Piezoelectric Actuated In-pipe Microrobot with P-type Iterative Learning Active Force Control

YASER SABZEHMEIDANI, M. MAILAH, MOHAMED HUSSEIN
Department of System Dynamics and Control
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
81310 UTM Johor Bahru, Johor
MALAYSIA
yaser7002@gmail.com, musa@fkm.utm.my

Abstract: - In this paper, a piezoelectric microrobot is modelled and simulated based on active force control (AFC) with a proportional (P) – type iterative learning algorithm (ILA) operating in a constrained environment for an in-pipe application. A mathematical model that represents the dynamic characteristics of microrobot has been developed considering the robot system subjected to different input excitations. The movement of the robot is based on an impact drive mechanism (IDM) strategy which causes the robot to move in a worm-like manner in the pipe. A dedicated feedback controller is integrated into this system that incorporates proportional-integral-derivative (PID) controller and active force control (AFC) with an embedded ILA. The primary objective of the scheme is to ensure a robust and accurate trajectory tracking control of the microrobot system is achieved. The performance of the proposed control system under different types of disturbances is evaluated through a rigorous simulation study. The obtained results clearly demonstrate an effective trajectory tracking capability of the worm-like microrobot in spite of the negative effects of the external disturbance conditions.

Key-Words: - Microrobot, piezoelectric actuator, active force control, iterative learning algorithm, in-pipe application

1 Introduction

Nowadays microrobots are widely used in a number of engineering applications since robots of this type may be able to operate in unstructured environment thanks to their enhanced adaptability to effectively operate even under hostile conditions such as radioactivity, electromagnetic field and high temperature gradients. One such application of interest is the operation of microrobot in a pipe line that can perform a number of tasks such as in-pipe inspection, fault diagnostics, condition monitoring and obstacle removal. Some basic research on mobile mechanisms for use in pipes has been reported in which many are driven by piezoelectric [1], giant magnetostrictive [2], pneumatic [3] or electromagnetic actuators [4].

Research and development on the use of piezoelectric actuators and micro mechanisms for microrobots has been actively carried out [5]. Compared to other actuators, the piezoelectric type proves to be more promising and practical because of its high power and better response. A number of piezoelectric actuators have been proposed, such as those based on stacked, bimorph and unimorph configurations. Characteristics of the new piezoelectric linear step locomotive mechanism for an in-pipe micro inspection robot were studied [6]. It can move not only in a straight pipe but also through a curved or bent configuration.

In this paper, a microrobot with AFC controller incorporating ILA is modelled and simulated for in-pipe application. A mathematical model that justifies the dynamic characteristics of the microrobot is first presented. Then, the dynamic response of the robot system subjected to different input excitations is investigated. AFC controller which is implemented with ILA is applied to the microrobot system to follow the desired trajectory, while at the same time reject the undesired disturbances which may be created due to friction forces or fluid viscosity in the pipe. An intelligent method based on ILA is used to approximate the AFC parameter related to the estimated mass. The performance of the control system under the influence of the introduced disturbances is evaluated through a rigorous simulation study presented in this paper.
2 Robot Modelling

2.1 Motion Mechanism

The main mechanism for the microrobot movement is based on the Impact Drive Mechanism (IDM) [7]. This motion mechanism is used for systems under friction by applying impulsive force. Rapid and slow displacement of actuator caused impulsive force which utilizes static friction. In this mechanism we have three parts: the main body, actuator and the inertial weight. When the actuator makes rapid extension or contraction, a strong inertial force is generated and the main body is moved against static friction. When the actuator makes slow retraction, the inertial force could be smaller than the static friction so that the main body maintains the position. Repeating the fast and slow actuator displacements produces the worm-like motion. Fig. 1(b) shows the mechanism assembly.

![Motion mechanism assembly](image)

Fig. 1: (a) Motion mechanism (b) 3D mechanism assembly

2.2 Dynamic Modelling

A mass-spring-damper system with two degrees of freedom for modelling the system is defined. For dynamic modelling of the system, a state-space model could be derived, firstly by considering the following differential equations:

\[
\begin{align*}
m_1 \ddot{x}_1 + k_p (x_2 - x_1) + C \dot{x}_1 &= F_p + \frac{C}{m_1} (x_2 - x_1) + u \\
m_2 \ddot{x}_2 + k_p x_2 + C \dot{x}_2 &= k_p x_1 + C \dot{x}_1
\end{align*}
\]

