Control Approaches and Detecting Function of Intelligent Cylinder for Human Adaptive Mechanism

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This research will be realizing Human Adaptive Mechanism for Physical Human Machine interaction by applying several intelligent pneumatic cylinders. Each cylinder consists of optical encoder, force sensor, valve and controlled by PSoC as the central processing unit. PSoC will handle I2C communication, input and output data from ADC, counter and PWM module. Four types of control approaches were used and done experimentally towards realizing the final goal which is position servo control, force control, compliance control and viscosity control. By applying these control approach, the intelligent cylinders have the ability to detect objects with different stiffness and damping characteristics for future Intelligent Chair Tool.

Key word: Pneumatic Actuator, Human Adaptive Mechanism, Physical Human Machine Interaction, Intelligent cylinder

1. Introduction

Recently, application of pneumatic actuators are increased because of their advantages of high power-to-weight ratio, relatively low cost, easy to maintain, lightweight and having simpler structure compared to other actuators [1-3]. These advantages make pneumatic actuator, especially pneumatic cylinder suitable in many applications such as in physical human machine devices [4].

This paper presents a human adaptive mechanism for physical human machine interaction application by integrating several intelligent pneumatic actuators to form an Intelligent Chair Tool. Undeniably, comfortable seating is an important issue in creating mutual environment towards excellence in health and in daily work [5]. This actuator can interact physically with human and able to adapt mechanically to give ergonomics form to suit ones bodies back. By having the advantage of intelligent pneumatic cylinder, it can provide tracking position, compliance with different stiffness and damping function to suit the proposed design.

To facilitate easier experiment towards the final goal of human-machine interaction achievement, a unified control system is designed inside PSoC enabling better position, force, compliance and viscosity control. Due to simplicity, cheapness and can easily be controlled through proposed distributed control, the on/off valve is essential in multiple cylinders application. An extensive physical detecting function will be presented to determine stiffness, k, and viscous coefficient, c parameters for spring and damping characteristics.

2. Cylinder Mechanism

2.1 Pneumatic Actuators

The dynamics of pneumatic cylinder considering friction in chamber as in Fig. 1 can be described using Newton’s Principle;

\[ m\ddot{x} = F_d - F - F_r \]  

where \( m, x, F_d, P_e, P_r, F, A_1, A_2 \) are mass, piston position, driving force, pressure, friction force, load force and cross sectional area respectively.

![Fig. 1 Pneumatic cylinder and nomenclature](image)

In this research, the cylinder is designed to have PSoC as a microcomputer for communication and control. Pressure sensor is also attached for chamber pressure feedback reading and on/off valve is used towards combination of all elements in a single actuator for the proposed Intelligent Chair Tool as in Fig. 2.

![Fig. 2 Intelligent chair Tool](image)

PSoC will handle I2C communication between PC and other PSoC, input and output data of ADC for pressure sensor reading, counters for encoder reading and PWM to control the valve.

2.2 Experimental setup
Towards realizing the final goal to create physical human machine interaction to Intelligent Chair Tool, four different experiments are conducted using the developed pneumatic cylinder actuator. The experimental setup in this study is shown in Fig. 3

![Experimental setup with linear guide and DC motor](image)

Fig. 3 Experimental setup with linear guide and DC motor

3. Control Algorithm and Experiment
A unified control system is designed inside PSoC with an inner loop to control force by receiving chamber pressure feedback, while an outer loop of position control for tracking the desired position and commands desired force to the inner loop. Fig. 4 shows the control block diagram and Table 2 details the parameters for each control algorithm.

![Control system block diagram](image)

Fig. 4 Unified control system block diagram

<table>
<thead>
<tr>
<th>Experiments</th>
<th>$c$ (Viscous coefficient parameter)</th>
<th>$k_s$ (Stiffness parameter)</th>
<th>$k_f$ (Force Parameter)</th>
<th>$k_p$ (Position parameter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Force</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Compliance</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Viscosity</td>
<td>$\sqrt{3}$</td>
<td>$\sqrt{3}$</td>
<td>$\sqrt{3}$</td>
<td>$\sqrt{3}$</td>
</tr>
</tbody>
</table>

$\sqrt{3}$ - Parameter used

Through the unified control system, position, force, compliance and viscosity control are possible to be experimented easily in embedded distributed methodology. The communication ability and local control functions will reduces the number of cables connected as well as providing more delicate and high performance of actuator motions.

3.1 Position and force control
Position control and force control using intelligent pneumatic cylinder and on/off valves had been realized by unified control block diagram as in Fig. 4. The target position and force is input from PC and the error between the readings from encoder and difference of force is calculated respectively. PI control was used with suitable gain value to drive the on/off valve to achieve e the target cylinder position and target force. Fig. 5 and Fig. 6 show the experimental result of a sine wave and force tracking.

![Experimental results of sine wave tracking](image)

Fig. 5 Experimental results of sine wave tracking

3.2 Compliance control
The compliance control was achieved using equation $F_e = k_s (X_c-x)$ where $F_e$, $k_s$, $X_c$ and $x$ represent the force reference, stiffness parameter, target position and actual position from the encoder respectively. The working function of compliance control is shown in Fig. 4 where the system will try to achieve the target position by giving the appropriate value of force.

