

## Research Article

# Airborne Laser Communication System with Automated Tracking

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The acquisition, alignment, and tracking system is an important part of airborne laser communication and is the prerequisite and guarantee for the normal communication link. In order to solve the problem of automatic tracking of laser communication links in the airborne environment, the rapid capture, alignment, and tracking of beams between terminals are realized. This article proposes a stepping motor as a control servo system and a four-quadrant detector as an automatic tracking method for the detection unit. The pulse width modulation signal controls the rotation speed of the stepping motor and combines the position distribution of the light spot on the four-quadrant detector to achieve high-precision beam tracking. On this basis, indoor simulation experiments are carried out. After many experiments, the tracking accuracy is better than  $2.5 \mu\text{rad}$ , which shows that the system can be applied to airborne laser communication, and it is verified that this method has good automatic tracking performance for airborne laser communication.

## 1. Introduction

As a type of free-space optical communication (FSO), unmanned aerial vehicle (UAV) airborne laser communication has the advantages of large communication capacity, good concealment, strong anti-electromagnetic interference ability, and small terminal size. Compared with ground laser communication, airborne laser communication will not be blocked and interfered by obstacles on the ground, and it has better mobility. However, airborne laser communication is not only affected by environmental factors such as atmospheric turbulence and background light, but the relative movement of the UAV platform and the size of the equipment also increase the difficulty of establishing a laser communication link [1, 2].

In the laser communication system, the methods of capture, alignment, and tracking are used to establish and maintain accurate and reliable laser communication links. At this stage, due to the large size and heavy weight of traditional APT systems, aircraft, high-altitude platforms, or large unmanned aerial vehicles are generally used as the

carrying platform for communication relays for airborne laser communication. However, this article uses a small six-rotor UAV as the carrying platform, so a light and fast deployment airborne laser communication automatic tracking control system is needed.

The use of four-quadrant detector (QD) as a system for capturing and tracking detectors does not require additional high-power beacon lasers, beacon transmitting branches, and beacon light receiving detectors. It can minimize the complexity, power consumption, and volume of the system and contribute to the realization of lightweight and miniaturized laser loads [3, 4]. The four-quadrant detector studied by the US Naval Research Laboratory [5] can achieve a detection sensitivity of  $-50 \text{ dBm}$  when used in communication reception, and its response is  $-55 \text{ dBm}$  when used in tracking. In 2017, the United States planned to carry out the "Laser Communication Relay Demonstration Verification" experiment [6]. This experiment will be used to verify the data relay capability of the laser communication system and the radio frequency communication system. The system receives the beam signal from the ground station and then

forwards the signal to another ground station to verify the effectiveness and reliability of the laser communication technology. At present, many domestic institutions have successively carried out research on airborne laser communication technology. Among them, Changchun University of Science and Technology completed the communication test experiment between two Y-12 aircraft in 2013 [7], with a communication distance of 144 km and a communication rate of 2.5 GB/s. In 2017, the 34th Research Institute of China Electronics Technology Group [6] launched a research on small rotary-wing drones and conducted drone communication experiments with a communication rate of 1.25 Gb/s and a communication distance of 6.7 km. The National University of Defense Technology [8] studied the influence of a four-quadrant detector for laser beam riding guidance seeker on the signal light tracking, and its position detection sensitivity can be accurate to  $0.947 \mu\text{m}$ . In the system tracking test conducted by Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences [9], the static tracking accuracy reached  $0.18 \mu\text{m}$ . However, compared with international research and development, our country's research and experiment on airborne laser communication technology are relatively lagging behind, and there is insufficient experience in the design of light and miniaturization of laser communication systems, especially the research on UAV laser communication systems.

This article aims at the miniaturization and lightweight requirements of the airborne laser communication automatic tracking system of the six-rotor UAV. We design a new type of airborne laser communication structure, using stepper motors and four-quadrant detectors to achieve beam capture, alignment, and tracking.

