Initial Alignment Scheme and Tracking Control Technique of Free Space Optics Laser Beam

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Abstract: This paper describes the laser beam alignment techniques for free space optical communication. Bilateral laser transmission system is designed between two active free-space-optical apparatuses, which are equipped with galvanic scanners, E/O and O/E converters and are able to control laser beam discharging directions. Two alignment strategies are proposed with regard to the transient and steady state of optical signal transmission. Search method for initial alignment is established based on the Gaussian beam optics, and a tracking control system is constructed for laser beam to maintain stable telecommunication between roaming transmission equipments. Experiments reveal that the proposed techniques enable the free space optics system to locate the target receiver and to pursue the unstable transmission apparatus.

1 INTRODUCTION

Free space optics (FSO) is an alternative to the main telecommunication technology such as optical fiber network or wireless local area network. It realizes telecommunication by transmitting collimated laser beam in the air (Willebrand, 1999) (Ghimire, 2011) (Yamashita, 2011). FSO system is superior to optical fiber system in installation time and cost. It provides securer broadband communication than wireless LAN against phone tapping because laser beam does not spread like radio wave. On the other hand, conventional FSO is considered not to be ubiquitous but stationary telecommunication technology as it is designed for fixed point-to-point communication.

We have proposed active FSO technology (Tsujimura, 2004) to realize ubiquitous broadband communication in the user network where the transmission length is around 100 meters. It can be improved to an optical mesh network that serves as a rural area network as shown in Fig. 1. This figure illustrates a prospect of a free space optics network among islands, where the stationary FSO apparatuses relay transmission laser beam.

Each apparatus contains a transmitter and a receiver. Laser beams transmit bi-directionally between two pieces of apparatus. It is necessary to achieve long-distance transmission with thin laser beam from the transmitter to the receiver in the air. The positional relationship between the apparatuses is not always stationary but may shift by inches.

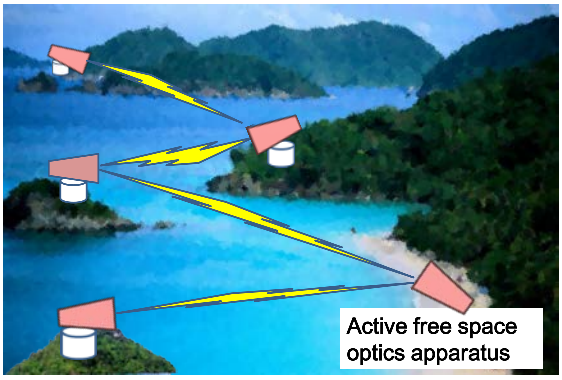

Figure 1: Optical network based on free space optics.

One of remarkable features of active FSO system is the mobile terminal tracking technique (Tsujimura, 2004). We are planning to apply this system to the hundreds-of-meter-long transmission. Laser beam alignment is essential to complete communication between remotely separated transmission apparatuses, and communication quality depends on the alignment accuracy (Yoshida, 2004).

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We are studying on laser beam alignment method. Bilateral free space optics apparatus is designed and a prototype of the distributed control system is constructed using a galvanic scanner to steer the laser beam direction. Two types of laser beam alignment strategies are proposed according to the transmission condition and the alignment procedure is established. Experiments confirm the validity of the proposed searching algorithm for optical signal connection and the tracking control system in the active free space optics communication.

2 ACTIVE FREE SPACE OPTICS SYSTEM

Figure 2 indicates the block diagram of the active FSO system, where two FSO setups discharge laser beam each other to realize bilateral optical communication. Each is equipped with a PC to control both a receiver and a transmitter. The galvanic scanner guides the laser beam direction based on the arrival point of the laser beam on the opposite receiver.

The proposed active FSO system tracks a mobile terminal maintaining broadband communication using the laser positioning scheme. Positioning error of laser beam is detected by the dedicated sensor device and is transferred to the feedback controller carried upon the upstream transmission line directing from the opposite transmitter. The feedback control signals are superposed on the optical signals transmitting communication data.

The transmitter is composed of an E/O converter and a galvanic scanner. The E/O converter contains an AlGaIn laser diode whose frequency bandwidth is up to 1.2 GHz. We use 658 nm-wavelength laser diode in this paper. The E/O converter discharges a transmission laser pulses to realize broadband communication. The laser beam is focused several millimetres in diameter.

The galvanic scanner is equipped with two motor-driven reflection mirrors. It reflects laser beam and discharges it spherically in the air. Those mirrors are attached to the orthogonal axes of motors. They are controlled by servo motor drivers with a resolution of 4.77×10^{-4} deg, which corresponds to an accuracy of 4.16×10^{-2} mm on the receiver plane.

