Design of Pneumatic Drive and Its Control System for A SkilMate Hand
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Abstract:
In this paper, we focus on linear modeling and design of a self-tuning PID controller for a pneumatic cylinder system for applicable to a SkilMate hand for astronauts’ Extra-vehicular activity (EVA). For the purpose of giving the initial values to the PID controller, we develop linear modeling by applying first-order Taylor series expansion, and design a self-tuning PID controller with applying real-time system identification capability utilizing fuzzy curve fitting. Finally, we verified the validity of the controller by simulation the system behavior.

1 Introduction
To overcome the problem that experts confront when they need to wear special suits to protect themselves under hazardous environments, we have proposed to attach SkilMates [1,2], wearable intelligent machines, which are capable of assisting in affording such working surroundings that they can exhibit their skills even in the heavy suits. We proposed to apply small-sized pneumatic cylinders to a SkilMate hand for power assisting the movement of finger joints of an EVA glove in expectation of the advantageous of human compatibility of pneumatic actuators.

One of the related studies was reported by Shields et al. They extensively worked on the development of an anthropomorphic hand exoskeleton system for assisting metacarpophalangeal (MP) and interphalangeal (IP) joints of the pointing through the index fingers [3]. The controller commands were determined by a state-of-the-art programmable microcontroller using pressure sensor information. These commands are applied to PWM-driven DC motor array which provide the motive power to move the exoskeleton fingers. Later, Sorenson et al. made a more practical approach to the conjunction design of a power-assisted space suit glove joint. The cable tension for exerting the extension torque of a MP joint is applied by a geared DC motor contained within the actuator housing, and implementation of the control strategy is used for feedback control system enhancement [4]. More recently, Lovchik and Diftler [5] presented the Robonaut hand, this five-fingered-hand, combined
with its integrated wrist and forearm has fourteen independent degrees of freedom.

How to simplify the power assist mechanism is discussed in each of the above reports. However, SkilMate, wearable intelligent machines, must have high human-friendliness and the stabilization when astronauts wear it in EVA.

A pneumatic servo system is one of the desirable actuator systems to be applied to human-machine contact tasks because of its function of the intrinsic impact force absorption and the possibility of sophisticated force control [6]. Consequently, pneumatic cylinders were introduced to driving the finger joint in the study. However, the driving system exhibits low stiffness due to the air compressibility, and the coulomb friction at the cylinder-piston system fluctuates due to the change in the air temperature (very high/low temperature). In addition, it is difficult to strictly build the dynamic model of a pneumatic cylinder-piston system and to control them accurately because we can hardly grasp the nonlinear orifice mass flow into the chamber [7].

Figure 1 shows the basic structure of one proposed SkilMate hand that is composed of a glove, power transmission mechanisms, and pneumatic cylinders. In this paper, we discuss self-tuning PID controller of finger joint driving systems. For setting initial values of the PID, we use the first-order Taylor series expansion to linearize the kinematic model of the regulator-cylinder-load system about the piston position located at the center of the cylinder, and obtain a third-order transfer function in Section 2. In Section 3, we set the optimal gain and phase margin tuning for the PID controllers that allow on-line self-tuning of the PID parameters based on the preceding modeling results of system identification at very high/low temperature. A method of system identification utilizes fuzzy curve fitting with least square principles in real-time. Finally, we verify the validity of designing the finger joint driving systems by showing some simulation result of the system behavior in Section 4.

2 MODELING

2.1 Linear modeling

Figure 2 shows a model of a pneumatic cylinder for deriving kinematic modeling of the regulator-cylinder-load system.

Load dynamics is expressed by

\[ m\ddot{y} + f\dot{y} = S_1 p_1 - S_2 p_2 - F_r \]  

where \( y \): axis displacement, \( S_{1,2} \): effective sectional areas of the cylinder, \( p_{1,2} \): inside pressures of the cylinder, \( F_r \): friction, \( f \): coefficient of viscous friction, \( m \): load mass.
The chamber dynamics is formulated as

\[
\begin{align*}
\dot{p}_1 &= \frac{K R T_1}{S_1 y} q_1 - \frac{K p_1}{y} \dot{y} \\
\dot{p}_2 &= \frac{K R T_2}{S_2 y} q_2 - \frac{(2 - K) p_2}{y} \dot{y}
\end{align*}
\] (2)

where \( t_{1,2} \) : temperature in each chamber, \( R \) : air-gas constant, \( K \) : specific heat ratio, \( q_{1,2} \) flows into each chamber.

