Coordinated Control of Precision Conveyor Based on Array Piezoelectric Actuators

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Abstract—**Due to the problems of the traditional transmission platform device, such as low transmission accuracy and single transmission path, a precision conveyor based on array piezoelectric actuators is present. In order to meet the requirements of the two-DOF drive motion, a structure of double-V orthogonal two-DOF piezoelectric actuator is adopted. The advantages and disadvantages of three different layout methods are discussed, and the layout of four ultrasonic drivers with regular hexagon for conveyor is determined. The working principle of the ultrasonic piezoelectric transmission platform module is classified and discussed according to the regular hexagon layout, and the output speed of each ultrasonic driver under different required motion angles is obtained, so as to achieve the effect of coordinated control. According to the layout and working principle of the GSA-based fuzzy PID controller and piezoelectric precision conveyor, the coordinated control simulation model of the precision conveyor is built on the Simulink. A coordinated control experimental platform is built to validate whether the piezoelectric conveyor can move things translationally and rotationally. The results show that the translation and rotation displacement of the carried objects can be realized.**

Keywords- Piezoelectric precision conveyor; Ultrasonic actuator; Coordinated control

I. INTRODUCTION

A single piezoelectric actuator (such as a piezoelectric ceramic sheet or stack) has the advantages of large output force, high resolution and fast response, and the driving and positioning accuracy can reach the nanometer level, although through the cooperation of multiple piezoelectric actuators, which has been successfully applied in ultra-precision machining platforms [1], micro-aircraft [2], optical adjustment [3] and other systems. However, the drive displacement of a single piezoelectric driver is generally less than 100μm, and it is difficult to achieve the output of more than mm. The precision transmission platform for the material device needs hundreds or even thousands of millimeters, so a single piezoelectric driver is difficult to meet the needs of the transmission platform for driving displacement.

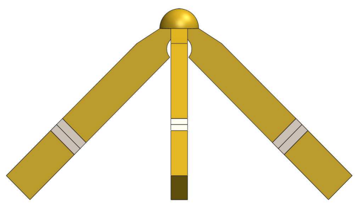
Ultrasonic motor can achieve large linear or angle motion of driving load under continuous actuation model, so that it can be applied to aerospace, precision positioning platform and other fields. Wang et al. applied a sandwich double-ring piezoelectric ultrasonic driver to the mobile subsystem of a micro-lunar rover [4]. Li conducted research on the V-shaped linear ultrasonic motor and tried to apply it to the autofocus system [5]. Xin et al. developed a ring linear ultrasonic motor with a maximum driving speed and driving force of 248 mm/s and 2.6 N, respectively [6]. Zhang and Yu et al. developed a series of ultrasonic motors with different structures and degrees of freedom [7], and applied piezoelectric drivers to precision smoothing control systems [8]. Zhang et al. developed a new type of adaptive non-contact rotating ultrasonic motor [9].

In the field of micro-assembly, micro manipulator mechanism is generally adopted for the transfer and transmission of micro-material devices, and the spatial transfer of micro-material devices is realized through micro-clamping and vacuum adsorption. However, in order to avoid secondary damage to the transferred object, it is necessary to consider the non-destructive clamping and adsorption technology. With the development of intelligent logistics, AGV (Automated Guided Vehicle), which integrates sensing, driving and control, is widely used in commodity sorting and delivery [10]. In recent years, a new intelligent transmission system Celluveyor is developed, through computer program design, and drive the universal wheel to achieve different transmission paths [11]. However, the Celluveyor transmission system, due to the size limitations of traditional electromagnetic motors and their transmission devices, makes the size of each module unit larger and is suitable for the transmission of large-size items in logistics.

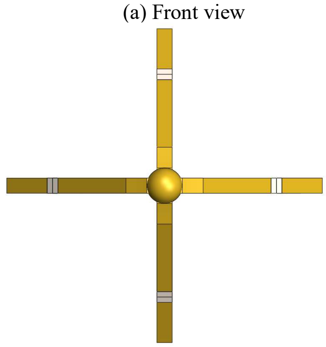
In this paper, due to the problems of the traditional transmission platform device, such as low transmission accuracy and single transmission path, it is difficult to meet the needs of precision transmission of micro and small transport material path planning, the control of precision conveyor based on array piezoelectric drivers will be carried out.

