Research on APT Spot Detection Algorithm in Space Optical Communication

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Abstract. In space laser communication system, the coarse tracking accuracy of the APT system directly affects the field of view selection and accuracy of fine tracking system, and the accuracy of the selection of the spot center position directly affects the accuracy of the coarse tracking system. Therefore, the selection of reasonable spot detection algorithm is an important guarantee for the stable establishment of APT system. Centroid method, hough transform method, and circle fitting method are often used in the analysis of spot center and the realization of spot tracking. In order to improve the detection accuracy and anti-jamming performance, this paper compares and analyzes several commonly used spot detection methods, and obtains the applicable conditions of each algorithm.

1. Introduction

The biggest difference between wireless laser communication and other communication methods is that it requires a sophisticated APT (acquisition, pointing and tracking) system for precise alignment and the link needs to stay aligned throughout the communication until the communication is complete. In the APT system, the coarse tracking loop has a large field of view and a low servo bandwidth. It mainly achieves fast capture and stable coarse tracking, enabling the beacon spot to reliably enter the fine tracking field of view. The fine tracking loop has small dynamic range, high servo bandwidth and high tracking accuracy. It further effectively suppresses the coarse tracking residuals and has a strong ability to suppress wide-spectrum spectral vibrations to ensure fast and highly accurate alignment and tracking.

The target tracking uses the photoelectric image sensor to pick up the image video signal and send it to a computer for image processing and analysis, then it tracks the target spot in the scene, calculates the offset of the spot target in each frame, and controls the antenna axis to achieve automatic acquisition, pointing and tracking of communication terminals [1]. In order to establish and maintain the link, the optical sensor of the tracking system must be able to timely and accurately determine the position of the centroid of the spot image to calculate its deviation from the standard position, and then correct the deviation by the controller, so that the beam could point correctly at the other side.

The common algorithms of spot tracking include centroid method, Hough transform method, correlation tracking algorithm, phase shift tracking method and curved surface fitting method, etc. [2,3]. In this paper, the centroid method, Hough transform method, circle fitting method are compared and analyzed.

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2. Spot tracking algorithm

2.1. Centroid method

In order to obtain the specific location of the centroid, the surface moments of each discrete signal of CCD output are first computed, and then the surface moments are accumulated one by one. Finally, the integral of all signals on CCD is obtained. The centroid position of the spot signal is the quotient of the former and the latter [4,5].

Assuming that the receiver beacon light spot is composed of $m \times n$ pixels, each pixel corresponds to the determined space coordinates (X, Y) and gray value $p_{ij}(x, y)$,

$$p_{ij}(x,y) = S_{ij} + n \tag{1}$$

S_{ij} 、 n is the gray value of original spot image and image noise respectively.

Suppose S_{stan} is the threshold for processing the beacon light at the receiving end, and the centroid coordinate of the spot is (X_{gra}, Y_{gra}) :

$$S_x = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} x_i \cdot p_{ij} \tag{2}$$

$$S_y = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} y_i \cdot p_{ij} \tag{3}$$

$$S_\Sigma = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} p_{ij} \tag{4}$$

$$p_{ij}(x,y) = \begin{cases} p_{ij}(x,y), & p_{ij}(x,y) \geq S_{stan} \\ 0, & \text{else} \end{cases} \tag{5}$$

Then the centroid coordinate of the spot is:

$$X_{gra} = \frac{\sum_{i=0}^{m-1} \sum_{j=0}^{n-1} x_i p_{ij}}{\sum_{i=0}^{m-1} \sum_{j=0}^{n-1} p_{ij}} \tag{6}$$

$$Y_{gra} = \frac{\sum_{i=0}^{m-1}\sum_{j=0}^{n-1} y_i p_{ij}}{\sum_{i=0}^{m-1}\sum_{j=0}^{n-1} p_{ij}} \quad (7)$$

2.2. Hough transform method

The principle of Hough transform to detect arbitrary curve is as follows:

$$a_n = f(a_{1,} \cdots a_{n-1}, x, y) \quad (8)$$

It is the parametric equation of the curve to be detected, where $a_{1,} \cdots a_{n-1}$ is the shape parameter, x and y are the image point coordinates of the spatial domain.

