Abstract
In recent years, Japanese society has been aging, engendering a labor shortage of young workers. For a robot that is often in contact with people and which must provide safety and flexibility in nursing and welfare, the development of a soft, lightweight, and compact actuator has been sought. Particularly robots that are intended for use in fields of medical care and welfare should be safe when functioning around humans because they often come into contact with people. Therefore, a tendon-driven balloon actuator (balloon actuator) has been developed for a robot hand to be used in such environments. For this study, we developed a stroke control system for the balloon actuator using a predictive functional control (PFC). The PFC is one of model predictive control (MPC) schemes, which predicts the future outputs of the actual plant over the prediction horizon and computes the control effort over the control horizon at every sampling instance. This paper reports the PFC control performance of the balloon actuator. We compared the control performance for the actuator with that of the PFC and a PID control system.

Key words: Predictive Functional Control, Pneumatic Balloon, Tendon-Driven System, Soft Actuator

1. Introduction

Recently, because of the progress of rapid aging and the decrease of younger workers in Japan [1][2], robots are anticipated for use in nursing cares and welfare services, mainly for the performance of rehabilitation and daily domestic tasks [3]. Safety is a particularly important characteristic of robots intended to use in environments with humans. Safety necessitates dexterous, flexible movements similar to those made by humans. Therefore, impact force has been decreased by reducing robot weight. Furthermore, robots that use passive transformation elements have been developed. In the past [4]–[7], pneumatic artificial muscles were developed with a passive transformation element, to be lightweight with high output power for decreasing the impact force. Furthermore, the actuators had characteristics resembling those of human muscles. Research into robots that have high affinity with humans has advanced. Under such circumstances, we developed a pneumatic tendon-driven balloon actuator (balloon actuator) [8] with a long stroke and a high power.
ratio. Moreover, it is compact and lightweight. Then the balloon actuator was applied to a robot hand [9][10].

The robot hand must control a finger joint angle to manipulate an object with dexterity. However, for pneumatic rubber actuators including the balloon actuator, it is difficult to maintain exact control because these actuators have nonlinear properties that change their characteristics. Therefore, robust control systems such as sliding mode control and H-infinity control have been attempted for pneumatic rubber actuators [11][12]. However, it is complex and difficult for many people to understand the robust control theory. From this reason, it has not penetrated the industry to any great degree. In contrast, PID control systems have been commonly used in industry. However, it takes much time and effort to find adequate gains that achieve good control performance for plants that have nonlinear properties, although the PID control system is a simple structure that is easy to use.

In this study, predictive functional control (PFC) [13][14], which has high robustness and easily tuned control parameters to achieve good control performance, is applied to a balloon actuator. The PFC has one of model predictive control (MPC) schemes that have been originally developed for use in industry. Generally, the calculated load of the MPC is high because it demands a solution of a nonlinear optimization problem every sample time. Therefore, the MPC has been often applied to chemical plants, at which the sample time is long. However, calculated load of the PFC is low because its control law consists only of a basis function. Furthermore, it is easier to tune control parameters because there is only one parameter. Moreover, because the PFC control system has an internal model, it has high robustness for varying properties and disturbances. Herein, the PFC control performance for the balloon actuator is evaluated. Moreover, comparison between the PFC and the PID Control System for the actuator is conducted.

2. Predictive Functional Control

In this section, we briefly present an overview of the PFC. Figure 1 portrays the basic concept of the PFC. Presuming that the current time is labeled as a time step \( k \), then a set-point trajectory can be defined as a command signal that the process output \( y_P(k) \) should follow. The value of the set-point trajectory at the current time step is denoted as \( c(k) \). Additionally, a reference trajectory denoted by \( y_R \) is shown. This trajectory starts at the current process output \( y_P(k) \) and defines a desired trajectory along which process output \( y_P \) is expected to approach the set-point trajectory. The reference trajectory has a few coincidence points at which the performance index is defined and the process output \( y_P(k) \) is expected to coincide with the reference trajectory \( y_R \). Three coincidence points are portrayed as an example in Fig. 1. The optimal control input trajectory is then calculated based on the performance index and the coincidence points.
computed based on the predicted output. Once a future control input trajectory has been computed, we apply only the first element of the control input trajectory to the process. At the next time step, we repeat the entire cycle from the definition of the reference trajectory to the application of the first element of the optimal control input trajectory. We designate this mode of control as the receding horizon control.