Thus we can direct the laser beam, discharged from the laser diode, to the objective direction by controlling the motors of the galvanic scanner.

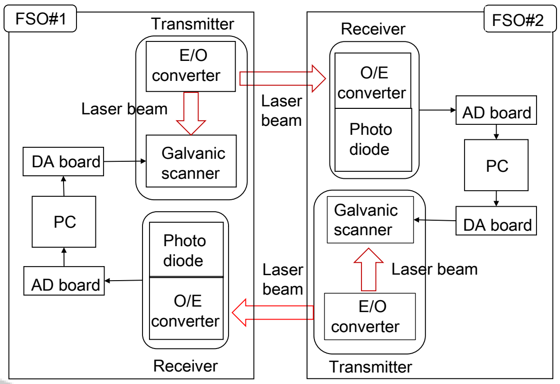

Figure 2: Distributed control system of bilateral FSO.

The receiver involves both the transmission photodiode and the positioning ones. An O/E converter for fiber optics use serves as the transmission photodiode by modifying to FSO transmission by adjusting its optical system. A SiPIN photodiode is built in the O/E converter. Its maximum frequency bandwidth and wavelength range are 1 GHz and 400 to 1000 nm, respectively.

The positioning photodiodes are designed and manufactured as shown in Fig. 3, where four positioning photodiodes are surrounding the transmission photodiode (Muta, 2013). They are SiPIN photodiodes, whose wavelength range and cutoff frequency are from 320 to 1100 nm, and 25 MHz, respectively.

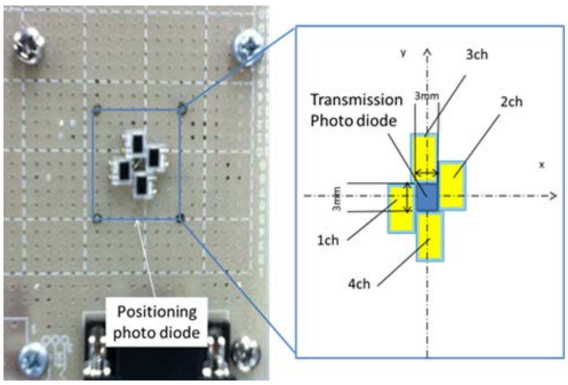

Figure 3: Positioning photodiode.

They are used only for detection of laser luminescence. The positioning photodiode unit outputs four values of voltages representing laser intensities of the corresponding positions of each photodiode.

3 LASER BEAM CONTROL TECHNIQUES

Free space optics communication is performed between two pieces of FSO apparatus. Single channel of the bilateral transmission lines is illustrated in Fig. 4, which describes only a transmitter and a receiver of its neighbouring apparatus tens of meters away. A thin laser beam is introduced from a transmitter to an opposite receiver to realize broadband communication.

The system keeps the laser spot within the sensible range of the receiver by controlling the discharge direction of the laser beam with a galvanic scanner. The scanner is equipped with two pairs of servo motor driven mirrors to reflect laser beam to a designating direction. The objective mirror angles are calculated based on the laser intensity measured by the positioning photodiode.

The receiver contains two types of detectors: the transmission photodiode and positioning photodiodes. The arrived laser beam is introduced to the transmission photodiode to catch the optical transmission signals. The function of the latter photodiodes is evaluation of positioning error of the laser beam. Their output data is transferred to the galvanic scanner to generate feedback control command.

The thin laser beam is required to keep hitting the small receiver to maintain communication even if the target drifts.

We have prepared two modes of laser beam alignment: the transient and the steady state. In the former state, communication is not established yet, as the optical signals do not successfully reach the receiver. It is necessary to find out presice travelling route of the laser beam from the transmitter to the receiver.

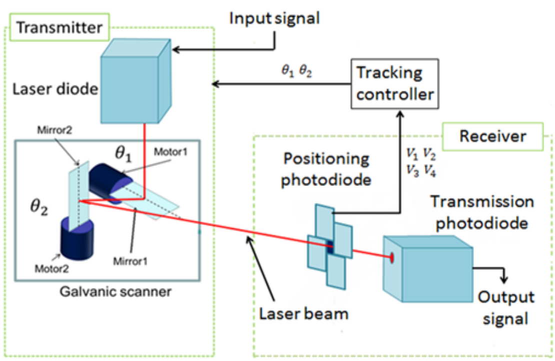

Figure 4: Active free space optics system.