In the above formulation, we assume that air is a perfect gas and that pressures and temperatures in the chambers are homogenous. We also neglect the kinetic energy of air. If we choose the regulator as the input to the system and we suppose constant temperature \( T_1 = T_2 = T \). The corresponding state equation of motion in the Y axis is expressed as

\[
X = E(X, I),
\]

\[
\dot{X} = [y \ \dot{y} \ p \ p_2]' , I = [i_1 \ i_2]'
\] (3)

\[
E = \begin{bmatrix}
\frac{\dot{y}}{y} & -\frac{F_m}{m} - \frac{f}{m} \dot{y} + \frac{S_1}{m} p_1 - \frac{S_2}{m} p_2 \\
-\frac{K p_1}{y} \dot{y} + \frac{K R T_1}{S_1 y} q_1 (i_1, p_1) \\
-\frac{(2 - K) p_2}{y} \dot{y} + \frac{K R T_2}{S_2 y} q_2 (i_2, p_2)
\end{bmatrix}
\] (4)

where \( i_{1,2} \) : output of the regulators, \( E \) : nonlinear function of \( X \) and \( I \), \( q_{1,2} (I) \) : air flows into the cylinders.

Expression (3) is a nonlinear mathematical model because of the orifice flows. This model can be linearized in the neighborhood of an equilibrium point (center point \( y = y_0 \equiv L/2 \), \( L \) : full stroke of the cylinder).

Thus, we can rewrite the state variable from the linearized model as

\[
\dot{X}^* = O(X^*_0, I^*_0), X^*_0 \text{ being given by}
\]

\[
\begin{bmatrix}
0 & 1 \\
0 & -f/m
\end{bmatrix} \begin{bmatrix}
0 & 0 \\
\frac{K R T_1}{S_1 y_0} [q_1 (i_1, p_1)]_0 \\
\frac{K R T_2}{S_2 y_0} [q_2 (i_2, p_2)]_0 \\
0 & K p_0 \\
0 & K R T_2 [q_2 (i_2, p_2)]_0
\end{bmatrix}
\] (5)

where \( y_0 = x_0 = y_{20} = L/2 \), \( p_{10}, p_{20} \) : mean pressures. The expression of the linearized model corresponds to the first-order Taylor series expansion of \( E \).

\[
\begin{align*}
X^* &= \frac{\partial E(X^*_0, I^*_0)}{\partial X} X^* + \frac{\partial E(X^*_0, I^*_0)}{\partial I} I^* \\
I^* &= I^*_0 + I^*_1, I^*_1 &= \begin{bmatrix} i^*_1 \\ i^*_2 \end{bmatrix}
\end{align*}
\] (6)

and,

\[
X^*_0 = [0 \ 0 \ p_{10} \ p_{20}]', y^*_0 = y_{0} = 0 \\
p_{10} = p_{20} = p_{10}, i_{10} = i_{20} = 1 \text{atm.}
\]

Thus, we can rewrite the state variable from the linearized model as

\[
\dot{X}^* = O(X^*_0, I^*_0), X^*_0 \text{ being given by}
\]

\[
\begin{bmatrix}
0 & 1 \\
0 & -f/m
\end{bmatrix} \begin{bmatrix}
0 & 0 \\
\frac{K R T_1}{S_1 y_0} [q_1 (i_1, p_1)]_0 \\
\frac{K R T_2}{S_2 y_0} [q_2 (i_2, p_2)]_0 \\
0 & K p_0 \\
0 & K R T_2 [q_2 (i_2, p_2)]_0
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Thus, we can rewrite the state variable from the linearized model as

\[
\begin{bmatrix}
0 & 1 \\
0 & -f/m
\end{bmatrix} \begin{bmatrix}
0 & 0 \\
\frac{K R T_1}{S_1 y_0} [q_1 (i_1, p_1)]_0 \\
\frac{K R T_2}{S_2 y_0} [q_2 (i_2, p_2)]_0 \\
0 & K p_0 \\
0 & K R T_2 [q_2 (i_2, p_2)]_0
\end{bmatrix}
\] (5)
Figure 3 shows the block diagram corresponding to this equation. The model can still be simplified by the assumption of identical pneumatic cylinders (with same effective sectional area $S_1 = S_2 = S$), and

