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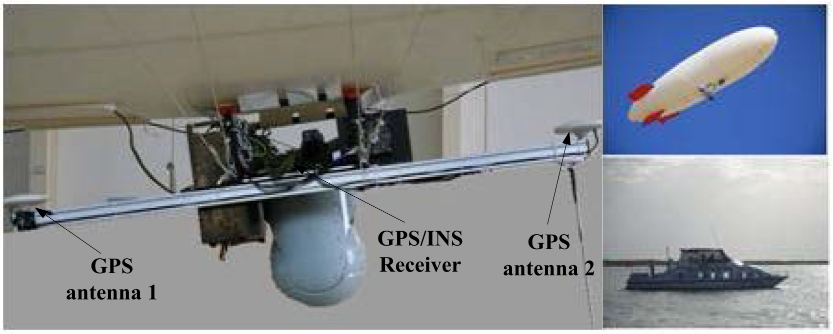

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Initial Pointing Technology of Line of Sight and its Experimental Testing in Dynamic Laser Communication System

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Abstract: The initial pointing unit of the line of sight (LOS) operating in the open-loop mode is an important part of the space laser communication system, which directly determines the size of the field of uncertainty (FOU) and the length of the scan time. In this paper, the composition and working principle of the initial pointing of the LOS in the dynamic laser communication system are studied in detail. The initial pointing angle (IPA) of the LOS is derived by applying the principle of coordinate transformation, and the factors affecting the size of the FOU are analyzed. It is proposed to introduce the extended Kalman filtering technique into the initial pointing to reduce the size of the FOU. In the demonstration experiment of the dynamic laser communication (including airship–ship and aircraft–aircraft), the dual-antenna global positioning system/inertial navigation system composite device is applied to obtain position, attitude, and other parameters in real-time to realize the performance test of the initial pointing system. The size of the FOU is measured with a target-viewing camera, and the filtered and unfiltered results were compared.

Index Terms: Dynamic laser communication system, line of sight, initial pointing, filed of uncertainty, extended Kalman filter.

1. Introduction

Because of its advantages of high speed, small size, low power consumption, good security performance, and the absence of bandwidth restrictions, the space laser communication system has the potential for widespread applications in commercial, civil, military, and other fields [1]. The pointing, acquisition and tracking (PAT) subsystem is an important part of the space laser communication system, and is the premise and guarantee for the normal operation of space laser communications [2]–[5]. In November 2001, the first-generation of laser communication terminal equipped with the SPOT-4 low-orbit satellite and the ARETMIS high-orbit satellite equipped with laser communication terminal established an inter-satellite communication link for the first time, which completed the performance verification of the PAT system [6]. The initial pointing of the line of sight (LOS) is the first step in the work of the laser communication system, and its importance is self-evident [7]. The initial pointing principle of laser communication between two stationary points is relatively simple, and the

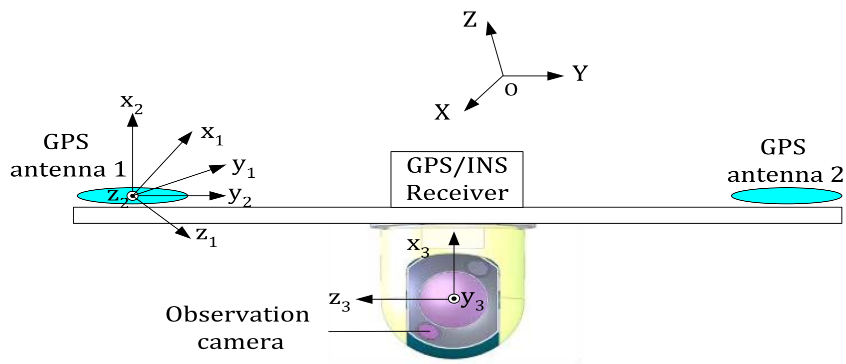

Fig. 1. Composition principle of dynamic space laser communication system.

