

Dynamic spot tracking system based on 2D galvanometer in free space optical communication for short distance

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Abstract Dynamic tracking of laser spot is a key process in the establishment of free space optical communication. In this paper, a dynamic tracking system was presented. In this system, a two-dimensional (2D) galvanometer was used to change the angle of the optical axis of the incident beam at a certain scanning frequency as optical signal jitter simulator, and another galvanometer was used to track the jitter with quadrant detector (QD) and data processing module to acquire the position information of laser spot. Results indicated that the tracking accuracy of this system mainly composed of 2D galvanometer was as high as 27.8 μrad , and its linear deviation was less than 0.013. The system could still keep the dynamic tracking of the spot stable when the jitter frequency of the optical signal was less than 1000 Hz. Those results suggested that this system could be suitable for the short distance in free space communication due to its simple structure, easy to control and low cost compared with conventional system.

Keywords free space optical communication, dynamic tracking, optical signal jitter, two-dimensional (2D) galvanometer

1 Introduction

Acquisition, pointing and tracking (APT) technology, which mainly completes large range, high probability, fast spatial capture, dynamic tracking as well as optical axis aligning between motion platforms, is one of the key technologies in free space optical communication [1].

The dynamic tracking system of the APT in free space optical communication had been usually composed of

three parts which include a detector, a microcontroller unit (MCU) and an adjustment unit. It got the information of spot position by using quadrant detector (QD), position sensor detector (PSD) or charge coupled device (CCD) [2]. Then, the information obtained from the detector was processed by the MCU part. Finally, the fast steering mirror (FSM) driven by piezoelectric, which was controlled by MCU, was adopted as the optical axis adjustment unit to achieve the adjustment of the optical axis. System composed of these structures had realized a tracking accuracy with microradian level and with response frequency higher than 1 kHz [3–7], while it had several disadvantages, such as the complex MCU, the expensive cost, the complicated structure.

In this paper, a dynamic tracking system, which is mainly composed of the two-dimensional (2D) galvanometers, the data processing unit, QD and complementary metal-oxide-semiconductor transistor (CMOS) unit was proposed. The galvanometer was used to generate optical jitter as well as make adjustment of optical axis. The spot information was obtained by QD to provide the feedback signals for data processing unit to control the galvanometer in turn. In addition, a CMOS camera was used to investigate the spot changes through the splitter. The tracking accuracy of the system can still reach 27.8 μrad with a response frequency of 1000 Hz. Compared with the conventional system, this system designed in the paper has many advantages such as low cost, easy to control, simple structure so that it is suitable for short distance free space optical communication.

2 Set-up of spot dynamic tracking system

The spot dynamic tracking system including both transmitting and receiving terminals is a closed-loop control, as shown in Fig. 1. The transmitting terminal