## 2. Method of Beam Acquisition, Pointing, and Tracking

*2.1. Automatic Tracking Control System Structure.* The airborne laser communication automatic tracking control system is composed of a laser emitting unit, an aiming actuator, a through-hole four-quadrant detector, an amplifier, and a control unit. The experimental schematic diagram is shown in Figure 1. The direct light emitted by the laser on the ground side passes through the Cassegrain telescope and the collimating lens to emit parallel light, and after being transmitted through the atmospheric channel, it reaches the mirror surface controlled by the stepping motor on the UAV side [10]. At this time, the stepping motor starts scanning. When the laser beam is reflected and received by the optical receiving device composed of an optical lens and a four-quadrant detector, it is focused on the photosensitive surface of the through-hole four-quadrant detector through an optical lens, and the four-quadrant detector generates a photocurrent according to the light energy received by each quadrant. The current signal is processed by the amplifier circuit and then the voltage signal is output, and the control unit converts the voltage signal into position information of the light spot and feeds it back to the stepping motor to realize the light beam capture. After the capture is completed, the

stepper motor is then driven to fine-tune the position of the light spot, and the alignment work is performed until the light spot position voltage meets the set threshold, that is, the communication link is established through the central through hole of the four-quadrant detector.

*2.2. The Working Principle of Stepper Motor.* Traditional APT systems mostly use a large servo turntable to directly move a huge optical antenna to achieve capture, alignment, and tracking functions. The large servo turntable has numerous optical precision equipment, has complex structure, is difficult to assemble, and has long deployment time. Therefore, it is difficult to establish a wireless laser communication link in a short time. In this paper, two stepping motors are used to form a two-dimensional rotating stage to control the mirror, adjust the reflection angle of the laser, thereby controlling the position of the laser spot, and realize the capture, alignment, and tracking of the laser. Moreover, the two-dimensional rotating stage does not require precise optical components, has a simple structure, is easy to assemble, is easy to maintain, deploys quickly, and can quickly establish a point-to-point laser communication link in a short time.

A stepping motor is a device that converts electrical pulse signals into angular displacement [11], its movement progresses step by step at a fixed angle [12], and this angle is called the basic step angle  $\theta$ . When the basic step angle or the integral multiple of the basic step angle cannot reach the required rotation angle, the stepping motor needs to be subdivided [13]. The subdivision is the equal division of the basic step angle. If the subdivision number is  $x$ , the actual step angle of the stepping motor is  $1/x$  of the basic step angle. From this, the relationship between the rotation angle of the stepper motor and the number of pulses can be obtained [14]:

$$\theta_s = \frac{\theta}{x} \times A, \quad (1)$$

where  $\theta_s$  is the actual rotation angle of the motor;  $\theta$  is the basic step angle of the motor;  $x$  is the number of subdivisions; and  $A$  is the number of pulses received by the drive. The relationship between the speed of the stepper motor and the pulse frequency can also be obtained:

$$N = \frac{\theta}{360 \times x} \times f \times 60, \quad (2)$$

where  $N$  represents the actual speed of the motor;  $\theta$  is the basic step angle of the motor;  $x$  is the number of subdivisions; and  $f$  is the pulse frequency of the pulse received by the drive. Therefore, the angular displacement can be controlled by controlling the number of input pulses to achieve accurate positioning; at the same time, the speed of motor rotation can be controlled by controlling the pulse frequency to achieve the purpose of speed regulation [15].

*2.3. The Working Principle of the Four-Quadrant Detector.* Four-quadrant detectors have the characteristics of wide dynamic range, fast response, high sensitivity, and small size

