An Angle Trajectory Tracking for a 3-DOF Pneumatic Motion Platform by the NI Compact RIO Embedded System

Yuan-Ming Cheng and Yu-Song Chen
Department of Mechanical and Automation Engineering, Kao-Yuan University, Kaohsiung 821, Taiwan

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Abstract: An angle trajectory tracking of a 3-DOF (Degree Of Freedom) pneumatic motion platform by the NI Compact RIO control system was investigated. In this study, the positions of moving platform are changed by extension or shortening of the three pneumatic cylinders. The response of pneumatic cylinder is relatively slow for motor actuator and can get a good single-axis trajectory control by traditional P controller, but the trajectory tracking of platform has a delay phenomenon for angle instantly larger change. To improve this situation in this study, Fuzzy system is used in the trajectory pre-compensation. By the angle changes and the angle rates of change in Fuzzy systems, the value of a pre-compensation output and each axis value are calculated using the Jacobian matrix after compensation in each axis. Through experiments, this Fuzzy pre-compensation method is proved to be able to improve the delay situation of angle trajectory tracking.

Key words: Parallel mechanism, Fuzzy controller, Compact RIO, trajectory tracking.

1. Introduction

After the appearance of the Stewart platform mechanism in 1965 [1], the research about the Stewart parallel platform mechanism was booming. The traditional Stewart platform had six driven shafts, and every driven shaft was connected to a mobile plate with a 3-DOF (Degree Of Freedom) ball joint and a fixed plate with a 2-DOF universal joint. The traditional Stewart platform was a 6-DOF mechanism. However, because of the closed loop characteristic, the workspace of the mechanism was limited. Therefore, in Refs. [2-4], Tsai probed to simplify the traditional Stewart platform into a 3-DOF platform, and compared the mechanical characteristics with the 3- RUU, 3-PUU (with intersecting rails) [5] and 3-PUU (with parallel rails). These 3-axis platforms had the advantages of the parallel mechanism, and also could overcome the disadvantage of small workspace and increase the sensitivity. Although a 3-axis platform and a 6-axis platform have their advantages and disadvantages, for the moveable platform applications, safety is considered as the overriding factor. At present, the common drives of actuators are pneumatic, hydraulic and servo motor. In the above drives, because the air is quite difficult to ignite, and the pneumatic will not be destroyed due to the overloading, the pneumatic is the safest. Moreover, when configured, only the mono-tube configuration without backflow needs to be done. However, the drawback of the pneumatic is that the air compressor will cause large noise, the strength is relatively small and the air is compressible. Therefore, the pneumatic would be used only for mechanical controls. The hydraulic has low speed and high pressure, and the highest pressure can reach to several...
tons. Because of the large driving force, the mechanism will be destroyed easily. There also exist the problems related to the leaking and combustibility. The Servo motor has the advantages of precise positioning, small size, high efficiency and absolute position detecting, but its cost is very expensive. In current research, the pneumatic cylinder will be selected as the drive.

The Compact RIO which was developed by the National Instruments is a small rugged industrial control and acquisition system powered by RIO (Reconfigurable I/O) FPGA (Field-Programmable Gate Array) technology for ultrahigh performance and customization. NI Compact RIO incorporates a real-time processor and reconfigurable FPGA for reliable stand-alone embedded or distributed applications, and hot-swappable industrial I/O modules with built-in signal conditioning for direct connection to sensors and actuators. Compact RIO embedded systems are developed using high-productivity Lab VIEW graphical programming tools for rapid development. With NI Compact RIO, you can rapidly build embedded control or acquisition systems that rival the performance and optimization of custom-designed hardware circuitry. Therefore, in current research, the Compact RIO will be employed as controller to investigate the trajectory pre-compensation of a 3-axis pneumatic motion platform.

The mechanical characteristics of the 3-axis pneumatic motion platform such as the workspace, singular surface and rigidity have been discussed in Ref. [6]. Although the pneumatic cylinder has the advantages of low cost and safety, it is a non-linear component [7]. Therefore, it is difficult to position in comparison with the hydraulic and Servo motor. In previous research, the Fuzzy [8-9], PID [10] and PI were employed in single axis trace control. In current experiment, the pneumatic cylinder is a slower actuator axis. In order to obtain a good single axis trace control, the traditional P controller is employed, and the calculation time of the controller can also be shortened.