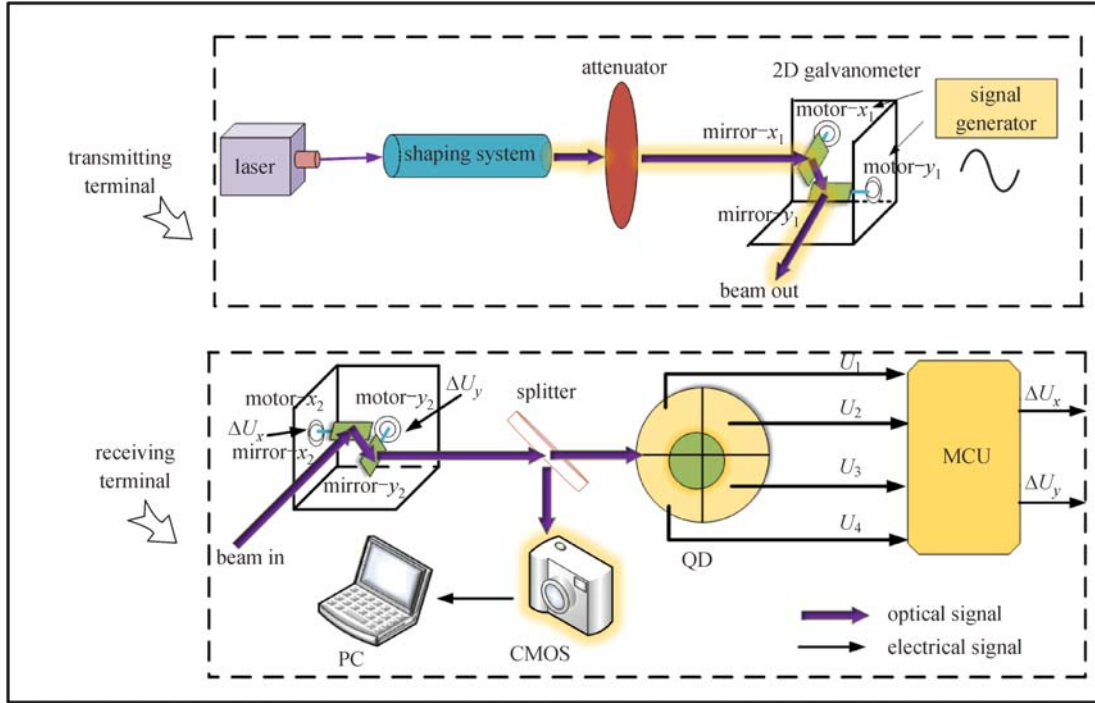


Fig. 1 Block diagram of spot dynamic tracking system

performs as an optical jitter simulator. The emitted laser finally reaches the mirror- x_1 of the 2D galvanometer via shaping system and an attenuator. Then, the beam is reflected twice by mirror- x_1 and mirror- y_1 which are under the control of a signal generator [8]. A sinusoidal signal with a certain frequency is generated by the signal generator to drive the motor- x_1 or motor- y_1 directly.

At the receiving terminal, the jitter beam is reflected by mirror- x_2 and mirror- y_2 then sent to the splitter. After the splitter, the transmitted beam is received by the QD to obtain the spot position information and the reflected beam is acquired by the CMOS camera to observe the tracking error directly. The spot position information will be processed by MCU and correct voltages ΔU_x , ΔU_y will be output to control the motor- x_2 and motor- y_2 , respectively.

The beam used in the experiment was a laser of 532 nm wavelength. It is shaped into a spot with a radius of 2 mm which was half of the radius of the active area of QD in order to meet the best appropriate conditions with a wide linear region [9]. The max resolution of the CMOS camera was 4384 H \times 3288 V and the pixel size was 1.4 μm \times 1.4 μm . The optical distance from mirror- y_2 to CMOS camera and QD was $L = 275$ mm.

3 Principle of spot dynamic tracking

The spot received by QD distributes in I, II, III, IV

quadrants with corresponding area A_1 , A_2 , A_3 , A_4 , respectively, as shown in Fig. 2. $o(x, y)$ coordinate is the spot center, r is the radius of spot. Assuming that Δx and Δy are the miss distances of the spot center in x and y directions, respectively.

Under the condition of light intensity with uniform distribution, the output voltage of each quadrant of the QD is proportional to the area of the spot distribution in each quadrant. Generally $r \gg x$ and $r \gg y$, conclusions can be drawn from Fig. 2 as follows [10,11].

$$\Delta x = \frac{\pi r}{2} \left(\frac{U_x}{U_{\text{sum}}} \right), \quad (1)$$

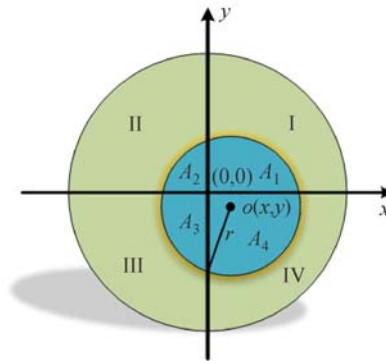


Fig. 2 Distribution of spot in I, II, III, IV quadrants received by QD

$$\Delta y = \frac{\pi r}{2} \left(\frac{U_y}{U_{\text{sum}}} \right), \tag{2}$$

where $U_x = U_2 + U_3 - U_1 - U_4$, $U_y = U_4 + U_3 - U_1 - U_2$, $U_{\text{sum}} = U_1 + U_2 + U_3 + U_4$, U_1, U_2, U_3 and U_4 are the corresponding output voltage of the QD from I, II, III and IV quadrant, respectively. Assuming that the optical distance between the QD and the mirror is L , the tracking accuracy α can be expressed by the following formula [12]:

$$\alpha = \frac{\sqrt{\Delta x^2 + \Delta y^2}}{L}. \tag{3}$$

In Fig. 3, for example, in the x direction, when the correct voltage input is , the deflection angle of mirror is θ , and the axis of the beam is deflected 2θ which causes that the offset of spot center reaches x after the transmission distance L . It realizes the dynamic spot tracking by ensuring that the offset caused by 2D galvanometer is equal to the x coordinate of spot got from QD all the time. In this system, θ is usually very small, so that $\tan 2\theta \approx 2\theta = \frac{x}{L}$. The deflection angle of the 2D galvanometer is satisfied that $\theta = 2^\circ/V \times \Delta U$. Therefore,

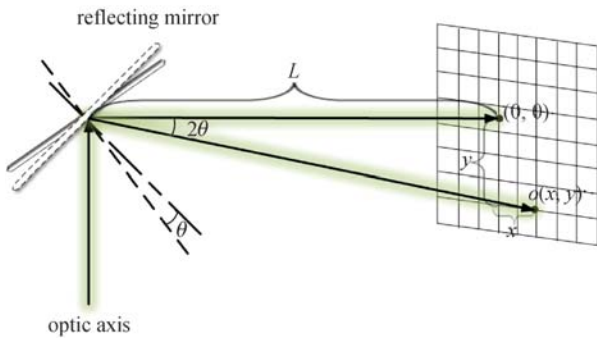


Fig. 3 Adjustment of the beam

$$\Delta U_x = 22.5 \left(\frac{r}{L} \right) \times \left(\frac{U_x}{U_{\text{sum}}} \right), \tag{4}$$

$$\Delta U_y = 22.5 \left(\frac{r}{L} \right) \times \left(\frac{U_y}{U_{\text{sum}}} \right), \tag{5}$$

where ΔU_x and ΔU_y are the correct voltages of the motor- x_2 and motor- y_2 , respectively. Under the condition of constant optical power and radius, the U_{sum} will be constant too, a linearity relationship can be found between ΔU_x and U_x as well as ΔU_x and U_y which could be unified as $\Delta U = kU$.

4 Experimental results and discussion

4.1 Linearity of this system

System with good linearity is of great benefit to process the output voltages of QD and can be directly controlled through the simplest algorithms. When the optical power was equal to 0.2 and 0.3 mW respectively, considering that there is a linearity relationship between ΔU and U , we can get that $k \approx 0.1387$ and $k \approx 0.1023$, respectively. The relationship between the measured voltages- $\Delta U_x, U_x, \Delta U_y, U_y$ and the theoretical curve was shown in Fig. 4.

From Fig. 4, it is found that measured data are consistent with the theoretical curve very well and suggesting the system has a good linearity between the feedback correct voltage and the spot position information. The data standard deviation σ of Figs. 4(a) and 4(b) are only 0.013 and 0.011, respectively.

Several reasons can be explained for the deviations. First, the light distribution of spot in the experiment is not completely uniform which will cause that the output voltage of each quadrant of the QD is not proportional to the area of the light spot distribution. Secondly, the shape