II. LAYOUT PRINCIPLE AND COORDINATED CONTROL OF PIEZOELECTRIC PRECISION CONVEYOR

The piezoelectric actuator used in the precision conveyor in this paper is a two-degree-of-freedom (two-DOF) linear piezoelectric actuator. At present, there are two typical types of linear piezoelectric actuators: tower type and V-shape. The tower piezoelectric driver structure, the vibration structure of the tower, the whole structure of the tower piezoelectric driver is completely symmetrical structure, with two degrees of freedom; The V-shaped piezoelectric actuator has the advantages of large output force, high output speed and large push-to-weight ratio. In order to realize the demand of high-thrust two-DOF piezoelectric actuator for precision transmission, two V-shaped piezoelectric actuators are connected orthogonal at the driving foot to realize the output of positive and reverse driving force in the direction of two degrees of freedom by referring to the orthogonal symmetrical surface of the tower piezoelectric actuator. In this paper, the structure of double-V orthogonal two-DOF piezoelectric actuator is adopted. The double-V orthogonal two-DOF piezoelectric actuator has two orthogonal symmetric planes. In either of the symmetric planes, the stator's operating modes are the local bending vibration modes of the oscillator, one is symmetric mode and the other is antisymmetric mode, as shown in Figure 1



(a) Front view

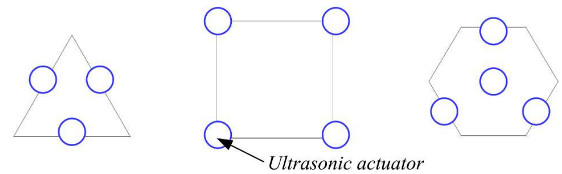


(b) Top view

Figure 1. Double-V orthogonal two-DOF piezoelectric actuator

The actuator layout of the piezoelectric precision conveyor includes triangular, square and regular hexagonal layouts. The triangular layout includes three ultrasonic actuators, and the square layout and regular hexagonal layout include four ultrasonic actuators. The specific layout is shown in Figure 2.

Firstly, the triangular layout has only three two-DOF piezoelectric actuators and needs less space, which is helpful for minimizing the delivery platform. However, this layout method does not have an actuator parallel to the certain direction of a movement, which is not good for linear moving. Moreover, in the process of module combination, the relative position of the ultrasonic actuator will change continuously, which will have an adverse impact on the coordinated control of the entire platform. Next, the square layout has four ultrasonic actuators. This type of layout has a good effect on linear movement. But, due to the limitation of the two-DOF piezoelectric actuators' size, there will be a space in the middle part, and the space utilization is low. Finally, the regular hexagon layout combines the advantages of the first two layouts, makes full use of the working space. It does well in both linear and curved motion, and can realize the rotation of the carried materials. Figure 3 shows the basic movement of the carried materials with the regular hexagon layout in the conveyor.



(a) triangle (b) square (c) regular hexagon

Figure 2. The location of the ultrasound actuator in different layouts.

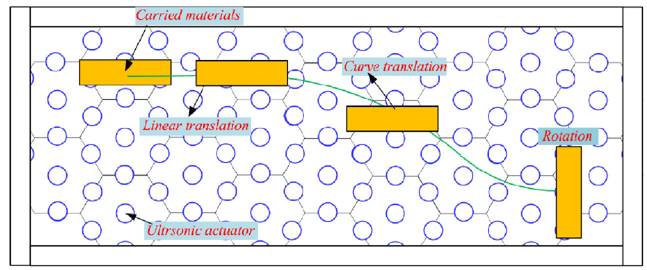


Figure 3. The basic movement of carried materials with regular hexagon layout in the precision conveyor.