In the steady state, the laser beam arrives within the detection range of the positioning photodiodes. Based on the measured optical intensity, the tracking control is applied to adjust the laser hitting point onto the midst of the positioning photodiodes where the transmission photodiode is installed.

Each of two control schemes is applied according to the state as shown in Fig. 5.

It starts with the transient state in general as the laser beam is wide of the receiver. Thus, the system scans the laser beam around over the area where the target receiver is possibly located, searching for the line-of-sight from the transmitter to the receiver. After monitoring the intensity of the received laser luminescence, the optimum physical relationship between the transmitter and the receiver is determined by adjusting the laser beam direction so that received signal intensity would be the highest.

Once the receiver detects the laser luminescence, a feedback control algorithm steers the laser beam direction so that the laser spot keeps within the sensible area on the receiver. In the steady state, the laser beam can track the receiver automatically. The target motion is estimated based on the output of positioning photodiodes that catch the laser luminescence discharged from the opposite transmitter.

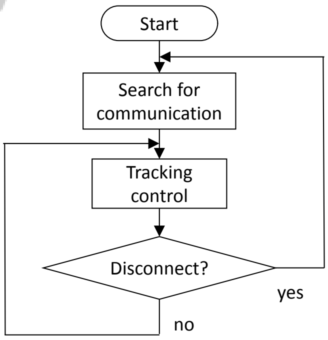

Figure 5: Laser beam alignment procedure.

If the laser beam misses reaching the target receiver by accident and the transmission is disconnected, the system is incapable of estimation and loses track of the target. Then the mode is turns to the transient state, and starts searching again.

3.1 Initial Alignment Scheme to Capture Optical Signals

The proposed system searches for the line-of-sight of the laser beam in the transient state. When the distribution of the laser beam intensity is previously known, it helps the search easier than observing all over the space. If the laser beam corresponds to Gaussian beam optics, it is possible to analytically estimate the peak of the distribution. That means we can adjust the optical axis of the laser beam just onto the receiver.

Let us consider the formulation of the laser beam in the x-y-z coordinate system, assuming the optical axis is parallel to the z-axis. When a laser beam hits at (a, b) on the x-y plane, the optical intensity, E_{xy} of a Gaussian beam at (x, y) on the x-y plane is theoretically formulated as

$$E_{xy} = E_0 \exp\left(-\frac{(x-a)^2+(y-b)^2}{w^2}\right) \quad (1)$$

where E_0 is the maximum intensity, which is observed on the optical axis (a, b).

By locating the positioning photodiode at (x_0, y_0), we obtain the laser luminescence intensity, E_{x0y0} at that point. Then equation (1) gives the following equation.

$$(x_0-a)^2+(y_0-b)^2 = -w^2 \log\frac{E_{x0y0}}{E_0} \quad (2)$$

Because this equation contains four unknown parameters, four independent conditions are necessary to solve the simultaneous equation in general. If we prepare four positioning photodiode at (x_0, y_0), (x_0, y_1), (x_1, y_0), (x_1, y_1), position (a, b) of the intensest laser spot is determined, by solving four simultaneous equations in terms of four variables, as

$$a = \frac{L_1^2(x_0^2+y_0^2-y_0y_1)y_0 + L_1^3x_1^2y_0 + L_{23}^{14}x_1^2y_1}{2\{L_1^2x_0y_1 + L_1^3x_1y_0 + L_{23}^{14}x_1y_1\}} \quad (3)$$

$$b = \frac{L_1^2x_0y_1^2 + L_1^3(x_0^2+y_0^2-x_0x_1)x_1 + L_{23}^{14}x_1y_1^2}{2\{L_1^2x_0y_1 + L_1^3x_1y_0 + L_{23}^{14}x_1y_1\}} \quad (4)$$

where L_1^2, L_1^3, L_{23}^{14} represent

$$\log\frac{E_{x1y0}}{E_{x0y0}}, \quad \log\frac{E_{x0y1}}{E_{x0y0}}, \quad \log\frac{E_{x0y0}E_{x1y1}}{E_{x0y1}\,E_{x1y0}},$$

and E_{x0y1}, E_{x1y0}, E_{x1y1} are the laser luminescence intensity measured at (x_0, y_1), (x_1, y_0), (x_1, y_1), respectively.

We have carried out a fundamental experiment to confirm the analysis. The planar distribution of the laser beam intensity is actually measured by the positioning photodiode. It can be approximated by a Gaussian distribution at $E_0 = 8.0$ and w = 5.0.