When the 3-axis pneumatic motion platform was used in the angle trajectory tracking and when the transient change of the angle trajectory was big, the delay phenomenon would be found in the trajectory. In order to improve this phenomenon, the Fuzzy system will be employed to compensate the trajectory in current research. According to the relationship between the change of angle and the changing rate of angle in Fuzzy system, a compensation value could be output when the change of angle was big. The compensation value of every axis could be obtained by the Jacobian matrix. Finally, the experiment demonstrated that the Fuzzy pre-compensation method could improve the delay phenomena of angle trajectory tracking. The paper is organized as follows: Section 2 discusses 3-PRS (prismatic revolute spherical) kinematics of mechanism includes inverse kinematics, Jacobian analysis and solution of forward motion; section 3 introduces experimental setup; section 4 is experimental rustles and discussion; section 5 is conclusions of this paper.

2. 3-PRS Kinematics of Mechanism

2.1 Kinematics of Mechanism

In current research, the study object was a 3-DOF 3-axis motion platform which employed three pneumatic cylinders as the actuators (See Fig. 1). The positions of the motion platform \( Z, \alpha, \beta \) could be changed by the lengthening and shortening of the actuator axis. Firstly, in order to obtain the center of the mobile plate and the elongation of the driven shaft, the inverse kinematics of the 3-axis mechanism was derived.

2.2 Inverse Kinematics

The positions of the platform could be transformed into the elongations of three actuator axis by inverse kinematics. As shown in Fig. 2, all connection points of the top and bottom platforms could be obtained, and the specific locations are as follows:

\[
U_i = r \cdot \begin{bmatrix} C\theta_i \, S\theta_i \, 0 \, 1 \end{bmatrix}^T ; \quad i = 1 \sim 3 \quad (1)
\]

\[
B_i = R \cdot \begin{bmatrix} C\theta_i \, S\theta_i \, 0 \, 1 \end{bmatrix}^T \quad \quad (2)
\]

where \( r \) is the radius of circumradius of the mobile plate, and \( R \) is the radius of circumradius of the fixed plate.
An Angle Trajectory Tracking for a 3-DOF Pneumatic Motion Platform
by the NI Compact RIO Embedded System

\[ aR_{u} = R_{y, \beta} = \begin{bmatrix}
\cos \beta & \sin \beta \cdot \sin \alpha & \sin \beta \cdot \cos \alpha \\
0 & \cos \alpha & -\sin \alpha \\
-\sin \beta & \cos \beta \cdot \sin \alpha & \cos \beta \cdot \cos \alpha
\end{bmatrix} \]  

(5)

Therefore, the connection point on the mobile plate can be transformed into the coordinate system of the fixed platform:

\[ ^bU_i = ^bT_u \cdot ^iU_i = \begin{bmatrix}
^bU_{i_x} \\
^bU_{i_y} \\
^bU_{i_z}
\end{bmatrix} = \begin{bmatrix}
 r \cdot C\theta_i \cdot C\beta \\
r \cdot S\theta_i \\
Z - r \cdot C\theta_i \cdot S\beta
\end{bmatrix} \]  

(6)

Using the vector to express the connecting rod:

\[ D_i = ^bU_{i} - ^bB_i \]  

(7)

The length of the connecting rod:

\[ D_i^2 = (^bU_{i_x} - ^bB_{i_x})^2 + (^bU_{i_y} - ^bB_{i_y})^2 + (^bU_{i_z} - ^bB_{i_z})^2 \]  

(8)

where \(^bB_{i} = 0,\)

\[ D_i^2 = (^bU_{i_x} - ^bB_{i_x})^2 + (^bU_{i_y} - ^bB_{i_y})^2 + (^bU_{i_z} - ^bB_{i_z})^2 \]  

(9)

The square root of Eq. (10) is the length of connecting rods:

\[ D_i = \sqrt{(^bU_{i_x} - ^bB_{i_x})^2 + (^bU_{i_y} - ^bB_{i_y})^2 + (^bU_{i_z} - ^bB_{i_z})^2} \]  

(10)

2.3 Jacobian Analysis

The parallel mechanism has the characteristic of closed loop, so the constraints of the mechanism movement could be expressed as

\[ f(L, q) = 0 \]  