Where \( m_1 \) is the mass of the moving part, \( m_2 \) is the extended mass, \( k_p \) represents the elastic/stiffness constant and \( C \) is the damping constant. Eq. (1) can be simplified as:

\[
\begin{align*}
\ddot{x}_1 + \frac{C - \mu k_F N}{m_1} \dot{x}_1 + \frac{k_p}{m_1} x_1 &= \frac{C}{m_1} \ddot{x}_2 + \frac{k_p}{m_2} x_2 + \frac{u}{m_1} \\
\ddot{x}_1 + a_1 \dot{x}_1 + a_2 x_2 &= b_0 \ddot{x}_2 + b_1 \dot{x}_2 + b_2 x_2 + b_3
\end{align*}
\]

where:

\[
\begin{align*}
a_1 &= \frac{C - \mu k_F N}{m_1}, \quad a_2 = \frac{k_p}{m_1}, \quad a_3 = 1, \quad b_0 = 0, \quad b_1 = \frac{C}{m_1}, \\
b_2 &= \frac{k_p}{m_2}, \quad b_3 = \frac{u}{m_1}
\end{align*}
\]

The following constants are also defined:

\[
\beta_0 = b_0 \\
\beta_1 = b_1 - a_1 \beta_0 \\
\beta_2 = b_2 - a_1 \beta_1 - a_2 \beta_0 \\
\beta_3 = b_3 - a_1 \beta_2 - a_2 \beta_1 - a_3 \beta_0
\]

In addition, the following expressions are also used based on previous definitions:

\[
\gamma = x_1 - \beta_0 x_2 = x_1
\]
\[
u = \dot{x}_1 - \beta_1 x_2 = \dot{x}_1 - \frac{C}{m_1} x_2
\]

Eqs. (1) and (2) can be rewritten as:

\[
\begin{align*}
x_2 &= u + \beta_2 x_2 = u + \frac{C}{m_2} x_2
\end{align*}
\]
Thus, the following state-space relationship is established:

\[
\begin{align*}
\dot{x}_1 &= 0, \\
\dot{x}_2 &= \frac{c}{m_1} x_1 - \frac{k_p}{m_1} x_1 - \frac{c(C-\mu_k F_N)}{m_1^2} u + \frac{1}{m_1} \frac{k_p}{C-\mu_k F_N} u
\end{align*}
\]  

(10)

Thus, the following state-space relationship is established:

\[
\begin{align*}
\dot{x}_1 &= -a_2 x_1 - a_1 x_2 + \beta_2 u = \frac{k_p}{m_1} x_1 - \\
&\quad \left(\frac{c-\mu_k F_N}{m_1}\right) x_2 + \frac{k_p}{m_1} - \frac{c(C-\mu_k F_N)}{m_1^2} u
\end{align*}
\]  

(9)

Fig. 2 shows a schematic that describes a free body diagram of the system. From the diagram, equilibrium equations in x and y directions can be derived. Finding the normal force of the three legs needs one more equation which is derived based on momentum equilibrium in one of the legs that acts on the pipe inner surface. Normal forces are derived as:

\[
N_2 = N_3 = W + 3kx_1 + 2kx_2
\]  

(11)

The equilibrium equation for point B which is shown in the free body diagram can be written as:

\[
N_1 = W + 3kx_1 - 2kx_1 + N_2
\]  

(12)

The total normal force is thus:

\[
N = N_1 + N_2 + N_3
\]  

(13)

3 Control Scheme

3.1 Active Force Control

The AFC method is a technique that relies on the appropriate estimation of the inertial or mass parameters of the dynamic system and the measurements of the acceleration and force signals induced by the system if practical implementation is ever considered. The research on active force control (AFC) is initiated by Johnson (1971) and later Davison (1976) based on the principle of invariance and the classic Newton’s second law of motion [8]. For theoretical simulation, it is normal that perfect modelling of the sensors is assumed and that noises in the sensors are totally neglected. In AFC, it is shown that the system subjected to a number of disturbances remains stable and robust via the compensating action of the control strategy. A more detailed description on the mathematical treatment related to the derivation of important equations and stability criterion [9]. For brevity, the underlying concept of AFC applied to a dynamic rotational system is presented with reference to Fig. 3.

Where \(G(s), G_a(s), G_c(s), K_{AFC}, H(s), F, F^*, m,\) and \(a\) are the dynamic system transfer function, actuator transfer function, outer loop controller, AFC constant, weighting function, applied force, estimated force, estimated mass and linear acceleration, respectively. The estimated disturbance is obtained by considering the following expression:

\[
F^* = F - m a
\]  

(14)

\(F\) can be readily measured by means of a force sensor and \(a\) using an accelerometer. \(m\) may be obtained by assuming a perfect model, crude approximation or intelligent methods [10]. \(F^*\) is then passed through a weighting function \(H(s)\) to give the ultimate AFC signal command to be embedded with an outer control loop. This creates a two degree-of-freedom controller that could provide excellent overall system performance provided that the measurement and estimated parameters were appropriately acquired. The outer control loop can
be a proportional-integral-derivative (PID) controller, resolved motion acceleration controller (RMAC), intelligent controller or others deemed suitable. It is apparent that a suitable choice of $H(s)$ needs to be obtained that can cause the output to be made invariant with respect to the disturbances such that:

$$G_a(s)H(s) = 1$$  \hspace{1cm} (15)$$

A set of outer control loop control is applied to the above open loop system, by first generating the world coordinate error vector, which would then be processed through a controller function, $G_c(s)$, typically a classic PID controller. The main computational burden in AFC is the multiplication of the estimated inertial parameter with the angular acceleration of the dynamic component before being fed into the AFC feed forward loop. The effectiveness of the AFC scheme applied to rigid robot arms has been demonstrated [11]. Robust intelligent AFC method that is capable of controlling a vehicle suspension system and effectively suppressing the introduced disturbances.