The working conditions of the piezoelectric precision conveyor are divided into two categories: translation and rotation. Besides, the motion of each actuator can be determined when translating or rotating according to the certain layout. Figure 4 shows the distribution of actuators with the regular hexagonal layout of the piezoelectric precision conveyor.

As shown in Figure 4, the piezoelectric precision conveyor with regular hexagonal layout has four ultrasonic actuators, each of which has two degrees of freedom directions for moving. The motion directions of ultrasonic actuators are as follows: 1) The x-axis and y-axis direction of the ultrasonic actuator 1 is the same as the x-axis and y-axis direction of the precision conveyor respectively; 2) The x-axis of ultrasonic actuator 2, 3 and 4 are toward ultrasonic actuator 1 respectively, and the y-axis of actuator 2, 3 and 4 is perpendicular to the x-axis respectively. In the next section, the working principle of translational and rotational motion will be analyzed respectively.

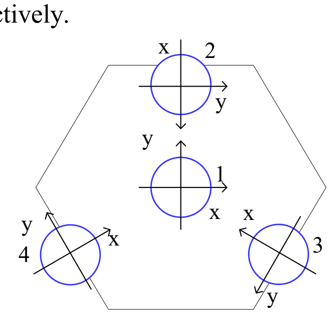


Figure 4. Actuator distribution with the regular hexagonal layout of the piezoelectric precision conveyor.

The ultrasonic actuators 1 and 2 produce the same displacement to promote the linear movement of the carried materials. In contrast, the rotational movement of the carried materials will be achieved by the coordinated work of actuators 1, 3 and 4 according to different angles. The relationship between the specific angles and the ultrasonic actuator is shown in Figure 5.

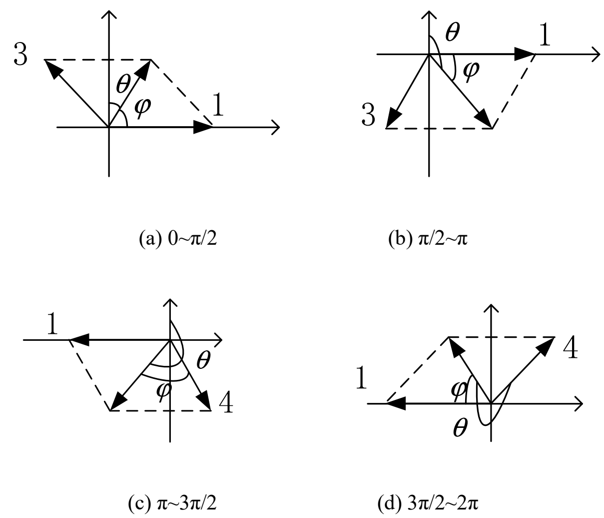


Figure 5. Solution of each motion angle range.

In order to move rotationally, the speed ratio of the two ultrasonic actuators should be determined for them to work together. Then, set the maximum speed of the ultrasonic actuator as v, and the proportional coefficients of the two ultrasonic actuators were set as m and n at the same time to satisfy the formula $m+n=1$. So, knowing the movement angle of the combined movement and the length of the two sub-movements, the values of the two proportional coefficients m and n are obtained, so as to the speed proportional relationship of the two ultrasonic actuators.

In Figure 5, θ is the rotation angle for the actual movement. When the motion angle is 0~π/2, let the speed v_1 of the ultrasonic actuator 1 be mv, and the speed v_3 of the ultrasonic actuator 3 be nv. According to $\varphi=\pi/2-\theta$ shown in Figure 5(a), there are the proportional relationship between v_1 and v_3:

$$\begin{cases} v_1 = mv \\ v_3 = nv \\ m+n=1 \\ \dfrac{v_1}{\sin(\pi-\frac{\pi}{6}-\varphi)} = \dfrac{v_3}{\sin\varphi} \end{cases} \quad (1)$$

After the calculation, the values of m and n are obtained.

$$\begin{cases} m = \dfrac{\sin\theta+\sqrt{3}\cos\theta}{2\cos\theta+\sqrt{3}\cos\theta+\sin\theta} \\ n = \dfrac{2\cos\theta}{2\cos\theta+\sqrt{3}\cos\theta+\sin\theta} \end{cases} \quad (2)$$

