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Rapid and Effective Technology Development for 3D-Model-Based Solar Access Analysis and Comparative Study with Fish-Eye Camera

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Abstract: In this study, we developed a 3D-model-based technology that can evaluate solar access by analyzing solar radiation and shade to find the optimal location for a solar system. We developed an algorithm that can quickly calculate viewshed by applying ray-casting technology, which is useful in the field of computer graphics. To apply the developed technology, an unmanned aerial vehicle (DJI MAVIC 3) was used to create a 3D model by taking 320 photos of the Kangwon National University Samcheok campus. To verify the developed technology, a comparison with image-based analysis using a 360-degree camera was performed for 30 points. As a result of applying the developed technology to the study area, it was possible to calculate the solar access for each point. In general, image-based analysis exaggerates the effects of objects such as trees, whereas the developed technique can produce realistic results if the 3D objects were well built. If the technology is further developed in the future, it can be used to increase the efficiency of solar power generation.

Keywords: solar access; viewshed; ray casting; 3D model; fish-eye camera



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1. Introduction

Renewable energy supply policies are being promoted worldwide to reduce greenhouse gas emissions [1,2], but in general, renewable energy has a disadvantage in that the power generation efficiency is lower compared to the initial investment cost. Photovoltaic power generation, one of the most popular renewable energy sources, has been rapidly increasing in recent years, but it is indiscriminately installed in urban areas or mountainous areas, causing various problems. Therefore, in order to efficiently generate solar power and minimize environmental problems, it is necessary to increase power generation efficiency and manage solar modules by considering the incidence angle of the sun, the temperature of the solar module, and the shade caused by surrounding objects. To increase the efficiency of the solar module itself, many studies have been conducted using a quantum dot semiconductor device that absorbs light of a wide wavelength range [3–5]. In addition, it is very important to consider the surrounding environment to increase efficiency. The shade formed by surrounding objects is an important factor that greatly affects the total amount of power generation because it is directly related to the energy incident on the solar module. Consequently, if a power generation system is installed in the wrong location, shadows are generated by buildings or surrounding objects, resulting in a decrease in power generation efficiency.

In particular, as the number of solar panels installed in urban areas increases, shadows from buildings or trees have a great influence on solar power generation efficiency. To effectively evaluate the suitability of a photovoltaic generation site, it is necessary to calculate the solar energy incident rate considering the shade. The incident ratio of solar energy that can reach a solar panel out of total solar radiation is called solar access, and image-based analysis studies using fish-eye lenses have mainly been performed to calculate it [6–8]. This method generally uses a device equipped with a fish-eye lens (typically, Solmetric's SunEye 210) to capture surrounding images and displays them in polar coordinates, thereby determining the path of the sun and whether it is shaded accordingly, along with the solar power system's suitability. Such image-based shading analysis studies have been conducted for photovoltaic power plants installed on rooftops of buildings as well as floating photovoltaics installed on lakes and photovoltaic modules installed in abandoned mine areas [9–13]. Since this analysis method is based on images, it has the advantage of being able to accurately capture the surrounding objects. However, since the image classification algorithm has limitations, artificial processing must be performed to accurately classify the objects. In addition, the image-based analysis method requires direct shooting to obtain a result for a specific point, so in order to analyze a large number of points, it is necessary to shoot the corresponding number of times, and there is a limitation that application is impossible for difficult-to-access points.

Research on geographic information system (GIS)-based analysis, another shading analysis technology to calculate the incident energy of sunlight, is also being conducted [14]. This technology uses a digital surface model (DSM), which is data in the form of pixels with the height value of each point, and determines whether it is shaded by considering the slope between points and the position of the sun [15]. The ArcGIS Solar Radiation toolset is mainly used for this type of analysis. However, since raster data can have only one height value per pixel at each point, there is a limitation in that all objects are considered pillars. In addition, a calculation is performed between all pixels, so there is a limitation that the amount of calculation of the algorithm may increase.

To supplement the limitations of image-based shading analysis or 2D GIS shading analysis, technology using 3D models can be used. With a 3D model, it is possible to determine whether sunlight is incident by considering the 3D space without shooting directly like the image-based method. In addition, as planning and development for smart cities are progressing recently, 3D modeling of all city buildings and roads is occurring [16,17]. Therefore, it is expected that more effective solar power evaluation will be possible if the technology is linked with 3D city spatial data in the future. Solar-powered vehicles are also increasingly popular and continuously developed, so the technology for 3D models can be linked with them. Recently, in a situation where hydrogen energy is attracting attention as a future energy source, the importance of renewable energy is increasing in order to produce green hydrogen.

Some cases of solar access analysis using 3D models have been reported, but most of them were performed by converting 3D models into 2D GIS models. In some cases, 3D models are directly analyzed, but mostly, they are used only in commercial software, making them less universally useful. In this study, an algorithm that can quickly analyze solar access for a general 3D model was developed, and an image-based analysis algorithm was derived to compare the results. To verify the applicability of the developed technology, an experiment was conducted with the buildings and trees of the Samcheok Campus of Kangwon National University. A 3D model was constructed by taking drone images of the study area and applying photogrammetry technology. To evaluate the accuracy of the developed technology, the viewshed and solar access values were compared with image-based results by using fish-eye cameras at 30 points. The developed technology can quickly obtain the coordinates of obstructions and determine whether the sun's rays are incident by reducing the amount of calculation. In addition, it can be utilized in conjunction with various 3D technologies.

