}{v_s}} \right) \text{sgn}(v) + D \cdot v
\]  

(1)

Here, \( F_C \) is Coulomb friction, \( F_s \) is stiction force and \( D \cdot v \) is viscous friction. When using this friction model, you can see that nonlinear properties can be taken into account near the low-speeds as shown in Figure 5. Furthermore, \( v_s \), \( \alpha \) and \( \beta \) are adjustment parameters.

Figure 5 LuGre friction model

Each coefficient of the friction model was fitted using the least-squares method.

Table 2 shows the result of identification.

<table>
<thead>
<tr>
<th>( F_s )</th>
<th>( F_C )</th>
<th>( v_s )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4159</td>
<td>0.0088473</td>
<td>0.029821</td>
<td>0.55682</td>
<td>0.50011</td>
</tr>
</tbody>
</table>

Figure 6 shows the friction characteristics at this time.

Figure 7 shows the measurement result and the simulation result when incorporating the friction model. Using the LuGre friction model, we were able to confirm that stick-slip phenomenon can be reproduced even in simulations. If we can suppress the stick-slip phenomenon by designing and evaluating controllers using this model as target of control, we predict that the same performance can be achieved when implementing a controller designed for the experimental unit.
SIMPLE ADAPTIVE CONTROL SYSTEM

Simple Adaptive Control (hereafter abbreviated as SAC) [13],[14],[15],[16],[17],[18] was first proposed by Sobel, Kaufman and Mabius in 1982, and later examined by Bar-Kana and others. In Japan, continuous research and expansion of SAC were carried out by Iwai and others. The advantage of SAC is that when structuring an adaptive control system or adaptive controller, the number of identifying parameters are generally fewer in number compared to the adaptive control methods proposed in the past, allowing the adaptive controller to be simple. Furthermore, conventional control methods other than adaptive control generally require plant information, especially accurate plant parameter information. In the case of SAC, however, such information is not needed and carries an extremely high advantage from the practical aspect.

As shown in Figure 8, the basic structure of SAC is an adaptive control system with two-degree-of-freedom control that guarantees output feedback with the stability of the control system and matches output with the reference model using feed forward.

![Figure 8 Block diagram of the SAC system](https://via.placeholder.com/150)

Adaptive gain \( k_x(t) \), \( k_u(t) \) and \( k_y(t) \) are adjusted so that output \( y \) of control target \( G(s) \) complies with output \( y_m(t) \) from reference model \( G_m(s) \) showing the ideal response according to output error \( e_y(t) \), quantity of state of reference model \( x_m(t) \) and input \( u_m(t) \). Here, \( u(t) \) are given in equation (2) and regression vector \( z(t) \) and adaptive gain \( k(t) \) are given in equation (3). Furthermore, equation (4) is also referred to as adaptive adjusting law.

\[
u(t) = k(t)^T z(t)
\]  
\[
z(t) = [e_y(t), x_m(t), u_m(t)]^T
\]
\[
k(t) = [k_x(t), k_y(t), k_u(t)]
\]
\[
e_y(t) = y(t) - y_m(t)
\]
\[
\Gamma_1 = \Gamma_1^* > 0
\]
\[
\Gamma_p = \Gamma_p^* > 0
\]
\[
\sigma(t) = \frac{\sigma e_y^2(t)}{1 + e_y^2(t)} + \sigma_1, \quad (\sigma, \sigma_1 > 0)
\]

Since the third equation of equation (4) contains a square expression of the error on the right, there is a risk of dispersion due to disturbance. Hence, correction expression \( \sigma(t) \) is used. Hence:

\[
P_{out}(s) = \frac{366554}{(s + 1.21)(s + 13.47)}
\]

SAC requires a reference model that indicates the target response of the plant. Although it is sufficient if the degree of the reference model is equal to or less than the control target, a Second Order Lag System such as shown in equation (9) was used to incorporate angle and angle speed provided by the reference model into adaptive gain \( k_x(t) \).

\[
G_m(s) = \frac{\omega_m^2}{s^2 + 2\zeta_m\omega_m s + \omega_m^2}
\]

Furthermore, parameter \( \zeta_m, \omega_m \) was set as shown in Table 3 to minimize overshooting and reduce set time.
Table 3 Reference model parameters

<table>
<thead>
<tr>
<th>$\zeta_m$</th>
<th>$\omega_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2 \times \pi \times 100$</td>
</tr>
</tbody>
</table>

