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HORIZONTAL TRAJECTORY TRACKING SYSTEM BASED ON ROTATING MIRROR

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Abstract- ***Target track is an important research dot in weapon performance testingfiled, to stable track the flying target in optical detection system and testing instrument, horizontal trajectory tracking system based on rotating mirror was researchedin this paper.A horizontal trajectory tracking method was proposed for the tracking problem in the process of the projectile flight, the design of rotating mirror was analyzed and designed;the calculation method of the rotating mirror tracking system were derived, and the influence factors were studied and analyzed, the rotating mirror rotation control algorithm without considering effect of gravity flight targetwasanalyzed and the angular displacement and angular velocity of the rotating mirror were given in the effective tracking range. Through experiment and calculation, the results show that the tracking system can achieve stable tracking of flying target.***

Index terms: projectile; tracking; rotating mirror; horizontal trajectory.

I. INTRODUCTION

Trajectory tracking system is a kind of system which can be tracked in real-time during the projectile flight[1]. In the weapon shooting range testing system, in order to ensure the stability and safety of flying target, the continuous target flight image test must be carried out.Because of the influence of the uncertainty in the experimental environment which will greatly reduce the accuracy of the test data, the favorable theoretical reference data for the follow-up testcan not be provided.According to the image data obtained in the process of the flying target using real time tracking of the flying target,the more comprehensive and reliable test data can be provided through the analysis and processing[2].

In the field of weapon shooting range test research, the original test research process through the field test constantlyto ensure the stability and safety of flying target. However, because the interference of unpredictable external parameters in the test environment, the expected results is hard to be obtained through the experiment and themode of this test,and the experimental data are normally incomplete which is difficult to analyze the regularity.Therefore, it is necessary to take the real-time tracking of flying target.The complete testdata can be obtained through the real-time trackingduring the process of experiment.According to the analysis of experimental data,part parameters of the flying target can be modified to avoid the same problems in the subsequent experiment. The tracking system is extraordinary significant to reduce the development cost of weapon system.

From the aspects of flight stability and safety, attitude analysis, and other aspects of the Target flight process, the image acquisition of target flight process is very important to complete the recording and analysis of parameters, such as speed, angle of attack, acceleration and velocity.

The traditional method of observing the target in the exterior ballistic trajectoryis using a high speed ballistic camera with a high resolution along the trajectorywhich is placed in a specified positionto collect a single image of a flying target through the camera's fixed field of view[5-7].Although this method can get a high resolution image of the projectile, but the position of the camera is fixed and the number of the camera is limited, so the shot to the flying area is small, the effective data of the projectile is also rare.The solution to this problem in the past is to choose a parallel path outside the trajectory of the projectile, and then install many CCD high speed cameras equipments on this path according to the requirements of the certain distance. Through the related image processing software[8,9], the target images taken by each camera are acquired by the relevant techniques, such as denoising, cutting, splicing etc., to obtain more complete information of flying target. High speed camera shooting record of flying target flight status and abnormal phenomenoncan provide real-time view parameters, in order to test the follow-up research and reference for flying target performance evaluation, fault analysis to provide sufficient information. But each camera's field of view is limited, complicated and very easy to get rid of many important information in the image processing of multiple CCD ballistic high speed cameras [10]. In addition, the high speed camera isexpensive and it needs a very long time to arrange the multiple cameras in each measurement position[11].Through the relevant speed control system to control the rotation speed of the tracking frame to synchronize tracking flying targets, such as photoelectric theodolite [12].Research and development of photoelectric theodolite is related to many fields of optics, electronics, mechanics, computer and other high-end technology.It is composed of a number of subsystems, capable of high precision measurement of the flying target, get the precise measurement data. The main purpose of the photoelectric theodolite is to target track and capture the flying target. Fast acquisition and tracking control system is the key to capture the target and maintain the target of the photoelectric theodolite [13]. In practical application, the photoelectric theodolite mainly in a variety of missile target emission process and the application of auxiliary process of carrier rocket flight and projectile shot in real-time process; taking into account the photoelectric theodolite research is difficult and high cost, it is rarely used to track for smaller flying target.

In this paper, a new method for simultaneous tracking and shooting flying targetbased on rotating mirror is proposed, and a singlehigh speed camera is used to synchronize the images of flying target. The method is useful for tracking small caliber projectiles with high speed.

II.WORKING PRINCIPLE OF TRACKING SYSTEM

The trajectory tracking mirror system is a device whichadds a lens before the camera, in order to increase the target view of the high speed camera obtained.The attitude of the flying target flight through projection into the camera lens,by hosting the lens of the rotation driving system, to achieve a clear observation of the flying target outside ballistic flight attitude. With the development of control technology, the trajectory tracking mirror system equipped with advanced control system has become a kind of brand-new tracking device.

For the measured projectile, firstly, the flight velocity is measured by the laser speed measuring system.At the same time, the delay time of start rotating mirror is calculated by the embedded system according to the flight speed of flying target.The rotating mirror to match the projectile speed real-time tracking the projectile.High speed camera acquisition and storage the images of the projectile[14].

A. system constitution

The tracking system is mainly composed of laser speed measurement module, rotating mirror module, embedded control module, highspeed camera and so on.The working principle diagram of tracking system is shown in figure 1.