2. Methods

2.1. Study Area

To apply the developed technology, the Samcheok Campus of Kangwon National University in Samcheok-si, Gangwon-do, was selected as the research area (Figure 1). The coordinates of the study area are latitude 37.45 and longitude 129.15, the altitude is 90 m~100 m, and the total study area is about 254,009.4 m². There are a total of 21 buildings on campus, and some of the buildings have solar modules installed, and the buildings face southeast. The 3D-model-based technology developed in this study can be applied to all points where the 3D model is built, but the image-based technology cannot capture all points. Therefore, pictures were taken using a fish-eye lens, mainly on roads or sidewalks with easy access, and the analysis results were compared. In addition, since there are few high buildings in the study area, the experiment was conducted in a lower area than the buildings to simulate the shading effect of the buildings in the downtown area. In order to effectively confirm the usefulness of the developed technology, the points were selected mainly in the northwest of the buildings where shadows are formed.



Figure 1. Satellite image of Kangwon National University Samcheok Campus.

2.2. 3D Modeling through Drone Image Analysis

In this study, a total of 320 images were taken with a drone (DJI MAVIC 3) to create a 3D model of Kangwon National University Samcheok campus (Figure 2). A 3D model was created based on the image data taken through an optical sensor (digital camera) attached to the drone. In general, photos taken with a camera are 2D, but it is possible to convert them into 3D by determining the x, y, z coordinates of a specific point using two or more photos. Collinearity condition refers to the condition that the target point on the ground, the image point of the target point captured in the photograph, and the exposure points are located on a straight line [18–20]. By combining the coordinates of the drone from two or more pictures and applying the collinear condition, the coordinate value of the desired point can be obtained. In this study, 3D modeling was performed by synthesizing photos taken at a height of 140 m above the ground. For the mapping, the Pix4DMapper program produced by Pix4D in Switzerland was used. Mapping work consists of initial processing, point cloud and mesh generation, DSM and orthoimage generation. The initial processing step is the process of arranging the photos taken by the drone using coordinates in the software. Next, the overlapping parts are found by comparing the photographed pictures, and the coordinates are calculated by applying the collinear condition. At this time, the

cluster of points representing the overlapping parts is called a point cloud. The empty parts between point clouds are not completely calculated, but are replaced with appropriate values inside the software to form a triangular mesh. In this study, the mesh-type 3D model produced in this way was extracted with the .obj extension so that the developed technology could be applied. Finally, by synthesizing these data, it is possible to create an orthographic image and a DSM, which can be used in 2D-based GIS analysis.

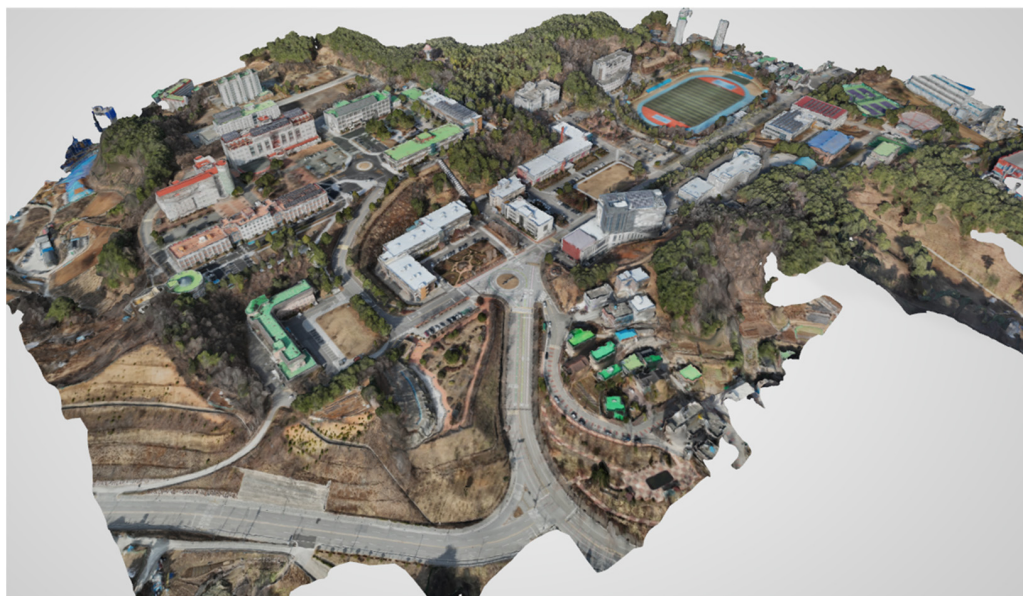


Figure 2. 3D model of Kangwon National University Samcheok Campus made by drone images.

2.3. Basic Principle of Solar Access Considering Viewshed and Sun Path

In order to measure solar radiation received by a solar module, it is necessary to measure the amount of solar radiation energy reaching a point. Solar radiation is classified into three types: direct radiation, which means radiant energy that comes directly from the sun to the surface of the earth without being disturbed; diffuse radiation, which comes to the surface after being scattered by atmospheric components such as clouds and dust; and reflected radiation that reaches the surface after being reflected from the surface of the earth. It is generally the case that direct radiation has the largest ratio among the total radiant energy, while reflected radiation has the smallest ratio. The solar energy incident at any point is greatly influenced by the topography and surface structure. Using line-of-sight analysis, as shown in Figure 3a, it is possible to evaluate these effects by checking the obstruction of the terrain and structures when looking at the sky from the current location. The gray area is where solar radiation is obstructed by terrain and structures, whereas white is areas that are not obstructed. Considering this result together with the polar plot of hourly solar zenith and azimuth (Figure 3b) when looking at the sky in a specific area, the radiant energy can be calculated directly. The patterns in this figure are called analemmas and show how the sun's path slowly shifts over the course of the year. The colored lines show the single-day sun paths for the winter and summer solstices as well as the spring equinox [21]. As the earth's axis of rotation is tilted by about 23.5 degrees, the sun's midday altitude decreases from summer to winter and the length of the day shortens. After measuring the direct radiation generated at each point, the total amount of direct radiation reaching the ground surface at the point can be calculated by classifying the overlapping and remaining portions (Figure 3c). Since the incident energy varies according to the altitude of the sun, the direction of incidence, the angle of the ground (or the angle of the solar module), etc., it is also necessary to consider them. Diffuse radiation is assumed to come from all directions in the sky, and the effect of scattering by atmospheric clouds or

