Trajectory Follow-up Control by Enclosing Control with Rotary Pneumatic 2-Link Manipulator *

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Abstract—The passive dynamic control (PDC) is a mechanical system control method based on an inherently safe design means using a brake mechanism effectively. Since control only with an actuator does not have a stopping mechanism, this kind of control cannot prevent deviation from the target trajectory in case of trouble. On the other hand, the PDC follow-up control can prevent deviation from the target trajectory by operating the brake mechanism. Since the PDC follow-up control can be envisaged as gradually narrowing down the wide area around a control object to enclose it toward the target trajectory, the authors designate this control as “enclosing control.”

This paper describes the application of the enclosing control to a rotary pneumatic manipulator. First, in a sine track trajectory follow-up control experiment using only one link, the effectiveness of the PDC is demonstrated in comparison with the PI control. Next, in a circular trajectory follow-up control experiment using a 2-link manipulator, the effect of the enclosing control is verified.

I. INTRODUCTION

The pneumatic system that can make soft motions to achieve affinity with humans may be easy to secure the safety. This system is expected to be applied to human-contacting machines, such as care equipment and service robots. However, the system is low in rigidity and slow in response due to air compressibility, and has nonlinear elements, such as sliding friction and plant characteristic fluctuation caused by air-temperature variation. For this reason, the pneumatic system may be difficult to obtain an accurate mathematical model and also difficult to achieve high-accuracy control, in principle. To solve these problems, various control theories have been applied to the pneumatic system [1], [2]. For example, control methods have been reported effective when they are applied with new control theories, such as control method to enhance robustness by using a disturbance observer [3] and a control method to use a neural network [4]. However, it may be limited to improve the rigidity only with the servo control.

In view of the above, the authors [5] have proposed a new safe control method named “passive dynamic control (PDC)” to secure the safety from the machine side under conditions that allow humans and machines to coexist with each other based on an inherently safe design [6]. Unlike conventional control methods that operate actuators actively, the PDC is designed to secure high safety by positively using and operating passive elements having variable characteristics, such as braking mechanism. The authors have developed a functionalized constant load balancer equipped with a Magneto-Rheological (MR) brake to apply the PDC, and proposed an inherently safe home elevator system [7]. The authors have also applied the PDC to pneumatic cylinders of linear motion type [8][9] and rotary motion type [10], and achieved not only higher safety but also high-response positioning and high-rigidity positional holding.

By the way, it is difficult for the trajectory follow-up control driven only by an actuator to prevent deviation from the target trajectory in case of trouble because of no stopping mechanism. A method using a brake mechanism for the pneumatic system has been reported [11][12]. However, this method aims to improve control performance (mainly for vibration suppression), and does not consider the countermeasures in case of trouble. An alternative method of follow-up control for the manipulator without using an actuator for safety was proposed by controlling the passive elements, where hand force was used as the power source[13]. The PDC can prevent deviation from the target trajectory and return the output to the target trajectory by operating the brake. Since this control method can be envisaged as gradually narrowing down the wide area around a control object to enclose it toward the target trajectory, the authors designate this control as “enclosing control” [14]. Then, the authors showed its effectiveness in a circular follow-up control experiment in the horizontal plane using 2 pneumatic cylinders.

In this paper, the authors apply the enclosing control to a rotary pneumatic actuator and perform the follow-up control to verify the effectiveness of the enclosing control. Section 2 outlines the PDC and the enclosing control. Section 3 describes the structure of a 2-link manipulator with 2 PDC rotary pneumatic actuators mounted with electromagnetic friction brakes and force sensors. Section 4 compares the PDC with the PI control in a sine track trajectory follow-up control experiment using only one link. Section 5 shows the effectiveness of the enclosing control in a circular trajectory follow-up control experiment using the 2-link manipulator.