Similarly, the speed of each actuator under other motion angles can be obtained, and the specific relationship is as follows:

$$v_{1x} = \begin{cases} 0, \theta=0 \\ \dfrac{(\sin\theta+\sqrt{3}\cos\theta)v}{2\cos\theta+\sqrt{3}\cos\theta+\sin\theta}, \theta\in(0,\frac{\pi}{2}] \\ \dfrac{(\sqrt{3}\sin\theta-\cos\theta)v}{\sqrt{3}\sin\theta-3\cos\theta}, \theta\in(\frac{\pi}{2},\pi) \\ 0, \theta=\pi \\ \dfrac{-(\sqrt{3}\sin\theta+\cos\theta)v}{\sqrt{3}\sin\theta+3\cos\theta}, \theta\in(\pi,\frac{3\pi}{2}] \\ \dfrac{-(\sqrt{3}\cos\theta-\sin\theta)v}{2\cos\theta+\sqrt{3}\cos\theta-\sin\theta}, \theta\in(\frac{3\pi}{2},2\pi) \end{cases}, \quad (3)$$

$$v_{1y} = \begin{cases} v, \theta=0 \\ -v, \theta=\pi \\ 0,\ \theta\neq 0,\ \pi \end{cases}$$

$$v_{2x} = \begin{cases} -v, \theta=0 \\ v, \theta=\pi \\ 0,\ \theta\neq 0,\ \pi \end{cases}, \quad (4)$$

$$v_{2y} = \begin{cases} v, \theta=\pi/2 \\ -v, \theta=3\pi/2 \\ 0,\ \theta\neq \pi/2, 3\pi/2 \end{cases}$$

$$v_{3x} = \begin{cases} \dfrac{2\cos\theta}{2\cos\theta+\sqrt{3}\cos\theta+\sin\theta}, \theta\in(0,\frac{\pi}{2}] \\ 0,\ \theta\in(\frac{\pi}{2},2\pi] \end{cases}, \quad (5)$$

$$v_{3y} = \begin{cases} \dfrac{-2\cos\theta}{\sqrt{3}\sin\theta-3\cos\theta}, \theta\in(\frac{\pi}{2},\pi) \\ 0,\ \theta\in[0,\frac{\pi}{2}]\cup[\pi,2\pi] \end{cases}$$

$$v_{4x} = \begin{cases} \dfrac{2\cos\theta}{2\cos\theta+\sqrt{3}\cos\theta-\sin\theta}, \theta\in(\frac{3\pi}{2},2\pi) \\ 0,\ \theta\in[0,\frac{3\pi}{2}] \end{cases} \quad (6)$$

$$v_{4y} = \begin{cases} \dfrac{-2\cos\theta}{\sqrt{3}\sin\theta+3\cos\theta}, \theta\in(\pi,\frac{3\pi}{2}] \\ 0,\ \theta\in[0,\pi]\cup(\frac{3\pi}{2},2\pi] \end{cases}$$

In the formulas above, v is the maximum working speed of the ultrasonic actuator. According to the layout and working principle of the GSA-based fuzzy PID controller and piezoelectric precision conveyor, the coordinated control simulation model of the piezoelectric precision conveyor is built on the Simulink is shown in Figure 6.

According to the Figure 6, the predicted path is given by the path generation module in the coordinated control simulation, and then a suitable ultrasonic driver is selected to drive according to the working mode of the two-DOF actuator, and the actual path is output at last. Then, the linear path and the curved path are tracked respectively to verify the ability of the ultrasonic piezoelectric conveyor to coordinate the tracking path. Figure 7 and Figure 8 show the simulation results of tracking straight and curved paths, respectively.