dust is considered. In this study, diffuse radiation was applied, and reflected radiation was not considered.

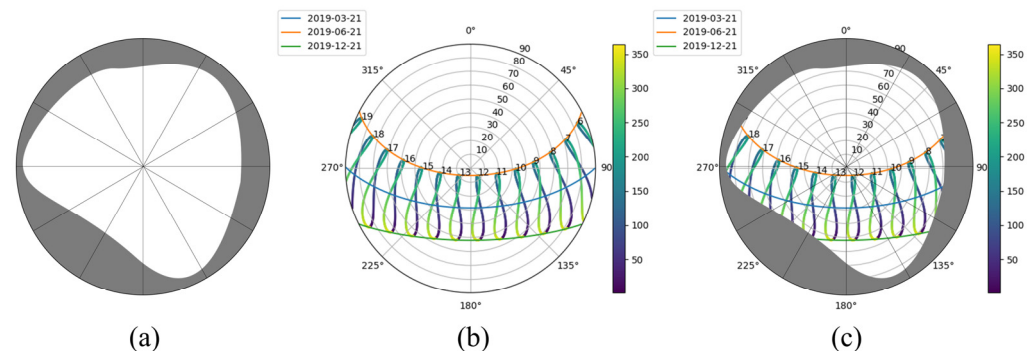


Figure 3. Basic principles for solar access analysis. (a) Viewshed, (b) solar path, and (c) overlay of viewshed with solar path.

2.4. Development of 3D-Model-Based Solar Access Analysis Algorithm

In this study, an algorithm that can calculate solar access was developed by considering the shadow effect of buildings or objects in 3D using the Python language. For the analysis of 3D models, Open3D, an open-source library that supports easy processing and development of 3D data, was used [22]. To analyze parameters related to the sun, the pvlib python library was used. The pvlib library can be used to calculate the incident angle, total solar radiation, other parameters of solar power facilities based on sun position, and solar radiation data by implementing various modeling techniques and algorithms commonly used in the solar industry. The pvlib python library was ported from the PVLIB MATLAB toolbox developed by Sandia National Laboratories [23,24].

Figure 4 shows the flow chart of the algorithm developed in this study. First, if a 3D model such as obj or stl is input using the Open3D library, the point cloud and mesh of the model can be recognized. If you click the point you want to analyze, you can get the x, y, z coordinates of that point. From this point, viewshed can be implemented by obtaining the coordinates of objects that come into view when the camera looks vertically upward (field of view (FOV) is about 180°) and expressing them in polar coordinates. Since polar coordinates are expressed in altitude and azimuth angles, even points at different locations are displayed at the same location on the polar map if they lie in the same direction and angle. Therefore, in calculating the viewshed, iteratively calculating the elevation angle and direction between the target point and all other points can be time-consuming and inefficient. In this study, the ray-casting algorithm provided by the Open3D library was used to quickly and effectively calculate the viewshed around the target point [25,26]. Ray casting is a technique widely used in computer graphics and game development, and is used to detect collisions between objects in 2D or 3D space. Ray casting uses the properties of light. It is a process of finding an intersection with another object by emitting a light line with a starting point and direction in space. At this time, if the light line intersects another object, it is determined that a collision with the object has occurred, and the 3D coordinates of the point where the collision occurred can be obtained in Open3D. In Figure 5a, for example, a sphere and a hexahedron collide with light and the coordinates of the collision points can be acquired, but the coordinates of tetrahedron cannot be acquired because it is behind the sphere. This is because the azimuth and elevation angles toward the tetrahedron from the target point (camera) overlap with the sphere, and the efficiency of the overall algorithm can be increased because there is no need to perform unnecessary calculations for the coordinates of these tetrahedrons. When light is emitted in ray casting, how to set the FOV and how much light to emit are also important. Figure 5b is a situation in which a small number of lights are emitted, and the FOV is 60 degrees on the left and 90 degrees on the right. For the analysis of solar incidence, it is not necessary to consider an angle lower than the ground surface, so the FOV can be set close to 180 degrees and the light

is radiated vertically upward. However, as the FOV widens, the interval between the light segments widens, so the interval at the point colliding with the object may become sparse. Therefore, as shown in Figure 5c, it is necessary to increase the number of collision points by increasing the number of lights. However, if too many light components are generated, the calculation time becomes long, so appropriate control is required. Figure 6a shows a conceptual diagram in which ray casting is applied to a 3D model including buildings and terrain. There are other reasons why it is useful to apply ray casting besides saving computational speed. For example, in the case of a simple hexahedron like Figure 6b, there are no points in the space within the object or on the mesh, so calculation is performed for only eight vertices (blue). On the other hand, when ray casting is performed, coordinates of points (green) that collide with the mesh are obtained, and operations are performed, so it can be applied to 3D models that are simply constructed.