II. PASSIVE DYNAMIC CONTROL AND ENCLOSING CONTROL

A. Conditions of Inherent Safety

The inherently safe design for the safety of machines under ISO 12100 [5] is intended to guarantee in the designing stage that no physical conditions, such as force and momentum (kinetic energy), will not cause any hazard to
humans (inherent safety), such as catching and bumping by machines. In short, defining the endurance limits of humans, this is intended to obtain assurance that machines will not produce an output exceeding the endurance limits of humans. However, if this is applied to human-friendly robots, only small robots like toys can be put into practical use. In addition, the inherently safe design by downsizing the machine is not preferable since it will reduce the capacity of the machine substantially. In general, the output of the machine is large, and the magnitude of the output is one of the important capacities of the machine. If all but small-sized machines are forbidden to be operated directly with humans for fear of possible erroneous output of power to humans, it may be the same as imposing hazardous work on humans. Rather, the large energy of the machine should be utilized to fulfill such conditions of the machine that can secure safety operation by humans (conditions of inherent safety).

B. Passive Dynamic Control (PDC)

The inherently safe design does not necessarily mean the downsizing of machines, but indicates how to operate them under such conditions that they do not cause any harm to humans at least. The authors [6] have proposed a new control method of producing the inherently safe design through control in a positive manner. Since this control method uses passive elements having variable characteristics, the authors designated this control method as “passive dynamic control (PDC).” In the PDC, machine operation is performed after confirming the safety condition that machine output is not exerted to humans beyond the endurance limits of humans.

Generally, in the mechanical positioning, 2 operation modes are required; the one is balancing operation for achieving the balance of force by eliminating force on the controlled object, such as external force and disturbance, and the other is moving operation for moving the controlled object toward the target position. In most conventional control methods, these 2 operation modes are executed simultaneously by operating an actuator. In contrast, the PDC on “the principle of safety confirmation” aims to achieve the intended purpose, i.e., the moving operation, by executing the balancing operation and the moving operation separately under conditions of inherent safety. In other words, since the balancing operation aims to generate the inherent safety conditions and does not satisfy the force conditions, this operation should be performed under conditions that controlled object does not move (safety confirmation). On the other hand, since the moving operation has possibility for the controlled object to contact humans while moving, this operation should be performed after it is confirmed that the balancing operation under conditions that the moving force has satisfied the inherently safe condition after the balancing operation. Therefore, the control process is divided into several security confirmable steps: generating the condition of the inherent safety (preparation), confirming whether the condition has been achieved, permitting the execution, and executing. That is, the performance of the moving operation is not permitted until it is confirmed that the moving operation force has satisfied the condition of inherent safety. To realize the permission/ non-permission of the performance, a braking mechanism is indispensable.

Main differences between the PDC and the various conventional control methods, such as the PID control, the LQ control and the sliding mode control (conventional methods), can be summarized as follows:

- In the conventional methods, the control system (controller) is designed based on the mathematical model of the controlled object. However, in the PDC, the mathematical model of the controlled object is not needed.

- The conventional methods execute control by operating the actuator actively. In some cases, they use passive elements, such as spring and damper, as an aid. In the actuator control of the PDC, during the movement of the controlled object, while the magnitude of the output is fixed, the output direction is controlled, in principle. The position control and the speed control are realized by operating the brake, a passive element.

- The conventional methods aim to improve the control performance, and the safety of the system is considered separately from the control method, such as interlock or failsafe. The PDC aims to secure the safety of the system as the primary objective. The control is performed by releasing the brake after confirming the normality, and it can be stopped immediately in case of trouble.

C. Enclosing Control

In general, the safety conditions of the area are applied to the safety of moving. For example, if the safety area is defined, it is not allowed to deviate from it. In the follow-up control by the PDC, the neighborhood of the trajectory is defined as a safety area, and the controlled object is controlled not to deviate from the safety area by the brake operation. To be specific, if the controlled object is about to deviate from the target trajectory, it is blocked by the brake operation to deviate from the target trajectory over the set area. This constitutes a system similar to the interlock, but since the interlock means the termination of control, the objective of the follow-up can no longer be achieved anymore. To solve this problem, a restricted area is set immediately before the interlock working area (interlock area), and if the controlled object tries to enter the restricted area, it is held by the brake operation. After blocking the controlled object, the moving force on it is detected, and if the moving force is working in the direction of the target trajectory (outside the restricted area), the release of the hold is allowed and the operation is resumed (Fig. 1). In this way, without interrupting the control operation, the follow-up control can be continued. Since this control method is envisaged that the controlled object is

