Study of Optical Wireless Power Transmission to Moving Objects

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Dissertation Abstract

Study of Optical Wireless Power Transmission to Moving Targets
移動体への光無線給電に関する研究

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ABSTRACT

Wireless Power Transmission (WPT) is a technique to transmit power from transmitter to receiver through medium wirelessly (without any cable) using electromagnetic wave. There are three methods of WPT: magnetic induction coupling WPT, microwave WPT and Optical WPT (OWPT). Among these WPT methods, OWPT has many advantages compared with the other methods. In OWPT, light sources such as laser and LED are used as the transmitter and solar cell is used as the receiver. By taking advantage of small size and divergence angle of laser beam, OWPT can be used to transmit high power density to longer distance than the other WPT method. Based on theoretical analysis in this research, OWPT can be used to transmit power through air (atmosphere) with more than 30% system efficiency for 1 km distance between transmitter and receiver using infrared laser and Si solar cell. This high system efficiency for long distance transmission is not achievable by the other WPT methods.

In this research, OWPT system using camera with color segmentation method and Galvano mirror to recognize the receiver (target) and steer the laser beam was designed and developed. 980 nm laser and Si solar cell were used as the transmitter and receiver, respectively. Using this method, OWPT to 1-dimensional moving target, multiple targets, 2-dimensional moving target and OWPT to moving target which was insensitive to the brightness of environment had been demonstrated. The system efficiency of this OWPT to moving target was calculated to be 3.8% for distance between transmitter and receiver was 60 cm. Additionally, OWPT through water and hybrid power and data transmission had also been demonstrated.

1. Introduction

Electronic device is an important element which cannot be separated from human's daily life. Every electronic device needs to be supplied with electric power. For mobile devices which have high mobility such as drone, Unmanned Underwater Vehicle (UUV) and smartphone, battery is used to supply the electric power. Unfortunately, the battery also has limited capacity. If the battery runs out of power, the mobile devices need to be charged using cable. This traditional charging method will limit the mobility and operational time of the mobile devices because it has to be charged regularly and during charging, it cannot be used. Nowadays, high capacity battery is developed as power supply for the mobile devices. However, the capacity of battery is proportional with its weight; hence, the higher the capacity of the battery, the weight will also increase. This battery weight problem will also limit the operational distance of mobile devices such as drone. In order to solve these problems, a system which can supply electric power to mobile devices from far away, in the other words, a system which can charge a mobile device without sacrificing its mobility is desirable [1-4].

Wireless Power Transmission (WPT) is a technique to transmit electric power from one place to another remote place without using any electric cable. In this technique, electromagnetics wave is used for power transmission. There are three methods of WPT which are currently developed. They are magnetic induction coupling WPT, microwave WPT and optical WPT (OWPT)..

Simple diagram of WPT system can be seen from Figure 1. Transmitter which converts electric power into electromagnetic wave, receiver which converts back electromagnetic wave into electric power which can be used to power up the electronic devices and medium in which the electromagnetic wave propagates from transmitter to receiver are three main components of WPT system. A pair of coils and antennas are used as transmitter and receiver at magnetic coupling WPT and microwave WPT, respectively. In OWPT, light sources such as laser and LED and solar cell are used as the transmitter and receiver, respectively. The other differences among three of WPT methods are summarized in Table 1.

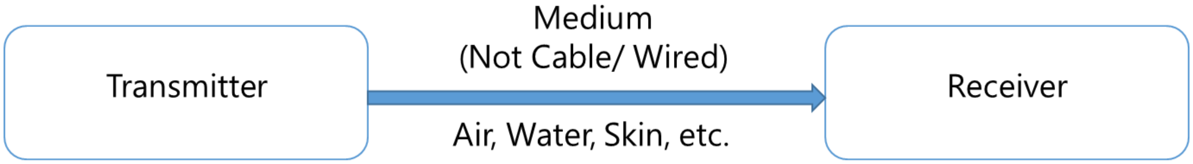

Figure 1. Basic diagram of wireless power transmission (WPT) system.

Table 1. Differences between wireless power transmission methods.

