Laser wireless energy supply system of high-potential monitoring equipment based on machine vision

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Abstract. Real-time monitoring of high-voltage power equipment is an important link to ensure the safe and stable operation of the power system. The independent power supply of the monitoring equipment can ensure that the monitoring data is stable and effective without being affected by the power grid. This paper designs and builds a laser wireless power supply system based on machine vision and tracking and targeting technology for the actual application needs of high-potential monitoring equipment in power grids. The article introduces the overall architecture of the laser wireless power supply system and elaborates on the control method and image processing strategy of the tracking and targeting unit. The article proves the feasibility of the scheme through experiments, and realizes the accurate matching of the position of the photovoltaic cell in the presence of background interference. The research results of this article can provide technical support for the energy supply of high-potential monitoring equipment of the power grid.

1. Introduction

With the development of power system automation and smart grid, real-time monitoring of high-voltage power equipment is increasingly important, and the application of smart electronic equipment and monitoring sensors in power transmission and transformation equipment is becoming more and more widespread. In order to accurately monitor multiple physical quantities of electrical equipment, a large number of various types of sensor nodes will be densely distributed in the area to be measured. Generally, low-voltage DC power supply is used for sensors and electronic equipment, but in the complex working environment of medium and high-voltage electrical equipment, the conventional method of manually supplementing the energy of the sensor node is no longer applicable, and its cost is also very large. In addition, due to geographical factors, high-voltage insulation and other conditions, the power of user equipment monitoring sensors cannot generally be directly provided by the low-voltage end, which leads to the power supply becoming a difficult problem that restricts the development of online monitoring systems. Therefore, in order to ensure the stable and effective operation of the monitoring device, the problem of power supply of the equipment monitoring sensor needs to be solved urgently.

At present, the power supply methods for IoT nodes/sensors mainly include: wire power supply, battery power supply, environmental energy extraction, etc. These power supply methods are mainly manifested in the following aspects in the engineering application of the monitoring equipment on the transmission line: (1) Poor reliability and high damage rate; (2) Poor maintainability; (3) Larger volume and heavier weight. The wireless power transfer (WPT) technology realizes the transmission of electrical energy without direct electrical contact through other forms of carriers. The technology has the characteristics of high mobility and strong environmental adaptability, which attracts more and more
attention. Laser Wireless Power Transfer (LWPT) technology replaces sunlight with controllable high-energy-density laser to achieve wireless transmission of energy. The technology has the characteristics of high energy density, small device size and long transmission distance [1,2].

Laser Wireless Power Transfer (LWPT) technology replaces sunlight with controllable high energy density laser to achieve wireless transmission of energy. The technology has the characteristics of high energy density, small device size and long transmission distance, etc. In the field of power, LWPT technology is a relatively new power supply technology for grid monitoring sensor networks. Compared with other wireless power transmission technologies such as electromagnetic induction and microwave, its outstanding advantage is that energy is transmitted in the form of light. In this way, the electrical isolation between high and low voltage is completely achieved, the power transmission is not affected by electromagnetic interference, and the technology can provide long-term safe and reliable power supply [3]. At present, relevant research on laser wireless energy supply technology has been carried out at home and abroad.

In 2011, Duke University conducted research on the LWPT system from the perspective of laser safety transmission. The experiment selects a semiconductor laser with a wavelength of 1400nm and a GaSb photovoltaic cell to form an LWPT system to charge mobile phones 4m apart [4].

In 2014, Shandong Institute of Aerospace Electronics Technology conducted an experimental verification of the spacecraft-oriented LWPT system. In the system, the laser wavelength is 810nm, the laser power is 28W, the maximum transmission distance of the system is 200m, and the overall transmission efficiency (the ratio of the system's output electric power to the input electric power) is about 15% [5].

In 2015, the Russian "Energy" Rocket and Space Group Company used a photoelectric receiving-converting device that converts infrared lasers into electrical energy (photoelectric conversion efficiency is about 60%) to convert lasers emitted 1.5km away into electrical energy and successfully charge a mobile phone [6].

In the application of this article, the laser wireless power supply system needs to supply power to the power supply device with a linear distance of at least 15m, the effective continuous output power is 1W, and the continuous power supply time reaches 1h. Due to the harsh on-site environment, during the charging process, there will be relative movement between the laser emitting end and the power take-off device due to shaking, which seriously affects the power supply efficiency of the system. Therefore, only by correcting the laser irradiation angle of the emitting end in real time can the efficiency of charging be ensured to the greatest extent. Fig.1 is a schematic diagram of the system application scenario.