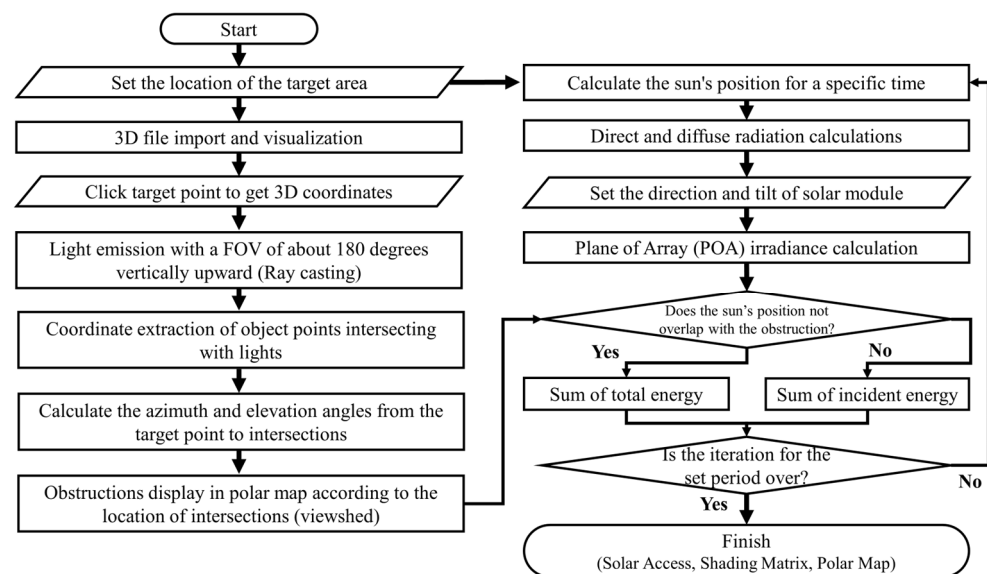


Figure 4. Flowchart showing the procedure of the developed technology.

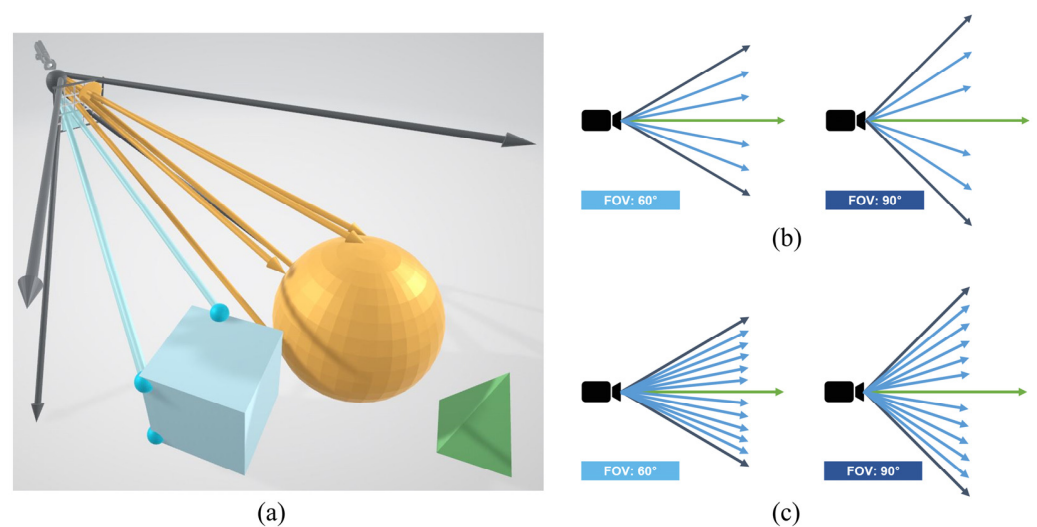


Figure 5. Basic principles of ray casting. (a) Obtaining the coordinates of the intersection points between light and object, (b) setting field of view (FOV), and (c) setting the number of rays.

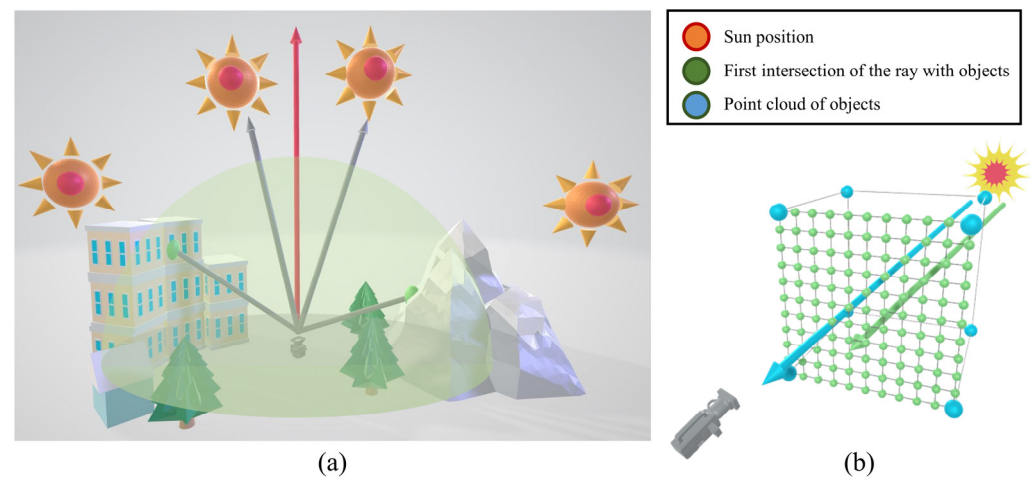


Figure 6. Application principle of ray casting for viewshed analysis. (a) Determination of whether sunlight is blocked, and (b) application to mesh.

