On Energy Transmission to Remote Location Using a Repeater

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Abstract. This paper discusses a power supply system to operate a small-scale monitoring system where the sun does not reach and power supply is difficult. When we try to operate a small monitoring system in a place where power supply is difficult, how to secure power is important. We consider a system that transmits light energy from the ground to the ground using a floating repeater. It is assumed that both the position and the angle of the receiver are fixed. It is also assumed that the repeater is affected by the disturbance. We aim to control the light to reach the receiver under any circumstances. Some experiments were conducted to verify whether we could perform the assume control by developing a system based on the proposed method on a small scale. As a result, it was confirmed that roughly assumed control could be performed.

1. Introduction

It is an important issue to consider how to supply power when a small monitoring system or the like is to be used in a place where it is difficult to arrange a power supply. Wireless power supply has a potential to solve this problem. There are various methods for wireless power transmission such as electromagnetic induction and resonance power transmission [1][2]. Some authors proposed a method to supply energy to a video capsule endoscope wirelessly [3]. As a method using light or laser, there is space solar power generation system (SSPS) [4]-[6]. In the field of optical wireless transmission, optical wireless communications are actively studied. According to the survey [7], optical wireless communications (OWM) not only includes the wireless communication with visible light but also includes infrared or ultraviolet spectrum. OWM system using visible light is often called visible light communication (VLC). VLC can simultaneously offer communication, illumination, and localization and are actively studied as a promising technology in the past decade [8]-[10]. We also can find some examples of underwater optical wireless communications in the recent years [11]-[13]. Although there are many studies on communication system using visible light, energy transmission is not much performed. SSPS is one of the few exceptions and is a long-term research goal to achieve the end of the 21st century. As a representative technology, two methods are well-known. One is a method of installing a huge solar panel on a geosynchronous orbit and converting the generated electric power into a microwave and sending it to the ground. The other is a method of collecting sunlight on a geostationary orbit, converting it into laser light, sending it to the ground, and obtaining electric power by carrying out photoelectric conversion at a light receiving station. In this study, we aim to construct a system to transmit power three-dimensionally by air transmission, inspired by the SSPS method. We aim to use our system for power supply to operate a small-scale monitoring system where the sun does not reach and power supply is difficult. When trying to operate a small monitoring system in a place
where power supply is difficult, how to secure power is important. By using visible light, power can be supplied using solar cells even when a small system is placed in a shadowed place. Power can be supplied using the proposed system even in closed spaces where the sun does not reach by using our system. Therefore, we will consider a method of emitting light from the ground and converting it to energy at the receiver side via a repeater floating in the air with reference to the latter method of obtaining electric power by performing photoelectric conversion light receiving base.

Some studies have been reported regarding the supply of energy to flying objects [14]. In the study, a small unmanned aircraft operates for a long time in order to grasp the situation of an environment site where it is difficult for human beings to approach and communicate information such as a disaster site. We constructed a small scale experimental apparatus with a reduced distance between transmitter, repeater and receiver and confirmed the feasibility of the proposed system by experiment.

2. Problem formulation and basic concept
In this section, we formulate a problem and describe the basic concept of the proposed system. The system proposed in this research consists of three elements: a transmitter that transmits visible light (including laser), a repeater that floats in the air and reflects light from the transmitter by a mirror, and a receiver that uses solar cells that receive light and convert it into energy. Figure 1 shows a schematic diagram. Physical constraints on transmitters, repeaters and receivers are as follows.

We assume that the system will be used at short distances (about a few meters), and do not consider light dispersion. We assumed that the positions of the transmitter and the receiver are fixed, and only the emission angle of light from the transmitter can be changed. On the other hand, positioning is possible for the repeater in the air, but positional deviation occurs due to disturbance. It is assumed that the positional deviation will occur in the vertical and horizontal directions. Hence, we consider the case where horizontal disturbance and vertical disturbance are added in this study. We then consider implementation of a system that can handle both of them after considering the problems theoretically. In either case of disturbance, control is performed so that the light of the transmitter does not come off the repeater.