![Diagram of System application scene](image)

This article will design a laser wireless energy supply system with tracking and aiming functions according to the above power supply parameters and functional requirements. The system will greatly expand the use range and application mode of LWPT, and provide technical support for the engineering of high-potential monitoring equipment energy supply technology.

2. System composition
The main part of the laser wireless power supply system is composed of the laser transmitter and the laser receiver, as shown in Fig.2.
The electrical energy in the power grid or storage battery at the transmitting end is provided to the laser by the laser power conversion, and the laser converts these electrical energy into laser light and transmits it through the optical system. After being transmitted in free space, the laser is absorbed by the photovoltaic cell at the receiving end and converted back to electrical energy. These electrical energy can charge the battery of the sensor or directly provided to other loads on the sensor. Before charging the sensor, the system's Acquisition Pointing Tracking (APT) unit starts and starts automatically searching for photovoltaic cells. After the optical component is aligned with the photovoltaic cell, the laser power is increased to start charging the battery. During this period, the tracking unit continuously adjusts the posture according to the battery position information parameters collected and fed back by the host computer in real time, and completes the real-time tracking and charging of the battery.

2.1 Laser selection
As an essential hardware for laser wireless energy supply system, laser can be divided into four categories according to working medium: gas laser, solid laser, semiconductor laser and dye laser. Thanks to the development of laser technology, the relevant literature can be summarized from the indicators of output power, conversion efficiency and beam quality. At present, the lasers suitable for the LWPT system mainly include solid-state lasers and semiconductor lasers.

According to the application of the system in this article, considering the output power volume, efficiency and other factors of the laser, the 808nm fiber-coupled semiconductor laser is selected as the light source in the design. The maximum power of the laser can reach 30W.

2.2 Selection of photovoltaic cells
Photovoltaic cells are the core components of the receiving end. At present, common photovoltaic cells (such as monocrystalline silicon or polycrystalline silicon solar cells) are mainly used in solar photovoltaic power generation occasions, and their conversion efficiency is about 20% to 30%. According to the spectral response characteristics of photovoltaic cells as shown in Fig. 3, the ability of different photovoltaic materials to absorb monochromatic laser light is related to the wavelength of the incident laser light, and each material has its corresponding absorption peak wavelength [7]. Therefore, in the occasion of laser energy transmission, in order to ensure the photoelectric conversion efficiency of the photovoltaic cell, the selected photovoltaic cell material needs to match the wavelength of the incident laser.
Because the laser at the emitting end uses an 808nm fiber-coupled semiconductor laser, in terms of photovoltaic cells, GaAs is selected as the material for photovoltaic cells. In this paper, GaAs single-junction battery is adopted in the system. The photoelectric conversion efficiency of this battery can reach up to 58%, which can better meet the requirements of power parameters of the system. In the early stage, the laboratory has used this battery to complete the static charging experiment of the LED lamp with a rated power of 1W at a distance of 15m. However, since the focus of this article is on the design of the tracking and targeting unit, the energy supply part will not be described in detail.

2.3. Tracking and targeting unit

Adding a tracking and aiming unit at the laser emitting end can realize real-time irradiation of the photovoltaic cell by the laser beam. Considering the distance between the transmitter and receiver, the tracking accuracy of the Pan-Tilt will directly determine the charging effect. Therefore, a high-precision direct-drive Pan-Tilt needs to be selected in the later stage, and the accuracy of the gimbal needs to reach 0.1~0.5arc-sec. The specific design of the tracking and targeting unit will be introduced in detail in subsequent chapters.

2.4. Energy monitoring unit

In the actual application scenario, the photovoltaic cell at the receiving end is at a higher distance from the ground. In order to avoid overcharging and over-discharging of the battery, a wireless energy monitoring unit is added to the receiving end. The transmitting end can monitor the battery power in real time through RFID. When the battery is full, the battery power status is transmitted back to the host computer at the transmitter end by radio frequency. After the host computer receives the command, the laser is turned off through the serial port, and the transmitter stops charging. When the battery power is too low, the laser is turned on in the same way, and the transmitter continues to charge. The unit realizes real-time management and monitoring of the input power, which improves the reliability of the system.