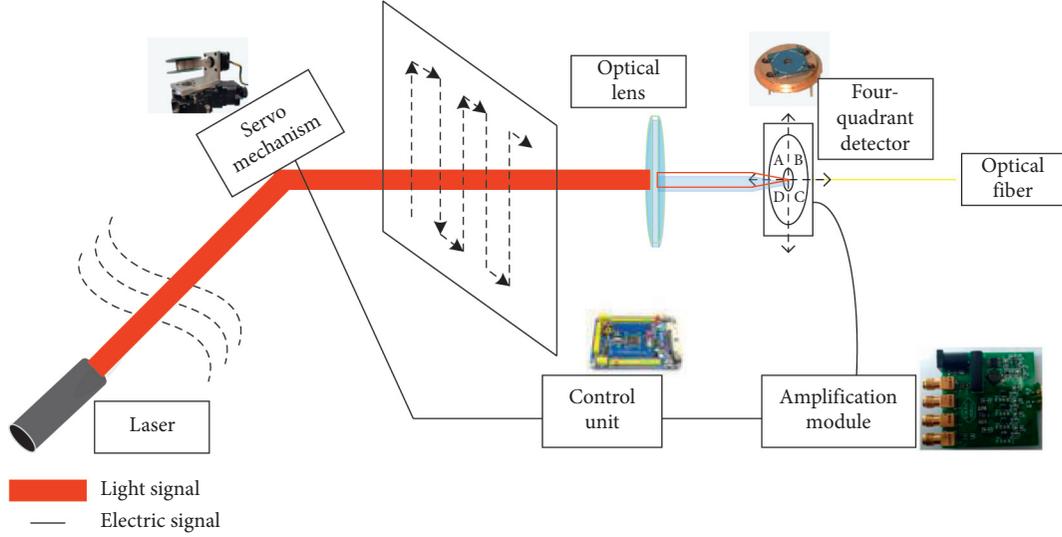


FIGURE 1: Schematic diagram of airborne laser communication automatic tracking control system.

and are widely used in the field of photoelectric tracking [16]. The four-quadrant detector is an optoelectronic device made by integrated circuit photolithography technology. The four-quadrant detector is an optoelectronic device made by integrated circuit photolithography technology. A photosensitive surface is equally divided into four areas with the same shape. Each area is equivalent to an independent optoelectronic device, and the four quadrants have the same performance parameters [15].

When the four-quadrant detector locates the light spot, the light spot falls on the photosensitive surface of the

detector, and the four-quadrant detector converts the four-channel photocurrent signal according to the magnitude of the received light energy. Assuming that the laser spot is a circular spot with uniform energy distribution, the photocurrent converted by each quadrant is proportional to the area of the spot on the photosensitive surface of the quadrant. Therefore, the relative offsets  $E_x$ ,  $E_y$  of the light spot center on the  $X$ -axis and  $Y$ -axis on the photosensitive surface can be obtained [17]:

$$E_x = K \frac{(S_A + S_D) - (S_B + S_C)}{S_A + S_B + S_C + S_D} = K \frac{(I_A + I_D) - (I_B + I_C)}{I_A + I_B + I_C + I_D} = K \frac{(U_A + U_D) - (U_B + U_C)}{U_A + U_B + U_C + U_D},$$

$$E_y = K \frac{(S_A + S_B) - (S_C + S_D)}{S_A + S_B + S_C + S_D} = K \frac{(I_A + I_B) - (I_C + I_D)}{I_A + I_B + I_C + I_D} = K \frac{(U_A + U_B) - (U_C + U_D)}{U_A + U_B + U_C + U_D},$$
(3)

where  $S_A, S_B, S_C, S_D$  are the areas of the light spots distributed on the four photosensitive surfaces, respectively;  $I_A, I_B, I_C, I_D$  are the currents of the light spots distributed on the four photosensitive surfaces, respectively;  $U_A, U_B, U_C, U_D$ , respectively, are the voltages of the light spot distributed on the four photosensitive surfaces; and  $K$  is the detection sensitivity of the four-quadrant detector.

### 3. Working Mode of Acquisition, Pointing, and Tracking

**3.1. The Working Method of Tracking and Targeting.** In the experiment, the frequency of pulse width modulation (PWM) waveform produced by a single-chip micro-computer is used to change the rotation speed of the stepping motor and realize the function of speed regulation. PWM is a square wave signal whose high- and low-level changes with a constant cycle and duty cycle can be

adjusted. Its high and low levels are  $V_H$  and  $V_L$ , respectively. The typical PWM waveform in the actual circuit is shown in Figure 2.