(12)

where \(L\) is a vector which indicates the variation of actuator axis, and \(q\) is a vector which indicates the position of the mobile platform. Taking the derivative versus time of Eq. (12), we can get

\[ \frac{df}{dt} = \frac{\partial f}{\partial L} \cdot \frac{dL}{dt} + \frac{\partial f}{\partial q} \cdot \frac{dq}{dt} \]  

(13)

Assuming

\[ J_L = -\frac{\partial f}{\partial L} \]  

(14)

and

\[ J_q = -\frac{\partial f}{\partial q} \]  

(15)

Then Eq. (13) could be re-written as
\[ J_L \cdot \ddot{L} + J_q \cdot \dot{q} = 0 \]  
(16)

\[ \dot{L} = J \cdot \dot{q} \]  
(17)

where

\[ J = \left[ -\frac{\partial f}{\partial L} \right]^{-1} \]  
(18)

\[ J = \begin{bmatrix} \frac{\partial L_1}{\partial \alpha} & \frac{\partial L_1}{\partial \beta} & \frac{\partial L_1}{\partial \beta} \\ \frac{\partial L_2}{\partial \alpha} & \frac{\partial L_2}{\partial \beta} & \frac{\partial L_2}{\partial \beta} \\ \frac{\partial L_3}{\partial \alpha} & \frac{\partial L_3}{\partial \beta} & \frac{\partial L_3}{\partial \beta} \end{bmatrix} \]  
(19)

### 2.4 Solution of Forward Motion

The trajectory of platform which is the unique solution of the axis’ elongation would be obtained by solving the inverse kinematics directly. According to

\[ \delta L = J \cdot \delta P \]  
(20)

According to Eq. (20), the solution of forward motion could be expressed as

\[ \delta P = J^{-1} \delta L \]  
(21)

The position of the mobile plate could be obtained by substituting the elongation of every axis into the forward motion equation (Eq. (21)), but it is not the unique solution [11]. Therefore, the Newton-Raphson algorithm [12] was often employed to solve the approximate solution.

### 3. Experimental Setup

#### 3.1 Experimental Instrument

The experimental setup of the 3-axis pneumatic motion platform was shown in Fig. 3. The controller was the Compact RIO which was developed by National Instruments, and integrated with one group real time controller, one group re-configurable case and I/O module. The NIcRIO-9004 was employed as the embedded real time controller that features an industrial 200 MHz Pentium-class processor for deterministic and reliable real-time applications. The module NI cIO-9263 could output 4channels voltage (±10 V) which controlled one pneumatic pressure proportional valve and three pneumatic proportional flow valve. The module NI cIO-9215 was four synchronous sampling analogy input channels, and this module was used to transform the voltage of the resistance gauge of pneumatic cylinder into the length value of the pneumatic cylinder.

#### 3.2 Single Axis Trajectory Controller

A PID (Proportional-Integral-Derivative) controller is a generic control loop feedback mechanism (controller) widely used in industrial control systems—A PID is the most commonly used feedback controller. A PID controller calculates an “error” value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process control inputs.

In current experiment, the pneumatic cylinder is a slower actuator axis. In order to obtain a good single axis trace control, the traditional KP controller is employed, and the calculation time of the controller can also be shortened. In order to obtain the parameter of the KP controller, the continuous loop method proposed by Ziegler and Nichols was employed, and the program was adjusted as

(1) Set \( K_P = 1, K_I = 0 \) and \( K_D = 0 \), and connected the controller to the system;

(2) Adjust the proportional gain \( K_P \) by manual adjustments, make the periodic of the oscillation be constant, and approximate to the ideal target 5 or 10. Fig. 4 shown the control tracing image when the proportional gain \( K_P = 0.8 \). The image showed that well single axis trajectory control could be obtained in this proportion. In the experiment, we also tried to adjust \( K_I \) and \( K_D \), but the results were the same as \( K_P = 0.8 \). In order to simplify the calculation time of the Compact RIO controller, the \( K_P = 0.8 \) was employed as the single axis trajectory controller.

#### 3.3 Fuzzy Controller

The two main problems of the conventional Fuzzy control are how to improve the steady state control precision and improve the intelligent level and adaptability, according to Refs. [7-9], in practical
An Angle Trajectory Tracking for a 3-DOF Pneumatic Motion Platform
by the NI Compact RIO Embedded System

Fig. 3  The experimental setup of the pneumatic 3-axis motion platform.