After calculating the viewshed by extracting the points through ray casting in the form of polar coordinates, the location of the sun and the angle to the observation point were calculated to determine whether the sun's rays were blocked by the objects. The position of the sun for 365 days was calculated considering the longitude and latitude of the observation point, and the direct and diffuse radiation in a clear sky were calculated. In addition, the energy actually incident on the module was calculated considering the installation direction and tilt of the solar module. Finally, we calculated solar access, which is the ratio that reaches the panel considering the objects compared to the total energy reaching the solar panel when there are no objects.

2.5. Image Analysis Using Fish-Eye Camera and OpenCV

Image-based analysis was used to verify and compare the accuracy of the developed 3D technology. In general, Solmetric's SunEye 210 Shade Tool is widely used for image analysis, but since this product was released a long time ago and the image resolution is low, this study used Ricoh's THETA Z1 360-degree camera, which can shoot the entire space using two fish-eye lenses. The product is capable of taking precise images of about 23MP (6720×3360) and has a subject distance of about $40 \text{ cm} \sim \infty$. Theta Z1 can perform omnidirectional shooting with two lenses, but in this study, only the area of 180 degrees FOV above the horizon was analyzed, so one lens was covered, and the open lens was directed vertically toward the sky. To analyze the captured images, the OpenCV library, which is one of the open-source computer vision libraries and focuses on cross-platform and real-time image processing, was used [27]. First, the edges were detected by classifying the objects except for the sky, and then, the boundaries of the sky and other objects were distinguished. Figure 7b is the result of performing this image processing on an image taken with a fish-eye camera (Figure 7a), and buildings and objects excluding the sky are expressed in red. Next, a process of converting the detected image into a polar coordinate form was performed. Figure 8a is the result of converting the upper horizontal image (Figure 7a) into polar coordinates, and Figure 8b is the result of converting the classified image (Figure 7b). In order to extract accurate azimuth and elevation angles from the image converted into polar coordinates, the distance from the center point and the elevation angle must be proportional to each other. To confirm this, as shown in Figure 8c, a transparent hemisphere marked with latitude was covered, and a picture was taken with a fish-eye camera. As shown in Figure 8d, it was confirmed that the distance from the center point and the elevation angle were proportional. In other words, if the developed image processing process is performed after adjusting the direction and level of the fish-eye camera, a viewshed in the form of polar coordinates can be obtained. After that, solar access can be calculated by performing the same process as the 3D-model-based analysis method.

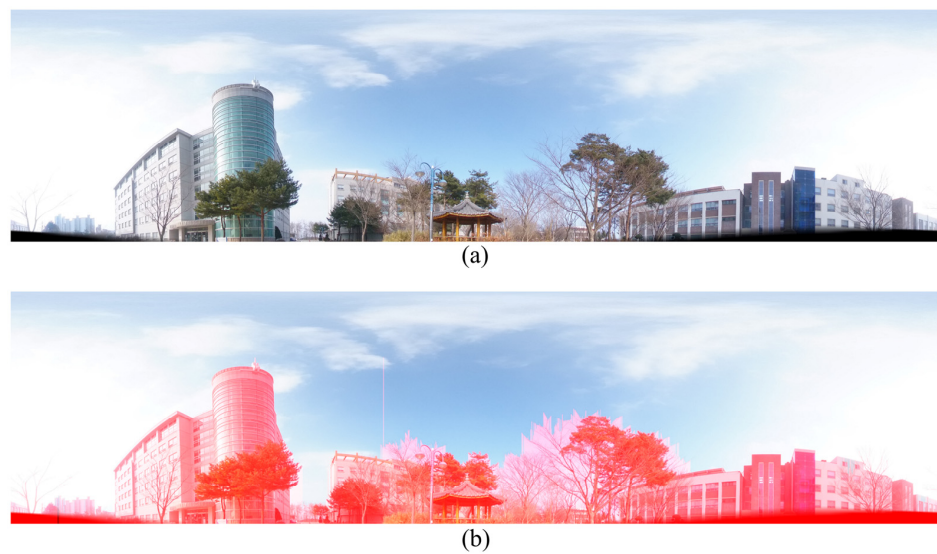


Figure 7. Example of (a) panoramic photo, and (b) sky classification result of the study area using the fish-eye lens of a 360-degree camera.