3. Tracking and aiming unit design

The tracking and aiming unit is mainly composed of three parts: a host computer, a camera, and a servo Pan-Tilt. The system structure of the unit is shown in Fig.4.
In order to achieve real-time tracking of photovoltaic cells, the host computer obtains video information from a camera fixed on the Pan-Tilt through a video capture card, and processes each frame of image in real time. According to the processed image information, the coordinates of the target in the camera field of view are obtained. Then the Pan-Tilt continuously adjusts the attitude according to the coordinate information to achieve the tracking and aiming of the target.

### 3.1. Target recognition and detection

In order to realize the real-time detection of photovoltaic cells, it is necessary to process the images collected by the camera: Find the smallest bounding rectangle of a photovoltaic cell area, and give the geometric center coordinates of the rectangle as the centroid coordinates of the target. The basic flow of image processing is shown in Fig.5.
The front side of the photovoltaic cell package used in the system is a square, which is a regular geometric figure, so the feature matching strategy is adopted in the design of the image processing of the battery.

When the camera collects the image, it needs to perform basic processing on the image, among which threshold segmentation is an indispensable part [8]. In order to facilitate the next processing of the image, the OTUS algorithm is used to complete this process. The idea is to select a threshold T, and divide the histogram into two parts according to the threshold T, \( T \in [0, m-1] \), where m is the gray level of the image.

Suppose the total number of image gray levels is N, the number of pixels with gray value i is \( n_i \), and the probability \( p_i \) and \( \mu \) of each gray value i are respectively:

\[
p_i = \frac{n_i}{N} \\
\mu = \sum_{i=0}^{m-1} i \cdot p_i
\]

Take the gray value \( T \), use \( T \) to divide all gray levels into two groups \( C_0=0…T-1 \) and \( C_1=T…m-1 \). The mean and probability of the two groups are expressed as:

\[
w_0 = \sum_{i=0}^{T-1} p_i; \mu_0 = \sum_{i=0}^{T-1} i \cdot p_i \]

\[
w_1 = \sum_{i=T}^{m-1} p_i = 1 - w_0; \mu_1 = \sum_{i=T}^{m-1} i \cdot p_i
\]

Calculate the variance between the two groups:

\[
\delta^2 = w_0(\mu_0 - \mu)^2 + w_1(\mu_1 - \mu)^2
\]

Repeat the above process to find the largest gray value i between groups, and use i to perform threshold segmentation of the image. The final threshold used in this article is 105.

Since the photovoltaic cell has wires and thermistor wires connected out, it will affect the extraction of the target contour, so it is necessary to perform morphological processing on the binary image. In this paper, the method of first corrosion and then expansion is used to remove the burrs on the contour, so that the image is smoother, which is conducive to the next target contour extraction [9]. This method is also called open operation. The calculation formula is as follows:

\[
B^0S = (B \ominus S) \oplus S
\]

In the formula, B represents the entire binary image, and S represents the selected structural element. The size and structure of the structure element are selected according to the actual situation.

Considering that the actual application environment is more complicated, when there is interference in the field of view, the candidate targets identified by the single frame image will contain false targets, which can be screened out according to the shape characteristics of the target [10]. In this paper, based on the characteristics of the battery, restrictions are set on the area, aspect ratio and color of the extracted target, which greatly enhances the discrimination between the target and the interference.

In the actual environment of the scene, due to random interference and various uncertain factors, even if multiple recognition constraints are added, it is still not guaranteed that the correct target can be recognized in each frame of image. Therefore, a mechanism is needed to ensure that the Pan-Tilt will not move randomly when the wrong target is recognized in the image. It can be known from the actual characteristics of the target that the photovoltaic cell is a static target, and there will be no sudden position changes except for weak shaking.

3.2. Servo head tracking control

The basic flow of the servo Pan-Tilt tracking control module is shown in Figure 6. The basic idea is: after the battery completely appears in the camera's field of view, the servo Pan-Tilt stops the inspection.
The pixel coordinates of the target are given by the image recognition link in the previous section, and the deviation from the set coordinates can be obtained. According to this deviation, the Pan-Tilt will adjust the position slightly and slowly to achieve the position matching of the target.

Fig. 6  Flow chart of APT

Traditionally, target tracking based on machine vision only needs to satisfy that the target appears in the center of the camera's field of view. In the system design of this article, since the optical system and the camera are not on the same horizontal line, there is a relative distance between the two. When the center of the battery profile matches the center of the field of view, the laser light emitted by the optical system will not irradiate the battery. Therefore, in the tracking design, a calibration position is required, so that when the center of the battery outline matches the calibration coordinates, the laser is just irradiated on the battery.

