Modelling and control of a piezo actuated micro robot with active force control capability for in-pipe application

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Abstract: In this paper, a piezo actuated micro robot with active force control (AFC) capability is modelled and simulated for an in-pipe application. A mathematical model that describes the dynamic characteristics of the micro robot is first presented. The dynamic response of the robot system subjected to different input excitations is then investigated by initially considering a conventional proportional-integral-derivative (PID) controller to perform a trajectory tacking task. Subsequently, a robust AFC-based controller is serially added to the PID controller, the primary aim of which is to reject the unwanted disturbances due to frictional forces in the pipe. The control system is tuned so that an accurate trajectory tracking control is achieved. The performance of the control system under different loading and operating conditions is evaluated through a rigorous simulation study. A sliding mode controller (SMC) was also included to provide another means of comparing the system performances apart from the pure PID control scheme. The obtained results clearly demonstrate the robust trajectory tracking performance of the proposed AFC-based micro robot system in spite of the negative effects of the external disturbances.

Keywords: active force control; AFC; micro robot; piezo actuated; in-pipe application; robust trajectory tracking.


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1 Introduction

Micro robots 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 micro robot 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 actuators (Aoshima et al., 1993; Idogaki et al., 1995; Matsumoto et al., 1994; Deng and Inoue, 2009), giant magnetostrictive actuators (Fukuda et al., 1991), pneumatic actuators (Suzumori and Abe, 1993; Takahashi et al., 1994), or electromagnetic actuators (Iwashita et al., 1994).

Kato et al. (2003) propose a pneumatically actuated mobile micro robot that can move in a long pipe whose diameter is not fixed. The robot is required to handle the variation in pipe diameter to the radius direction and at the same time able to drive the robot to longitudinal direction using the friction force by holding the pipe and then move forward through a worm-like mechanism produced by the bellows. Lim et al. (2008) invented an inchworm like micro robot by using only one pneumatic line. It is based on drilling different-sized micro holes in two plates among three chambers. The rear clamp, the elongation module, and the front clamp work sequentially as the air flows to each chamber. It enables the robot not only to generate inchworm like locomotion, but also to allow significant reduction of the stiffness of pneumatic lines and the drag force due to one pneumatic line. In order to operate the robot efficiently, the stroke according to the supplied pneumatic pressure is investigated. In another design, a pneumatic flexible robot prototype for in-pipe inspection was designed and experimented as described in Bertetto and Ruggiu (2001). A dynamic model which takes into account the flexibility, damping and friction was developed. A number of experiments were carried out in order to characterise the robot and provide the input for the numerical model. The model was validated by comparing the experimental and numerical robot gait in time domain. The robot motion for different pipes network geometry is also presented in the research. The works described above mostly focus on the principle of actuation and assume an open loop control configuration that does not include sensory feedback information and control algorithm for critical task applications.

In another application, a shape memory alloy (SMA) design was proposed in which the mechanism based on a resilient-rigid coupling SMA actuator (RRSA) was used to drive the micro-wheeled-robot in a pipe line (Jun et al., 2004). A hybrid linear motor that produces precise resolution with long travelling distance under inchworm motion principle is developed by Kim et al. (2002). The motor consists of one push and two clamping devices. The clamping and push devices are assembled and a control sequence is applied. In another application, Dooley et al. (1998) developed magnetostrictive actuator for use as actuator in cryogenic devices. They present developments in material processing and characterisation for low temperature in micro positioned for space telescopes. A micro in-pipe mobile machine with the micro valves is fabricated by Liu and Jiang (2007). The micro valves control bellows-type micro actuators and the in-pipe mobile machine can move like inchworms. Performances of the in-pipe mobile machine were examined extensively in this paper.