The PWM waveform of Figure 2 can be expressed as

$$f(t) = \begin{cases} V_H, & kT_p \leq t \leq T_s + kT_p, \\ V_L, & kT_p + T_s \leq t \leq (k+1)T_p, \end{cases} \quad (4)$$

where  $T_p$  is the cycle time of PWM;  $T_s$  is the high-level time of PWM; and  $k$  is the number of harmonics. Then, the average voltage across the load can be expressed as [18]

$$V_{avr} = \alpha(V_H - V_L) + V_L, \quad (0 \leq \alpha \leq 1), \quad (5)$$

where  $V_{avr}$  is the average voltage across the load and  $\alpha$  is the duty cycle of PWM. Assuming that the low-level voltage value of PWM is 0 V, formula (5) can be simplified as

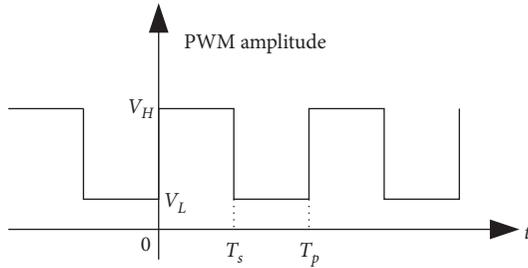


FIGURE 2: Typical pulse width modulation waveform.

$$V_{avr} = \alpha V_H. \quad (6)$$

It can be seen that PWM changes the average voltage across the load by adjusting the duty cycle [19].

**3.2. The Working Model of Light Spot Detection.** The beam position detection system is mainly composed of a signal amplification processing unit and a tracking processing unit, and its basic composition is shown in Figure 3. The four-quadrant detector used in this article has an aperture with a diameter of 1.5 mm in the middle for the signal light to pass through. When the detector outputs a weak current signal, the photocurrent converts the weak current signal into a larger voltage signal through the trans-impedance amplifier, then converts the negative voltage into the positive voltage through the reverse amplification method, and sends it to the tracking processing unit through the output buffer circuit. The tracking processing unit uses a single-chip micro-computer as the main control chip, which mainly realizes the configuration of the tracking unit, data receiving and processing, and data feedback.

When the light spot information is detected on the detector, the motor is decelerated and controlled, that is, the rotation speed of the azimuth and pitch of the two-dimensional turntable is slowed down to improve the alignment accuracy and start the alignment procedure. At this time, there are four situations corresponding to the four quadrants, as shown in Figure 4. The following uses the first quadrant as an example to describe the four situations in detail. When the light spot is in the first quadrant, the tracking mechanism will move the light spot horizontally to the right, and there will be two situations. Case A: when the light spot moves to the boundary between the first quadrant and the second quadrant, that is, when the output voltage of the second quadrant is greater than the threshold, the azimuth movement stops, the pitch movement starts, and the light spot moves vertically downward. When the four output voltages are less than the threshold, the tracking mechanism stops moving and the alignment is completed. Case B: in the process of moving to the right, at a certain moment, the four output voltages are all less than the threshold, the tracking mechanism stops moving, and the alignment is completed. The movement track of the first quadrant alignment spot is shown in Figure 4(a).

## 4. Experimental Study

### 4.1. Hardware Selection.

- (a) **Microcontroller:** the system control unit adopts STM32F103ZET6 microprocessor with 32-bit Cortex-M3 core. Its operating frequency is 72 MHz, and it has cache memory, which can realize high-speed data transmission between the memory and peripheral devices [19].
- (b) **Tracking and aiming actuator:** the system selects two two-phase hybrid stepping motors to form the tracking and pointing actuator for the azimuth and pitch movement of the mirror. The motor needs to cooperate with the corresponding drive circuit to work normally. The SD-20403 subdivision driver is selected here, which can drive all kinds of two-phase motors.
- (c) **Four-quadrant detector:** the through-hole four-quadrant detector used in the system is QSQ16-THD. The diameter of the photosensitive surface is 5.05 mm, the detector sensitivity corresponding to the 650 nm laser is 0.4 A/W, and the signal output amplitude range is 0~5 V. A four-quadrant detector has a through hole in the middle of 1.5 mm in diameter to transmit laser light. It needs to cooperate with the amplification module to process and analyze the detected signal and feed the signal back to the processor.

