Development of Solar-Panel Monitoring Method Using Unmanned Aerial Vehicle and Thermal Infrared Sensor

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Abstract. Interest in solar energy, which is clean energy, is growing due to continuously high oil prices because of the unstable situation in the Middle East and the explosion of the Fukushima nuclear-power plant in Japan. South Korea has made various efforts to develop renewable energy, and facilities using solar energy are rapidly growing. Periodic inspection of solar panels is very important for the effective management of photovoltaic (PV) modules. In this study, a method to monitor and diagnose faulty solar modules through an Unmanned Aerial Vehicle (UAV)-based thermal infrared camera and GIS spatial analysis is discussed. First, the image of the PV module was taken by installing an RGB camera and thermal infrared camera on the rotor blade of the UAV. The images were generated by using Pix4D SW, and the normal operation of the PV module was diagnosed using the orthoimage. In particular, thermal infrared cameras are very sensitive to reaction speed, unlike optical sensors, so it is very important to find appropriate monitoring methods, such as shooting speed. Therefore, we suggest a way to utilize an optical sensor and thermal infrared sensor together through various attempts. In the images, GIS spatial analysis was used to extract abnormal heat or faulty modules. Using the Virtual Reference Service (VRS) survey method, UAV images could be 3D-mapped with a very precise temperature, within 2 cm in x, y, and z direction errors. The rapid development of PV power-generation facilities and of monitoring technologies is a very important factor for improving energy efficiency. The result of this study is providing a stable solar-panel-monitoring technology by comparing features of ground observation and UAV-based thermal infrared sensor observation. The developed monitoring technology was able to accurately analyze the failure point and temperature of the PV module.

Keywords: solar panel; monitoring; unmanned aerial vehicle; thermal infrared; VRS survey.

1. Introduction
The greatest feature of solar-power generation is the fact that the energy source is endless and clean. There is no danger of generating air pollutants such as CO₂ (carbon dioxide), SOx (sulfur oxide), and NOx (nitrogen oxides) during power generation, as in the case with thermal-power generation that generates electricity by burning petroleum. If the annual power generation of a 1 kW system is 1000 kWh, the CO₂ reduction effect of the crystalline–silicon solar cell is 541.5 kg/year/kW. The amount of crude-oil reduction is 227 l/year/kW. The lifetime of a solar-power generation system is comparatively longer, and the service life of the solar cell module used for solar-power generation is now more than 20 years. A solar module is the key component of a photovoltaic (PV) system. The module converts solar energy into electrical energy by connecting several solar cells and semiconductor devices, in series or in parallel. Therefore, the module is the most expensive component of the PV system and determines the lifetime of the entire system. The lifetime of the solar cell module is about 10 to 20 years, depending
on the manufacturing method, and there is the advantage of the system scale being able to freely be
determined from small to large depending on installation location, with little maintenance cost. However,
if one of the modules fails, it affects the entire module and causes a reduction in efficiency. Modules are
installed in a large area, and require a lot of maintenance and a large workforce. Therefore, finding a
way to quickly monitor a module is critical to saving costs and achieving stable efficiency.
The location of a solar-power plant is very important for the efficient operation of solar-power
generation. The decision for the location is carried out by analyzing the location of the solar-power plant
by applying a hierarchical-analysis or correlation-analysis method based on GIS. PV power plants are
affected by various factors, and are damaged or deteriorate in efficiency. At the beginning of the damage,
the cell is overloaded, and abnormal heat generation occurs; then, the whole module is short-circuited
and overall output is lowered. Therefore, it is important to use a monitoring system together with
periodic inspections of the solar-power plant to prevent this. Monitoring and failure of solar-power
generation has mainly been done by utilizing the workforce. However, since the solar module of the
solar-power plant is generally located at a high altitude, it is necessary to carry out the current test for
the solar module and array by ascending to the solar cell panel or, because of the risk, determining the
temperature change point by using the thermal camera. It takes much time to monitor the solar module
due to the solar-power plant having a large area and a high installation site, and there are various
problems in safety. Recently, various monitoring methods have been proposed. One of them is to use
Unmanned Aerial Vehicles (UAVs) and thermal infrared sensors. However, this is due to the fact that a
thermal infrared sensor is expensive, and the lack of technology to stably photograph the thermal
infrared sensor mounted on the UAV.
In this study, an experiment was conducted to automatically diagnose the failure of the module of a
solar-power plant by installing an optical sensor based on a UAV rotor blade and a thermal infrared
sensor.
The purpose of the study was to develop a technology to analyse and diagnose the temperature difference
by GIS spatial analysis for each solar module by superimposing the solar-module layer on the
temperature information acquired by the UAV-based thermal infrared sensor.

2. Materials and Methods

2.1. Field Monitoring Area
In order to develop a monitoring method for solar modules using a UAV-based thermal infrared sensor,
the target of this study was a PV solar-power station located in Gagok-ri, Ochang-eup, Cheongju-city,
Chungbuk, South Korea. The solar-power plant in the target area is composed of 36 pieces of 300 W
class modules, and can produce 10.8 kW power in total. Figure 1 shows the location of the solar-power
plant, and the observation point is marked with a red circle. The Virtual Reference Service Real-Time
Kinematic (VRS-RTK) survey was performed by selecting 6 GCPs for the ground reference point.