The position (a, b) of the laser beam optical axis is evaluated by applying the measured values of the photodiodes to the equations (3) and (4) with regard to various sensor placement. Figure 6 shows the estimation results on condition the photodiodes are arranged at four corners of 10 mm square. The vertical axis represents the estimation error of the optical axis position, while the horizontal axis denotes the distance between the photodiodes and the optical axis. It proves that the proposed method estimates the optical axis position of the laser beam within an accuracy of 10 mm.

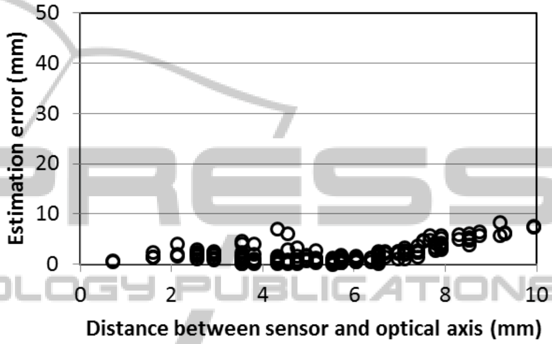

Figure 6: Estimation results of optical axis.

3.2 Tracking Control Technique for Laser Beam

The tracking control is conducted in the steady state to steer the laser beam to the midst of four photodiodes. A feedback control system is established between the transmitter and the receiver. A block diagram of proportional control system is shown in Fig. 7.

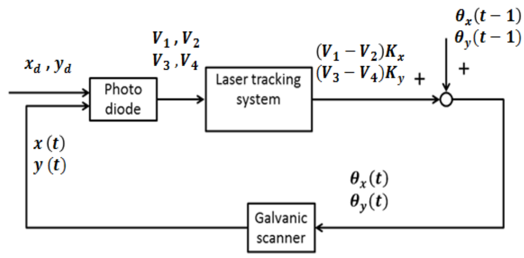

Figure 7: Block diagram of laser tracking system.

Equations (5) and (6) express the proportional control formulations in terms of the command mirror angles for two-degree-of-freedom laser beam angles, where θx(t) and θy(t) represent the mirror angles, Kx, Ky do the feedback gains, V_1, V_2, V_3 and V_4 do the output voltages of the positioning photo diode, and θx(t-1), θy(t-1) do the previous angles.

$$\theta x(t) = (V_1 - V_2)K_x + \theta x(t-1) \qquad (5)$$

$$\theta y(t) = (V_3 - V_4)K_y + \theta y(t-1) \qquad (6)$$

This system controls the laser beam to make these four outputs equal. Each positioning photodiode covers a part of the laser spot, and generates voltage of the corresponding share of the laser intensity. When the laser beam shifts aside, the output voltages of four photodiodes increase or decrease with regard to the shift direction. The feedback controller directs the laser beam to compensate the gap based on the balance of the photodiode outputs. Thus, the proposed tracking system is able to chase the target belatedly.

Some experiments are conducted to the active FSO system to track moving photodiodes. A motorized stage carries the target positioning photodiodes along a designated trajectory and the control responses are measured and evaluated.

The positioning photodiodes are guided to trace a vertically reciprocating trajectory, shown by a solid line in Fig. 8, on the condition that the target speed is 90 mm/s, the distance from the galvanic scanner to the positioning photodiode is 5 m, and its motion amplitude is 50 mm.

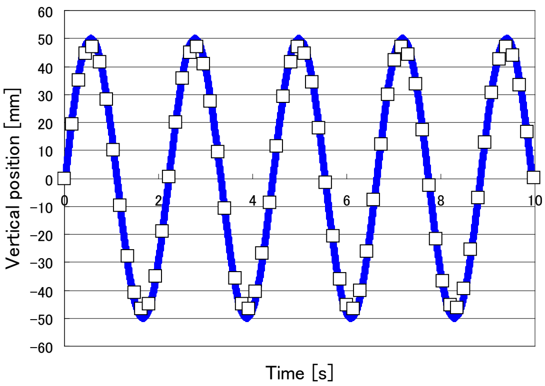

Figure 8: Trajectory of target and laser beam.

Channels 1 and 2 catch the horizontal motion. Channels 3 and 4 observe the vertical motion. Figure 9 (a) and (b) indicate the amplified output voltages of the positioning photodiodes, channels 3 and 4. They vary as much as 7.5±2.5 V. Their oscillation phases shift each other by π/2 according to up and down motion of the target. Results suggest that the laser beam is chasing after the photodiodes synchronously. Output of channel 1 and 2 is almost unchanged, because the laser beam swings vertically.