Research and development on the use of piezo actuators and micro mechanisms for micro robots has been actively carried out (Bart et al., 1988; Hayashi, 2000). 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. Precise positioner utilising rapid deformation of a PZT stack has been proposed and presented in Sun et al. (2001) and Liu et al. (2003). Liu et al. (2009) developed an in-pipe micro robot providing stable and accurate locomotion inside a tubular structure. This micro robot driven by impulsive voltages, deflections of the piezoelectric bimorphs are generated and then converted into translational locomotion. Idogaki et al. (1995) studied characteristics of the new piezoelectric linear step locomotive mechanism for an in-pipe micro inspection robot in which it can move not only in a straight pipe but also through a curved or bent configuration.

In this research, a piezoelectric micro robot with active force control (AFC) capability is modelled and simulated for pipe inspection. Micro robot can be used for corrosion evaluation, fault diagnostics (fracture, cracks, leaks, etc.), obstacles detection and removal and other applications of in-door pipes. A mathematical model that justifies the dynamic characteristics of the worm-like micro robot is first presented. Then, the dynamic response of the robot system subjected to different input excitations is investigated. A proportional-integral-derivative (PID) controller is applied to the micro robot system to follow the desired trajectory, while an AFC controller is utilised to reject the unwanted disturbances which may be created due to friction forces or fluid viscosity in the pipe. Also, another type of controller based on sliding mode control (SMC) is applied to further benchmark the proposed AFC-based scheme in rejecting the unwanted disturbance. The performance of the control system under different types of disturbances is evaluated through a rigorous simulation study presented in this paper.

2 Micro robot modelling

2.1 Mechanism of robot movement

Impact drive mechanism (IDM) is a method for moving an object under friction by impulsive force. It utilises static friction and impulsive force caused by the rapid displacement of an actuator. The motion mechanism basically consists of 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 static friction so that the main body keeps the position. Repeating those fast and slow actuator displacements carries out the motion.

The mechanism is able to control the minute motion of several nanometres and at the same time has virtually unlimited movable range. The mechanism can be extended to multiple degree-of-freedom systems with multiple actuators and counter weights. The IDM is considered to be a suitable mechanism for micro systems since its construction is quite simple.

Figure 1 shows a basic motion principle of the piezo IDM. The motion mechanism consists of three components: the main body, the actuator and the inertial weight. The main body is laid down on the guiding surface with only the friction acting between the surfaces. On the one end of the main body an actuator is attached. The weight does not touch the surface. The motion process is described as follows:

a) The cycle starts with the actuator in extended state.

b) The actuator makes slow contraction so that the inertial force caused by the contraction should not exceed the static friction. The main body keeps the position.

c) At the end of contraction process, a sudden stop of the motion is made to small move the main body.

d) Then, a rapid expansion of the actuator causes impulsive inertial force, which results in the step-like motion of the main body.

Figure 1 Principle of operation (towards left)

Making slow extension and rapid contraction can carry out motion toward the other direction. The motion amplitude of the actuator can control the step size of the motion. By repeating the process (a) through (d), a relatively long distance motion is made possible.

2.2 Mathematical modelling

Different friction models have been established for studies. A typical stick-slip friction involves the combination of static friction, rising static friction, a negative viscous slope, frictional memory, and hysteresis (Johnson, 1988). In this research, a typical static friction model is selected to express the frictional coefficient induced in the interface between elastic feet of the robot and inner wall of the pipe. The frictional coefficient denoted as $\mu$ is a continuous function of the sliding rate of the moving body,

$$\mu = \mu_s + (\mu_s - \mu_k) e^{-d}$$  \hspace{1cm} (1)

where $\mu_s$ and $\mu_k$ represent the static and kinetic frictional coefficients, respectively, $d$ represents the decay coefficient, and satisfies

$$d = -\frac{1}{x_p} \ln \left( \frac{-\mu_k}{\mu_s - \mu_k} \right)$$  \hspace{1cm} (2)

where $x_p$ is the corresponding reference velocity. Finally, the frictional force $F_f$ can be expressed as

$$F_f = \left[ \mu_k + (\mu_s - \mu_k) \exp \left( \frac{1}{x_p} \ln \left( \frac{-\mu_k}{\mu_s - \mu_k} \right) \right) \right] F_n$$  \hspace{1cm} (3)

where $F_n$ represents the total normal force acting on the sliding surface, and includes the pre-pressure and the weight of entire body of the in-pipe robot. The governing equations are therefore derived from the free-body diagram as the following two coupled equations:

For $m_1$ we have:

$$m_1 \ddot{x}_1 = -k_p \left( x_1 - x_2 \right) - C_p \left( \dot{x}_1 - \dot{x}_2 \right) - F_p + F_f$$  \hspace{1cm} (4)

Also, for $m_2$ we have:

$$m_2 \ddot{x}_2 = -k_p \left( x_1 - x_2 \right) - C_p \left( \dot{x}_1 - \dot{x}_2 \right) + F_p$$  \hspace{1cm} (5)

where $m_1$ and $m_2$ respectively represent the masses of the main body and the weight, and their corresponding displacements are expressed as $x_1$ and $x_2$. The stiffness and damping coefficients of the piezoelectric actuator are symbolised as $k_p$ and $C_p$, respectively. $F_p$ is the piezoelectric force and $F_f$ is the frictional force. The IDM could be regarded as a mechanical vibration system with two degree-of-freedoms, and equations (6) and (7) are used for describing the dynamic behaviour after applying the Laplace method with initial conditions, $t = 0$, $F_f = F_p = 0$ for both sides of the coupled equations (4) and (5).

$$m_2 s^2 X_2 = \left( k_p + C_p s \right) X_1 - \left( k_p + C_p s \right) X_2 + F_p(s)$$  \hspace{1cm} (6)

and

$$m_1 s^2 X_1 = k_p \left( X_2 - X_1 \right) + C_p(s) \left( X_2 - X_1 \right) - F_p(s) + \left( \mu_s - \mu_k \right) \left( m_1 + m_2 + m_p \right) g \left( \frac{\mu_s - \mu_k}{\mu_s - \mu_k} \right)$$  \hspace{1cm} (7)
where $m_p$ is the actuator mass.

By deriving $X_2$ from equation (6) and inserting in equation (7), we have:

$$m_p s^2 X_1 = k_p \left( \frac{(k_p + sC_p)X_1 + F_p(s)}{m_2 s^2 + sC_p + k_p} \right) +$$

$$sC_p \left( \frac{(k_p + sC_p)X_1 + F_p(s)}{m_2 s^2 + sC_p + k_p} - X_1 \right) - F_p(s) + (8)$$

$$\left( \mu_s - \mu_k \right) \left( m_1 + m_2 + m_p \right) g \ln \left( \frac{\mu_k}{\mu_k - \mu_s} \right)$$

Finally, the transfer function for this system can be obtained as:

$$T(s) = \frac{X_1}{F_p(s)} = \frac{A}{B}$$

$$A = m_2 s^2 + 2C_p + \left( \mu_s - \mu_k \right) \left( m_1 + m_2 + m_p \right) g \ln \left( \frac{\mu_k}{\mu_k - \mu_s} \right) + s + 2k_p$$

$$B = m_1 m_2 s^4 + m_2 \left( \frac{(k_p - \mu_k)}{(k_2 - \mu_s)} \left( m_1 + m_2 + m_p \right) g \ln \left( \frac{\mu_k}{\mu_k - \mu_s} \right) + \right) s^3 +$$

$$C_p k_2 s + \left[ k_p (m_1 + m_2) + C_p m_1 \right]$$

The above dynamic model will be incorporated into the proposed micro robot controller schemes, namely the PID, SMC and AFC controllers.

### 3 Proposed control scheme

For testing the system effectiveness in producing and tracking the desired locomotion accurately, we applied three input sources in the form of step, square and sinusoidal input functions via feedback control techniques in order to determine the system responses. Two types of controllers, namely the PID and AFC controllers shall be applied and incorporated into the micro robot system.