![Figure 1. Unmanned aerial vehicle (UAV)-based solar-panel monitoring location map.](image-url)
2.2. Materials
The aerial observations of the solar-panel monitoring site were observed using DJI Inspire 2 (Table 1). 
Inspire 2 is equipped with a "vision positioning system" that only lands in a safe place, and a system that detects obstacles not only in the front but also up and down. In addition, the Inspire 2 was designed to allow two cameras to be installed so that the flight time could be extended and the solar panel could be observed in a dual-camera-attached structure. Observation sensors were installed with an RGB sensor and thermal infrared sensor on the UAV. The specifications of the used UAV and the specifications of the thermal infrared sensor are shown in Tables 1 and 2, respectively. The thermal infrared camera used for the field survey is shown in Table 3.

| Table. 1 Inspire 2 specifications |
|----------------------------------|
| **Item** | **Specifications** |
| Weight | 3290 g |
| Diagonal Distance (Propeller excluded) | 605mm |
| Max Flight time | 25 min |
| Max speed | 94km/h |
| Image sensor | Zenmuse X5s (red, green, blue) |
| Battery type | LiPo 6S/ 4280mAh |

| Table. 2 FLIR Vue Pro R specifications |
|--------------------------------------|
| **Item** | **Specifications** |
| Resolution | 640 × 512 |
| Size | 63×45×45 mm |
| Temperature range | –25 to 135℃ |
| Spectral range | 7.5 to 13.5 µm |
| Field of view (FOV) | 32°× 26° |
| Output Type | Radiometric JPEG, TIFF |

| Table. 3 FLIR T-420 specifications |
|------------------------------------|
| **Item** | **Specifications** |
| Weight | 880 g |
| Size | 106×201×125 mm |
| Temperature range | –20℃ to 650℃ |
| Spectral range | 7.5 to 13µm |
| Field of view (FOV) | 25°× 19° |
| Image mode | Thermal/Visual/P-i-P (Resizable and movable)/MSX/Thumbnail Gallery |
| Battery type/operating time | Li-lon/ >4 hours, display shows battery |

2.3. Methodology
In order to diagnose the monitoring and failure of PV modules, module boundaries must be layered for each array. In case of the failure of a solar-module diagnosis using a UAV-based thermal infrared sensor, the resolution of the thermal infrared sensor may be lower than that of the RGB image, resulting in errors in the module boundary. Therefore, it is necessary to use imaging and merging technology to grasp the precise boundary of the PV module. The orthoimage and PV module layers were imaged at the same time with a 2 cm resolution RGB camera. DJI's Inspire 2 model was used for orthoimage and 3D terrain modelling. Since the UAV (Inspire 2) and the thermal image sensor (Vue Pro R) are not
compatible with each other, they were modified so that they could be separately mounted and made a gimbal to fly together. UAVs were controlled by the Pix4d Capture application and commanded the shooting of the RGB sensor through the set redundancy during flight. Since the thermal image sensor cannot control the shooting with the automatic flight program, the shooting setting and control were performed separately. After setting the thermal infrared shooting environment, the photographing angle was adjusted through the gimbal setting, and the image was taken at the set time interval according to the automatic flight path by simultaneously commanding the shooting with the UAV take-off. UAV-based aerial-photographing procedures were performed in the order of 1) preplanning and data collection, 2) sensor calibration, 3) route setting and photography, 4) image correction, and 5) image matching.

2.4. Thermal Infrared Orthoimage Temperature Correction Method
Accuracy evaluation of the UAV-based thermal image sensor was performed by regression analysis of the obtained results from the comparative field survey. and the image was corrected with the obtained regression equation.

3. Results and Discussion

3.1. Optimal UAV Flight Condition for Thermal Infrared Orthoimage Production
Unlike ordinary optical sensors, thermal imaging is not easy with the Pix4d mapper software. Therefore, in the process of producing an orthogonal thermal infrared image, there are many cases where image fusion fails along with the error of calibration failure. In order to solve these problems, it is important to find flight conditions that have the best image quality through various conditions, such as image overlap, interval, and flight speed (Table 4).

Optimal flight conditions were investigated through 16 repeated test flights over three days, 23 and 28 November, and 1 December 2018 (Table 4). As a result of the flight-condition change test, it was found that an orthogonal thermal infrared image was possible when the image overlap was 85%, shooting time interval was 3 seconds, and flight speed was 2 m/s.