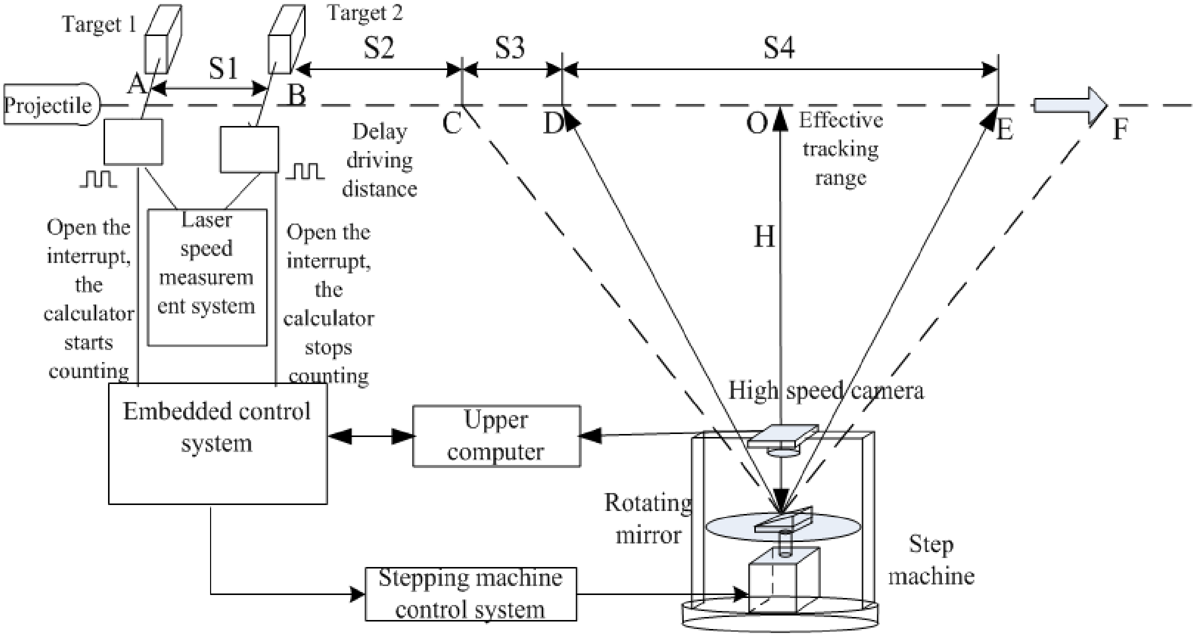


Figure 1.Working principle diagram of tracking system

When the system is working, the flying velocity of the flying target is obtained by the laser speed measurement module andtransmitted to the embedded control system.The delay time and rotation parameters are calculated according to the speed of the flying target. The rotating mirror control programis executed, so that the rotating mirror to match the speed of the flying target, then the image of the flying targetis collected and stored in the high speed camera.

B. laser speed measurement module

Sky target[15], screen target[16] and doppler radar, laser target, coil target and so on are used to test the exterior ballistic flying speed of weapon system. Different test methods have different characteristics.Such as the high accuracy of the doppler radar is not suitable for small caliber projectile velocity measurement, beasuse the equipment is huge and the price is also very expensive; screen target with good reliability, but the reaction speed of the system measurement accuracy is not high and fast in a short period of time; the anti-disturbance ability of the coil target to the external electromagnetic field is very poor; sky target can be easily influenced by outside environment, such as light, smoke, dust, rain and snow.

In comparison, the laser target is used in the photoelectric conversion method to achieve the effect of non-contact speed.Theequipment is easy to operate, the test precision is high, the system response speed is fast and the test area is very large, and it is not susceptible to weather changesin theapplication,so it is widely used in test of the projectile flight velocity[17].

Laser speed measurement consists ofthe timing instrument, two laser detecting surfaces which control the opening and stopping of the timerand signal processing circuit component[18]. The schematic diagram is shown in figure 2:

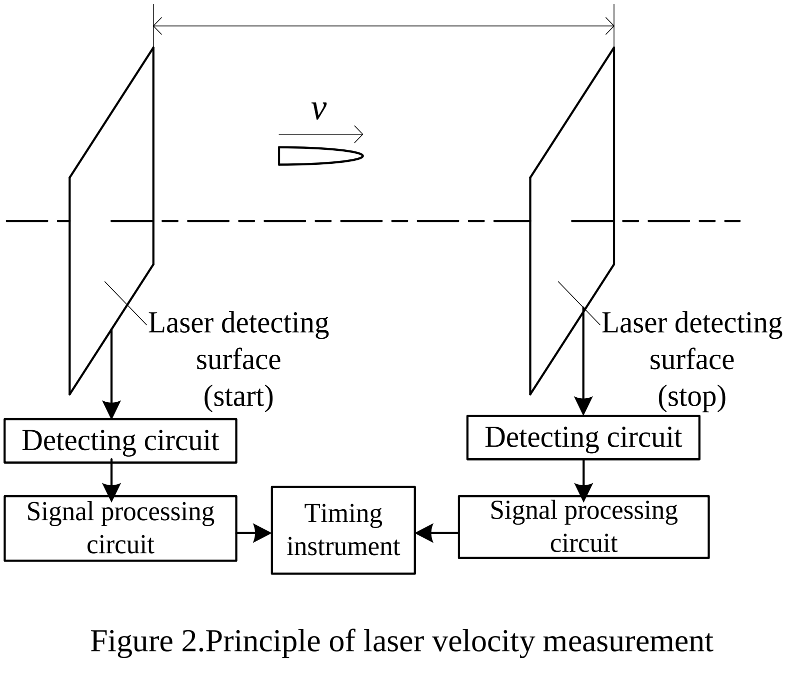


Figure 2.Principle of laser velocity measurement

Laser is obscuredby the flying targetwhen the flying target passes through the laser detecting surface.It causes the change of luminous flux. The signal processing circuit will transform the luminous flux change into the trigger signal of timing instrument.The trigger signalrespectively start and stop the timer to test the flight time of the target flying through the two laser detecting surfaces.The flight time is T. And the distancebetween the two laser detecting surfaces is S. The flight velocity of the flying targetisthe flight time T divided by the distance S.