#### 3.1 PID control

PID control is the most commonly used control algorithm in industry and has been universally accepted in industrial control. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner. A schematic diagram of a system employing a PID controller is shown in Figure 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1$</td>
<td>425 g</td>
</tr>
<tr>
<td>$C_p$</td>
<td>4.5 kg/s</td>
</tr>
<tr>
<td>$m_2$</td>
<td>120 g</td>
</tr>
<tr>
<td>$k_p$</td>
<td>150 KN/m</td>
</tr>
<tr>
<td>$m_p$</td>
<td>60 g</td>
</tr>
<tr>
<td>$g$</td>
<td>9.8 m/s²</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.4</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The basic idea behind a PID controller is to read a sensor, then compute the desired actuator output by calculating the proportional, integral, and derivative responses and summing those three components to compute the output.
The PID controller calculation (algorithm) involves three separate parameters; the proportional, integral and derivative terms. The PID control algorithm is given as follows:

\[ G_{PID} = K_p + \frac{K_i}{s} + K_D \]  

(10)

where \( K_p, K_i, \) and \( K_D \) are the proportional, integral, and derivative gains, respectively. In this study, the Ziegler–Nichols method is employed to tune the PID parameters. The final gains including \( K_p = 50, K_i = 10, \) and \( K_D = 8. \) For simulating, we assume the parameters of micro robot as shown in Table 1. The resultant tracking control based on the gains can be seen in Figure 3 and these gains shall be used throughout the simulation study.

### 3.2 Sliding mode control

Variable structure system (VSS) with SMC was first proposed and elaborated in the early 1950s in the Soviet Union by Emelyanov and co-researchers. Firstly, this method is well known for solving a number of specific control tasks involving second order linear and non-linear systems (Utkin, 1977). SMC is an important robust control approach to preserve the stability of the system.

In recent years, SMC is becoming a popular approach in control science because of the simple design method and its robustness and invariance to uncertainties which are based on external disturbances and modelling error. SMC is used both in linear and non-linear systems. But, this theory is based on state space and it has limitation. In other words, SMC method is used on systems with state space formulation.

**Figure 4** Schematic diagram of a SMC scheme

![SMC System](image)

The purpose of SMC is to control the non-linearities or uncertainties of a system. To do this, we can linearise the system and then apply the best control technique for the system or find a non-linear transformation which will convert the system into controllable canonical form (CCF) where the controller design is expedited. The SMC system is determined by the sliding mode dynamics, which is not in the same order with that of the original system. This was the reason which leads to the introduction of the robust controller design with sliding surface.

The SMC design approach consists of two components. The first involves the design of a switching function. The second is concerned with the selection of a control law which will make the switching function attractive to the system state. Consider the following uncertain dynamical system:

\[ \dot{x}(t) = Ax(t) + Bu(t) + Ed(t), \quad y(t) = Cx(t) \]  

(11)

where \( x(t) \) is the state vector, \( u(t) \) is the control input vector, \( y(t) \) is the output, \( d(t) \) is the external disturbance vector, and \( A, B, C \) and \( E \) are constant matrices, respectively. The system is in sliding mode when the state lies, slides and remains on the sliding surface after some finite time, i.e., \( S(t) = Gx(t) = 0, \) where \( S(t) \) is sliding surface and \( G \) is a constant matrix. The above condition should be satisfied during sliding mode. Thus, we have:

\[ S(t) = G\dot{x}(t) = GAx(t) + GBU(t) + GEd(t) = 0 \]  

(12)

where \( U(t) \) is defined as:

\[ U(t) = -\left[(GB)^{-1}G\dot{x}(t) + (GB)^{-1}GEd(t) - rS(t)/|S(t)|\right] \]  

(13)

where it is assumed that \( GB \) is non-singular (Mamani et al., 2010).

For this study related to equation (9) we derived the constant matrices as:

\[ A = \begin{bmatrix} -0.328 & 0.965 & -0.005 \\ 13.34 & -0.266 & -9.87 \\ 0 & 0 & -4.49 \end{bmatrix}, B = 4.49, \]

\[ C = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, G = 0.222, E = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \sin(t) & 0 \end{bmatrix}, \]

\[ r = 17.04 \]  

(14)

The controller parameter is derived by inserting these matrices into equation (13) and the simulation results for system under disturbance are shown in Figure 8.