initial pointing of the LOS can be completed by means of the global positioning system (GPS) [8], [9]. As for the laser communication link and network, Shim and Bernhard Epple respectively used the strap-down initial navigation system (INS) in combination with GPS as the initial pointing system sensor to realize the initial pointing of the LOS, analyzed the system composition principle, pointing error, acquisition time and so on, and completed part of the test experiment [10], [11]. In the aircraft laser communication demonstration experiment, Amita Shrestha and Xin Zhao both used the LOS calibration method to improve the performance of the pointing system, and the size of the field of uncertainty (FOU) of the measurement was 10 mrad [12], [13]. In the completed inter-satellite laser communication demonstration experiment, R. Fields added the least squares method to the LOS pointing system, and experiment determined that the size of the FOU was about 4 mrad [14]. In the laser communication system, noise adaptive fading Kalman filter can be used to improve beacon light tracking performance [15]. In terms of alignment of the LOS [16], Jozef Sofka and Gokhan Soysal respectively used a quadrant detector as a loop detector to form a closed-loop system, added Kalman filtering to the algorithm to improve the accuracy of the alignment, and completed the system modeling and ground demonstration experiments [17], [18].

It can be seen from the above content that the initial pointing of the LOS is a key technology in the space laser communication system. This paper studies the composition and working principle of the initial pointing system of the LOS based on the open-loop working mode, and proposes to introduce the extended kalman filtering (EKF) technology into the initial pointing system of the LOS to reduce the size of the FOU. In the demonstration experiment of dynamic laser communication (including airship-ship, aircraft-aircraft), the dual-antenna GPS/INS composite device is applied to obtain position, attitude and other parameters in real-time to realize the performance test of the initial pointing system, and the overall performance of the initial pointing system is tested.

2. Initial Pointing System of the LOS in Dynamic Laser Communication

The dynamic space laser communication system is mainly composed of a communication transceiver unit, a PAT unit, an optical machine unit and a total control unit. The basic structure is shown in Fig. 1. The PAT unit is an important part of the space laser communication system. It mainly performs three main functions, namely, the initial pointing of the LOS, coarse tracking and fine tracking. The initial pointing is the first step in the laser communication system to start working. The LOS rotates from the initial zero and points to the FOU of the other side. In order to complete the initial pointing function, it is necessary to know the position and attitude of one's own party, and the position of the other party, to calculate the initial pointing angle (IPA) of the LOS by using coordinate transformation, and to drive the rotation of the LOS through the servo turntable, so that the two sides of the communication complete the mutual initial pointing. The satellite-borne optical transceiver can obtain the position, attitude and other information through its

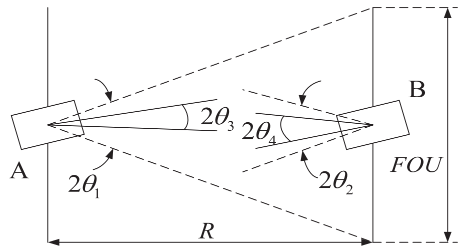

Fig. 2. Principle of initial pointing of the line of sight.

own sensor and ephemeris, while the dynamic space laser communication system needs to obtain the corresponding parameters through GPS, INS and other sensors.

Due to the factors such as position error, attitude error, dynamic hysteresis, platform vibration, and LOS stability error, the LOS will not point to the other party accurately, but points to a field – the field of uncertainty. Generally, the FOU is larger than the divergence angle of beacon beam and the receiving field of view. Therefore, after the initial pointing is completed, the coarse alignment of the LOS can only be achieved after the scanning of the LOS. The basic schematic is shown in Fig. 2. It can be seen that when the FOU is large, the probability of acquisition can be guaranteed, but the scan time will be increased. Under the premise of ensuring the probability of acquisition, if the FOU can be reduced by technical measures, the range of the LOS scan will be shortened, thereby reducing the acquisition time.

3. Initial Pointing Theory

3.1 Initial Pointing Angle

To dynamic optical communications the LOS pointing structure with different coordinate system is shown in Fig. 1. For calculating the IPA four separate coordinate systems are used, including the Word Geodetic System 1984(WGS-84) coordinates, East-North-Up(EUN) coordinates, carrier coordinates, and mount coordinates.