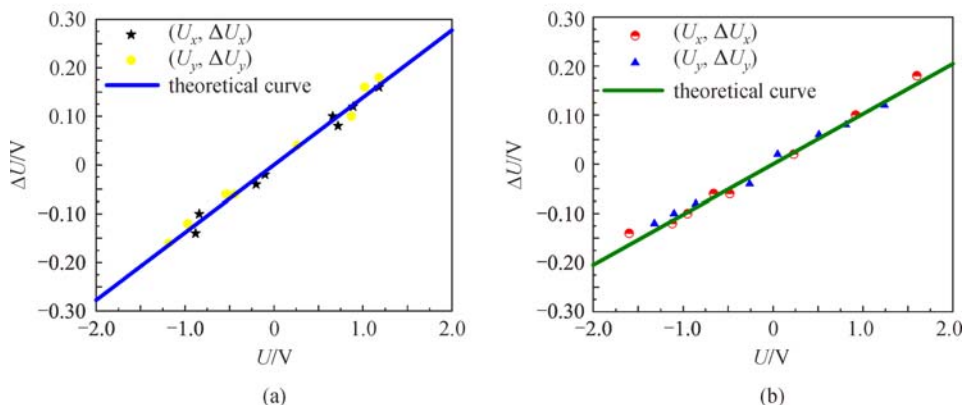
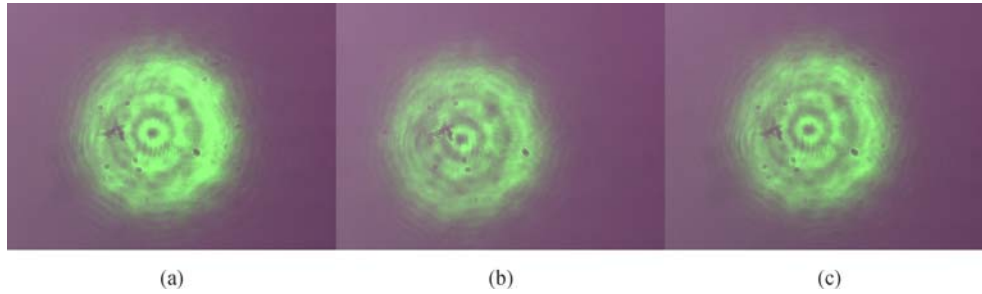


Fig. 4 (a) Optical power is 0.2 mW; (b) optical power is 0.3 mW

Table 1 Comparison of spot-center before and after tracking

groups	x/pixel		y/pixel		error /pixel	
	before tracking	after tracking	before tracking	after tracking	x	y
1	455.11	456.05	375.24	376.13	0.94	0.89
2	468.38	467.45	413.54	414.41	0.93	0.87
3	523.84	524.74	399.85	400.73	0.90	0.88
4	500.07	499.16	401.48	402.36	0.91	0.88

**Fig. 5** (a) Before tracking (normal); (b) missing target; (c) after tracking (back to normal)

of the spot will take changes due to the lens and splitter, which has influence on the accuracy of Δx and Δy . Thirdly, the noise is inevitable in the hardware circuit, which causes the error between the measured voltages and the actual voltages, and so on.

4.2 Tracking accuracy of this system

The tracking accuracy can be got via the spot image captured by the CMOS camera. The spot images were sent into personal computer (PC) for processing by VS2008 with barycenter method to obtain the coordinate parameters of the spot center [13] and the resolution of the images was $1024 \text{ H} \times 768 \text{ V}$. Several groups of the spot center coordinates (x , y) were randomly recorded before and after tracking for comparison.

As seen from Table 1, the average error of spot center is less than one pixel before and after tracking. Therefore, we can calculate that the miss distances Δx and Δy are 5.52 and 5.28 μm , respectively. According to Eq. (3), we can calculate that α was 27.8 μrad . The results showed that the system has good tracking stability.

A group of images captured by the CMOS camera are given by Fig. 5 during the process of the dynamic tracking.

From Figs. 5(a) and 5(c), it can be obviously found that the spot's position has slightly changes before and after tracking.

4.3 Jitter suppression of this system

Under the condition of different jitter frequency, the experiments were carried out to test the ability of the

system to suppress the jitter. The system operates without automatic tracking in the former 50 sampling and with automatic tracking in the latter 50 sampling periods, respectively. The results shown in Figs. 6(a) and 6(b) demonstrated that the system could suppress the jitter when the frequency is less than 1000 Hz, while it could not suppress the jitter effectively when the frequency increase to 1100 Hz shown as Fig. 6(c). In Figs. 6(a) and 6(b), we claim that the jitter is obviously suppressed which was consistent with the results of tracking accuracy described as above.