![Fig. 1 Image of enclosing control](image-url)
enclosed toward the target trajectory by narrowing down the wide safety area around the target trajectory, the authors designated the follow-up control by the PDC as “enclosing control” [14]. Then, in a circular trajectory follow-up control experiment using 2 pneumatic cylinders set horizontally, the authors demonstrated the effectiveness of the enclosing control, and proclaimed its possibility.

III. PDC ROTARY PNEUMATIC ACTUATOR

A rotary pneumatic actuator starts the rotary motion at an angle within a limited range when air is supplied. This actuator is divided into 2 types; vane type and piston type. The former causes a rotary motion directly, and the latter converts the reciprocating motion of the piston to a rotary motion. The actuator is featured by simple structure, large power density, and easily obtainable low-speed rotation.

The authors have developed a PDC rotary pneumatic actuator equipped with an electromagnetic friction brake (brake) as a hold device and a strain gauge for detecting the torque on the brake. Although servo valves (proportional valves) are used for high-performance control in general, the authors used ON/OFF valves (3-position 5-way valves) in this experiment to measure the effectiveness of the control by means of the brake without operating the supply air pressure.

The basic positioning control sequence of the one-link arm by using the PDC is as follows:

1. Hold: Applying the brake to fix the arm position.
2. Balancing: Adjusting the air pressure to reduce the torque on the brake and achieve the balance of force.
3. Generation of the moving force: Generating the moving force in the target angular direction by adjusting the air pressure when the target angle is given.
4. Confirmation and permission: Confirming the moving force detected by the torque sensor, and permitting the execution.
5. Execution: Releasing the brake to move the arm in the target direction.
6. Stopping: Stopping the arm by applying the brake when it reaches the target position, and upon stopping, achieving the balance of force by performing the balancing.

For follow-up control, balancing operation is not required.

In this study, the authors have developed a 2-link manipulator with PDC rotary pneumatic actuators stacked vertically one above the other (Fig. 2). The arm 1 is driven by the lower actuator, and the arm 2 is driven by the upper actuator via the pulley and the connected belt. Although the arm 2 is connected to the arm 1 by the shaft, it has so structured that the arm 2 is not affected by the driving of the arm 1.

IV. SINE TRACK FOLLOW-UP CONTROL BY ONE LINK

First, by the sine track follow-up control using only one link in the experimental setup of Fig. 2, the PDC is compared with the PI control, one of the model-based controls. As the target trajectory \( \theta_p(t) \), the following sine curve is applied:

\[
\theta_p(t) = \theta_0 \sin 2\pi f t \quad (1)
\]

where, \( \theta_0 \) is the amplitude and \( f \) is the frequency.

A. Control Sequence of PDC

When the changing direction of the target angle is set as positive, the control of the pneumatic pressure always generates torque in the positive direction. When the current angle \( \theta(t) \) is positioned before the target angle \( \theta_p(t) \) (\( \theta(t) < \theta_p(t) \)) and the torque is detected in the direction of the target angle (positive direction), the brake is released and the arm is moved in the target-angle direction. When the current angle exceeds the target angle (\( \theta(t) > \theta_p(t) \)), the arm is stopped by the brake. At this time, the target angle is changing in the current angle direction, i.e., in the safe direction, the arm is at a stop waiting until the target angle exceeds the current angle without generating any torque in the opposite direction. Therefore, the brake control method based on \( \theta(t) \) and \( \theta_p(t) \) is as shown in Table 1.