At the same time, the deviation of light to the solar cell is corrected by angle control of the mirror on the repeater. In order to perform such control, the optical sensor is installed at the repeater at regular intervals, and the arrival position of the light from the transmitter is fed back to the transmitter side. In addition, in order to detect the positional shift of the arrival light, a plurality of solar cells to serve as receivers are prepared so that positional deviation of the arrival light can be fed back to the repeater. In previous research, there is a method to estimate the deviation of light beam by reflecting light at the receiver and seeing the difference in intensity of the reflected light [15]. However, it is considered that the reflected light from the transmitter does not reach the transmitter stably as the angle of the mirror also changes in our assumption. Therefore, in this research, we directly observe the power generation of the solar cell and obtain the feedback information. Based on these restrictions, the goal of this research is to correct the deviation of the arrival light due to the positional shift of the repeater in real time by controlling the emission angle of the transmitter and the reflection angle of the repeater.

This section describes theoretical consideration on the relationship between control of emission angle and mirror angle in the proposed system.
3. Theoretical consideration

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3.1. On size of the mirror mounted on the repeater

We first consider the size of the mirror mounted on the repeater. Let $\Delta \theta$ be the control error of the angle with respect to the emission angle $\theta$ of the transmitter. Let $h [m]$ be the height from the transmitter to the repeater. Let $x [m]$ be the distance between the transmitter and the point where the perpendicular is drawn from the midpoint of the repeater to the ground. Figure 2 shows the outline of the system and the relationship between each variable. Let us consider the deviation of the light reaching the repeater when an error of $\Delta \theta$ is generated for the control of the light source. The relationship between $\Delta x$ and $\Delta \theta$ is described as follows.

$$\Delta x = h \frac{1 + \tan \Delta \theta \tan \theta}{\tan \theta - \tan \Delta \theta}$$

where $\tan \theta = \frac{h}{x}$. The size of the mirror was estimated using the equation (1). We set $\Delta \theta = 0.03^\circ$ on the basis of the angular control error of a general servo motor. We also assumed the height $h$ to be 10 m as we assume that the system will be used at short distances (about several meters).

We calculated the error of the arrival point of the beam when $x [m]$ was changed. It is noted that the limit of $x \to 0$ was calculated as $\tan \theta$ is not defined when $x = 0$. The calculation result is shown in Fig.3. We found that the shorter the distance to the repeater becomes, the smaller the size of the mirror becomes. We expect that the size of the mirror is sufficient when it is twice as large as the error of the arrival point of the light when the thickness of the light is ignored. Therefore, it is expected that the system can be realized with a realistic size of mirrors if the purpose is to transmit light at a distance of several meters as the reaching error is within 5 [cm] according to Fig.3.
3.2. On the control of the mirror when the repeater receives disturbance (horizontal direction)

Let us consider how much the deviation of the beam arriving at the receiver is when the repeater shifts by $\Delta x$ [m] due to the influence of horizontal disturbance or the like. As described in the previous section, the light from the transmitter is controlled so as to capture the midpoint of the repeater at all times. When we consider the model as shown in Fig.2, the deviation of the arrival point of light at the receiver is represented by $2\Delta x$. In order to compensate for this error, the angle of the mirror of the repeater may be changed by $\theta_1$ described as follows.

$$\theta_1 = \frac{1}{2} \tan^{-1} \left( \frac{\tan \theta' - \tan \theta''}{1 + \tan \theta' \tan \theta''} \right)$$

where $\theta'' = \theta' + 2\theta_1$, $\tan \theta'' = \frac{x - \Delta x}{h}$, $\tan \theta' = \frac{x + \Delta x}{h}$. $\theta_1$ is set to the counterclockwise direction in the figure.

3.3. On the control of the transmitter when the repeater receives disturbance (horizontal direction)

Let us consider the control of the emission angle of the transmitter when the repeater shifts by $\Delta x$ [m] due to the influence of the horizontal disturbance and so forth. As described in the previous section, the optical sensors are arranged at regular intervals in order to control the position so that the light from the transmitter is always in the center of the repeater.

Fig.4 shows the supposed model. When the light deviates by $\Delta x$ [m] from the center of the repeater, the emission angle can be changed by the following $\theta_2$.

$$\theta_2 = \tan^{-1} \left( \frac{h}{x - \Delta x} \right) - \theta$$

where $\tan \theta = \frac{h}{x}$. $\theta_2$ is set to the counterclockwise direction in the figure.

4. Experiment with small equipment
In this experiment, we constructed a system based on the proposed method on a small scale and confirmed whether it is possible to achieve real-time control such that the light from the transmitter always reaches the receiver.