	Magnetic Coupling	Microwave	Optical
Ease to steer the beam	Low	High	High
Mobility of target	Low	High	High
Operational distance	Short	Long	Long
Operational frequency	10 kHz - 1 MHz (Induction Coupling) 1 MHz - 100 MHz (Resonance Coupling)	1 GHz – 30 GHz	>100 THz
Back-to-back efficiency	~90%	~70%	~50%

Small size and divergence angle of laser beam which is used in OWPT give advantage in terms of its possibility to transmit high power to long distance and its high directivity. However, these characteristics of laser beam also raise a challenge in designing OWPT system. The laser beam has to be steered to point directly and only to the receiver. Hence in OWPT system, it is important to recognize the position of the receiver. Beam steering and target recognition system become an integral part of OWPT system.

In this research, OWPT system using Galvano mirror to steer the laser beam and camera to recognize the target was developed and the performance of such system was analyzed. Using this system, OWPT to multiple targets and 2-dimensional moving target had been realized and demonstrated. Moreover, OWPT system through water and a system which can be used to transmit data and power at the same time were also designed and analyzed.

2. Theoretical Analysis of System Efficiency

System efficiency of WPT system is the ratio of input electric power of the transmitter and output electric power of the receiver. In the other words, it shows how efficient the electric power can be sent using the OWPT system. The system efficiency of WPT system can be analyzed as:

$$\eta_{sys} = \eta_T \times \eta_{med} \times \eta_R \quad , \qquad (1)$$

Where η_T, η_{med} and η_R are the conversion efficiency of electric power into electromagnetic wave in transmitter, the efficiency of the medium which represents the loss during the propagation in the medium and the conversion efficiency of the transmitter to convert from electromagnetic wave into electric power, respectively.

Figure 2 shows the distance dependency of system efficiency of OWPT, magnetic coupling WPT and microwave WPT through atmosphere for the central wavelength of light is 980 nm, the frequency of magnetic coupling WPT and microwave WPT are 500 kHz and 2.45 GHz and 10 GHz, respectively. Among three WPT methods, OWPT is the method which has lowest back to back efficiency, however, it can be used to transmit power for longer distance than other WPT methods. Magnetic coupling WPT is the method which has highest back to back efficiency. Magnetic coupling WPT with 50 cm of diameter of coils can be used to transmit power for several tens of cm, on the other hand, microwave WPT can be used to transmit power to distance several tens of meter with 1 m diameter of antennas. Theoretically, OWPT can be used to transmit power to distance more than 100 m through high visibility atmospheric condition.

The wavelength dependency of OWPT system efficiency for distance between transmitter and receiver is 1 km through atmosphere under low visibility condition (vis = 1 km) and high visibility condition (vis = 30 km) can be seen from Figure 3. The solar cell is assumed to be Si solar cell. For comparison, the system efficiency for power transmission through optical fiber is also calculated. For simplification, the power conversion efficiency of the laser which is the light source in this OWPT is assumed to be 70%. The optical power density of incident light is assumed to be 1 W. The maximum system efficiency around 38.7% at 940 nm, 31.85% at 950 nm and 2.38% at 960 nm wavelength of incident light for power transmission through air with 30 km visibility, optical fiber and air with 1 km visibility respectively can be achieved [5-11].

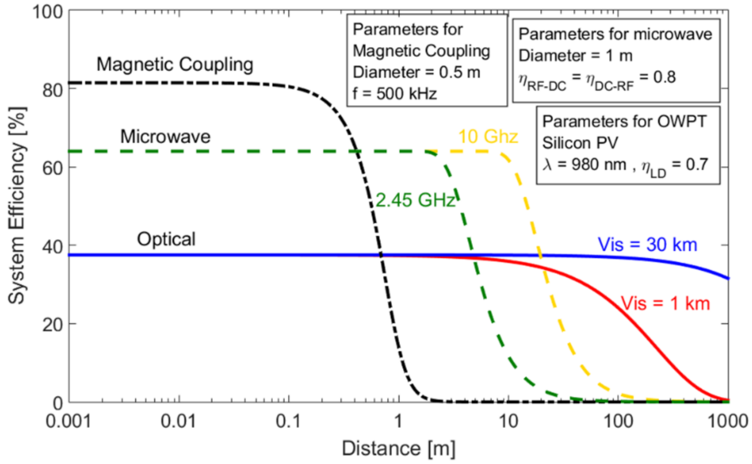

Figure 1. Comparison of system efficiency of WPT methods through atmosphere.