For any point in the image space (x_0, y_0), it can be transformed into a curve in parameter space$(a_{1,} \cdots a_n)$ with eq.(8). For each of the n points on the same curve in the spatial domain, the above transformations are performed one by one, then n curves are obtained correspondingly in the parameter space $(a_{1,} \cdots a_n)$. We can see from eq.(10) that n curves must pass through the same point $(a_{10,} \cdots a_{n0})$, finding the point in the parameter space determines the common parameter equations for detecting straight lines and circles in curve l. In the space domain, they are respectively:

$$\rho = x\cos\theta + y\sin\theta \quad (9)$$

$$r = \sqrt{(x-a)^2 + (y-b)^2} \quad (10)$$

Hough transform method will transform each point in spatial domain into the parameter equation $a_n = f(a_{1,} \cdots a_{n-1}, x, y)$. The calculation results will vote on the quantization points in the parameter space$(a_{1,} \cdots a_n)$. If the number of votes exceeds a certain threshold, then it is considered that there are enough image points on the curve determined by the parameter points [6]. For the detection of a circle represented by the formula (10), the parameter space is a three-dimensional (a, b, r), where (a, b) is the center point coordinate, and r is the radius of the circle.

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2.3. Circle fitting method

The laser spot center detection algorithm based on circle fitting method is based on the least square principle (The 2 - norm minimization of error vector r), and it uses the circle to approximate the laser spot contour.

Equation of circle:

$$(x-a)^2+(y-b)^2=r^2 \tag{11}$$

Error vector:

$$\varepsilon_i=(x_i-a)^2+(y_i-b)^2-r^2 \tag{12}$$

(x_i, y_i) – image boundary point coordinates; $i \in E$ - E represents a collection of all boundaries

Then the square sum function of the error vector is:

$$Q=\sum_{i\in E}{\varepsilon_i}^2=\sum_{i\in E}[(x_i-a)^2+(y_i-b)^2-r^2]^2 \tag{13}$$

According to the least square principle:

$$\frac{\partial Q}{\partial a}=\frac{\partial Q}{\partial b}=\frac{\partial Q}{\partial r}=0 \tag{14}$$

So:

$$\begin{cases}\frac{\partial Q}{\partial a}=2\sum_{i\in E}[(x_i-a)^2+(y_i-b)^2-r^2](-2)(x_i-a)=0\\ \frac{\partial Q}{\partial b}=2\sum_{i\in E}[(x_i-a)^2+(y_i-b)^2-r^2](-2)(y_i-b)=0\\ \frac{\partial Q}{\partial r}=2\sum_{i\in E}[(x_i-a)^2+(y_i-b)^2-r^2](-2)r=0\end{cases} \tag{15}$$

To simplify:

$$\begin{cases}a^2-2\bar{x}a+b^2-2\bar{y}b-r^2+x^2+y^2=0\\ \bar{x}a^2-2x^2a+\bar{x}b^2-2xyb-\bar{x}r^2+x^3+xy^2=0\\ \bar{y}a^2-2xyb+\bar{y}b^2-2y^2b-\bar{y}r^2+x^2y+y^3=0\end{cases} \tag{16}$$

After calculation, x, y satisfies the equation:

$$\overline{x^m y^n} = \sum_{i \in E} x_i{}^m y_i{}^n / \sum_{i \in E} 1 \tag{17}$$