A useful point to note is that, the constant $K_{AFC}$ can effectively served as a mode switch between the PID only scheme or PID and SMC method plus intelligent AFC method by simply setting the $K_{AFC}$ to 0 or 1, respectively. The in-between value of $K_{AFC}$ can also be experimented to show the effect of percentage $K_{AFC}$ which however is not covered in this study.

### 3.2 Iterative Learning Algorithm

The ILA is considered an intelligent strategy through which the performance of a dynamical system (based on some error criterion) becomes better and better as time increases. Arimoto et al. [11] have provided a sufficiently in-depth analysis of the convergence, stability and robustness of the iterative learning algorithm which has been employed in this study. Fig. 4 (a) demonstrates a schematic of the P-type IL algorithm. The input signal $u_k$ and the output signal $y_k$ are stored in memory each time the system operates. The learning algorithm then evaluates the system performance error, $e_k = y_d - y_k$, where $y_d$ is the desired output of the system. Based on this error signal, the learning algorithm then computes a new input signal $u_{k+1}$, which is stored for use on the next trial, i.e., the next time instant the system operates. The next input command is selected in such a way that it causes the performance error to be reduced on the next trial or iteration. Based on Fig. 4 (a), the next value of the input signal, $u_{k+1}$ can be expressed as:

$$u_{k+1} = u_k + \phi e_k$$  \hspace{1cm} (16)$$

where $\phi$ is the proportional learning parameter. One of the most important considerations in dealing with the IL is the convergence properties [12]. An iterative method computes successive approximations such that the output of the system approaches an appropriate value as time increases. The learning process, however, is accomplished infinitely with the possibility of over learning which could lead to instability of the system once it enters a ‘dangerous zone’. Thus, a stopping criterion should be incorporated into the algorithm so that the system knows when to stop the learning process.

![Fig. 4: (a) Arimoto’s P-type IL algorithm (b) Block diagram of the AFC loop with the ILA](image)

The property of eliminating the effect of disturbance (disturbance rejection) is known to be the most important and desirable characteristic of a feedback controller. In this investigation, an intelligent proportional controller based on acceleration feedback was employed to reject the vibratory disturbances affecting the microrobot. Fig. 4 (b) shows the block diagram of proposed intelligent AFC scheme with self-learning capability.

### 4 Simulation and Discussion

The applied disturbance considered in the study is a harmonic force that emulates a constant vibratory excitation with a magnitude of 1 N and frequency, 25 rad/s, i.e., according to the following function, $\sin 25t$. For simulating the proposed control scheme, a number of input sources were considered that are
related to step, random and square wave forcing functions as shown in Fig. 5. For simulation, the parameters of the microrobot as shown in Table 1 were assumed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1$</td>
<td>20 g</td>
<td>$C$</td>
<td>4.5 kg/s</td>
</tr>
<tr>
<td>$m_2$</td>
<td>15 g</td>
<td>$k_p$</td>
<td>150 kN/m</td>
</tr>
<tr>
<td>$m_p$</td>
<td>28 g</td>
<td>$g$</td>
<td>9.8 m/s²</td>
</tr>
<tr>
<td>$a_1$</td>
<td>0.25</td>
<td>$a_2$</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The resultant tracking control can be seen also in Fig. 5. Note that the PID controller gains were assumed to be appropriately tuned and consistently used throughout the simulation study.

From Fig. 5, it can be seen that the controller is able to perform the trajectory tracking task satisfactorily by bringing the responses to converge to the reference positions but at the expense of relatively large tracking errors with substantial ripples or oscillation, largely due to the nature of the applied disturbance (vibratory). This shows that the latter system is much more robust than its counterpart in compensating the harmonic disturbance at relatively high frequency. The proposed actuated microrobot is able to operate effectively based on the closed-loop control configuration with the given loading and operating conditions.

5 Conclusion
A piezoelectric microrobot for in-pipe application was modelled and simulated using IDM mechanism for motion and AFC controller with ILA to perform trajectory tracking task in the presence of the prescribed disturbances and interacting environments. The simulation results of the proposed schemes clearly demonstrate the effectiveness of the closed-loop control algorithms in executing the prescribed tasks with the AFC-based scheme significantly outperforms the PID counterpart. Future works may include a rigorous study on the effects of other loading and operating conditions on the system performance.

Acknowledgements
The authors would like to acknowledge the Universiti Teknologi Malaysia for their full support of this research through a research university grant (Vote No.: 01H71)

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