Next, we show the basic PFC algorithm using slightly modified formulation for handling dead time [15]. Now assuming that the plant is stable and has the dead time of $L$ and that the sampling time is $T_s$, then the development of the PFC algorithm is based on the following SISO discrete-time linear state-space model of the plant:

$$x_M(k+1) = A_M x_M(k) + B_M u(k)$$
$$y_M(k) = C_M x_M(k)$$

Therein, $x_M \in \mathbb{R}^n$ stands for the state vector, $u \in \mathbb{R}$ signifies the control input, $y_M \in \mathbb{R}$ denotes the model output. Here, the model output $y_M(k)$ is used to predict the future plant output $y(k+d)$, where $d$ is defined as the nearest integer of $L/T_s$. Then the reference trajectory is defined as presented below:

$$y_R(k+d+i) = c(k+d+i) - \alpha^i(c(k+d)-\hat{y}_p(k+d))$$

$$i = 0, 1, \ldots$$

In that equation, $\alpha \in \mathbb{R}$ is a parameter that adjusts the approaching ratio of the reference trajectory to the set-point ($0<\alpha<1$). Empirically, the parameter $\alpha$ has been chosen as

$$\alpha = e^{-3T_s/CLRT}$$

along with the following three coincidence points [16];

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} T_{CLRT} \\ \frac{T_{CLRT} T_s}{2T_s} \\ \frac{T_{CLRT}}{T_s} \end{pmatrix}$$

Therein, $T_{CLRT}$ denotes desired closed-loop response time, which represents the time required for the output response to arrive at 95% of the set point. In the PFC, $T_{CLRT}$ is the only design parameter. The speed of response and the robustness can be balanced by adjusting $T_{CLRT}$. In many cases, a performance index is defined as a quadratic sum of errors between the predicted process output $\hat{y}_p$ and the reference trajectory $y_R$ as

$$D(k) = \sum_{j=1}^{n_h} \left( \hat{y}_p(k+d+h_j) - y_R(k+d+h_j) \right)^2$$

where $h_j (j=0, 1, \ldots, n_h)$ and $n_h$ respectively denote the coincidence time point and the number of coincidence points. The future control input computed at every sampling instant is assume to be the sum of weighted orthogonal basis functions as follows:

$$u(k+i) = \sum_{i=1}^{n_B} \mu_i(k) U_{\beta_i}(i)$$

where $n_B$ is the number of basis functions, $\mu_i$ are unknown weight coefficients, and $U_{\beta_i}$ are basis functions. Usually, we adopt a time-dependent polynomial basis of the form

$$U_{\beta_i}(i) = i^{i-1}, i = 0, 1, \ldots$$

Once we have computed a future input trajectory as equation (6), we apply only the first element to the process; that is,

$$u(k) = \sum_{i=1}^{n_B} \mu_i(k) U_{\beta_i}(0)$$

It is possible to decompose model output at the time step $k+i$ as follows:
where $y_F$ and $y_{UF}$ are forced response and unforced response, respectively. The forced response $y_F$ is given by

$$y_F(k+i) = \sum_{i=1}^{N} u_i(k)y_{B_i}(i)$$

where $y_{B_i}$ represents the response to the basis function $U_{B_i}$. On the other hand, the unforced response $y_{UF}$ is given by

$$y_{UF}(k+i) = C_M A_M x_M(k)$$

Now suppose that prediction error at the time step $k+d+i$ can be expressed as

$$\hat{e}(k+d+i) = e(k+d) + \sum_{m=1}^{d} c_{m}(k+d)i^m$$

where $d_e$ and $c_m$ are respectively a degree of the polynomial approximation and unknown coefficients that are computed on the basis of past and present model error. Similarly, assume that future set-point trajectory can be approximated by the following polynomial function:

$$c(k+d+i) = c(k+d) + \sum_{p=1}^{d} c_{p}(k+d)i^p$$

where $d_c$ and $c_p$ are respectively a degree of a polynomial approximation and unknown coefficients. In fact, a constant prediction error and a constant set-point are often assumed.