Then:

$$\begin{cases} (\bar{x}^2 - \overline{x^2})a + (\bar{x}\bar{y} - \overline{xy})b = \frac{1}{2}(\overline{x^2}\bar{x} + \bar{x}\overline{y^2} - \overline{x^3} - \overline{xy^2}) \\ (\bar{x}\bar{y} - \overline{xy})a + (\bar{y}^2 - \overline{y^2})b = \frac{1}{2}(\overline{x^2}\bar{y} + \bar{y}\overline{y^2} - \overline{x^2 y} - \overline{y^3}) \end{cases} \tag{18}$$

The values of a, b and r are obtained by the above equations:

$$a = \frac{\left(\overline{x^2}\bar{x} + \bar{x}\overline{y^2} - \overline{x^3} - \overline{xy^2}\right)\left(\bar{y}^2 - \overline{y^2}\right) - \left(\overline{x^2}\bar{y} + \bar{y}\overline{y^2} - \overline{x^2 y} - \overline{y^3}\right)(\bar{x}\,\bar{y} - \overline{xy})}{2\left(\bar{x}^2 - \overline{x^2}\right)\left(\bar{y}^2 - \overline{y^2}\right) - 2(\bar{x}\,\bar{y} - \overline{xy})^2} \tag{19}$$

$$b = \frac{\left(\overline{x^2}\bar{y} + \bar{y}\overline{y^2} - \overline{y^3} - \overline{yx^2}\right)\left(\bar{x}^2 - \overline{x^2}\right) - \left(\overline{x^2}\bar{x} + \bar{x}\overline{y^2} - \overline{y^2 x} - \overline{x^3}\right)(\bar{x}\,\bar{y} - \overline{xy})}{2\left(\bar{x}^2 - \overline{x^2}\right)\left(\bar{y}^2 - \overline{y^2}\right) - 2(\bar{x}\,\bar{y} - \overline{xy})^2} \tag{20}$$

$$r = \sqrt{a^2 - 2xa + b^2 - 2yb + \overline{x^2} + \overline{y^2}} \tag{21}$$

The center of the spot (a, b) can be calculated by the upper formula. In order to further improve the accuracy, the a and b values calculated by the upper formula can be substituted eq. (22), then filter out some point with big error, and use eq. (19) and eq. (20) to obtain spot parameters, after many iterations it can further improve the detection accuracy.

3. Experiment and result

In order to verify the effect of different algorithms on tracking accuracy, a semi-physical simulation experiment was conducted in the laboratory. The analog beacon transmitting and receiving part is integrated on an optical platform. The transmitting part includes a beacon laser, a beam expanding and shaping part and a two-dimensional beam oscillating unit. The receiving part includes a coarse tracking CCD camera, a two-dimensional coarse tracking servo coiling (coarse tracking servo simulation system), a fine tracking camera and a two-dimensional fast tilting galvanometer (fine tracking servo simulation system), a control computer, etc. The devices used in each unit are as follows:

(1) Beacon laser: Vanadium acid memory solid state lasers emitting green light with a wavelength of 532 nm.

(2) Expansion beam shaping components: the central plate + the collimator with focal length of 550 mm, the beam divergence angle after shaping and beam expanding is 200urad.

(3) Two-dimensional beam swinging unit: The two-dimensional swinging mirror is used to change the visual axis direction of the light beam to simulate the two-dimensional visual axis deviation caused by the movement and vibration of the communication terminal. The size of the swinging mirror is 30 mm × 20 mm, and the response time is less than 0.7 ms. Driven by the swing motor, the drive signal is

a sine wave of a certain resonant frequency to simulate the relative motion and random vibration, the beam deflection amplitude, waveform and frequency can be set by parameters.

(4) Coarse tracking CCD: using TM7610-type camera with frame rate 120 Hz, resolution 648×484, and pixel size $9u \times 9u$, the optical system uses the longest focal length of 300 mm zoom lens to achieve the corresponding total field of view at about 15 mrad, the pixel resolution is 30 urad, which is similar to the actual system.

(5) Coarse tracking servo simulation system: using oscillating motor to simulate. the lens size is 50×20 mm, response time is less than 0.6 ms, the control accuracy and servo bandwidth consistent with the real coarse tracking servo platform characteristics that control accuracy is better than 75urad, control bandwidth is 5 ~ 10 Hz, control range is 15 degrees.