4.1. Experimental device
Fig. 5 shows the outline of the experimental equipment. The distance from the transmitter to the center of the receiver was set to 30 cm, and the repeater was arranged vertically 20 cm away from the line connecting the transmitter and the receiver. A small LED light with a brightness of 150 lumens was used for the transmitter. As the receiver, OptoSupply 0.37 W solar panel / OPL 15 A 25101 was used. The size of the solar cell was 90 mm × 50 mm, and the deviation of light was detected by installing a total of five pieces. Although the assumed control can be done with three solar cells, five solar cells were prepared in consideration of the performance of the prepared servo motor and the low directivity of the light source. A mirror with a size of 40 mm × 120 mm was prepared for the repeater. Three optical sensors were attached at the center of the mirror at intervals of 30 mm to detect deviation of light. In addition, servomotors (standard servomotor type 2 of VStone, Inc.) were used for changing the angle of the transmitter and the angle of the mirror of the repeater. Arduino was used to measure the amount of power generated by the solar cell, to measure the resistance value of the optical sensor, and to control the servomotor. Arduino connected to the transmitter controls the emission angle of the light source. Two Arduinos were connected to the repeater. One unit measured the resistance value of the optical sensor. The other controlled the servomotor based on the data obtained from the receiver. Arduino connected to the receiver measured the amount of power generated by the solar cell.

It is assumed that the transmitter, the repeater, and the receiver were located at separate places from each other. Therefore, a control computer was prepared for each of the transmitter, the repeater, and the receiver. During operation, wireless communication was performed between computers. The data of the amount of power generated by the solar cell of the receiver was sent to the control computer of the repeater. The data of the resistance value of the optical sensor of the repeater was sent to the control computer of the transmitter. Communication between computers was done using TCP/IP. We observed the amount of power generated by the solar cell on the receiver side and the amount of light to the optical sensor installed in the repeater independently through Arduino. At the time of control, the amount of light to the solar cell and the optical sensor was observed. When the position where the light amount becomes maximum deviates from the center, the servomotor was controlled so as to correct the position shift. Figures 5 show the overall overhead view of the small scale device actually created based on the above elements, respectively. Figure 6 shows the positional relationship of each element.
4.2. Experimental process
We experimentally confirmed whether it was possible to control the light to the three central solar cells of the repeater by using the developed system. We observed the power generation amount of the solar cell and the resistance value of the optical sensor with a control computer. We then checked whether it was possible to control the angle of the servo motor of the repeater based on the electric-generating amount of the solar cell, and to control the angle of the servo motor of the transmitter based on the optical sensors of the repeater.

In the preliminary experiments, we confirmed that the movement of the servomotor could not keep up with the sent data when the servo motor being used transmitted data at 500 ms interval or less. Hence, we decided to monitor the amount of power generated by the solar cell of the receiver and the resistance value of the optical sensor of the repeater every 500 ms and to send it to the repeater and the transmitter, respectively. The repeater was moved assuming horizontal disturbance as follows.

1) The repeater moved from the center by 7 cm to the right (transmitter side) as seen from the repeater.
2) The repeater returned to the center a few seconds after the servo motor stops moving.
3) The repeater moved 7 cm to the left (receiver side) a few seconds after the servo motor stopped moving.
4) The repeater returned to the center a few seconds after the servo motor stopped moving.

These operations were performed twice.

4.3. Experimental results on horizontal movement
In Fig. 7, the picture 1 corresponds to the start of the experiment, the picture 5 corresponds to the end of the first operation. Figure 8 shows the voltage observed at the receiver and control information to the servomotor according to the voltage and the servo motor angle of the repeater in time series. Figure 9 shows the voltage observed by the repeater and control information to the servomotor according to the voltage and the angle of the servomotor of the transmitter in time series. The solar cells of the receiver are numbered 1, 2, 3, 4, 5 in order from the left as seen from the repeater side. Likewise, the optical sensor of the repeater is numbered 1, 2, 3 in order from the left as seen from the transmitter side. The control computer determines which sensor receives most light at 500 ms intervals and sends the command value corresponding to the sensor information to the servomotor. The command value from the receiver to the repeater was set to 1 when light hit sensor 1, 2 when light hit sensor 2, 3, and 4, and 3 when light hit sensor 5. If the voltages of all the solar cells are lower than the fixed value, it is determined that the light is out of the receiver, and the command value 0 is sent to the servomotor. As the command value from the receiver to the transmitter, the number attached to the sensor was used as it was. When the command value 2 is sent to the servomotor, it is a state in which light is striking the sensor at the center among each sensor. When command values 1 and 3 are sent, it indicates that the servomotor should be controlled to correct the deviation. The graphs in Figure 11 and Figure 13 show the command values sent from the receiver and the repeater, respectively. It was possible to understand which sensor the light was hitting according to the command value. The
positive or negative of the control angle of the servo motor is determined with respect to the command value sent. The angle that the servomotor moves is set to 4 degrees of the minimum control angle. In addition, control is performed every time a command value is sent. When the command value 0 is sent, the servo motor is rotated by a random angle in the range of 4 to 7 in the positive direction when \( \theta_1 \) is negative, in the negative direction when \( \theta_1 \) is positive.