5 Conclusions

In this paper, a dynamic system based on 2D galvanometer was designed. The system has many advantages such as the simple adjusting structure, the low cost while the tracking accuracy of the system still can reach 27.8 μrad with a response frequency of 1000 Hz which could be considered as an appropriate choice in free space communication especially in a short distance.

In this study, we found that the tracking accuracy of the proposed system was mainly determined by the hardware parameters. Many efforts can be made to improve it, such as by using chips with higher resolution, 2D galvanometer with higher sensitivity. In addition, operating in a darkroom, using the beam of uniform intensity or designing a circuit with lower noise, can make the system have higher linearity. The system proposed in this paper can totally meet the requirements of optical communication in short distance and it is easy to realize.

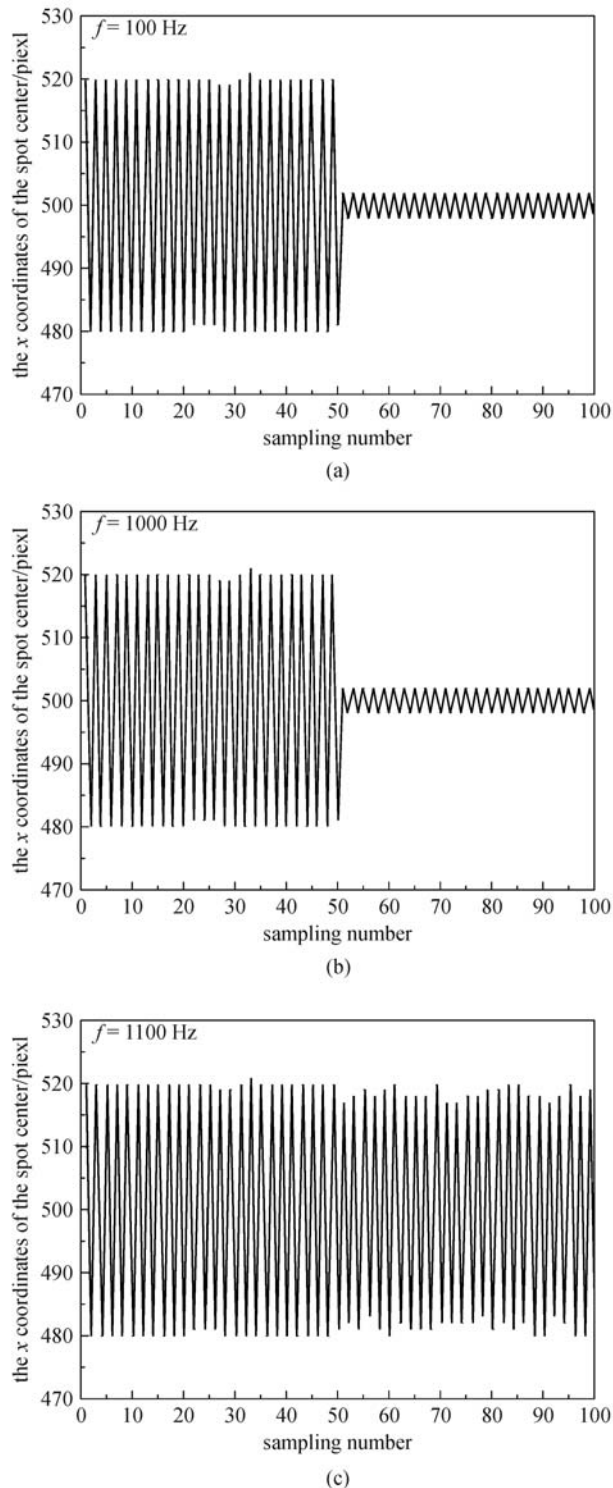


Fig. 6 Jitter suppression of this proposed system when (a) $f = 100$ Hz, (b) $f = 1000$ Hz and (c) $f = 1100$ Hz

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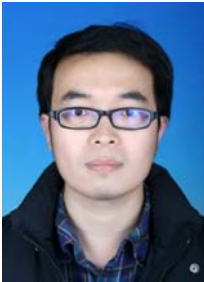
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