$$v = \frac{S}{T} \tag{1}$$

III.TRACKING ALGORITHM DESIGN

From the perspective of control, the tracking accuracy can be significant improved if achieve the position closed-loop control based on controlling. However, the most important thingin the practical application of the trajectory tracking mirror system is to ensure that the tracking speed and target speed synchronization. Moreover, the scanning curve of the rotating mirror is obtained from the calculated results according to the simplified mathematical model.The algorithm of position closed-loop control become complex and it Impact on real time performance of the systemif the system cannot provide the device to test the instantaneous velocity of target. Thus, the system applies the position cpen-loop control method, which means the scanning curve of rotating mirror is calculated and corrected by the pre-prepared progress.Meanwhile, the process of test and measurement for rotating control is the open-loop control[17].The control system which adopts the stepper motor is theposition open-loop control system.Becausethe electromotoris a stepper motor, ,the output of electromotorvelocity curve response sequence must be revised accordingly in the period of preparation[18]. The calculation of angular position control sequence is the main step of pre-prepared progress.The calculation based on the scope of the tracked target velocity and the system layout parameters isto obtain the accuracy of the tracked targetvelocity.The specializedsystem is applied to measure the velocity of one point which is located at the targettrajectory.The calculation of themaximum discrete interval is applied on the scanning rate of pre-prepared progress to obtain the numerical control sequence under different velocity. In the practical test, the rotation of rotating mirror is controlled by the calculated control sequence which closest approach to the actualvelocity under different velocities of tested target. The control of rotating mirror is a major component of the trajectory tracking mirror system which is crucial to formingthe images and the resolution of the images.

A. projectile flight trajectory

According to the relevant theory research,the size of the air resistance F is mainly determined by three factors: a. the shape, size and surface conditions of the flying target; b. atmospheric density, humidity and atmospheric pressure; c. the relative speed of the flying target withair[19]. Through the relevant information, it can be known that the air resistance value of the target is proportional to its maximum cross-sectional area.At the same time, if the resistance is greater and the airdensity is greater, the speed of the target is influenced more severely by environmental parameters. According to the relevant theory, the expression ofthe air resistance F is:

$$F = S\frac{\rho v^2}{2}C_{X0}(v/v_{yx}) \tag{2}$$

Among them: S is the maximum cross-sectional area of the flying target; $v$is the relative speed of the target and the air; $\rho$is atmospheric density; $C_{X0}(v/v_{yx})$is drag coefficient. It is a function of the ratio of the target velocity v and the velocity of sound v_{yx}. The C_{X0} of the function symbol "O" indicates the drag coefficient of the target trajectory and the velocity vector angle is zero.

Assuming that the flying target mass is m, the expression of the air drag acceleration can be obtained:

$$a = \frac{F}{m} = S\frac{\rho v^2}{2m}C_{X0}(v/v_{yx}) \tag{3}$$

The target flight trajectory equation can be calculatedaccording to the above formula.

B.Tracking system space position

As shown in figure 1, the laser speed measurementmodule is arranged at the starting end of the projectile flight.The rotating mirror and the high speed camera are arranged in the vertical trajectory of the projectile and its distance is H, the selection of H has an effect on the tracking range, target image size, rotation speedof therotating mirror, etc[20].

If the camera lens focus is f, the caliber of the projectile is D, the imaging size of the bullet in the image plane of the high speed camera is$l$, and the length of the camera lens vertically center reflector mirror is L,the imaging relationship of the flying object in the camera lens is:

$$\frac{f}{l} = \frac{L+H}{d} \tag{4}$$

According to the principle of plane mirror, tracking the target in the mirror image will through a "small - Big - small" change process. The length of the imaging of the flying object can be set according to the experimental conditions.The flying target length accounted for 1/5-1/3 of the length of the camera lens. Therefore, when the target has just entered the field of vision, the imaging length cannot be greater than the length of the camera lens 1/5.It cannot be more than 3/5 when the target is flying to the flight path perpendicular to the rotating mirror. Thus, to meet the imaging requirementsthe H value can be obtained by this formula:

$$\frac{5f}{3l}d - L < H < \frac{5f}{l}d - L \tag{5}$$

The tracking range of the rotating mirror is increased with the increase of H value. At the same time, the increase of the value not only plays a delaying role on the rotation time when the rotating mirror in the tracking process, but also for other modules to reduce the performance requirements. However, the distance change longer also brings some disadvantages that it increases the difficulty of camera imaging. A telephoto lens distance is required to obtain a clear image. Therefore, the value of H in the experimental test is generally 20-50m.