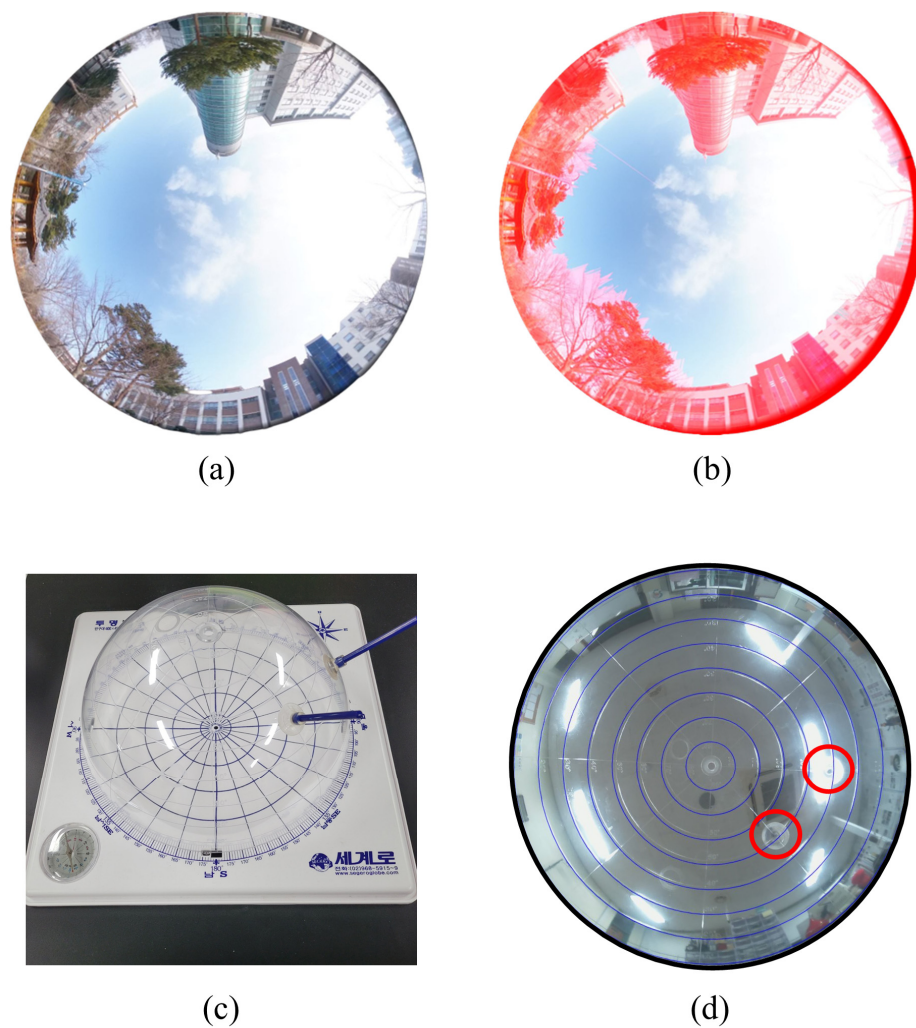


Figure 8. Conversion of panoramic image to (a) polar image, (b) result of sky classification, (c) transparent hemisphere, and (d) image taken within it (the red circles are the positions where the bars are attached).

3. Results

In general, photovoltaic modules are installed on the roof of a building, but for verification of the developed technology, 30 points were selected around the buildings, street lamps, and trees on the Samcheok campus of Kangwon National University (Figure 9). For that point, image analysis based on a fish-eye camera was performed and compared with the developed 3D analysis technology. Figure 10a shows the point cloud of the 3D model created from the drone image, and Figure 10b shows an example of the result of extracting the points where the light hits by performing ray casting on the temporarily designated observation point. The study area was divided into four sections around large buildings. Twelve points in area A, five points in area B, nine points in area C, and four points in area D were analyzed.



Figure 9. A total of 4 areas (A, B, C, D) and 30 analysis points in the study area.

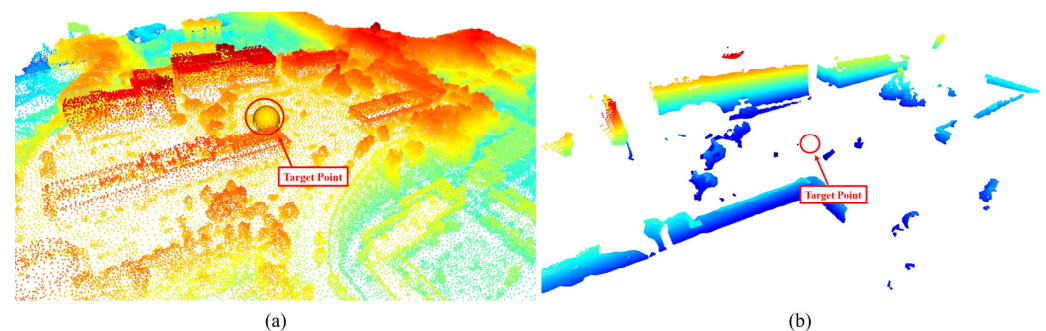


Figure 10. (a) Point cloud of the study area, and (b) intersection points obtained as a result of ray casting.

First, after recognizing the direction, the fish-eye camera was leveled and the image was taken with the camera facing the lens vertically. Afterward, the developed algorithm was applied to the captured images to classify the sky and obstruction, and then, the images were converted into polar coordinates. The left image of Figure 11 shows the image processing results, and it can be seen that the sky and the obstructions are generally well distinguished. Some points are exaggerated and classified as obstructions (for example, the spaces between trees), so solar access may be underestimated compared to reality. In SunEye 210, which is commercial equipment, users can arbitrarily edit classification results, but no artificial processing was performed in this study.