**4.2. Result Analysis.** The airborne laser communication system is used to achieve rapid laser capture and establish a communication link. The communication wavelength is 650 nm, and the emitted light power is 2 MW. The laser at the transmitting end loads the video signal, and the communication rate is 10 Mb/s. Figure 5(a) shows the transmitting end, Figure 5(b) shows the airborne control receiving end, and Figure 5(c) shows the communication receiving end.

The laser at the transmitting end is emitted after collimation and beam expansion, and after being transmitted through the atmospheric channel, it reaches the reflecting mirror controlled by the two-dimensional turntable of the stepping motor. The two-dimensional turntable at the receiver first carries out raster scanning. In the experiment, taking the azimuth motion range of 120 degrees as an example, the parameters of the PWM waveform are set, and the whole scanning time under different conditions is shown in Table 1.

As can be seen from Table 1, within the reaction time range of the stepper motor, the scan time is inversely proportional to the PWM input frequency. Although the scanning time of different duty ratios is the same under the same PWM input frequency, it is found in the experiment that different duty ratios have an impact on the smoothness of the stepper motor.

During the scanning process, the voltage value of each quadrant of the four-quadrant detector can be read through the serial debugging assistant. If the four-

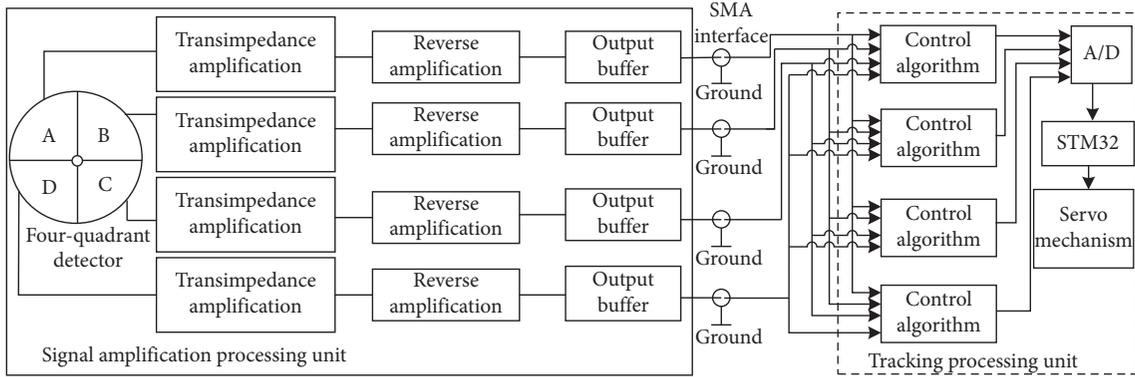


FIGURE 3: Beam position detection system.

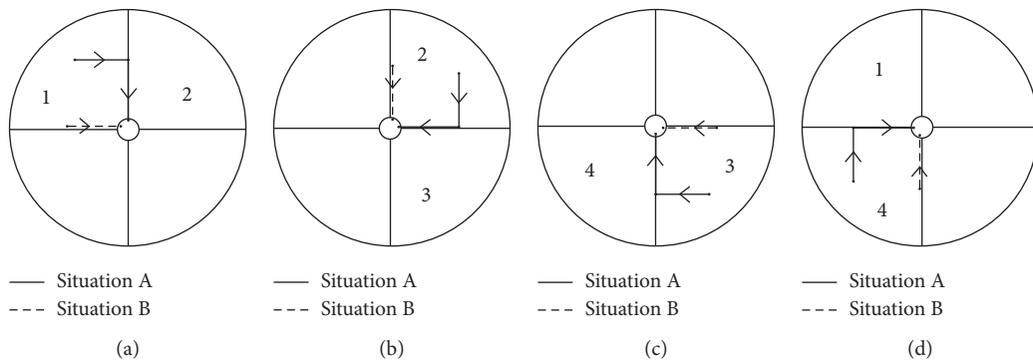


FIGURE 4: Light spot movement track. (a) Spot in the first quadrant. (b) Spot in the second quadrant. (c) Spot in the third quadrant. (d) Spot in the fourth quadrant.