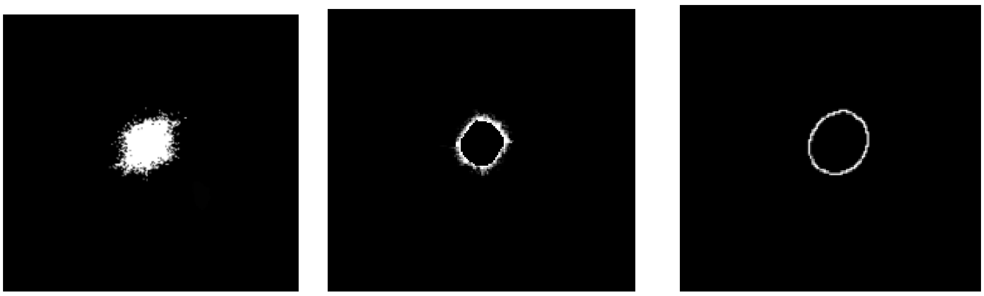
(6) Fine tracking light source: using the the beam rectified by coarse tracking servo mirror, parallel light is hit on the fast two-dimensional PZT galvanometer to carry out fine tracking correction after a semi-anti-half-mirror.

(7) Fine tracking CCD: adopts high frame rate CCD, model IPX-VGA210, the frame rate is 1600 Hz when the effective pixel is 228×164, the pixel size is $9\text{ um} \times 9\text{um}$, the optical system focal length of the parallel light pipe is 1.2m, fine tracked field of view is 1250urad, pixel resolution is 7. 5 urad, which is similar with actual fine tracking.

(8) Image processing unit: the acquisition is based on DSP real-time acquisition system, which can improve the system bandwidth, and the controller uses a server that supports 64 bit PCI.

(9) Fine tracking executive components: using fast two-dimensional PZT galvanometer 5-325 to achieve closed-loop control angle of 4 mrad, full load closed loop bandwidth is 400 Hz; data transmission uses IEEE488 bus, command transmission time is less than 20 us.

Firstly, the coarse tracking system is debugged by light and electricity, and the center point of the spot swing is in the center of the field of view of the CCD camera, and the corresponding field of view is about 7.5 mrad; Then, the fine tracking system is debugged by optical and electrical, so that the center point of the imaging spot swing is in the center of the field of view of the CCD camera, and the corresponding field of view is about 400 urad. Different algorithms are simulated by compute to compare the tracking accuracy and calculation time. Figrue 1. is experimental results of several algorithms.



(a) Centroid method (b) Hough transform method (c) Circle fitting method

Figure 1. Comparison of detection result.

4. Conclusion

The following conclusions can be drawn from Table 1, Figure 2, and Figure 3.

Centroid algorithm is a traditional detection algorithm, which has high precision, simple calculation, low requirement for hardware system, and it is more effective under simple background mode and medium or weak turbulence conditions. Calculating the centroid over a short period of time by traversing all the pixels of a frame will result in a longer processing time and less anti-jamming ability. When there is light interference, especially if there is a certain intensity and interference light incident from the side, the result will produce large error, tracking performance will decline.

Hough transform method is proposed for the application of laser scanning in large surface measurement. The Hough transform method is robust to the central detection of the circular spot. So long as the spot image can give most of the true edge of the spot, It can overcome various interferences (such as the surface reflection characteristics, partial occlusion, speckle, change, etc.) on the spot center positioning results. However, the algorithm has low detection accuracy and high time and computational complexity.

The circular fitting method approximates the outline of the laser spot according to the principle of least square. In addition to detecting the spot center, the algorithm can also detect laser spot whose radius reaches sub-pixel positioning accuracy. After the dimension reduction processing, the algorithm has very fast calculation speed and high precision. But when the random noise is in existence, the accuracy of the center operation will be reduced obviously. When the interference intensity is large, the center of the circle may be obviously wrong.