The terminal's positions are provided in WGS-84 coordinates, in this system it is defined at the center of earth center: the X-axis in the intersection point direction of international time service 1984. O zero meridian plane and CTP equator, the Z-axis in the direction of 1984. O protocol Earth's polar, and Y-axis is perpendicular to the plane formed by the X-axis and Z-axis. The terminal's attitudes are the angles between three axis of EUN coordinates and carrier coordinates. The EUN coordinates defined at the center of mass of terminal: x_1-axis in the east direction, y_1-axis in the north direction, and z_1-axis is perpendicular to the plane formed by the x_1-axis and y_1-axis. The carrier coordinates defined at the center of mass of terminal: the y_2-axis is aligned with the heading direction, the x_2-axis is perpendicular y_2-axis and points to the right side of the aircraft, and z_2-axis is perpendicular to the plane formed by the x_2-axis and y_2-axis. Because of optical mount is placed in specific location of terminal a mount coordinate system is used, it defined at the center of mass of the mount: the y_3-axis is aligned with the mount direction, the x_3-axis is perpendicular y_3-axis and points to the right side of the aircraft, z_3-axis is perpendicular to the plane formed by the x_3-axis and y_3-axis. All system are right-handed coordinate. The initial orientation of LOS is coincided with y_3-axis of the mount coordinate, what is displayed in the Fig. 1, if not, a LOS coordinates should been set to compensate the influence of misalignment between mount and LOS coordinates, in our design they are coincided together and a coordinate conversion process can been omitted.

The counter position $(B_2 L_2 H_2)$ in WGS-84 can be transform to the IPA, the transformation process is shown in Fig. 3.

The IPA of α in azimuth and β in elevation can be calculated according to the Equation 1.

$$\begin{cases} \alpha = 180^\circ \times \arctan(x/y)/\pi \\ \beta = 180^\circ \times \arctan(z/\sqrt{x^2 + y^2})/\pi \end{cases} \tag{1}$$

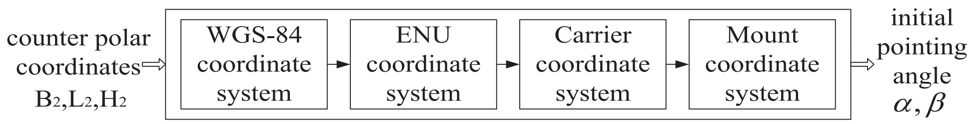

Fig. 3. Transformation process of the initial pointing angle.

Where (x,y,z) is the counter position in mount coordinate system, and it is given by Equation 2.

$$[x, y, z]^T = C_b^a \times C_n^b \times C_e^n \times [X_1 - X_2, Y_1 - Y_2, Z_1 - Z_2]^T \tag{2}$$

Among them, $X_1 Y_1 Z_1$ is the self real-time geodetic rectangular coordinate value, and $X_2 Y_2 Z_2$ is the real-time geodetic rectangular coordinate value of the counter terminal, which are obtained from the conversion of longitude, latitude, and elevation according to Equation 3.

$$\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} = \begin{pmatrix} (N_i + H_i)\cos B_i \cos L_i \\ (N_i + H_i)\cos B_i \sin L_i \\ \left(N_i\left(1 - e^2\right) + H_i\right)\sin B_i \end{pmatrix} \tag{3}$$

Where $i = 1, 2$; $N_i = \frac{a}{\sqrt{1-e^2(\sin B_i)^2}}$; $a = 6378137$ m is the long radius of the ellipsoid; $e^2 = 0.006694379995$ is the ellipsoid first partial heart rate square; $B_1 L_1 H_1$ is longitude, latitude and elevation value of self obtained by GPS system, and $B_2 L_2 H_2$ of counter terminal is obtained by the data transmission system.