C.Rotating mirror rotation algorithm

The effective tracking range of the rotating mirror to flying targetis shown in figure 3.The field of view of the high speed camera is $\emptyset$. Point A is the starting point of the effective tracking range of the flying targettrajectory[21]; the reference point of the point Mis the vertical distance of the projectile's flight path to the rotating mirror system, and the point P is the position of the rotating mirror, that is, the vertical distance MP is expressed by H; pointC is the end point of the effective tracking range of the flying targettrajectory. The angle betweenline AP and line BP indicates that the angle of the target is gradually changing.

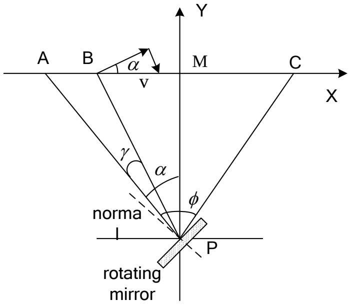


Figure 3.Rotating mirror tracking range

The angle between theline AP and the line MP of the projectile flight path to the rotating mirror system is α.Assuming that the angular velocity of the rotating mirror isω_{AP}. According to the calculation principle of angular velocity:

$$\omega_{AP} = \frac{vcos\alpha}{H/cos\alpha} = \frac{vcos^2\alpha}{H} \tag{6}$$

From the formula,the target flight speed and the angle of the rotating mirror are related to the target flight time.Thus the angular velocityof the rotating mirrorformula withthe target flight time variable is as follows:

$$\omega_{AP}(t) = \frac{v(t)cos^2\alpha(t)}{H} \tag{7}$$

Real-time tracking of the flying target using a rotating mirror to ensure that the image of target's movement is relatively static in the camera's field of view[21]. By the specular reflection theorem, when the angle of rotating mirror turns, the angle of the reflector mirror is:

$$\omega = \frac{vcos^2\alpha}{2H} \tag{8}$$

Not considering the influence of air resistance and gravity, the relationship between the effective tracking range of the rotating mirror and the vertical distance between the target trajectory and the rotating mirror system is:

$$AC = 2H \tag{9}$$

That is to say, when the projectile is flying, the effective distance measured in the field of rotating mirror is:

$$S = 2Htan\frac{\emptyset}{2} \tag{10}$$

According to the calculation, the angle between line AP and line MP can be expressed by the following formula:

$$\alpha = \begin{cases} arctan\frac{Htan\frac{\emptyset}{2}-vt}{H} & AM > vt \\ arctan\frac{vt-Htan\frac{\emptyset}{2}}{H} & AM < vt \end{cases} \tag{11}$$

At the same time, the rotation angle of the mirror is derived from the principle of specular reflection:

$$\theta = \begin{cases} \frac{\frac{\emptyset}{2} - \alpha}{2} \\ \frac{\frac{\emptyset}{2} + \alpha}{2} \end{cases} \tag{12}$$

Simultaneous formula 10 and formula 11, the relationship between the angle of the rotating mirror and the time is:

$$\theta = \begin{cases} \frac{\frac{\emptyset}{2} - arctan\frac{Htan\frac{\emptyset}{2} - vt}{H}}{2} & AM > vt \\ \frac{\frac{\emptyset}{2} + arctan\frac{vt - Htan\frac{\emptyset}{2}}{H}}{2} & AM < vt \end{cases} \tag{13}$$

The angular displacement of the mirror is:

$$\theta = \frac{1}{2}\left(\frac{\emptyset}{2} - arctan\frac{Htan\frac{\emptyset}{2} - vt}{H}\right) \tag{14}$$

Thus, the relationship between the angular velocity of the rotating mirror and the speed of the flying target can be deduced:

$$\omega = \frac{v}{2H}cos^2\left(arctan\frac{Htan\frac{\emptyset}{2} - vt}{H}\right) \tag{15}$$

S3 in figure 4 is the distance between the prepare position(-50 degrees) and tracking position (-45degrees). A formula of the distance between the prepare position(-50degrees) and tracking position (-45degrees) could be obtained when the maximum effective tracking angle is90 degrees. There are 5 degrees to make the angular velocity of the rotating mirror and the target flight speedsynchronous. The formula could be calculated out by the geometrical relationship in figure 4 as:

$$D = (tan50° - \tan45°) \times H \tag{16}$$

The figure of the prepare position(-50degrees) and tracking position (-45degrees) is shown below：