However, this simple control may cause large overshoot, making it difficult to achieve the follow-up control. To counter this problem, inching operation (pulse control) repeating ON/OFF of the brake while moving can be applied, so that the moving speed of the arm is slowed and the overshoot is decreased. In the pulse width, the OFF time is fixed at 3 ms, and the ON time is adjusted to a value in a range from 5 ms to 9 ms depending on the error.

B. PI Control

In the PI control, the mathematical model of the controlled object is indispensable. As a result of the step response experiment, the model was approximated to the secondary delay system of the following equation (2):

\[
P(s) = \frac{5}{s^2 + 2s + 6 + 1.5s + 2} \quad (2)
\]

<table>
<thead>
<tr>
<th>( s )</th>
<th>Brake</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>ON</td>
</tr>
<tr>
<td>1</td>
<td>OFF</td>
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Here, the proportional gain was set to 5 and the integral gain was set to 1 from the results of the simulations using MATLAB/ SIMULINK.

**C. Experiment**

Using only the arm 1 located in the lower part of the experimental setup, sine track follow-up control was performed. The rotary pneumatic actuator used here had a rotary range of 270°. When the working air pressure was 1.5 MPa, the actuator generated a torque of 0.5 Nm. As result of measurement, the static friction of the rotary part of the actuator was approx. 0.15 Nm, the holding power of the electromagnetic friction brake was approx. 2 Nm, and the response delay of the brake was approx. 14 ms. The angle was detected by a rotary potentiometer. The supply air pressure was adjusted within 0.1 – 0.3 MPa according to the desired frequency in the PDC considering the safety, and to a general 0.5 MPa in the PI control. Here, the proportional valve is used in the PI control.

The results of the experiment at $\theta_0 = 90^\circ$ and $f = 0.2 \text{ Hz}$ are shown in Fig. 3. Since the experimental setup had a large static friction of 0.15 Nm in the rotary part, a stick slip was likely to easily occur. For this large static friction, a heavy vibration occurred in the PI control, resulting in the maximum error of approx. 40.7°. In contrast, in the PDC, the stick slip was unlikely to affect the output by the brake operation, and the maximum error was controlled to 3.3°. The maximum error and the average error at each frequency are shown in Fig. 4. It was confirmed in this experiment that the PDC was able to achieve the follow-up control with a small error even in systems with a large static friction.

**V. CIRCULAR TRAJECTORY FOLLOW-UP CONTROL WITH TWO-LINK MANIPULATOR**

In this section, the circular trajectory follow-up control by using the 2-link manipulator is described. A safety area and a restricted area are set in the vicinity of the target trajectory, and the enclosing control is applied to them.
A. Sequence of Enclosing Control

How to achieve the circular trajectory follow-up control in a counterclockwise direction by using the PDC is as follows:

The rotation center of the arm 1 is set at O(0, 0) in absolute coordinates. The purpose is to make the tip of the arm 2 follow the path of a circular with the radius r and the center at the point R(Xr, Yr). The lengths of the arm 1 and arm 2 are assumed to be L1 and L2, respectively, and the coordinates of the tip of the arm 1 (i.e., the rotation center of the arm 2) are assumed to be G(Xg, Yg). As a result of calculation, it was confirmed that, regardless of the center coordinates and radius of the target circle, both the rotating angles \( \theta_1 \) and \( \theta_2 \) had the maximum value and the minimum value, respectively, while the trajectory was making a circuit. Therefore, 4 switching points A, B, C and D are set based on the increase/decrease of \( \theta_1 \) and \( \theta_2 \), and the space is divided into 8 segments inside and outside the circle and each point (4 segments each). The coordinates of the switching points A, B, C and D are given by the following equations.

\[
\begin{align*}
A & : \left( \frac{L1}{2}, 0 \right) + r \cos \left( \theta_1 \right), r \sin \left( \theta_1 \right) \\
B & : \left( \frac{L1}{2}, 0 \right) + r \cos \left( \theta_2 \right), r \sin \left( \theta_2 \right) \\
C & : \left( \frac{L1}{2}, 0 \right) - r \cos \left( \theta_2 \right), r \sin \left( \theta_2 \right) \\
D & : \left( \frac{L1}{2}, 0 \right) - r \cos \left( \theta_1 \right), r \sin \left( \theta_1 \right)
\end{align*}
\]