The C_e^n is transformation matrix that the counter WGS-84 coordinate system is transformed into ENU coordinate system, which compensates for the influence of the position change on the IPA.

$$C_e^n = \begin{pmatrix} -\sin(L_1) & \cos(L_1) & 0 \\ -\sin(B_1)\cos(L_1) & -\sin(B_1)\sin(L_1) & \cos(B_1) \\ \cos(B_1)\cos(L_1) & \cos(B_1)\sin(L_1) & \sin(B_1) \end{pmatrix} \tag{4}$$

The C_n^b is transformation matrix that the ENU coordinate system is transformed into carrier coordinate system, which compensates for the influence of the change of attitude angle on the IPA. y, p, and r respectively represent the self real-time yaw angle, pitch angle, and roll angle values (obtained by the GPS/INS combination system).

$$C_n^b = \begin{pmatrix} \cos(r)\cos(y) - \sin(r)\sin(p)\sin(y) & \cos(r)\sin(y) + \sin(r)\sin(p)\cos(y) & -\sin(r)\cos(p) \\ -\cos(p)\sin(y) & \cos(p)\cos(y) & \sin(p) \\ \sin(r)\cos(y) + \cos(r)\sin(p)\sin(y) & \sin(r)\sin(y) - \cos(r)\sin(p)\cos(y) & \cos(p)\cos(r) \end{pmatrix} \tag{5}$$

The C_b^a is transformation matrix that carrier coordinate system is transformed into the mount coordinate system, which compensates for the influence of the coordinate system with not being coincident to IPA during the installation. $\theta_x, \theta_y, \theta_z$ represents the three angles between the carrier coordinate system and the mount coordinate system.

$$C_b^a = \begin{pmatrix} \cos(\theta_x)\cos(\theta_y) - \sin(\theta_x)\sin(\theta_z)\sin(\theta_y) & \cos(\theta_x)\sin(\theta_y) + \sin(\theta_x)\sin(\theta_z)\cos(\theta_y) & -\sin(\theta_x)\cos(\theta_z) \\ -\cos(\theta_z)\sin(\theta_y) & \cos(\theta_z)\cos(\theta_y) & \sin(\theta_z) \\ \sin(\theta_x)\cos(\theta_y) + \cos(\theta_x)\sin(\theta_z)\sin(\theta_y) & \sin(\theta_x)\sin(\theta_y) - \cos(\theta_x)\sin(\theta_z)\cos(\theta_y) & \cos(\theta_z)\cos(\theta_x) \end{pmatrix} \tag{6}$$

3.2 Field of Uncertainty

In the stage of initial pointing the uncertainty of the IPA can be expressed by α and β. Usually two angles are Gaussian distribution, and the error of the IPA is Rayleigh distribution, it can be expressed by

$$f(\theta) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{\theta^2}{2\sigma^2}\right) \tag{7}$$

Where $\theta = \sqrt{\theta_\alpha^2 + \theta_\beta^2}$ is deviation of the IPA, θ_α is deviation in azimuth, θ_β is deviation in elevation, σ is the variance. If Gaussian distribution has the same variance in azimuth and elevation $\sigma = \sigma_\alpha = \sigma_\beta$, the acquisition probability is given by

$$P = \int\int_{FOU} \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{\theta_\alpha^2}{2\sigma^2}\right) \times \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{\theta_\beta^2}{2\sigma^2}\right) d\theta_\alpha d\theta_\beta \tag{8}$$

Equation 8 is simplified to a uniform distribution with a polar angle of $1/2\pi$, and the integral in polar coordinate system is

$$P = \int_0^{FOU/2} \frac{\theta}{\sigma^2} \exp\left(-\frac{\theta^2}{2\sigma^2}\right) d\theta \tag{9}$$

In order to achieve acquisition probability greater than 98.89%, that is P≥98.89%, $FOU \geq 3\sigma$ (on both sides) can be got.

For the dynamic laser communication system, we can see that there are position error σ_1 and attitude angle error σ_2 from GPS/INS; at the same time, in the process of the LOS pointing, there are the servo turntable pointing error σ_3, the platform stability error σ_4, the dynamic lag error σ_5 caused by data transmission and turntable execution lag and installation alignment error σ_6. So the system will have a large pointing error σ. Among them, the error σ_6 is a systematic error, which can be eliminated by using theodolite or the LOS calibration after the installation of the system [12], [13]. The others are random errors, the final pointing error is determined by the following formula.