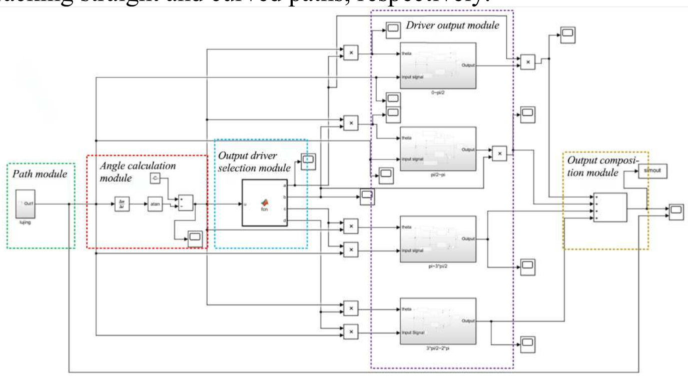


Figure 6. Block diagram of coordinated control simulation of piezoelectric precision conveyor.

According to Figures 7 and 8, due to the delay characteristics of the ultrasonic driver itself, it will delay the start of work for a period of time at the beginning, and then gradually approach the predetermined trajectory and always maintain within a certain error range. Thus, it can be concluded that the coordinated control and tracking path capability of the ultrasonic piezoelectric transmission platform is feasible.

Aiming at the coordinated control of piezoelectric conveyor, a coordinated control experimental platform is built to test whether the piezoelectric transfer module can move things translationally and rotationally.

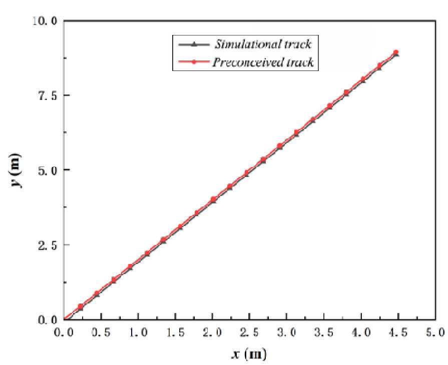


Figure 7. Tracking simulation results of straight line.

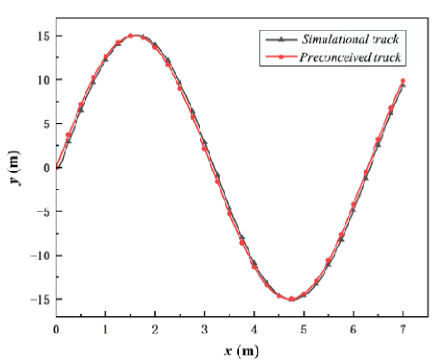


Figure 8. Tracking simulation results of curve line.

III. COORDINATED CONTROL EXPERIMENTS

In the coordinated control experiment, the experimental platform is mainly composed of a signal generator, a power amplifier, an oscilloscope, a displacement sensor, a data acquisition card and a PC. The power amplifier model in this experiment is HFVA-64, which can amplify the frequency range of the signal from 5kHz to 150kHz. Figure 9 shows how the coordinated control experimental platform is connected.

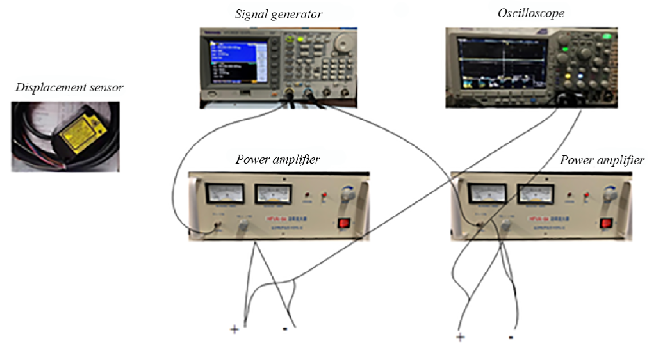


Figure 9. The connection of the coordinated control experimental platform.

The basic idea of this coordinated control experiment is as follows: 1) The signal generator generates a two-phase sine signal with a phase difference of 90°. The frequency of this signal is 69.2kHz, and the peak-to-peak voltage is 4V; 2) The two-phase sinusoidal signals are input into two power amplifiers respectively, which causes the peak-to-peak value of the excitation signal is amplified to 400V; 3) The amplified signal is input into the piezoelectric precision conveyor, which drives the module to move the carried object; 4) The displacement of the carried things are measured by the displacement sensor, and the output data is transmitted to the PC by the data acquisition card.