The minimization of the performance equation (5) leads to the optimal control input by using above equations as

$$u(k) = k_0 c(k+d) - y_F(k) + \sum_{m=1}^{d} k_m c_m(k+d)$$

$$- \sum_{m=1}^{d} k_m e_m(k+d) + \nu_d^T x_M(k) + \nu_{ad}^T x_M(k-d)$$

where $k_0$, $\nu_d$, $k_m$ and $\nu_{ad}$ are respectively given by

$$k_0 = \nu^T \begin{bmatrix} 1 - \alpha^{k_0} & \vdots & \vdots & \vdots \\ 1 - \alpha^{k_m} & \vdots \end{bmatrix}, \quad \nu_d = - \begin{bmatrix} C_M (A_M^{k_0} - \alpha^{k_0} I) \\ \vdots \end{bmatrix} \nu$$

$$k_m = \nu^T \begin{bmatrix} h_i^m \\ \vdots \\ h_{ab}^m \end{bmatrix}, \quad \nu_{ad} = \begin{bmatrix} (\alpha^{k_0} - 1) C_M \\ \vdots \end{bmatrix} \nu$$

In equation (15), $\nu$ is given by

$$\nu = \begin{bmatrix} y_{a}(h_1) & \cdots & y_{a}(h_m) \end{bmatrix} \left( \sum_{j=1}^{N} y_{a}(b_j) y_{a}(b_j)^T \right)^{-1} U_a(0)$$

where

$$y_{a}(h_i) = \begin{bmatrix} y_{a}(h_1) & \cdots & y_{a}(b_i) \end{bmatrix}^T, \quad U_a(0) = \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix}^T$$

3. Experimental System

3.1 Tendon-driven balloon actuator

The pneumatic tendon-driven balloon actuator (balloon actuator) is portrayed in Fig. 2.
More detailed schematic views are written in [17]. The balloon actuator has a high power-to-weight ratio and stroke-to-weight ratio. Therefore, it can generate sufficient stroke and force for the driving robot hand if it is installed in a small space of a robot hand. The balloon actuator is an air-pressure-drive type actuator comprising a silicone tube (balloon) and a tendon wrapped around a tube. The silicone rubber tube is an oval tube with 21 mm long diameter and 9 mm short diameter, with length of 25 mm. The tube is sealed at one end to produce a balloon. Compressed air is supplied through an opening at the other end to expand the balloon. The tendon is made of polypropylene. A nylon fiber sheet is adhered to one side of the tendon to decrease friction force generated between the tendon and the balloon. The tube is then fixed at both ends by acrylic plates. The wall is arranged on one side of the balloon to restrain its expansion. To decrease the loss of output efficiency, a roller is arranged in the part where the tendon direction is changed. The basic driving mechanism is the following: The tendon wrapped around the balloon is expanded as the balloon expands, which creates tensile force for the tendon drive. Specifications of the balloon actuator are presented in Table 1.

3.2 1-link finger system using balloon actuator

In this study, the stroke control performance of the PFC for the balloon actuator is evaluated by conducting a control experiment of the one-link finger system with the balloon actuator. Figure 3 presents a photograph of the one-link finger system used for this study. This finger system consists of the balloon actuator, tension spring, and finger. It is an antagonistic mechanism of the balloon actuator and the tension spring. The finger flexes by restoration force of the tension spring and extends by tensile force of the balloon actuator. Therefore, when this finger system is implemented in a robot hand, this driving mechanism can prevent the fall of an object because grip force can be secured by the spring if the system halts abnormally. In the finger design, the movable finger joint angle is set to 90 °, which is almost equal to the angle used by human fingers. The pulley radius is set to 11

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Specification of a balloon.</th>
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<tbody>
<tr>
<td>Material</td>
<td>Silicone rubber</td>
</tr>
<tr>
<td>Shape</td>
<td>Inner diameter</td>
</tr>
<tr>
<td></td>
<td>Outer diameter</td>
</tr>
<tr>
<td>Length</td>
<td>25mm</td>
</tr>
<tr>
<td>Long diameter</td>
<td>21.0mm</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>17.8mm</td>
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Fig. 2 Tendon driven balloon actuator.

Fig. 3 Photo of 1-link finger system using balloon actuator.
mm so that the stroke of the actuator installed in the one-link finger system is the same as that of the actuator installed in the human-like robot hand that has three-link fingers. The tension spring has a spring constant of 1.0 N/mm with initial force of 5.3 N, so that the finger joint angle is 90° when the input air pressure is the maximum (0.2 MPa).