Here, \( m \) and \( p \) are given by the following equations.

\[
\begin{align*}
m_A &= \frac{r \left( X_{g} - \frac{L1}{2} \right)}{2 \left( X_{g} - \frac{L1}{2} \right) + L2} \\
mp &= \frac{r \left( X_{g} - \frac{L1}{2} - L2 \right)}{2 \left( X_{g} - \frac{L1}{2} \right) - L2} \\
mc &= \frac{r \left( X_{g} - \frac{L1}{2} + L2 \right)}{2 \left( X_{g} - \frac{L1}{2} \right) - L2} \\
mp &= \frac{r \left( X_{g} - \frac{L1}{2} + L2 \right)}{2 \left( X_{g} - \frac{L1}{2} \right) + L2}
\end{align*}
\]

Here, the theoretical formulas for determining the switching points A, B, C and D are omitted. These switching points are the points for switching the 5-way solenoid valves.

The direction of movement is controlled by the brake depending on which segment the tip of the arm is in. That is, the direction of movement (CW or CCW) of each arm is switched as shown in Table 2 for each segment. The arm angle was set to be increase (CCW) viewed from the absolute coordinates when the valve was turned ON. Therefore, the command to the valve in each segment is as shown in Table 3. The present position is allocated to one of the 8 segments shown in Fig. 5, and the moving force is generated by controlling air pressure in the direction shown in each segment. By releasing the hold of the moving arm, the follow-up control is achieved. However, by performing the inching (pulse control) with the repetitive ON/OFF of the brake while moving, the moving speed of the arm is slowed and the overshoot is decreased.

B. Experimental Conditions

The circular trajectory follow-up control was conducted by using the 2-link manipulator experimental setup shown in Fig. 2. In this experiment, the width of the safety area was set to 0 mm in order to verify the control performance. Any interlock area was not set, but all areas were set to be restricted areas. The lengths of the arms were set to \( L_1 = 200 \) mm and \( L_2 = 200 \) mm, respectively. The central coordinates of the target circle were set to (200, 200), circles with radius \( r = 50 \) mm and 80 mm were drawn counterclockwise. A pulse whose width was 5 ms for each ON and OFF was applied to the brake of the arm. The control performance was improved by slowing the speed.

C. Result of Experiment

The results of the experiment at \( r = 50 \) mm and \( r = 80 \) mm are shown in Figs. 6 and 7, respectively. At \( r = 50 \) mm, the maximum error was 3.99 mm, the average error was 0.804 mm, and the maximum error was 0.848 mm, and the time required for drawing one circle was approx. 5 sec. At \( r = 80 \) mm, the maximum error was 4.81 mm, and the time required for drawing one circle was approx. 15 sec.

To the best of the authors’ knowledge, there have been no reports of experiments using similar manipulator. Also, from the results of Section 4, it seems difficult to achieve the circular trajectory follow-up control on this experimental setup by using the PI control.

VI. CONCLUSION

For machines that inevitably contact humans, such as human-friendly robots, high-level safety is required. The authors have proposed the control methods of the PDC and enclosing control to enable moving operation under...
inherently safe force conditions, and follow-up control and positioning under conditions that do not allow deviation from the safe area. The authors have developed the 2-link manipulator with the electromagnetic brake incorporated in the rotary pneumatic actuator to apply the PDC. And, with the sine track follow-up control experiment using the one link and the circular trajectory follow-up control using the 2-link manipulator, the effectiveness of the proposed method have been verified. As a result, without using proportional valves, good experimental results have been obtained.

The enclosing control lays an emphasis on safety. Its design philosophy is different from that of various conventional control methods aiming to improve the control performance. The improvement of the control performance due to the brake pulse width adjustment, the comparison with the conventional methods, and the verification of safety are tasks assigned to us.

REFERENCES