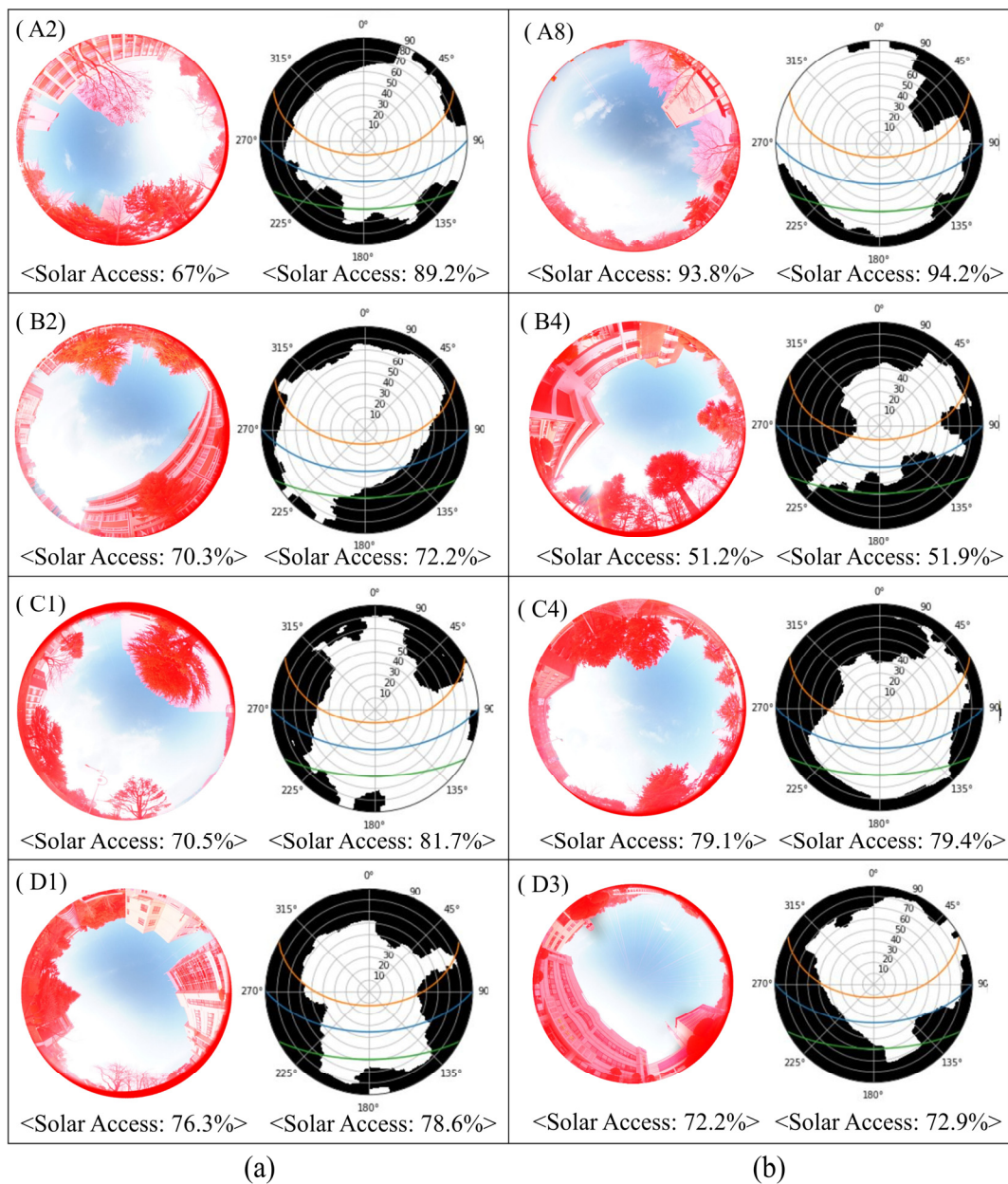


Figure 11. Polar image comparison of image analysis and 3D analysis. (a) The points (A2,B2,C1,D1) where the deviation of the analysis result is large, and (b) the points (A8,B4,C4,D3) where the deviation is small.

The results of 3D analysis are shown in the right image of Figure 11. The image analysis results and the 3D analysis results are similar. In Table 1, it can be seen that the solar access was calculated significantly low at points with many nearby buildings and obstructions, whereas the solar access values were high at the points with few obstructions. Trees were not represented at some points in the 3D analysis results, either because they were out of the drone's range or because a precise 3D model was not created. Therefore, for more precise analysis, it is necessary to create a 3D model with a higher density by increasing the number of pictures using drones. Figure 11a shows the point where the deviation between the image-based analysis and the 3D analysis is the largest in each area, and Figure 11b shows the point where the deviation is smallest. It can be seen that the deviation is quite large at point A2, but the overall shape is well reflected. However, since the tree at the bottom was omitted in the 3D model and the bare tree was exaggeratedly classified in the image, the deviation would have been large. A large deviation was also

found at point C1. Likewise, the image around the tree was exaggeratedly classified as an obstruction, while the tree was not properly modeled in the 3D model. In other points, it can be confirmed that the 3D model generally reflects reality well, and these results will become more accurate as the 3D model is made accurately.

Table 1. Comparison of solar access results of image analysis and 3D analysis for 30 points.

Area	Point	Image Analysis Results		3D Analysis Results		Deviation
		Solar Access (%)	Average (%)	Solar Access (%)	Average (%)	
A	A1	88.3	71.6	89.5	76.5	1.2
	A2	67.0		89.2		22.2
	A3	79.2		82.8		3.6
	A4	87.5		92.3		4.8
	A5	55.6		64.6		9
	A6	72.0		77.0		5
	A7	65.1		67.0		1.9
	A8	93.8		94.2		0.4
	A9	73.1		75.1		2
	A10	65.2		68.4		3.2
	A11	32.2		34.2		2
	A12	80.9		83.7		2.8
B	B1	93.2	69.6	95.0	71.1	1.8
	B2	70.3		72.2		1.9
	B3	49.8		51.2		1.4
	B4	51.2		51.9		0.7
	B5	83.8		85.3		1.5
C	C1	70.5	77.1	81.7	79.9	11.2
	C2	68.7		69.6		0.9
	C3	86.5		87.2		0.7
	C4	79.1		79.4		0.3
	C5	55.3		57.7		2.4
	C6	88.2		89.6		1.4
	C7	93.4		96.0		2.6
	C8	63.2		68.6		5.4
	C9	89.5		90.0		0.5
D	D1	76.3	67.6	78.6	69.0	2.3
	D2	73.8		75.3		1.5
	D3	72.2		72.9		0.7
	D4	48.3		49.2		0.9
Average		72.4		75.6		3.2