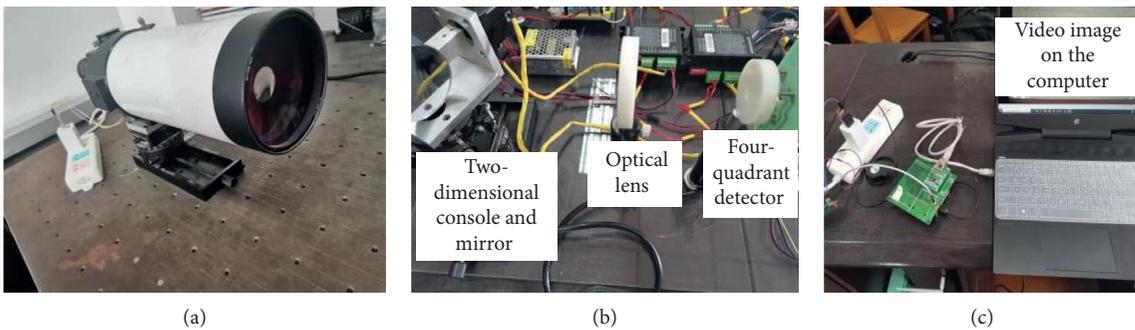


FIGURE 5: Indoor experiment of airborne laser communication. (a) Transmitter. (b) Airborne control receiver. (c) Communication receiver.

TABLE 1: Scanning time of azimuth motion in different situations.

Pulse width modulation input frequency (Hz)	Duty cycle ( $\alpha$ ) (%)	Scan time ( $t$ ) (s)
100	50	60
	80	60
200	50	30
	80	30
400	50	15
	80	15
1000	50	Motor stops moving

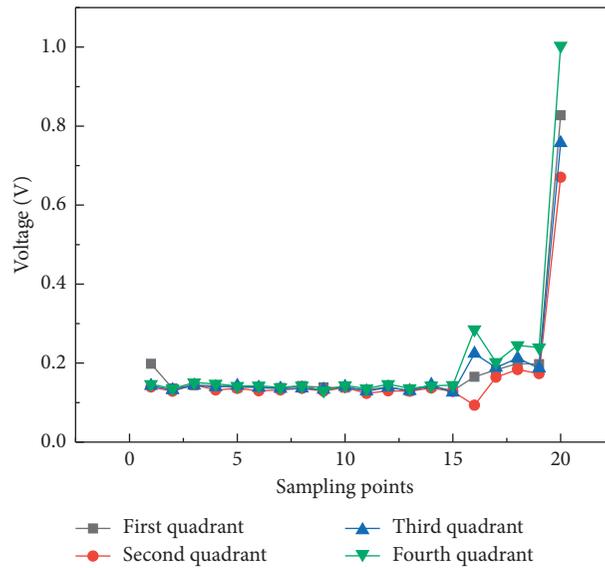


FIGURE 6: The voltage value of each quadrant after the capture is completed.

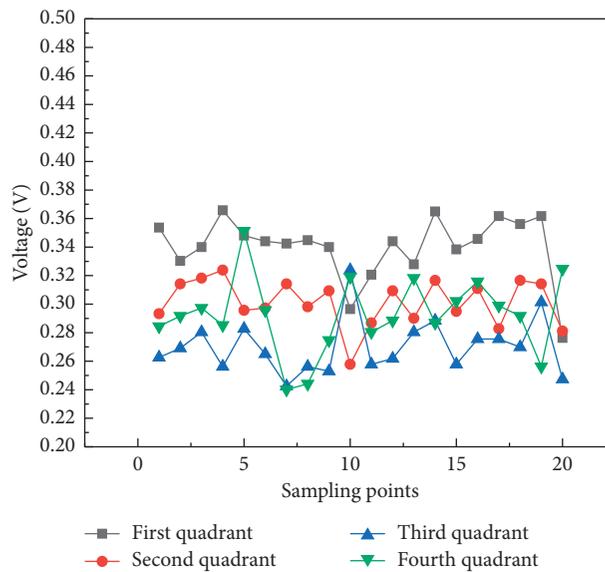


FIGURE 7: Voltage value of each quadrant after alignment.

quadrant detector detects the spot signal, it will stop the scan command. As shown in Figure 6, taking 20 samples before capture, the experimental results at a certain moment show that the voltage value of the first quadrant is 0.827 V, the voltage value of the second quadrant is 0.670 V, the voltage value of the third quadrant is 0.757 V, and the voltage value of the fourth quadrant is 1.003 V. At this time, the system has completed the acquisition operation.