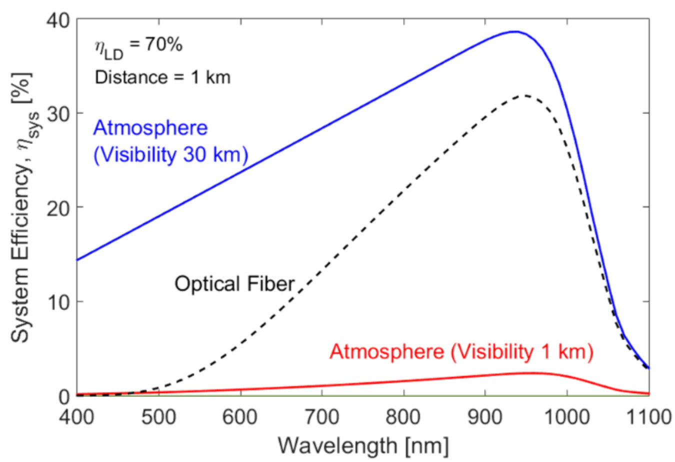

Figure 3. Calculated system efficiency of OWPT through atmosphere.

3. OWPT System to Moving Target(s)

Basic diagram of OWPT system to moving target can be seen from Figure 4. Target recognition and beam steering processes can be described as follow [12]:

1. Web camera recognizes the moving target.
2. Camera sends the pixel position of target to computer.
3. Computer calculates the movement of target by calculating difference of the pixel positions of target and converts it to driving angle.

4. Computer sends the command to the drivers to drive the Galvano mirror according to the calculated angle.
5. Mirror steers the laser beam to the target.

The camera which is an ordinary web camera was set to capture image with 30 fps frame rate. Size of the captured image was 640 x 480 pixels. As the light source, 980 nm laser was used because based on theoretical analysis, infrared laser is the most suitable for OWPT through air. Small toy car was chosen as the target. Si solar cell was put on top of the target to convert incoming laser beam to electric power which is used to power the mini car up. The mini car was not equipped with battery; hence, it could only move if it received enough electric power from solar cell.

As target recognition method, color segmentation method is used. In this method, a specific color can be chosen as the target which will be recognized by the camera. The color captured image of the target and recognition by the camera can be seen from Figure 5. In this case, red color was chosen as the target. Then a color marker was put on the target and the camera recognize it as the target. The red circle which encircle the color marker is called recognition circle. This circle only appears if the target is recognized well by camera. Using this method, OWPT to 2-dimensional moving target and multiple targets had been demonstrated and can be seen from Figure 6 and 7, respectively. For multiple targets, each target was equipped with marker which has different colors and the camera will periodically change the color which would be recognized as target; hence, the recognized target would be changed periodically and since, the response of mirror was fast, it can steer beam to multiple targets smoothly.

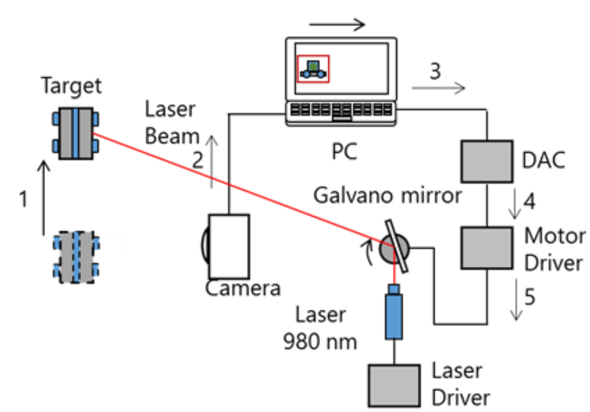

Figure 4. OWPT system using camera and galvano mirror.

Figure 5. Target recognition by camera using color segmentation method.

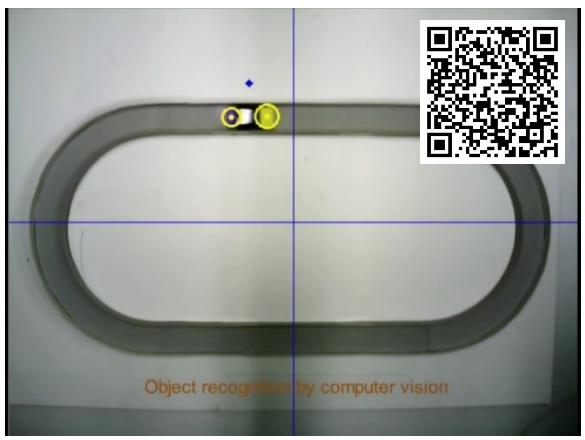

Figure 6. Demonstration of OWPT to 2-dimension moving object using single camera. (Note: Scan the QR code to watch the video.)