Next, the physics model of the one-link finger can be described as follows. Figure 4 shows a one-link finger model used for this study. To model the finger accurately, various parameters that affect response characteristics such as propagation velocity of compressed air, material nonlinear properties of a balloon, frictional force between the balloon and tendon, and viscoelasticity of a tendon, must be identified. However, it is extremely difficult to model them accurately by considering all of these parameters. In this study, because the purpose of the experiment is to conduct a comparative evaluation, the following simple mathematical model is used. The equation of motion of the actuator is given as

\[ J\ddot{\theta}(t) + D\dot{\theta}(t) + r^2K\theta(t) = rf(t) \]  

(18)

where \( J \) is the moment of inertia including the pulley and the arm, \( D \) is the viscous damping coefficient, \( r \) is the pulley radius, \( K \) is the spring constant and \( f \) is the tensile force of the balloon actuator. We assume here that, for a fixed internal pressure, the force has the following first order dynamics:

\[ f(t) + \alpha \dot{f}(t) = \beta p(t) \]  

(19)

where \( p \) is the internal muscle pressure, and \( \alpha \) and \( \beta \) respectively represent unknown coefficients that depend on \( p \). In this study, these model parameters are identified by the experiment explained in the next section.

4. Control Experiment

4.1 Experimental setup

Figure 5 shows an experimental setup for stroke control of a balloon actuator. In this experiment, the compressed air that is input to the balloon is provided by an air compressor [YC-4; Yaezaki Kuatsu K.K.]. The input air pressure is arranged using an electropneumatic regulator [ETR200-1; Koganei Corp]. The finger joint angle is measured using a potentiometer [SV03; Murata Manufacturing Co. Ltd.] installed in the finger joint. The measured angle is input to a PC through an AD/DA board [Q4 PCI board; Quanser] with the sampling time set to 2 ms.

4.2 Model Identification

A PFC control system requires the internal model of the plant because it controls it using the predicted future plant output. Therefore, parameters of mathematical model
described in the previous section are identified by an experiment. By equations (18) and (19), a transfer function from the applied internal pressure (MPa) to the finger angle (°) can be approximated by a following 3rd order system.

\[
G(s) = \frac{d}{s^3 + as^2 + bs + c}
\]  

(20)

Therein, \(a = \alpha + D/J\), \(b = (r^2K + aD)/J\), \(c = \alpha r^2K/J\) and \(d = \beta r/\alpha \).

However, the balloon actuator has nonlinear characteristics between the input pressure and the finger joint angle because it is a rubber actuator. Therefore, it is difficult to identify the plant model using only equation (20) because the transfer function cannot express nonlinear characteristics. In this study, a static characteristic of the finger joint angle \(\theta\) for the input pressure \(p\) is identified as a following quadratic function instead of a static characteristic \(\beta/\alpha r K\) in the equation (20).

\[
\theta = 3511.2p^2 - 65.5p - 1.7
\]

(21)

Each parameter in equation (21) is identified by curve fitting using least-squares method from measured data. Next, a transfer function of the dynamic characteristic, which is a characteristic without the static characteristic \(\beta/\alpha r K\) of the equation (9), is identified as a following equation.

\[
G_s(s) = \frac{6400}{s^3 + 137s^2 + 3728s + 6400}
\]

(22)

In the identification of each parameter in equation (22), after the step response characteristic of the finger joint angle for the input pressure is measured, model parameters are identified by curve-fitting using non-linear least squares from the measured data. In this study, the characteristic of which the input pressure is 0.2 MPa, that is highest gain calculated from equation (10) (maximum pressure of the actuator is 0.2 MPa), is used for identification.

Because the discrete state space model such as equation (1) is necessary in the PFC control, the continuous transfer function model identified of equation (22) is discretized by Zero-Order Hold. It is transferred to the state space model.

The plant has dead time in the dynamic characteristic. Therefore, a smith compensator [18], which is a dead time compensation method, is applied to the PID control system. It can move the dead time to the outside of the feedback loop by changing the control system characteristic using the plant model. A transfer function model of dead time \(G_d(s)\) is necessary to construct a PID control system with a Smith compensator. In this study, using Pade approximation, dead time is expressed in the transfer function model. The dead time of
a one-link finger is 0.06 s through measuring the step response. Then the transfer function of
dead time \( G_L(s) \) is identified by quadratic Pade approximation, as shown in the following
equation.

\[
G_L(s) = \frac{s^2 - 12s + 48}{s^2 + 12s + 48}
\]

(23)

Details of the Smith compensator are described in ref. [18].