$$\begin{bmatrix}
0 & 0 \\
0 & 0 \\
0 & \frac{KRT}{S_2 y_0} \left[ \frac{\partial q_2}{\partial i_2} \right]_0
\end{bmatrix} \times I^* \quad (8)$$

$$\frac{\partial q_1}{\partial p_1}_0 = \frac{\partial q_2}{\partial p_2}_0 = -N$$

$$\left[ \frac{\partial q_1}{\partial i_1} \right]_0 = \left[ \frac{\partial q_2}{\partial i_2} \right]_0 = G$$

$$\left[ q_i(i, p_i) \right]_0 = -\left[ q_i(i, p_i) \right]_0 = N \quad (9)$$

If we define $\Delta p = p_1 - p_2$ and take into account (7), (8), and (9), we can express the resulting model the system in the Y axis as follows

Figure 3: Block diagram of the exhaustive linearized model.
\[
\begin{bmatrix}
\dot{y} \\
\ddot{y} \\
\Delta p
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 \\
0 & -\frac{f}{m} & -\frac{S}{m} \\
-\frac{2KRTN'}{Sy_0^2} & \frac{2p_0}{y_0} & -\frac{KRTN}{Sy_0}
\end{bmatrix}
\begin{bmatrix}
y \\
\dot{y} \\
\Delta p
\end{bmatrix}
\]

Equation (10) stands for a three state-variable model whose state variables are position, velocity and the differential pressure between the chambers. If we adopt the state variable representation in the canonical form for the linearized model we obtain:

\[
\dot{X} = AX + BI \\
Y = CX
\]

where

\[
A = \begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1 \\
-\frac{f}{m} & -\frac{S}{m} & -a
\end{bmatrix},
B = \begin{bmatrix}
0 \\
0 \\
-e & -d
\end{bmatrix},
C' = \begin{bmatrix}
1 \\
1
\end{bmatrix},
X = \begin{bmatrix}
y \\
\dot{y} \\
\ddot{y}
\end{bmatrix}
\]

and

\[
a = \frac{f + KRTN}{m Sy_0}, b = \frac{fKRTN}{mSy_0} - \frac{2p_0S}{my_0},
\]

\[
c = \frac{2KRTN'}{my_0}, d = \frac{KRTG}{my_0}, e = -\frac{KRTG}{my_0}.
\]

Equation (11) is the model we propose to describe the behavior of the piston in the Y axis where the state variables are the position, velocity and acceleration. The corresponding transfer function in Laplace transform is:

\[
G_0(s) = \frac{Y(s)}{I(s)} = \begin{bmatrix}
e & 0 \\
0 & \frac{d}{s^3 + as^2 + bs + c}
\end{bmatrix}
\]

where \(s\) is the Laplace variable. Figure 4 shows the block diagram of the linearized model that is finally adopted.

### 2.2 Model discussion

In the study, we assume certain amount of delay time in pressure transmission in both of the regulators and pneumatic cylinder. We also regard friction \(F_r\) as a modeling parameter with a disturbance when designing the control system due to the possibility of the change temperature in the chambers.
The orifice characteristic of the pressure-flow is modeled as

\[ q = SP \sqrt{\frac{2}{RT_j}} \phi\left(\frac{p_c}{p_i}\right) \]

where

\[ \phi(z) = \sqrt{\left(\frac{K}{K-1}\right)} \left[z^{2K} - z^{(K+1)/K}\right] \]

for \( 0.528 \leq z \leq 1 \), and

\[ \phi(z) = \sqrt{\left(\frac{K}{K+1}\right)} \left(\frac{2}{K+1}\right)^{2/(K-1)} \]

for \( 0 \leq z \leq 0.528 \), and

\[ z = p_c / p_i \quad p_c: \text{inside pressure of chamber}, \quad p_i: \text{pressure of air supply}. \]

We study a control system of high compliance and stability which is applicable to pneumatic cylinders with perturbation of parameters and possibility of changes in the order of the modeling equation.