Table 1. Comparison of calculation time.

Pixel (648 × 484)	Time (s)	Time Complexity
Centroid method	0.12	O (n^2)
Hough transform method	0.32	O (n^4)
Circle fitting method	0.08	O (n)

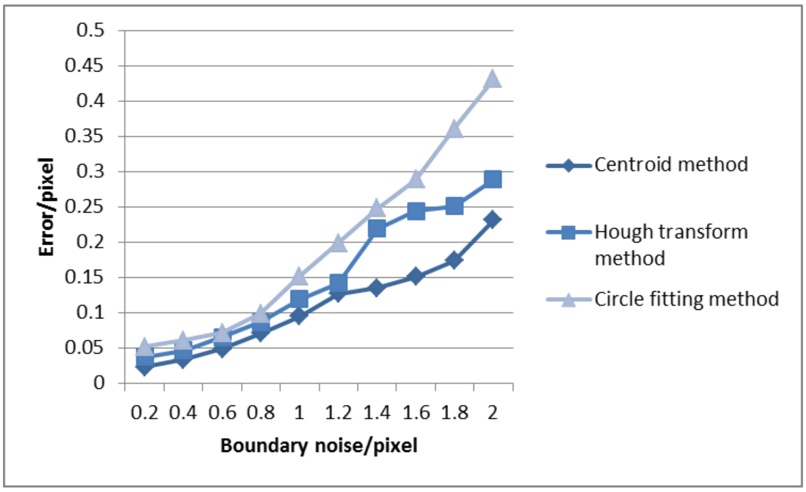


Figure 2. Comparison of detection error.

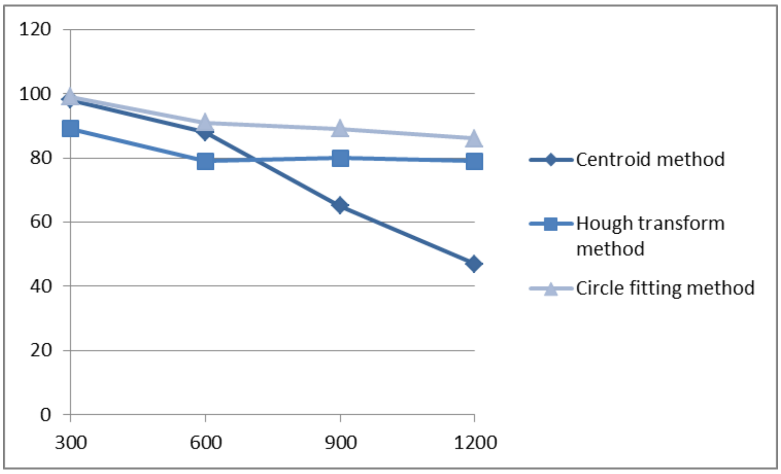


Figure 3. Comparison of accuracy.

References

[1] Siwei Zhang. Research on tracking algorithm of APT subsystem in free space laser communication. [D]. Changchun: Changchun University of Science and Technology, 2006.
[2] Langjun Wei. Research and design of APT system for laser communication. [D]. Wuhan: Huazhong University of Science and Technology, 2008.
[3] Xue Zhao. Initial acquisition and error analysis of APT in space laser communication. [D]. Changchun: Changchun University of Science and Technology, 2012.
[4] Xin Zhao, Yunqing Liu, Shoufeng Tong. Initial orientation modeling and verification of boresight in dynamic space laser communication system [J]. Chinese laser.Vol.41, No.5.2014.
[5] Lixin Wang. Research on Capture and Tracking Technology in Airborne Laser Communication. [D]. Changchun: Ji Lin University, 2014.
[6] Xu Wang. Research and implementation of APT tracking algorithm in space optical communication. [D]. Sichuan: University of Electronic Science and technology of China, 2006.