The motor plane was moved using DC motor forward and backward from the origin position (18mm) to see the effect of stiffness parameter to the feedback force. Experimental result in Fig. 7 shows the feedback force which depends on $k_s$ value and the position from the origin. Five values of $k_s$ were experimented where bigger $k_s$ value give steeper feedback force while large position error increase the feedback force value.

![Experimental results of compliance control](image)

Fig. 7 Experimental results of compliance control
Moreover, the experimental results show that the stiffness characteristic was successfully applied to the intelligent actuator and the experimental \( k \) data is identical with the theoretical data with minimum errors as in Table 3.

### Table 3 Comparison of experimental and theoretical data for Compliance control

<table>
<thead>
<tr>
<th>Cases</th>
<th>Cylinder Experiment (N/mm)</th>
<th>Theoretical data (N/mm)</th>
<th>Error (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.3481</td>
<td>0.338</td>
<td>0.010</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.6941</td>
<td>0.676</td>
<td>0.0181</td>
</tr>
<tr>
<td>Case 3</td>
<td>1.0589</td>
<td>1.014</td>
<td>0.0450</td>
</tr>
<tr>
<td>Case 4</td>
<td>1.3863</td>
<td>1.352</td>
<td>0.0343</td>
</tr>
<tr>
<td>Case 5</td>
<td>1.6563</td>
<td>1.69</td>
<td>0.0337</td>
</tr>
</tbody>
</table>

#### 3.3 Viscosity control

Viscosity control was realized with the combination of two control approaches, position and force control and having feedback of speed, \( \dot{x} \) and viscous coefficient, \( c \) variable. For this control, the value of \( k \) in Fig. 4 is set to zero to find suitable \( c \) as reference for the inner loop. PI control was applied for error elimination, \( e = c \cdot \dot{x} - f \) and for adjusting the duty cycle to give appropriate PWM signal for cylinder stroke force. For viscosity experiment, the speed of the cylinder stroke depends on the movements of DC motor which is controlled by PC. Table 4 shows the setting frequency and the equivalent motor speed to move the cylinder with expected drive force. Fig. 5 shows the compliance control experimental result.

### Table 4 Speed and expected force according to motor frequency

<table>
<thead>
<tr>
<th>Cases</th>
<th>Frequency (kHz)</th>
<th>Speed (mm/s)</th>
<th>Expected force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1</td>
<td>1.36</td>
<td>1</td>
</tr>
<tr>
<td>Case 2</td>
<td>2</td>
<td>2.66</td>
<td>2</td>
</tr>
<tr>
<td>Case 3</td>
<td>4</td>
<td>5.27</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 8 Experimental results of compliance control

### 4. Detecting Function

The proposed Intelligent Chair Tool will have combinations of intelligent cylinders where each cylinder is identical and not depends on each other. The importance of detecting function is that it can detect different physical property of person weight, body shape, posture and body compliance thus responds accordingly to give damping and spring characteristics hence suit the ergonomics form of one's body. The equation that relates spring and damping characteristics is given below

\[
F = k \cdot x + c \dot{x}
\]

where \( F, k, x, c \) and \( \dot{x} \) are force, stiffness, position, viscous coefficient, and speed respectively. In this experiment, the cylinder can detect two major parameters for ergonomics characteristics which are stiffness, \( k \), and viscous coefficient, \( c \) of an object. For this experiment, Voigt model is used where a viscous damper and purely elastic spring are connected in parallel. Four types of different material in Fig. 9 assumed to have this model is selected and tested to find their \( k \) and \( c \) parameter.

Fig. 9 Different material for physical detecting function

![Different material for physical detecting function](image)

Fig. 10 Responds of force and cylinder position for different material

### Table 5 Comparison of detecting function of four different materials

<table>
<thead>
<tr>
<th>Material</th>
<th>( k ) (N/mm)</th>
<th>( c ) (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic plastic</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rubber</td>
<td>3.1942</td>
<td>19.08</td>
</tr>
<tr>
<td>Hand pad</td>
<td>1.1301</td>
<td>2.014</td>
</tr>
<tr>
<td>Sponge</td>
<td>0.5359</td>
<td>0.634</td>
</tr>
</tbody>
</table>

5. Conclusion

In this paper, an intelligent pneumatic cylinder was introduced for human adaptive mechanism and four control approaches; position, force, compliance and viscosity have been successfully constructed using PSoc. The new intelligent pneumatic hardware system applied pressure sensor for pressure feedback and implemented on/off valve because of simplicity and cheapness. The experiment results are presented and compared.
with theoretical value and previous works. The characteristics of future Intelligent Chair Tool were also realized with detecting function experiment where different materials physical property can be differentiate from \( k \) and \( C \) parameter obtained.

Acknowledgement
The Author would like to thank Universiti Teknologi Malaysia for granting the scholarship.

References