3 Control

In the study, the design values of the transfer function of the PID controller are determined by the application the ISE-GPM (Integral Square Error-Gain and Phase margin) method [8], which searches both the initial values for the linear modeling, and design parameters of the PID controller via on-line system identification.

3.1 PID controller

We simplify the third-order transfer function in equation (12) to a first order plus dead-time process model expressed in the following by applying SRG (Sub-optimal Reduction Algorithm) [9] for determining the values of the PID controller.

\[ G_c(s) = \frac{Y(s)}{I(s)} = \left[ \frac{K_1}{\tau_1 s + 1} \exp(L_1 s) \right. \]

\[ \left. 0 \quad \frac{K_2}{\tau_2 s + 1} \exp(L_2 s) \right] \]

where

\[ L_1 = 0.8432, K_1 = 0.1160, K_2 = 0.908 \]

\[ L_2 = 0.2099, A_m = 1.0082, K_2 = 0.3678 \]

\[ T_0 = 0.7022, A_m = 0.9061, K_2 = 0.328 \]

\[ \forall i = [1,2] \]

We apply equation (13) to design the initial values of the controller as way by the applying ISE-GPM method, the PID controller transfer function is given as

\[ G_c(s) = K_c (1 + \frac{1}{sT_i} + sT_a) \]

where

\[ K_c = \frac{1.7022}{K_1} A_m^{-0.8432} \phi_{mi}^{-0.116} (L_i / \tau_i)^{-0.908} \]

\[ T_i = 1.2497 \tau_i A_m^{-0.2099} \phi_{mi}^{0.0082} (L_i / \tau_i)^{0.3678} \]

\[ T_a = 0.4763 \tau_i A_m^{-0.0961} \phi_{mi}^{-0.328} (L_i / \tau_i)^{0.0317} \]

and,

\[ \phi_{mi} = \arg\left[ G_c(jw_{gi})G_0(jw_{gi})\right] + \pi \]

\[ A_{mi} = \left[ G_c(jw_{pi})G_0(jw_{pi})\right]^{-1} \]

\[ w_{gi}, w_{pi} \] are given by

\[ |G_c(jw_{gi})G_0(jw_{gi})| = 1, \]

\[ \arg\left[ G_c(jw_{pi})G_0(jw_{pi})\right] = -\pi \]

The equation (15) is suitable for determining the initial values and their on-line real-time implementation similar to the equations used in other schemes such as in auto-tuning or self-tuning PID controls.

3.2 Modeling identification

3.2.1 Least square principles

We change equation (13) ( \( i = 1 \) for example in follows) to obtain a first-order time-variant

\[ y(t) = m_1 y(t-1) + n_1 u(t-h-1) + n_2 u(t-h-2) \]

where \( h \) is a maximum integer and can satisfy \( L_i \geq h k_i \) (\( k_i \) : sampling interval) in discrete-time systems, and the relations between equation(13) and (16) are expressed as in following:

\[ \tau_i = -k_i / \log e^n \]

\[ k_i = (n_1 + n_2) / (1 - m_i) \]

\[ L_i = k_i (h + 1) + k_i \log m^n [1 + n_1 (m_1 - 1) / (n_1 + n_2)] \]
where $m$, $n_1$, and $n_2$ are unknown parameters. Using the above equation, and a set of ordered pairs $[y(t), y(t-1), u(t-h-1), u(t-h-2)]$, $t \in [0,1,\ldots,n]$.

We can find the parameter $m$, $n_1$, and $n_2$. The procedure involves minimization of the sum of the squares of the residuals as given below:

$$f(m, n_1, n_2) = \sum_{j=1}^{M} e_j^2 = e_1^2 + e_2^2 + \ldots + e_M^2$$  \hspace{0.5cm} (18)

$$e_j = m_j y_j (t-1) + n_j u_j (t-h-1) + n_j u_j (t-h-2) - y_j (t)$$  \hspace{0.5cm} (19)

where minimization is computed when $\frac{\partial f}{\partial m}, \frac{\partial f}{\partial n_1}$, and $\frac{\partial f}{\partial n_2}$ are equated to 0. After some simplification, it is possible to obtain three normal equations that are shown below:

$$\sum_{j=1}^{M} y_j (t-1) e_j = 0$$

$$\sum_{j=1}^{M} u_j (t-h-1) e_j = 0$$  \hspace{0.5cm} (20)

$$\sum_{j=1}^{M} u_j (t-h-2) e_j = 0$$

From the above three equations we can compute three parameters $m, n_1$, and $n_2$. For the use the least squares method we should know that the number of data points should be greater than the number of parameters of the functions.