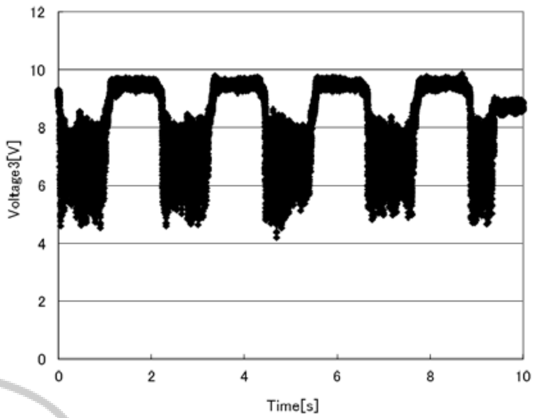

Figure 9 (a): Output voltage of photodiode, ch. 3.

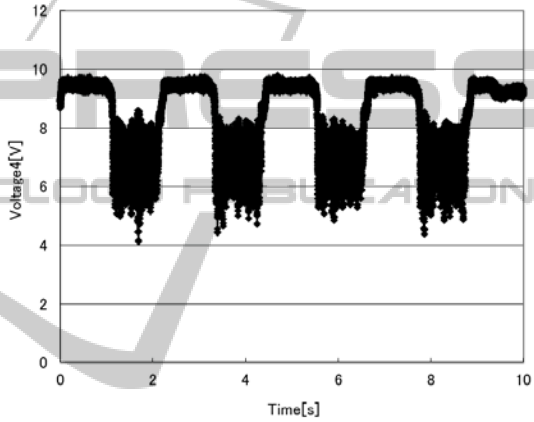

Figure 9 (b): Output voltage of photodiode, ch. 4.

The reflection mirrors equipped in the galvanic scanner are controlled by servo motors according to the proportional control algorithm. Their command angles are determined based on the positioning photodiode output values. Figure 10 (a) and (b) show the rotation angles of the horizontal and vertical mirrors, respectively. The vertical mirror rotates as much as 0.65 deg in amplitude, while the horizontal mirror holds still.

Actual motion of the laser beam is compared with the target photodiode trajectory in Fig. 8, where white squares indicate the measured trace of the laser spot. It reveals that the proposed control system is successful in tracking a mobile target with the laser beam scanning system from far away.

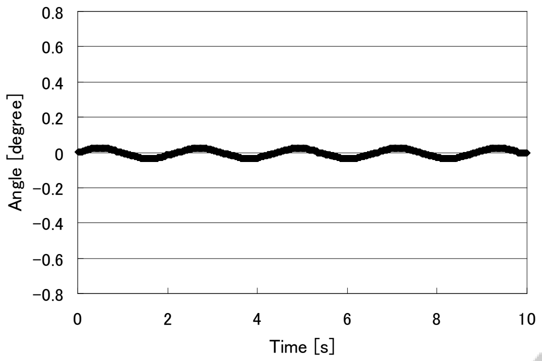

Figure 10 (a): Motion of horizontal mirror.

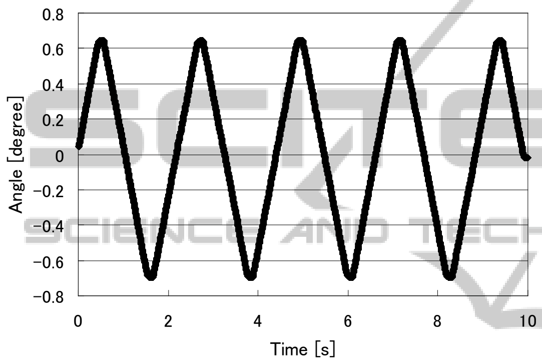

Figure 10 (b): Motion of vertical mirror.

4 CONCLUSIONS

Bilateral telecommunication system of the active free space optics system is proposed which is equipped with distributed control system of the laser beam scanners to apply to longer-distance optical transmission in the air. Dedicated apparatus is designed and prototyped both for communication and laser beam control. The feedback control system is also designed to adjust the laser beam travelling from the distant transmitter within the receiver by steering the laser beam direction based on the positioning photodiodes.

Two states are assumed with respect to optical signal transfer, and the alignment strategy is proposed according to the state. Searching method is investigated for the transient state, and its algorithm is established to determine the summit of the laser luminescent by analysing the Gaussian beam optics. It enables the galvanic scanner to efficiently hunt for the target receiver.

Tracking control is adopted for the scanning system to maintain optical communication in the steady state. It directs the laser beam to follow the target motion and to remain on the receiver. Experiments clarify that the proposed system successfully steer the laser beam to follow the target receiver. It enables the transmitter to maintain long-distance transmission in high quality even when the receiver fluctuates.

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