The plane image taken by the camera is shown in Fig. 7. The intersection of the horizontal and vertical solid lines in the figure is the center of the field of view, \(O\) is the calibration position, and \(ABCD\) is the circumscribed rectangle of the target. The purpose of target tracking is to control the head so that the center of the circumscribed rectangle of the target always matches and locks the calibration position.

Fig. 7  Block diagram of Target’s coordinate

By performing a difference operation on the target contour center coordinate \(O'\) and the calibration position coordinate \(O\), the difference values \(\Delta x\) and \(\Delta y\) between the two in the field of view coordinate axis can be obtained. In the design process of this article, set the positive direction of the horizontal axis and the tilt axis of the head to the right and up respectively, and the resolution of the camera is 640×480.
Through repeated debugging, it is finally determined that the coordinate of $O$ is (310,240). So the calculation formula for $\Delta x$ and $\Delta y$ is:

$$\begin{align*}
\Delta x &= x - 310 \\
\Delta y &= 240 - y
\end{align*}$$  \hspace{1cm} (5)

After obtaining $\Delta x$ and $\Delta y$, by transforming them into the control amount that makes the Pan-Tilt rotate, the Pan-Tilt can enter the fine-tuning link, and finally achieve coordinate matching.

4. Experimental results and analysis

Taking the limitations of the laboratory into account, the size of the tracking target and the tracking distance are reduced in proportion. The target chose a battery of the same type with a package size of 7cm×7cm. According to the reduction ratio of the battery, the tracking distance is set to 3m, and the corresponding simulation tracking and aiming experiment platform is built, as shown in Fig.8.

![APT experiment platform](image)

Fig.8 APT experiment platform

The experiment uses a dual-axis steering gear Pan-Tilt to replace the actual tracking servo system, which can achieve continuous rotation of $-90^\circ$~$+90^\circ$ on the horizontal axis and $0^\circ$~$180^\circ$ on the pitch axis. The software environment is VS2013, C# is used as the programming language, and the image processing part uses the computer vision library EmguCv3.0.

4.1. Target contour extraction

Considering the complexity of the actual environment, in order to facilitate the later on-site debugging, a scene simulation is done in the laboratory according to the on-site environment, as shown in Fig.9. Among them, the fake target 1 is similar in color, and the length and width are twice the size of the actual battery; the fake target 2 is similar in area, but the ratio of length to width is inconsistent; the fake target 3 is similar in size, but the color is quite different. The environmental interference is set in order to achieve a similar effect to the outdoor plant background to verify the reliability of the target recognition link.
Figure 10 shows the stepwise experimental results of extracting the target.

After the image is segmented by OTUS, the false target 3 is eliminated, and then the false targets 1 and 2 are eliminated through feature screening, and finally the background interference is eliminated to achieve target extraction.

Through the experiment, continuous 200 frames of images were collected multiple times, and the results are shown in Table 1. According to Table 1, the average recognition rate is 88.6%, and the average time for each frame of image processing is 43.6ms.

| No. | Frames correctly recognized | Processing time of 200 frames/s |
|-----|-----------------------------|-------------------------------|
| 1   | 181                         | 8.17                          |
| 2   | 179                         | 8.69                          |
It can be seen from the experimental results that in a more complex background environment, the image recognition part can complete the extraction of the target contour and meet the system requirements. This method can be well used for on-site target recognition and detection.

4.2. Target tracking results
The target tracking experiment is carried out indoors, and the tracking and aiming unit is 3m away from the target. It is chosen to be carried out under night light and weak natural light during the day. The experimental results are shown in Fig.11 and Fig.12.

It can be seen from the experimental results that in two different scenarios, the tracking unit can complete tracking and finally achieve position matching.

5. Conclusion
The application of smart electronic devices and monitoring sensors in power transmission and transformation equipment is becoming more and more extensive, and how to continuously, efficiently
and safely supply power to the sensors is also particularly important. Based on the current laser wireless energy supply technology, this paper builds a laser wireless energy supply system platform with tracking and aiming functions through the design of key modules for laser wireless energy transmission and verification of core functions. The accuracy and efficiency of wireless power supply are improved by using machine vision to accurately align the receiver and transmitter from a distance.

In the next step, the system will be transplanted to actual applications, and the tracking and targeting optimization plan will be proposed according to the on-site environment and actual power supply parameter requirements to further improve the accuracy and safety of the system, improve the system composition, and enable the system to be successfully engineered.

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