After the acquisition is completed, the pointing command is executed, and the serial debugging assistant detects the voltage value of each quadrant of the four-quadrant detector in real time. After successful pointing, the voltage value of each quadrant of the four-quadrant detector can be

read through the serial debugging assistant, and 20 samples are randomly selected, as shown in Figure 7. The voltage value of the first quadrant is 0.276 V, the voltage value of the second quadrant is 0.281 V, the voltage value of the third quadrant is 0.247 V, and the voltage value of the fourth quadrant is 0.325 V. The voltage values of the four quadrants are all less than the threshold voltage.

Figure 8 shows the spot position distribution at the alignment time. During the test, through 4500 realignment experiments after spot drifting, a picture of the spot realignment time was collected, and the spot centroid coordinates after the alignment were obtained through image processing. In Figure 8, the black “+” is the target’s bull’s eye position; let its coordinates be (0, 0), and the blue “☆” is the

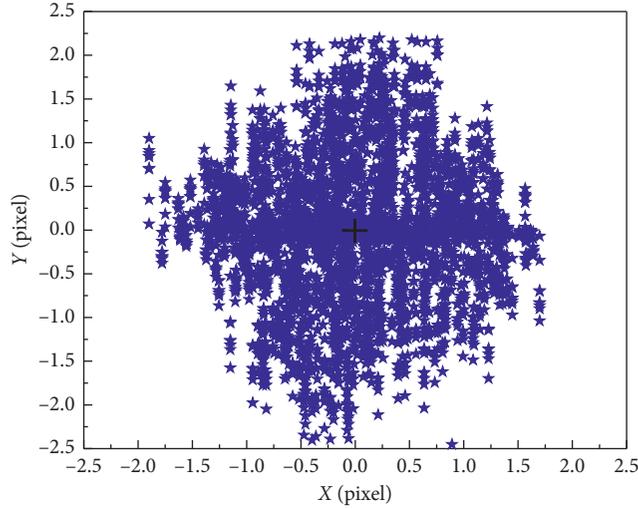


FIGURE 8: Spot position distribution at different times.

offset position of the spot center relative to the target's bull's eye at the time of alignment.

Assuming that the error angles corresponding to the azimuth direction and the pitch direction are  $x_i$  and  $y_i$ , respectively, for  $n$  measurements, the radial angle deviation  $r_i$  and its mean value  $\bar{r}$  can be expressed as

$$r_i = \sqrt{x_i^2 + y_i^2},$$

$$\bar{r} = \frac{1}{n} \sum_{i=1}^n r_i. \quad (7)$$

Then, the alignment accuracy of  $3\sigma$  can be expressed as

$$\varepsilon = \bar{r} + 3 \sqrt{\frac{1}{n-1} \sum_{i=1}^n (r_i - \bar{r})^2}. \quad (8)$$

Calculated by formula (8), the realignment accuracy ( $3\sigma$ ) of this system can reach  $2.42 \mu\text{rad}$ .

## 5. Conclusion

This article starts with factors such as cost, safety, size, and flexibility, taking into account the requirements of lightness, miniaturization, and low power consumption of the airborne laser communication system. A scheme of using stepping motors, mirrors, and through-hole four-quadrant detectors to realize the combined detection of capture and tracking is proposed, and a lightweight and fast-deployable airborne laser communication automatic tracking control system is designed. The system uses the STM32 processor as the core to construct a control loop and uses the tracking method of the photoelectric detection of the four-quadrant detector to complete the real-time tracking of the light spot, which has been tested and verified. The test results show that the tracking accuracy is better than  $2.5 \mu\text{rad}$  in the indoor simulated airborne environment, which verifies the feasibility of the scheme.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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