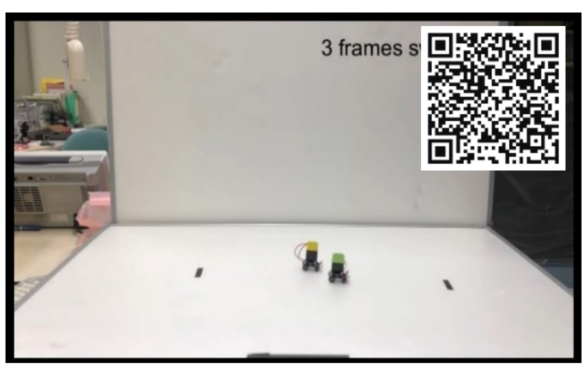

Figure 7. Demonstration of OWPT to multiple moving objects using single camera and single set of Galvano mirror. (Note: Scan the QR code to watch the video.)

4. LED Marker for OWPT System in Dark Condition

During the demonstration of OWPT to moving target using camera with color segmentation method, some problems regarding target recognition were encountered. The main problem was the sensitivity of the target recognition to the brightness of environment and the condition of lighting of the environment. It was found that the recognized color by camera might change and the camera would fail to recognize target if the brightness of environment and the color of light source that illuminates the room changed. The second problem in target recognition using color segmentation method was the disturbance by the same color objects in the environment. Color segmentation method which was used in this OWPT system recognize the target based on the color marker which was attached on the target. However, if there were other objects which have the same color as the marker, the camera might recognize wrong object as the target.

The sensitivity to environmental brightness problem of target recognition could be solved by using active color marker such as LED instead of passive color marker which was used in previous demonstration. Furthermore, it was found that the camera could detect not only visible spectrum of light but also near infrared spectrum. In this case, to solve the disturbance which was caused by same color objects in visible spectrum, near infrared wavelength marker could be used instead of visible spectrum color marker. Then, infrared LED marker is chosen as the solution of these problems as can be seen from Figure 8 [13].

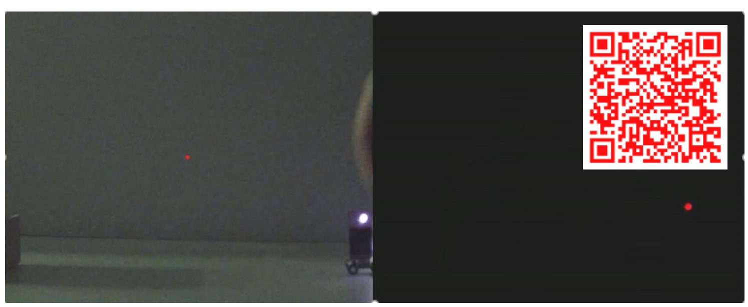

Figure 8. Demonstration of OWPT to moving object using led marker at dark environment. (Note: Scan the QR code to watch the video.)

5. OWPT through Water and Hybrid Power and Data Transmission

In this demonstration of OWPT through water, 440 nm blue laser were used as the transmitter as can be seen from Figure 9. The Si solar cell and tap water were used as the receiver and medium of power transmission, respectively. The water was contained in water container which was a small aquarium. It was predicted that the output electric power of the solar cell will decrease into e^{-1} value of its maximum value when the distances of the laser and solar cell (depth of water) for OWPT through water were 1.5 meter for 440 nm blue laser. It was predicted that the performance of OWPT system could be enhanced more by using wider bandgap solar cell such as GaN based solar cell which would increase the conversion efficiency of blue light.

Hybrid system which allows data and power transmission at the same time as can be seen from Figure 10 was designed and analyzed. 660 nm red laser and 980 nm infrared laser were used for data transmission and power transmission, respectively. As the receivers, the Si photodetector (PD) and Si solar cell were used to detect the data transmission and power converter, respectively. Two identical dichroic mirrors were used to combine and separate the axes of propagation of 660 nm and 980 nm lights. The dichroic mirrors were 900 nm long pass dichroic mirror. These mirrors were transparent for wavelength more than 900 nm which meant that these mirrors would be transparent for 980 nm of light, on the other hand, 660 nm of light will be completely deflected by the mirrors. The mirrors were set to be 45° angle, hence, the 660 nm red light would be deflected at 90° angle.