Firstly, an experiment which is for the translation of its carried things is carried out by the coordinated control of the piezoelectric precision conveyor. So, the frequency of the excitation signal is 69.2khz, the peak-to-peak voltage is 400V, the phase difference between the two trust signals is set as 90°, and the load weight of the material is 9.5g. The experimental results are shown in Figure 10.

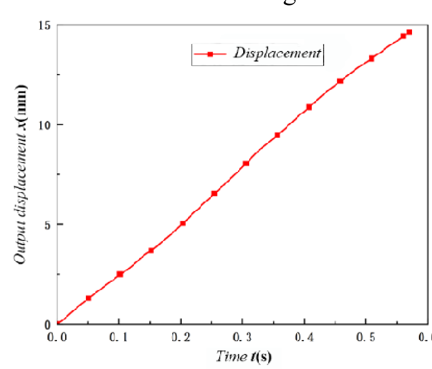


Figure 10. The output curve of the translation displacement of the carried objects.

Shown in Figure 10, the average speed during the translational process of the carried objects is calculated to be

25.61mm/s. The linearity of the translational displacement of the carried objects is good during the experiment. Though the experiment, it is further verified that the piezoelectric precision conveyor can control the translation coordinately and achieve excellent results.

The following experiment is to realize the rotational motion of the carried objects through the coordinated control of the piezoelectric precision conveyor. In this time, the excitation signal is the same as it in the motion experiment, and the weight of the objects to be carried is 25.6g. The experimental results are shown in Figure 11.

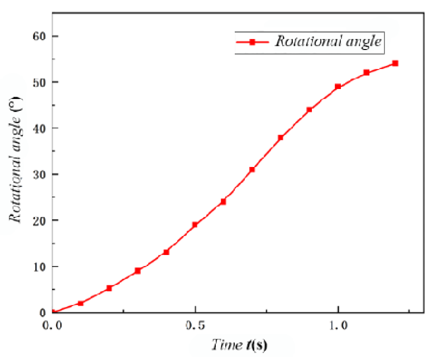


Figure 11. The output curve of the rotation angle of the carried objects

Shown in Figure 11, the average speed of the rotational movement of the carried objects is calculated to be 45°/s. However, the linearity of the curve decreases slightly for a period of time near the end of the curve. The reason is that since the piezoelectric precision conveyor is consist of four ultrasonic actuators, and the four ultrasonic actuators are not completely the same due to processing errors, their driving effects will also be different. In the rotation experiment, when the carried objects rotate through a certain angle, there will be a situation that the rotational angular velocity slows down as the driving ability of a certain ultrasonic actuator may be slightly worse than that of the others. In the follow-up research work, the consistency of each actuator's output performance can be achieved through the process improvement and motion control compensation of the piezoelectric precision conveyor.

IV. Conclusion

In this paper, a precision conveyor based on array of piezoelectric actuators is used for driving and transmitting the small carried materials. The drive layout of ultrasonic piezoelectric transmission platform module is studied, and the layout of the ultrasonic drive module in the form of a square hexagon is determined by combining the characteristics and working principle of the ultrasonic piezoelectric transmission platform itself. The working principle of the ultrasonic piezoelectric transmission platform is analyzed, and the relationship between the output speed of the ultrasonic drive in two degrees of freedom and the required motion angle is derived.

The performance test platform of the ultrasonic piezoelectric transmission platform is built. Experimental tests are conducted to verify the driving performance of the ultrasonic actuator by varying the velocity of the transported material in the two degrees of freedom directions with the frequency, peak-to-peak value and phase difference of the excitation signal. The coordinated control experiments of the ultrasonic piezoelectric conveyor are carried out and the results showed that the coordinated control of the ultrasonic piezoelectric conveyor could realize the translational and rotational motion of the carried materials.

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