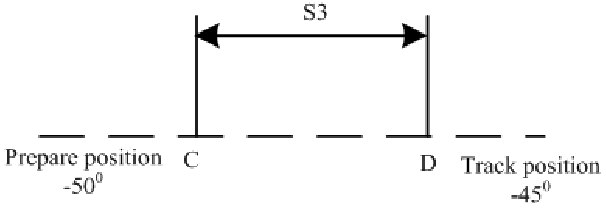
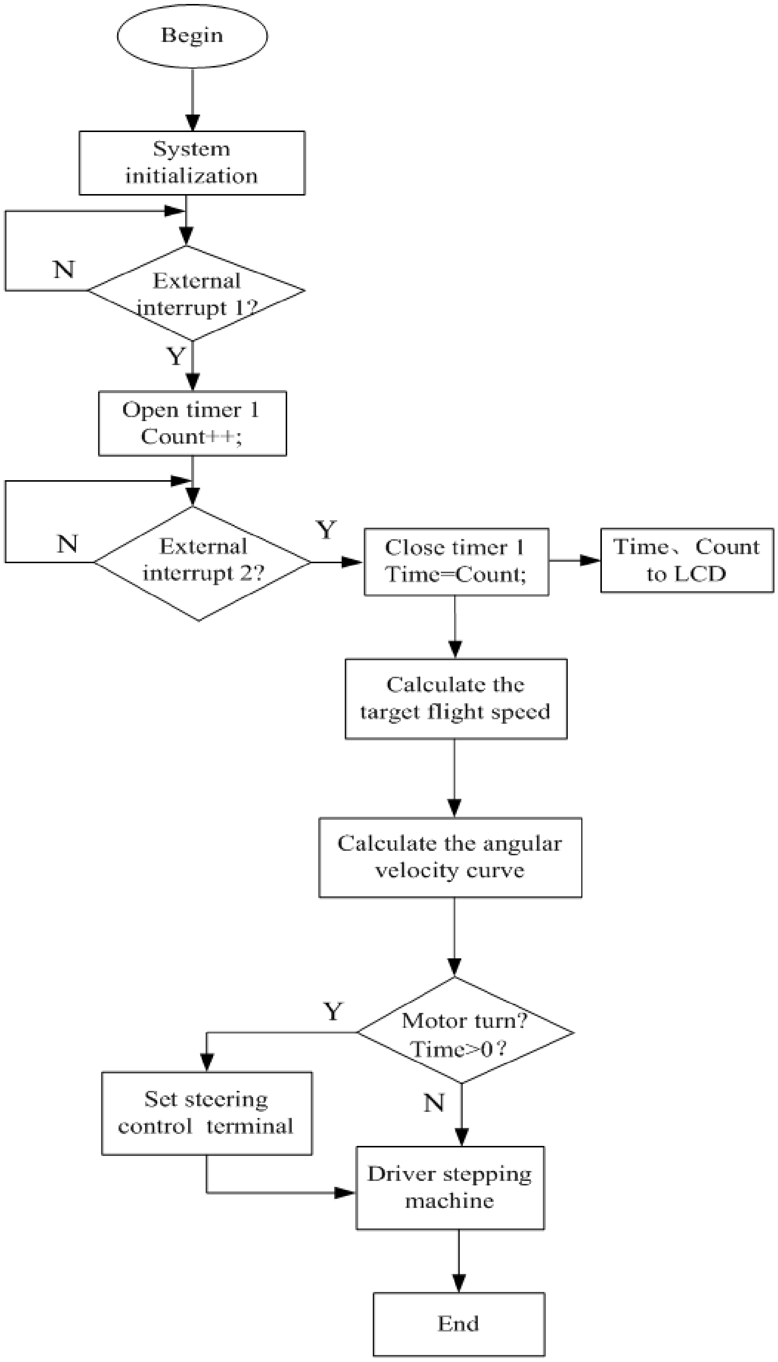


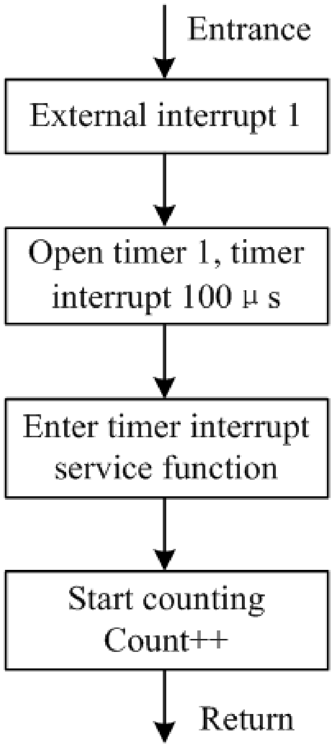
Figure 4. The principle diagram of the ballistic flight after reference points

Ⅳ.PROGRAM DESIGNING

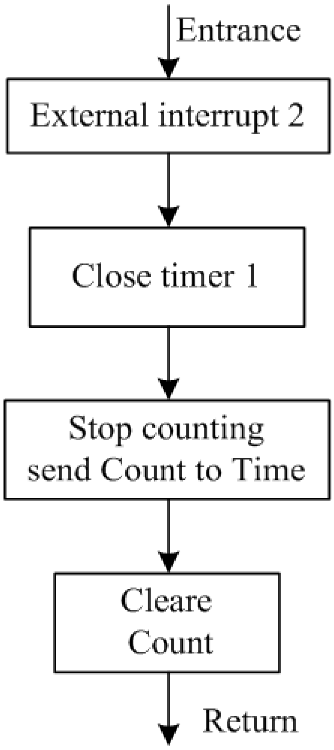
According to the above discussion, Thecontrol program was designed, the flow chartsare shown in figure 5.