Since the relative degree of the control target used in this research is 3 as the result of equation (8), not meeting the previously described ASPR condition, SAC cannot be applied as is. Hence PFC was used to add ASPR characteristics to the expansion system added with PFC so that SAC can be applied. Although various design methods of PFC have been proposed, equation (10) was adopted according to document \(^{[14,17]}\) since the relative degree of the control target is 3.

$$F(s) = \frac{k_1}{(1+T_1 s)(1+T_2 s)} + \frac{k_2}{1+T_1 s}$$ \hspace{1cm} (10)

In order to reduce the number of adjusting parameters, $k_1$, $k_2$, $T_1$ and $T_2$ of equation (1) were expressed as follows with $k_{p,pfc}$ and $T_p$ as adjustment parameters.

$$k_1 = 0.01 \times k_{p,pfc}, \quad k_2 = 0.001 \times k_{p,pfc}, \quad T_1 = T_2 = T_p$$ \hspace{1cm} (11)

**SIMULATION**

This section shows the simulation result of joint 1 when controlling each joint of Figure 4 using angle instructions for the trajectory of the manipulator fingertip of Figure 3. For the control target, nominal model of equation (8) and nonlinear friction model of equation (1) were used. The adjusting parameters of PFC were decided as shown in Table 4 through trial-and-error.

Table 4 PFC parameters

<table>
<thead>
<tr>
<th>$k_{p,pfc}$</th>
<th>$T_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Now, expansion control system $G_d(s) = G(s) + F(s)$ is expressed as shown in equation (12).

$$G_d(s) = \frac{2.37 \times 10^{-5} s^4 + 6.35 \times 10^{-5} s^3 + 4.43 \times 10^{-6} s^2 + 1.46 \times 10^{-7} s + 0.23 s + 1.41}{4.74 \times 10^{-5} s^2 + 4.17 \times 10^{-7} s + 1.47 \times 10^{-3} s^2 + 2.60 \times 10^{-2} s + 0.23 s + 0.94 s + 0.83}$$ \hspace{1cm} (12)

Notice that the relative degree is 1 and the leading coefficient is $2.37 \times 10^{-5} / (4.74 \times 10^{-7}) > 0$. Figure 9 is the result of plotting the pole and zero positions of equation (12). (Pole: × and zero: ○) As shown in Figure 7, you can see that the zero points are on the left half, indicating that expansion control system $G_d(s)$ meets the ASPR condition and that SAC can be applied. On the other hand, each control parameter of SAC was selected as shown in Table 5. $I_{2\times2}$ indicates the identity matrix of size 2. The result of the simulation is shown in Figure 10. For PID, you can see a major position deviation near 5[s] where there is overall vibration due to stick-slip phenomenon and the cylinder is being driven at low speeds. In the case of SAC, stick-slip phenomenon is suppressed, achieving the target angle smoothly.

Table 5 SAC parameters

| & $\Gamma_{pu}$ & $\Gamma_{iu}$ & $\Gamma_{px}$ & $\Gamma_{ix}$ |
|----------------|---------|---------|---------|---------|
| $\Gamma_{pe}$  | 5000    | 50000   | $5000I_{2\times2}$ | $50000I_{2\times2}$ |
| $\Gamma_{ie}$  | $\sigma_1$ | $\sigma_2$ | 0.1      | 0.001   |

Figure 9 Pole-zero plot of extended control system

Figure 10 Simulation result: joint 1 angle
EXPERIMENT

Figure 11 shows the results of experiments when applying PID and SAC. The target angle is changed smoothly using the cubic function. Figure 12 shows the angle error of PID and SAC. For PID, the angle error of 1st joint increases from 5[s], with the largest error of 10[deg]. When looking at the angle rate instruction of Figure 13, it can be seen that the influence of nonlinear friction increases since the angle rate is almost 0[deg/s] at 5[s], not being able to carry out due to the stick-slip phenomenon. SAC, on the other hand, the stick-slip phenomenon is suppressed and that the operation is smooth with target angle within angle error of ±2[deg].

Figure 14 shows the performance of disturbance control. We applied angle disturbance about 20[deg] to 1st Joint from a steady state. SAC removes disturbance in the speed of 5 times in comparison with PID.
CONCLUSION

In this paper, we reproduced the stick-slip phenomenon on a simulation by taking into account nonlinear friction and incorporating the LuGre friction model in the model of the pneumatic servo system of the manipulator joints. Furthermore, we confirmed through experiments that simple adaptive control was superior to PID by applying it to a pneumatic servo system. We were also able to confirm that suppression of stick-slip phenomenon was especially effective compared to PID.

In the future, we would like to examine not only the control and positions but to also take in the control of fingertip strength as a comprehensive system of the manipulator rather than just the joints.

REFERENCES