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 + \sigma_5^2} \tag{10}$$

Depending on the analysis of each error term mentioned above, σ_1, σ_2, and σ_5 are mainly to the LOS initial pointing system due to the effect of the data error of the GPS/INS output and delay factors, and are the main factors that influence the pointing accuracy. Considering the characteristics of dynamic terminal motion and error terms, The EKF is applied to improve pointing accuracy, and the data form GPS/INS is smoothed, dynamic hysteresis is reduced by prediction of filter.

3.3 Filter Model Principle

In the practical application, an extended kalman filter model is established according to the filtering principle to carry out data smoothing and prediction, so as to improve the pointing accuracy. The state equation of the filter is established with the position, velocity and attitude of the carrier as the state vectors, and the observation equation is established with the position and attitude data output by the dual-antenna GPS/INS combined system as the observation vectors. The details are shown below.

$$\begin{cases} X(i) = f(i-1, X(i-1)) + G(i-1)w(i-1) \\ Z(i) = HX(i) + v(i) \end{cases} \tag{11}$$

Among them, X: nine-dimensional state vector, $X = [x; y; z; v_x; v_y; v_z; yaw; pitch; roll]$, (x, y, z) is the three-dimensional position coordinate, (v_x, v_y, v_z) is the three-dimensional velocity, $(yaw, pitch, roll)$ is the attitude angle of the motion carrier.

F: nine by nine dimensional state transition matrix. According to the local linearization property of the EKF nonlinear function, the first-order Taylor expansion of the function is performed. The

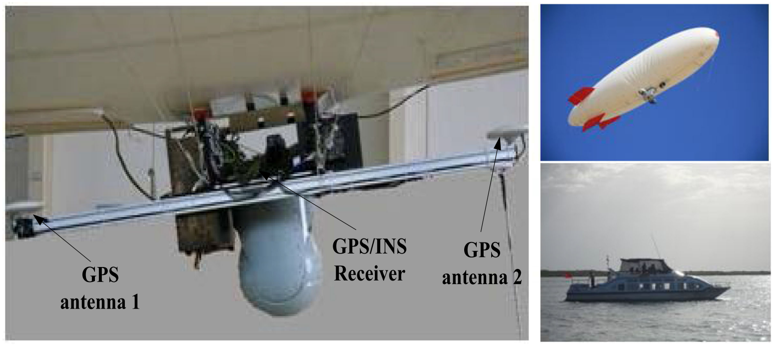

Fig. 4. Dynamic space laser communications test between airship and ship.

transition matrix is replaced by the Jacobian matrix of the function, namely:

$$F(\mathrm{i}) = \frac{\partial f}{\partial X} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_9} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_9} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial f_9}{\partial x_1} & \frac{\partial f_9}{\partial x_2} & \cdots & \frac{\partial f_9}{\partial x_9} \end{bmatrix}.$$

G: nine by six dimensional control matrix,

$$G = \begin{bmatrix} T^2/2 * eye(3), zeros(3); \\ T * eye(3), zeros(3); \\ zeros(3), T * eye(3) \end{bmatrix}.$$

Z: six-dimensional observation vector, $Z = [x; y; z; yaw; pitch; roll]$.
H: six by nine dimensional observation matrix,

$$H = \begin{bmatrix} eye(3), zeros(3), zeros(3); \\ zeros(3), zeros(3), eye(3) \end{bmatrix}.$$

ω is the system process noise; v is the observation noise. Both ω and v are subject to Gaussian white noise distribution and independent of each other. zeros(3) is a three by three zero matrix; eye(3) is a three by three unit matrix; T is the sampling time.