4.3 Experimental method

Block diagrams of the PID control system with the Smith compensator and the PFC
control system used for this study are depicted in Fig. 6. The one-link finger is driven by the
balloon actuator. The balloon might explode easily if high air pressure is input into it.
Therefore, the maximum air pressure must be limited to 0.2 MPa, which constitutes a
constraint condition related to the input pressure \( p \) (MPa) in the control system as shown in
the following equation.

\[
p < 0.2
\]

(24)

The pressure limiter that satisfies equation (24) is set between the PID controller and
the plant in the PID control system. Moreover, an Anti Reset Windup (ARW) compensator
is set to the controlled system to prevent the controlled variable from a windup phenomenon
as shown in Fig. 6 (a). On the other hand, the pressure limiter is set between the PFC
controller and the plant in the PFC control system. The output signal from the limiter is sent
to the internal model as well as to the plant, as depicted in Fig. 6 (b). The PFC control
system can prevent the controlled variable from the windup phenomenon easily by sending
the output signal from the limiter to the internal model [19].

In the experiment, the desired finger joint angles are set to 30 °, 60 °, and 90 °. Then the
control output for the step input is examined. Furthermore, the control output for the
sinusoidal input is also experimented. Bias, amplitude and angular frequency of the
sinusoidal input are set to 60 °, 60 ° and 3.14 rad/s respectively. Parameters of the PID
controller are chosen using the CHR method with measured data of the step response of the
finger. Results show that the proportional gain, integral time and derivative time are,
respectively, 2.1, 0.62 s and 0.02 s. A parameter of the PFC controller is \( T_{CLRT} \), which is
called the desired closed-loop response time as described above. The response speed
increases when \( T_{CLRT} \) is decreased because it indicates the desired closed-loop response
time. However, in that case, the robust stability decreases because it is affected easily by
4.4 Experimental results

First, control performances for step input are discussed. Figure 7 presents experimentally obtained results for the PID and the PFC control of the finger joint angle. A black solid line represents a desired value. A blue dashed line and a red solid line represent results of the PID and the PFC control. Regarding comparison of the transient characteristics when the desired angle is 90°, settling time of the PID control is 0.56 s, and that of the PFC is 0.57 s. Therefore, these dynamic performances are almost identical in 90°. For characteristics of which the desired angles are 60° and 30°, the settling times of the PID control are 0.90 s and 1.11 s respectively. Those of the PFC are 0.35 s and 0.18 s, respectively. Therefore, the control performance of the PFC is better than that of the PID control in 60° and 30°. These results indicate that the PFC control system for the balloon actuator has high robustness for a nonlinear plant. A balloon actuator has high nonlinear properties. Therefore, the characteristics are changed when input air pressure is changed. Because of this, in the PID control, the transient characteristics worsened in 30° and 60°, although the characteristics show good performance in 90°. However, in the PFC control, the transient characteristic did not worsen when the desired angle is changed because the PFC control system has high robustness for the nonlinear plant.

Next, steady state characteristics are discussed. Figure 8 presents control error for the PID and the PFC control. A blue dashed line and a red solid line represent results of the PID and PFC control. The steady state error of the PFC control is lower than 0.05°. However,
those of the PID control are 0.39 °, 0.17 ° and 0.30 °, respectively, when the desired angles are 90 °, 60 °, and 30 °. Consequently, the steady state characteristics of the PFC are better than those of the PID control under condition of high friction of the balloon actuator. Generally, the normal PID control system is difficult to compensate the frictional force. However, the PFC control system showed high performance for a plant with high friction in an earlier study [20]. These control system property differences might affect such experimentally obtained results.

Figure 9 (a) shows the experimental result of stroke control to sinusoidal input. A black solid line represents the desired value. A blue dashed line and a red solid line represent results of the PID and the PFC control respectively. As a result, the controlled value of the PID is delayed for the desired value greatly. On the other hand, the controlled value of the PFC tracks well for the desired value. Figure 9 (b) shows error angle of controlled value. The maximum error of the PID and the PFC are 22.8 ° and 4.3 ° respectively. These results indicate that the tracking performance of the PFC is better than that of the PID.

5. Conclusions

This study evaluated stroke control characteristics of the balloon actuator by the PFC control using the one-link finger system. Our conclusions are following: In the experiment of step input, the control performance of the PFC is better than that of the PID control in 60 ° and 30 ° although that of the PFC is the same as that of the PID control in 90 °. These results reflect that the PFC control system for the balloon actuator has the high robustness for the nonlinear plant compared with the PID control. In addition, the steady state characteristics of the PFC are better than those of the PID control under condition of high friction of the balloon actuator. The PID control system is fundamentally difficult to compensate the frictional force. However, the PFC control system has the high performance for the plant that has high friction. These differences of control system properties might be shown in such experimentally obtained results of control error. In the experiment of the sinusoidal input, the error angle of the PFC is much lower than that of the PID control. Therefore, the tracking performance is also better than that of the PID control.

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