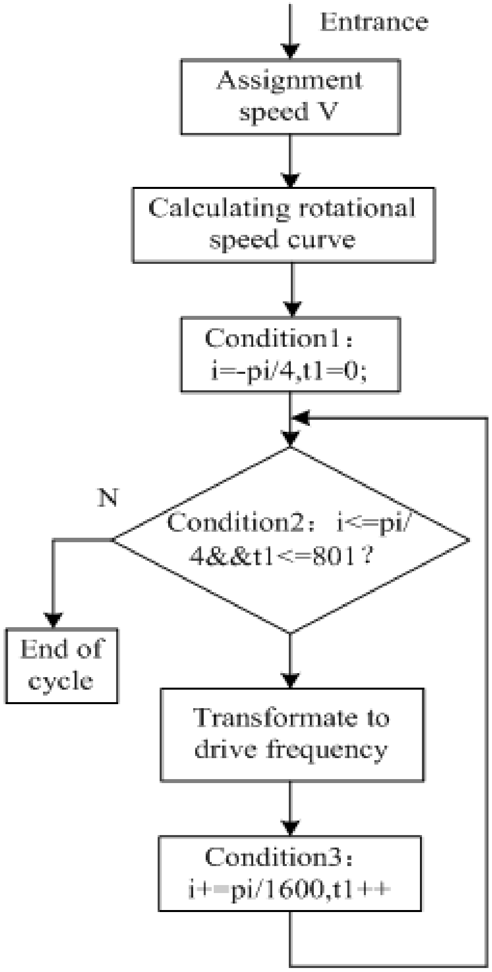
(a). System overall flow chart



(b). External interrupt 1 response program flow chart



(c). External interrupt 2 response program flow chart



(d). Step machine system interrupt response program flow chart

Figure.5 The rotating mirror control program flow chart

When the first trigger signal is detected, the external interrupt 1 is executed to open timer 1(Count is defined as the counting period 1 us). The external interrupt 2 is executed to close timer 1and the time of the two interrupt was calculatedwhen the second trigger signal come in. According to the time, the speed curve of rotating mirror was calculated to control the stepper motor.

Ⅳ.SYSTEM SIMULATION AND EXPERIMENTAL ANALYSIS

According to the above deduction, not considering the influence of the air resistance and gravity of the target, the rotating angle and angular velocity of rotating mirror can be simulated. Assuming that the target takes 1000m/s as a uniform linear motion, the distanceH is 50m. The angle of the flying target and the curve of the angular velocity versus time are shown in figure5 and figure 6:

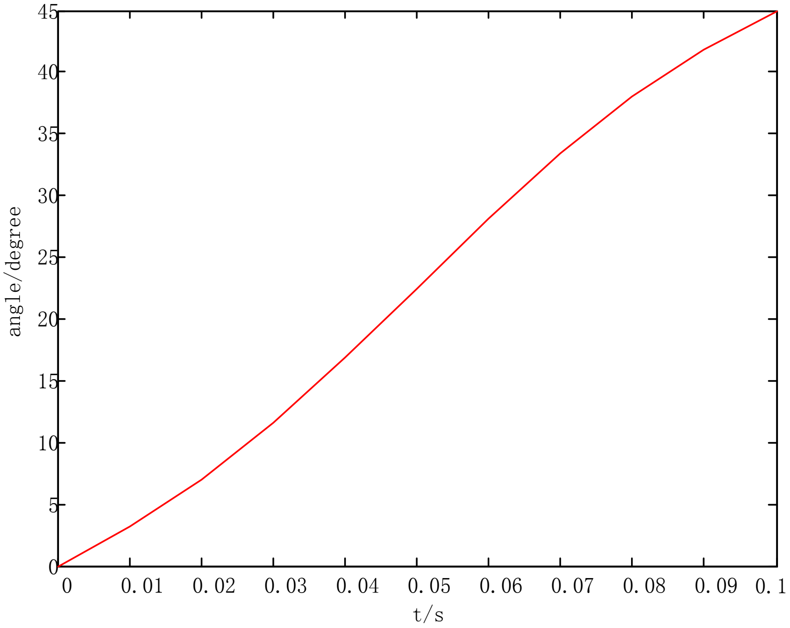


Figure 5. Rotating mirror angle change curve

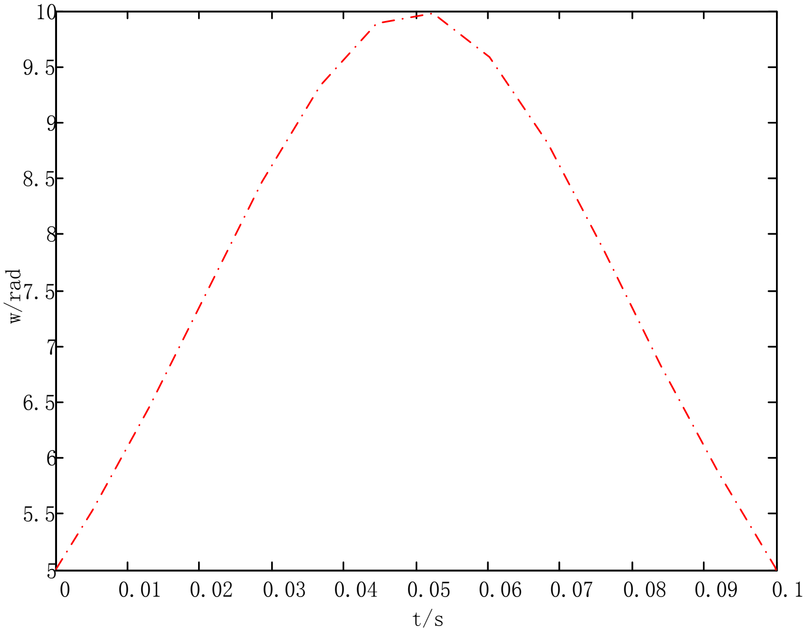


Figure 6. Rotating mirror angular velocity change curve

The essence of the rotating mirror system working normal is that the stepper motor system is required to work in accordance with the requirements of the experiment. According to the principle of stepping motor, the angular displacement of the rotating mirror can be obtained by the output pulse number of the controller. At the same time, motor speed is closely related with the output pulse frequency. So, the rotating mirror system should be able to track the flying target in real time. The mirror must rotatesaccording to the angular velocity fitting curve which take the speed of the flying target as a reference to rotate.