4. Experiment and Analysis

We separately conduct demonstration experiments of the dynamic laser communication system of the airship-ship (shown in Fig. 4, which is the same as install mode in Fig. 1), and the aircraft-aircraft (shown in Fig. 5, which is opposite to install mode in Fig. 1, the corresponding angle value takes a negative value in the application). While various performance indicators of the communication system are testing, the tests of performance of the pointing system and pointing accuracy are completed. The test link is 15 km from the nearest and 150 km from the farthest. The dual-antenna GPS/INS combined system used in the experimental test has a position error of less than 5 m, and the attitude angle errors respectively are 0.2 degree in the yaw angle, 0.1 degree in the pitch angle and the roll angle. The data update rate is 20 Hz.

A key prerequisite for ensuring the normal operation of the laser communication system is the consistency of the line-of-sights of the coarse tracking, the fine tracking and the communication. In the experiment process, in order to facilitate the observation of various experimental phenomena, a target-viewing camera is set. The LOS of the target-viewing camera is also parallel with the above

Fig. 5. Dynamic space laser communications test between aircraft-aircraft.

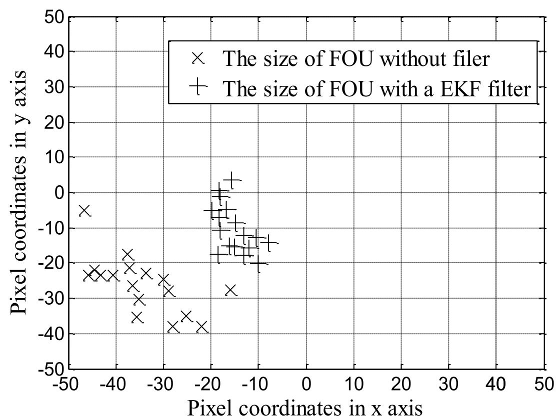

Fig. 6. Experimental data of light spot coordinates recorded by the target-viewing camera.

three axes. The spot observation of initial pointing, recording and evaluation criteria of the size of the FOU can be completed. The single pixel resolution is 100 μrad and the total field of view is 52.4 mrad. Fig. 6 shows the test results recorded in a demonstration experiment.

In the experimental results recorded of the Fig. 6, the data with the "$\times$" sign is the unfiltered result. The farthest distance between the spot and the center of the target surface is 50.3 pixels and the nearest is 32.0 pixels. The maximum angle of the center of the initial pointing offset target surface is 5.03 mrad and the minimum is 3.2 mrad. According to the bilateral calculation of its maximum offset angle, the maximum size of the FOU is 10.06 mard. The data with the "$+$" sign is the result of the EKF. The farthest distance is 25.3 pixels and the nearest is 16.3 pixels, the maximum of the FOU is 5.06 mrad. The data is concentrated than the data with the "$\times$" sign and close to the center of the camera. It is indicated that the data fluctuation decreases after the EKF, and at the same time the filter prediction function reduces the dynamic lag, which reduces the size of the FOU and improve the performance of initial pointing system of the LOS.

5. Conclusion

The initial pointing of the LOS is an important part of the laser communication acquisition system, which is the key to the success of laser acquisition, and plays a decisive role in the technical indicators such as acquisition probability and acquisition time. This paper systematically studies the initial pointing technology of the open-loop of the LOS in the dynamic laser communication system, which gives the composition principle, working principle and calculating method of the pointing angle of the LOS pointing system, and proposes to add the EKF technology to the pointing system to reduce the size of the FOU. In the demonstration experiment of the dynamic laser communication system, the performance of the pointing system is verified and the size of the FOU is tested. In addition, the calculation of the IPA and method of the EKF studied in this paper are universal, and can also be applied to the initial pointing of the LOS of aircraft-ground, aircraft-satellite and other communication systems. For example, in the initial pointing of the LOS of the satellite-borne optical communication, the satellite-borne terminal can obtain the position, attitude, speed and other information by looking up the ephemeris table and its own attitude sensor. Under the strict time unification, the two sides can perform the initial pointing of the loop. The correct modeling of the initial pointing system of the LOS and the successful demonstration of the dynamic experiment lay a foundation for the smooth progress of the dynamic laser communication system.

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