Table 4. Success and failure of image merges according to flight conditions.

| Day           | Image overlap (%) | Interval (sec) | Flight speed (m/s) | Image merging | Success and failure |
|---------------|-------------------|----------------|--------------------|---------------|---------------------|
| 23 November 2018 | 65                | 1              | 4                  | ×             | Calibration failure |
| 23 November 2018 | 70                | 1              | 4                  | ×             | Calibration failure |
| 23 November 2018 | 75                | 1              | 4                  | ×             | Calibration failure |
| 23 November 2018 | 80                | 1              | 4                  | ×             | Calibration failure |
| 23 November 2018 | 85                | 1              | 4                  | ×             | Calibration failure |
| 28 November 2018 | 75                | 2              | 3                  | ×             | Calibration failure |
| 28 November 2018 | 75                | 3              | 3                  | Δ             | Partial success     |
| 28 November 2018 | 75                | 4              | 3                  | ×             | Calibration failure |
| 28 November 2018 | 85                | 2              | 3                  | Δ             | Partial success     |
| 28 November 2018 | 85                | 3              | 3                  | Δ             | Partial success     |
| 28 November 2018 | 85                | 4              | 3                  | ×             | Calibration failure |
| 1 December 2018  | 85                | 3              | 2                  | ○             | Success             |
| 1 December 2018  | 85                | 3              | 3                  | Δ             | Partial success     |
| 1 December 2018  | 85                | 3              | 3                  | ○             | Success             |
| 1 December 2018  | 85                | 3              | 4                  | ×             | Calibration failure |
3.2. Improved Accuracy through VRS-RTK Survey Method

In this study, GCP targets were placed and surveyed. Error between the RGB image and the thermal image was minimized through performing image correction by inputting the coordinates of the GCP point in the image joining process through the VRS-RTK survey method. As a result of improving the positional accuracy of the two images, the orthoimages of the visible light and the thermal external image could be overlapped and analyzed at the same time (Figure 5). UAV images using the VRS-RTK survey method enabled very precise 3D mapping in the x, y, and z directions within 2 cm when creating the digital surface model (DSM).

![Figure 5](image-url) Comparison results before and after position-accuracy correction using the Virtual Reference Service Real-Time Kinematic (VRS-RTK) method.

3.3. Correlation Analysis between UAV-based Thermal Image and Ground Thermal Imaging Sensor

The thermal-infrared-camera images installed on the UAV were acquired as R-JPEG and TIFF images, and the correlation between the temperature information and the DN value, and the temperature information measured by the thermal camera on the ground were investigated. The R-JPEG and TIFF images based on the UAV were highly correlated, as shown in Figure 3, as a result of the ground survey and regression analysis. In particular, TIFF-type files had higher correlation than the R-JPEG files.

![Figure 6](image-url) Correlation Analysis between UAV-based and ground thermal imaging sensor.

3.4. Development of Solar-panel Monitoring Application Technology

There have not been many examples of orthoimages that were equipped with thermal cameras in UAVs. In the case of PV solar applications, there is a study on a PV solar-module fault-diagnosis experiment using a fixed-wing UAV. Most of these studies were performed by installing a rubber cover on a solar module to determine whether the solar module failed or not, and calculating the average temperature for each module based on the temperature information obtained from the thermal infrared camera and the solar-module layer. A fixed-wing UAV is advantageous in that it can be taken lightly and for long enough to shoot a large area. However, since it is difficult to cope with unexpected situations, a fixed-wing UAV flies at higher altitudes than rotor-type UAVs. Therefore, the image resolution of the fixed-wing UAV is lower than that of the solar-panel module. In this study, we tried to solve these problems by observing the precise temperature at the low altitude of 30 m using a rotor-type UAV. However, most of the problems are caused by the frequent occurrence of overall-performance degradation due to the failure of one cell, so it is important to solve the problems related to that [3]. Figure 4 shows the result of orthoimage production of the RGB and the thermal infrared images. As shown in Figure 8, it was...
concluded that it is possible to not only analyze the cell unit, but also the array unit through the production of the orthoimage using the UAV. Cell-by-cell analysis can detect cool spots that are not identified in the RGB image, indicating that the bypass diode of the solar panel is defective. The point where the temperature drops like in the image may not be a problem in the short term, but if the phenomenon continues to periodically occur, we are able to detect the problem and take action.

Table 5. RGB and thermal infrared image acquisition conditions and results.

| Sensor     | Shooting altitude (m) | Number of shots | Spatial resolution (cm) | Max. Temp. (℃) | Min. Temp. (℃) |
|------------|-----------------------|-----------------|-------------------------|----------------|----------------|
| RGB        | 30                    | 189             | 0.7                     | -              | -              |
| Vue Pro R  | 30                    | 424             | 2.8                     | 57.66          | -0.92          |

Figure 7. Result of orthoimage production of RGB and thermal infrared images.

Figure 8. Case of performance-degradation point based on UAV-based thermal-infrared-image analysis.

4. Conclusion
In this study, to solve the compatibility problems between UAVs and thermal image sensors, a mount and gimbal that could be separately mounted, and data-acquisition equipment necessary for orthoimage production were constructed. The thermal infrared image joining method proposed various conditions of automatic flight, and a thermal-image control method and the optimal condition of thermal infrared orthoimages under various conditions of image overlap, image-acquisition interval, and flight speed. UAV photogrammetry enables highly precise 3D temperature mapping in the x, y, and z directions within 2 cm when creating a temperature DSM using the VRS-RTK surveying method by placing the GCP target on the path. We proposed precise temperature-monitoring technology for each cell and array by superimposing the RGB image and a thermal infrared image, and presented application examples in the field.
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