Table I shows the movements of the emission angle of the transmitter and angle of repeater mirror based on the data from Fig. 8 and Fig. 9. As repeater moved 7 cm horizontally this time, when it moves from the center to the left and right, the transmitter will be 15.1 degrees and the repeater mirror will move 13.0 degrees from the calculation formula described in Section 3.2 and Section 3.3. However, in many cases, the motor moved only at an angle smaller than expected.

**Figure 7.** Experimental photo (move the repeater horizontally)

**Figure 8.** Voltage observed by the receiver (horizontal) and Signal sent from receiver to repeater and change of the repeater servomotors angle (horizontal)
Figure 9. Voltage observed by the repeater (horizontal) and Signal sent to transmitter and change of transmitter servomotor angle (horizontal)

Table 1. Angle of movement of servomotor

| Repeater movement | Repeater mirror angle $\theta_1$ | Transmitter emission angle $\theta_2$ |
|-------------------|----------------------------------|--------------------------------------|
| Center→right      | $8^\circ$                        | $12^\circ$                           |
| Right→center      | $4^\circ$                        | $8^\circ$                            |
| Center→left       | $-8^\circ$                       | $0^\circ$                            |
| Left→center       | $4^\circ$                        | $4^\circ$                            |
| Center→right      | $12^\circ$                       | $12^\circ$                           |
| Right→center      | $4^\circ$                        | $8^\circ$                            |
| Center→left       | $-12^\circ$                      | $-4^\circ$                           |
| Left→center       | $0^\circ$                        | $0^\circ$                            |

4.4. Discussion
We could confirmed that the control was continuously performed to keep the light in the middle of the receiver at all times from the actual experiment conditions and the graph of the obtained voltage about both horizontal movement and vertical movement. Through the experiments, the angle at which the servomotor moved became smaller than the theoretical value. It is considered that these results were because the directivity of the light of the light source was low and there were many sensors in the receiver that determine the center.

In addition, it sometimes happened that the mirror of the repeater continued to move to the left and right and did not stop with the device used this time. The reason is that the resolution of the servomotor being used is low, fine angle control cannot be performed, and the light passes through the middle solar cell, and the directivity of the light of the light source being used is low.

As these are problems that depend on the hardware being used, it is considered that it can be solved by using good performance hardware.

5. Conclusion
In this paper, we aimed at energy supply at the time of severe disaster, and examined an energy transmission system consisting of a transmitter that emits light, a repeater that reflects light from the transmitter, and a receiver that receives light. In addition, we made a small-scale system, and conducted an experiment to confirm that it was possible to control the system so that the light from the transmitter could reach the receiver.

In the experiments, it was possible to control the servo motor of the repeater using the data observed by the solar cell of the receiver, and to control the servo motor of the transmitter using the
data of the optical sensor attached to the repeater. As a result, it was confirmed that the control which always applies light to the receiver by using the repeater can be achieved in the situation where horizontal disturbance and vertical disturbance are assumed respectively. However, it is necessary to increase the scale of the equipment and conduct experiments in a state where the repeater is floated in the future as the experiment was conducted with the equipment on a small scale and with the repeater on the ground. Hardware improvement is also required as we found that the mirror of the repeater continued to move to the left and right due to the hardware limitation.

One of the issues for practical realization is securing a light source capable of long distance transmission. For this purpose, a semiconductor laser as used in [6] is a candidate to be used. In addition, it is necessary to consider how to cope with three dimensional disturbances in which both vertical and horizontal disturbances are mixed. The system will be improved so that the control performed this time can be performed on a plane in order to cope with two-dimensional disturbance in the horizontal direction as one-dimensional control is performed at present. After that, it is necessary to study the control when disturbance is added in the vertical direction. We also would like to implement an algorithm that can be back to light the receiver again if the light from the transmitter deviates from the repeater or receiver.

Acknowledgments
This research was supported by JSPS KAKENHI Grant Number JP20H02412, the research grant of Support Center for Advanced Telecommunications Technology Research and by the research grant of Foundation for the Fusion of Science and Technology.

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