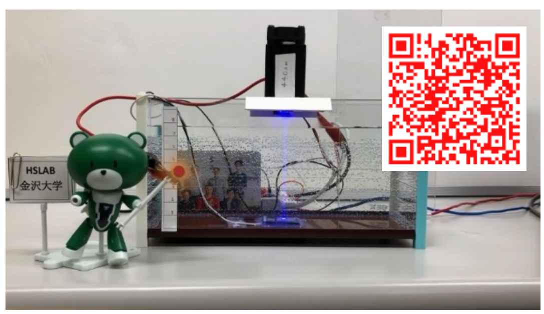

Figure 9. Demonstration of OWPT through water using blue laser. (Note: Scan the QR Code to Watch the Video)

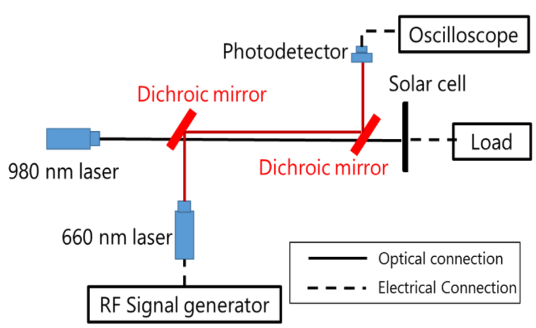

Figure 10. Diagram of hybrid power and data transmission system.

6. Summary

Optical Wireless Power Transmission (OWPT) is one of the Wireless Power Transmission (WPT) methods which can be used to transmit electric power wirelessly. Due to small size and small divergence angle of laser beam which is used as transmitter in OWPT, OWPT can be used to transmit power to longer distance than other WPT methods (magnetic induction coupling and microwave WPT). Based on theoretical analysis, OWPT can be used to transmit power to distance more than 100 m or even until 1 km using 980 nm laser as light source and Si solar cell with system efficiency more than 30%. This high efficiency for long distance transmission is not possible for other WPT methods.

Laser beam has to be steered to point directy and only at the receiver. Hence, target recognition and beam steering system becomes an integral part in OWPT system. In this research, camera with color segmentation method and Galvano mirror which has fast response were used as the target recognition and beam steering methods in OWPT system. Using this method, OWPT to 2-dimensional moving target and multiple moving targets using one set of mirrors and camera were demonstrated. Moreover, target recognition which is insensitive to the brightness of environment had also been realized using infrared LED marker. Additionally, OWPT through water and hybrid power and data transmission system had been sucessfully demonstrated.

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令和　2年　7月　30日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

Study of Optical Wireless Power Transmission to Moving Objects

(移動体への光無線給電に関する研究)

2．論文提出者　(1) 所　　属　電子情報科学　　　専攻

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3．審査結果の要旨（600～650字）

当該学位論文に関し、令和2年（2020年）7月30日に第1回論文審査委員会を開催し、提出された学位論文及び関係資料について詳細に検討した。さらに同日に行われた口頭発表後に第2回論文審査委員会を開き、協議の結果、以下のように判定した。

本論文は移動体への無線給電をレーザーと太陽電池を用いて実現する光無線給電に関する設計、システム構築及び評価についての報告である。まず、光無線給電において高効率を実現する波長帯を数値解析により明らかにした。シリコン太陽電池を用いる場合、空気中伝搬では最適波長 940nm、水中伝搬では最適波長 440nm であることを明らかにした。次に物体の位置検出手法を検討し、テンプレートマッチングと特定色画素領域抽出とを比較し、後者はブラーの影響を受けないためこの方法を採用した。ビームステアリング技術は、高速かつ高精度の方向制御が可能であるガルバノミラーによる手法を採用した。そして上記技術を融合し、かつ位置予測技術を導入することで、2次元移動体や複数移動体への光無線給電システムを開発した。さらに応用として、水中における給電や給電とデータが同時に送電（送信）するシステムを提案し構築した。

以上のように、本論文は移動体への光無線給電に関して有用な知見を得ており、学術的及び工学的な価値が高く、当該研究分野における十分な知識と自立して研究活動を行う能力を有することが論文の中で証明されていることから、博士（工学）に値するものと判定した。

4．審査結果　(1) 判　　定（いずれかに○印）　(合　格)・　不合格

(2) 授与学位　博　士（　工　学　）