Fig. 4  The control tracking curve of $K_p = 0.8$ proportional gain.

application, by combining the Fuzzy control or the idea of Fuzzy reasoning with other relatively mature control theory and method, and their strengths, we can obtain the more ideal control effect.

Using the accurate-Fuzzy hybrid control which combined the accurate control with Fuzzy control; combining the prediction control with Fuzzy control, the control result could be obtained by using the prediction model. According to the target error and the empirical rule Fuzzy control of the operator, the controller was inserted by the format of Fuzzy logic. According to the difference of the output and input variable based on the rule of Fuzzy inference, the Fuzzy controller could fall into two categories: PI-like (Velocity type) Fuzzy controller and PD-like (position type) controller, and the related parameters are as follows:

(1) PI-like Fuzzy controller

IF $e_k$ is A and $\Delta e_k$ is B then $\Delta v_k$ is C

(2) PD-like Fuzzy controller

IF $e_k$ is A and $\Delta e_k$ is B then $v_k$ is C

where $e_k$ is the position error, $\Delta e_k$ is the variation of the position error, $v_k$ is the control of output. The rising time of PD-like was quite quickly, but the steady state error could not be suppressed effectively. The steady state error PI-like could be suppressed effectively, but the rising time was very long. Although both of them had their advantages and disadvantages, the pneumatic cylinder had the disadvantages of low position precision and slow response. Therefore, the PD-like is the best selection for the pneumatic cylinder. In current experiment, the membership function of input error $\alpha, \beta$ are shown in Figs. 5-6. The membership function of error variation $\alpha, \beta$ are shown in Figs. 7-8. The membership function of output is shown in Figs. 9-10. The rule base is shown in Fig. 11. Figs. 12-13 showed the virtual spaces of $\alpha, \beta$ respectively.
4. Results and Discussion

Fig. 14 shows the flow chart of trajectory pre-compensation using Fuzzy system on a 3-axis pneumatic motion platform. In current research, the angle circular trajectory is \( \alpha = 10\cdot\cos(\omega t) \) and \( \beta = 10\cdot\sin(\omega t) \), \( \omega = \pi/\text{sec} \) is the turning speed. The sampling time \( t \) is set to 50 ms. In the experiment, firstly, input the sampling time into the formula of trajectory, when the value was obtained, the elongations of three axes could be obtained by inverse kinematics, and then the trajectory control of every axis could be achieved. After saving the length of the three axes, the position of the mobile plate could be obtained by the forward kinematics.
Fig. 14  The flow chat of trajectory pre-compensation using Fuzzy system on a 3-axis pneumatic motion platform.

Figs.15-16 are the trajectory of $\alpha$ and $\beta$ when the single axis $K_p = 0.8$ controller is used. In these two figures, the blue curves are target value and the red curves are measurement values. The results show that the red measurement value always lags behind the blue target value, that is, the trajectory has delay phenomenon. In order to improve the situation, the Fuzzy system was used in the trajectory pre-compensation. Based on the angle change $e_\alpha$ and angle changing rate $\Delta d\alpha$ in Fuzzy system, the pre-compensation value rate $\Delta dv\alpha$ could be obtained when the angle change is large. Then the pre-compensation value of every axis could be obtained by Jacobian matrix. Figs. 17-18 show the trajectory tracking image of $\alpha$, $\beta$ when the Fuzzy controller is used. Figs. 17-18 reveal that the red measurement values are much closer to the blue ideal value. Therefore, it is true that the Fuzzy pre-compensation method could improve the delay phenomenon effectively.

5. Conclusions

The pneumatic cylinder is the slow response drive, so it is not easy to be used in the 3-axis trajectory tracking. In present research, the Compact RIO developed by NI is used to construct embedded control system. When the instantaneous change of the platform angle trajectory is big, the delay phenomenon would...
appear, for this problem, the Fuzzy system is used in the trajectory pre-compensation. Based on the angle change and angle changing rate in Fuzzy system, the pre-compensation value rate could be obtained when the angle change is large. Then the pre-compensation value of every axis could be obtained by Jacobian matrix. Therefore, it is true that the Fuzzy pre-compensation method could improve the delay situation.

References