For rotating mirror of the rotational speed of$n$:

$$n = w/2\pi \tag{16}$$

In this experiment, we choose the two phase six wire hybrid stepping motor with open-loop control.The distance between the rotor and the rotor are evenly divided into 50 parts.It should be strictly to ensure that the stator and rotor tooth width and tooth spacing are equal. When the stator windings are in accordance with the eight beat power,the step angleis 360°/(50×8)=0.9°. By the stepper motor rotation principle, it can be seen that the step motor every step needs a pulse signal.As shown in figure 3, the angular velocity of the motor is a variable. So, the frequency value of the pulse signal which controls the motor operation is also changed. The pulse frequency is :

$$f = \frac{360°w}{2\pi \times 0.9°} = \frac{1000v\cos^2\alpha}{\pi H} \tag{17}$$

The formula of angular displacement and angular velocity of the rotating mirror are derived according to the above.MATLAB is used to simulate the scanning curve of the ideal state. Assuming that the vertical distance H is 50m, the target velocity is 0 to 1000m/s, the range of the angle is [-45°,45°], respectively, the parameters are brought into the formula 16. The relationship between the pulse frequency of the stepping motor and the angular velocity of the rotating mirror is simulated, and the simulation curves are shown in figure 7.

As the picture shows, 3D images in a graph is express the relationship curve between the stepper motor pulse frequency, rotating mirror angular velocity and flying target speed. The two-dimensional image in the graph is the projection of the curve in the two-dimensional plane, and the whole image is shown in figure 8.

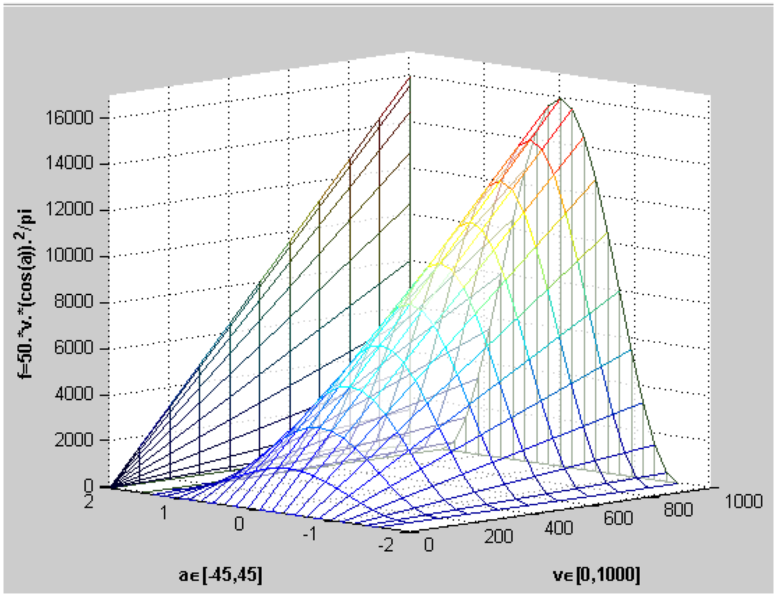


Figure7.The relationship between the motor operating pulse frequency and the angular velocity of the rotating mirror