4. Discussion

In this study, we developed a 3D-model-based solar access analysis technology that can be used to select the optimal installation area for photovoltaic power generation facilities. The developed technology applies a ray-casting algorithm to quickly acquire the coordi-

nates of obstructions and determine whether the sun's rays are incident. The advantages of the technology developed in this study are summarized as follows: (1) While image-based methods can be applied only in areas accessible to people, the developed technology can be applied anywhere where 3D models are built. (2) Accurate analysis is possible even for objects that are not bulky, such as trees or streetlights, if they are accurately constructed as 3D models. This is an advantage of 3D analysis compared to 2D GIS, in which is difficult to consider them. (3) If applied to a 3D modeling tool, it is useful for predicting a virtual design and its results. This approach is practically difficult in image analysis and would be quite cumbersome in 2D GIS. (4) By applying the ray-casting method, the calculation speed is significantly improved. There is no need to compute for every point in a point cloud, and the calculation speed can be further improved by improving the algorithm. (5) As cases of 3D-based smart cities and digital twins increase, this study can be usefully employed in conjunction with 3D models. This will be especially useful when a building's shape is complex or when it is necessary to consider a virtual building. However, there are some points to be considered and improved:

The ray-casting algorithm applied in this study determines the number of lights emitted by setting the FOV close to 180 degrees from the direction the camera faces. As the FOV is set wider, the spacing between the rays widens, so the intersection points become sparse. Additionally, since a ray travels in a straight line from a point, if the obstruction is far away, the intersection points will be sparse. The sparse intersection points mean that obstructions cannot be accurately recognized. Therefore, more accurate analysis is possible as more rays are generated within a certain FOV, but this means an increase in the amount of computation. The algorithm developed in this study completes the analysis in a very short time (less than 1 s after execution), but the analysis time can be further increased by increasing the number of rays for more precise analysis.

The technology developed in this study is useful for applying to objects with a small lower volume and a large upper volume, such as trees. However, making realistic trees in 3D is quite a challenge. Even when drones were used in this study, there were cases where trees were omitted or unrealistically formed in the 3D model. In order to build a more realistic 3D model of a tree, technologies such as LiDAR can be applied, but much effort is required for this as well. In addition, since most buildings in the real world are columnar, reasonable results can be obtained by applying image-based analysis or 2D GIS analysis. Of course, there are various types of buildings in cities, so the developed technology will be useful for non-column buildings. In other words, if a sufficiently precise 3D model is prepared, the technology developed in this study can be the most effective and realistic analysis technology. Above all, since it can be applied to virtual 3D models, it can be used to predict the results of changes in the surrounding environment.

When the developed technology is applied, the coordinates of the points where the mesh of objects and rays intersect are obtained, and the shape of the obstruction is expressed by displaying them on a polar map. That is, since "points" are displayed on the polar map, the position of the sun is likely to be located in the empty space between the points. As a result, even if the light is actually blocked by the obstruction, it can be evaluated as being incident to the observation point. Although this was not described in detail in advance, in order to prevent this problem, the polar map in this study was divided into several sections (for example, azimuth and elevation angles at one-degree intervals). If there is a point marked by an obstruction in the section, the entire section is set as having an obstruction. The more detailed the divided polar map is, the more precisely the shape of the obstruction can be expressed, but this is only the case when the points are densely formed. How densely the points are formed is an issue related to what was discussed in the first discussion, and means that appropriate settings are required for effective analysis.

5. Conclusions

In this study, we developed a technology that can quickly calculate solar access in consideration of surrounding buildings or obstructions using 3D models, and to apply this,

the Samcheok campus of Kangwon National University was imaged as a 3D model using drones. For comparison and verification of the developed technology, polar images were acquired using a fish-eye camera, and solar access calculations were also performed through image analysis. As a result of applying two types of analysis, it was confirmed that the developed 3D analysis technology can reflect the actual topography and buildings well and generally estimates higher solar access values compared to image-based analysis. This is because image analysis tends to classify thin objects such as trees and streetlights, whereas when 3D analysis technology is applied, these objects are not accurately made as 3D models. To improve this, it is necessary to use technologies such as LiDAR to obtain precise 3D data along with building a 3D model of a wide area using drones. The developed technology has many advantages, but the image-based method and the 2D GIS-based method also have their own advantages. If you need to accurately capture images in the field and only results at specific points are important, image-based analysis will be most useful. The 2D GIS technique can be more useful if you want to map only the solar access values over a large area. Therefore, it is necessary to apply an appropriate method according to the purpose. Considering that photovoltaic systems will continue to increase in the future, this technology can be very useful. In addition, this study will be of great value in shifting the energy paradigm based on hydrogen energy in that it contributes to green hydrogen production. Hydrogen energy is generally considered clean energy, but if hydrogen is produced from fossil fuels, it is called gray hydrogen because carbon dioxide is emitted during the hydrogen production process. On the other hand, hydrogen produced by water electrolysis based on renewable energy is called green hydrogen since it is a true clean energy [28–30]. There are still many challenges to overcome in the stability and economic efficiency of the green hydrogen production process, but in the long term, the production of green hydrogen is indispensable for reducing carbon dioxide. In order to improve the economic efficiency of green hydrogen, it is also important to increase the efficiency of solar power generation, and this study will be able to contribute to this.

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