### 3.3 Active force control

The research on AFC was initiated by Johnson (1971) and later Davison (1976) based on the principle of invariance and the classic Newton’s second law of motion. It has been demonstrated that it is possible to design a feedback controller that will ensure the system set point remains unchanged even in the presence of the disturbances or adverse operating and loading conditions provided that the actual disturbances can be modelled effectively. Hewit and Burdess (1981) proposed a more complete package of the system such that the nature of disturbances is oblivious to the system and that it is readily applied to multi-degree of freedom dynamic systems. Thus, an effective method has been established to facilitate robust motion control of dynamical systems in the presence of disturbances, parametric uncertainties and changes that are commonly prevalent in the real-world environment. Mailah and Ong (2001) extended the usefulness of the method by introducing intelligent mechanisms to approximate the mass...
or inertia matrix of the dynamic system to trigger the compensation effect of the controller.

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. 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, can be found in Davison (1976). For brevity, the underlying concept of AFC applied to a dynamic rotational system is presented with reference to Figure 5.

The notations used in Figure 5 are as follows:

\[ G(s) \] dynamic system transfer function

\[ G_a(s) \] actuator transfer function

\[ G_c(s) \] outer loop controller

\[ K_{AFC} \] AFC constant

\[ H(s) \] weighting function

\[ F \] applied force

\[ F^* \] estimated force

\[ m \] estimated mass

\[ a \] linear acceleration.

The estimated disturbance is obtained by considering the following expression:

\[ F^* = F - ma \] (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 (Pitowarno et al., 2002). \( F^* \) 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 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:

\[ G_c(s)H(s) = 1 \] (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. Mailah and Ong (2001), Mailah (1998) and Mailah et al. (1996) have demonstrated the effectiveness of the AFC scheme applied to rigid robot arms. Mailah and Priyandoko (2007) have equally shown a 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 serve as a mode switch between the PID only scheme (AFC – OFF) or PID plus AFC method (AFC – ON) 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.

4 Simulation results and discussion

The applied disturbance considered in the study is a harmonic force that emulates a constant vibratory excitation with a magnitude of 20 N and frequency, 25 rad/s, i.e., according to the following function, \( 20 \sin 25t \) as shown in Figure 6. The disturbance shall act as a test for the robustness of the system performance via observation of the response obtained.

\[ \text{Figure 6} \quad \text{The applied harmonic disturbance considered in the study} \]

\[ \text{Figure 5} \quad \text{A schematic diagram of an AFC scheme} \]

For simulating the proposed control schemes, i.e., PID, SMC and AFC, a number of input sources as the commanded or referenced trajectories were considered that are related to step, sinusoidal and pulsating square wave forcing functions. The responses to these inputs are shown in Figures 7 through 9.
From Figure 7, it can be seen that the PID 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). Figure 8 shows responses of system under the given disturbance with SMC controller. It is obvious that this method works better than
the PID method but the robustness and tracking trajectory performance are still subject to significant error. This is in stark contrast to the results shown through the third set of graphs (Figure 9) in which it is clearly demonstrated that the PID with AFC scheme (AFC – ON) manages to accurately and readily track the desired responses. This shows that the latter system is much more robust than its counterparts in compensating the harmonic disturbance at relatively high frequency. The proposed piezo electric actu ated micro robot is able to operate effectively based on the closed-loop control configuration with the given loading and operating conditions.

5 Conclusions

In this study, a piezoelectric in-pipe micro robot was modelled and simulated using a hybrid control strategy, i.e., PID with AFC, to ensure an accurate trajectory tracking of the robot system under the presence of the prescribed disturbances and operating environment. The SMC control strategy provides an ‘in-between’ performance, i.e., performs better than the PID only controller but falls short of the AFC counterpart. The simulation results of the proposed schemes clearly demonstrate the effectiveness of the closed-loop control algorithms in executing the prescribed tasks. Future works may include a rigorous study on a sensitivity analysis related to the effects of other loading and operating conditions. The possibility of performing practical experimentation on the micro robot system for validation purpose is currently under investigation.

References


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