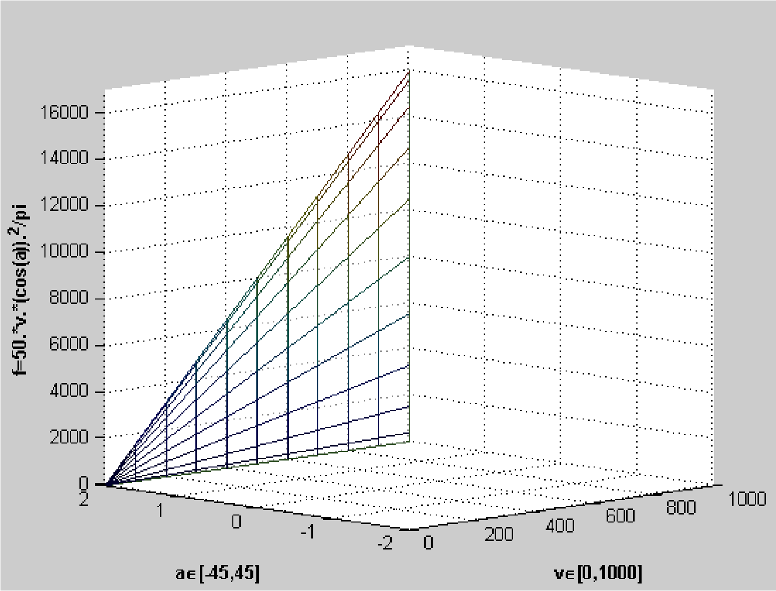
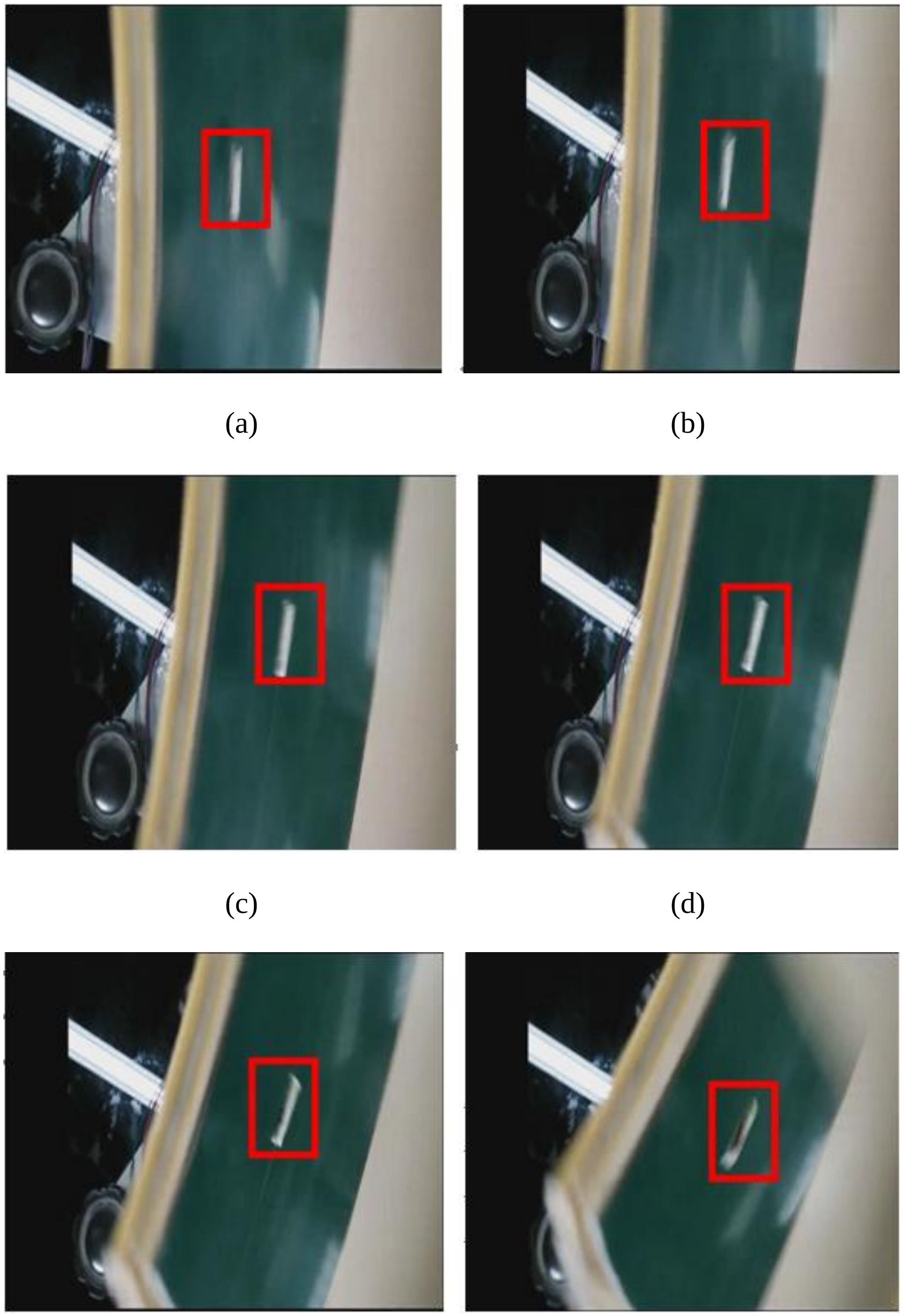


Figure8. Two dimensional plane projection curve of motor working pulse frequency

As shown infigure 9, the point of view of the system is discrete, and the speed of the target is also discrete.Then, under a certain speed value,theflying target frequency change curves of different points within the effective distance of rotating mirror trackingcan be gotten. According to the rotation frequency curve of step angle stepper motor, the control precision of the system can be improved.

Tracking experiments are carried out using the initial flight speed of 50m/s simulation target. 6 picturesof different moments are capturedfrom the high-speed video, as shown in figure 9.The simulated target is taken in the rectangular box in the picture.



(a) (b)

(c) (d)

(d) (e)

Figure9.Simulation of flight target tracking image

According to the results of the experiment, when the simulatedtarget passes through the laser speed measurement module, the embedded control module can obtain the flight speed and correct the rotation parameters in real-time. The rotating mirror can achieve the tracking of the flight target, and the target is always maintained at the center of the high speed camera imaging plane.

Ⅴ. CONCLUSIONS

In this paper, the horizontal trajectory tracking method based on rotating mirror is proposed for the tracking problem in the process of the projectile flight.The working principle and constitution of the tracking system are analyzed.The rotation mirror rotation control algorithm for flight target with no consideration of the gravity effect is deduced.The function of the angular displacement and angular velocity of the rotating mirror in the range of effective tracking are given.The rotating mirror speed change and the relationship between working pulse of stepping motor and the rotating mirror speed is simulatedrespectively. Tracking experiments were carried out using the simulatedtarget of flight velocity 50m/s.The experiment results show that the tracking system can tack the flying target stably, and keep the flight target always in the center of the camera's field of view.

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