### 3.2.2 Curve fitting with fuzzy numbers

The three equations shown in (20) are derived by the use of symbolic manipulation and mathematical reasoning. The actual arithmetic of those simultaneous equations is done in the end to compute the parameters. At this juncture, we use fuzzy variables instead of real variables. Thus, to get a fuzzy quadratic equation:

$$[\omega, \omega_m, \omega_f] = [m, m_1, m_2, n_1, n_2, n_2] \otimes [w_i, w_{ix}, w_{iy}] \oplus$$

$$[n_1, n_2, n_1, n_2] \otimes [w_{ij}, w_{iix}, w_{iyy}]$$  \hspace{0.5cm} (21)

$$[n_2, n_2, n_1, n_2] \otimes [w_{jj}, w_{jjx}, w_{jjy}]$$

Similar to the classical method we can deduce three fuzzy equations, and they are:

$$\sum_{j=1}^{M} [y_j, y_{m}, y_j] \otimes [v_j, v_{im}, v_{jm}] = 0$$

$$\sum_{j=1}^{M} [u_{ij}, u_{im}, u_{ij}] \otimes [v_j, v_{im}, v_{jm}] = 0$$  \hspace{0.5cm} (22)

$$\sum_{j=1}^{M} [u_{ij}, u_{im}, u_{ij}] \otimes [v_j, v_{im}, v_{jm}] = 0$$

where

$$[v_j, v_{im}, v_{jm}] = [\omega, \omega_m, \omega_f] - [y_j, y_{m}, y_j]$$  \hspace{0.5cm} (23)

for $j \in \{1,\ldots,M\}$. Solving the above three equations, we obtain $[m, m_1, m_2, n_1, n_2, n_2]$.

Fuzzy inference can be accelerated once we the fuzzy function has been computed as described above. Using the equation, and given input pairs $[y_j, y_{m}, y_j], [u_{ij}, u_{im}, u_{ij}]$, and $[u_{ij}, u_{im}, u_{ij}]$, it is easy to compute output $[\omega, \omega_m, \omega_f]$ from the function given below:

$$[\omega, \omega_m, \omega_f] = [m, m_1, m_2, n_1, n_2, n_2] \otimes [y_j, y_{m}, y_j] \oplus$$

$$[n_1, n_1, n_1] \otimes [u_{ij}, u_{im}, u_{ij}]$$  \hspace{0.5cm} (24)

$$[n_2, n_2, n_2, n_2] \otimes [u_{ij}, u_{im}, u_{ij}]$$

We use conduct fuzzy the fundamental operations, addition, and multiplication, and the three simultaneous equations can be solved by using fuzzy arithmetic described by Koczy et al. [110].

### 4 Simulation and conclusions

For verifying the validity of the method for eliciting a linear model and the correspondingly proposed PID controller, we simulated the SkilMate hand system behavior under problematic conditions of friction perturbation and delay time fluctuation. Our simulation condition allowing the piston position from keep a steady position are as following:

. The friction perturbation (random 3% change) at $t=0.3\sim0.7$s, a close situation of air temperature
(random high/low temperature change) in space.

The fluctuating delay time (random change 0.02→0.04s), a close situation of delayed pressure transmission due to the orifice characteristic of the pressure-flow and pressure transmission of both the regulator and cylinder.

From figure 5 shows that control system have quick response which indicate the proposed linear modeling and a scheme of designing the initial PID values are appropriate.

For keeping steady position response against friction perturbation is shown in a figure 5. The proposed method of system identification and the self-tuning PID controller of SkilMate drive showed fine compliance.

The way the system keeps steady position against some delay change is shown in a temperature change as shown in figure 5. The proposed method proves system stabilization.

We show the proposed fuzzy inference scheme can reduce the time required for the system identification. As future work, we need to improve our method, and verifying the effectiveness by practically experimenting the controller for driving a SkilMate hand.

![Figure 5: Displacement keeping response](image)

**References**


