Precise Localization of a UAV with Single Vision Camera and Deep Learning

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***Abstract*—This paper suggests a novel method of detecting and estimating the position of Unmanned Aerial Vehicle (UAV) with a single monocular camera only. As the leverage of UAV is keep on increasing, the related research has been extremely developed. To successfully use a UAV in a variety of missions, a precise localization technique is essential. However, there is still a lack of research to accurately measure the vehicle's present altitude. Thus, this study conducted a simple but accurate altitude measurement method using a camera. First, UAV detection is initially proceeded by using a deep learning approach. After determining that the object displayed in the image is UAV, the altitude is calculated with a distance measuring formula using the camera's Field of View (FOV). Besides, zooming, cropping, and some image processing are performed to enhance the accuracy of the altitude value. As a result, average errors of less than 5% and errors of up to 60cm were obtained, which is an improvement over previous altitude measurement techniques. This method can calibrate the altitude of the UAV immediately in a relatively inexpensive and simple way.**

***Index Terms*—UAV, Localization, Altitude, FOV, Deep learning**

I. Introduction

Unmanned vehicle technology is developing steeply over time. Under these circumstances, the usage of Unmanned Aerial Vehicles (UAVs) is increasing day by day. UAVs are used everywhere from a simple toy to industrial drones that can provide a larger network infrastructure [1,2,3]. Recently, there is even serious consideration of using UAVs for communication networks (e.g. FANET), especially in the 5G Network technology [4,5]. To properly use the UAV in various fields, high-level technologies such as sensing, positioning, control, battery, etc. should be combined.

The most vital technology among the various UAV related technologies is 3D localization because it is compulsory to know the exact location of itself to perform a variety of missions successfully. There are typically three representative factors in 3D localization measurement, which are longitude, latitude, and altitude data (which can set to be the distance value in X, Y, and Z-axis direction, respectively.). In particular, the altitude information is a parameter that is difficult to obtain accurately, compared to other localization data due to its high error-proneness [6]. Performing missions without UAVs having proper altitude information can cause serious problems. For example, the drone show displaying can be failed if the altitude of each UAV was not precisely drawn during the performance. This kind of drone performance failure will not only result in the quality of the show but also safety problems that occur when the UAV falls. Furthermore, in the future, the industry using the advanced information of UAV altitude will be further developed. According to the recent report by companies such as Uber, Audi, and Ehang, suggests that autonomous drone taxi will be widely used near in the future. To make the autonomous drone taxi to safely drive in the city with a determined altitude road, it is essential to accurately estimate its altitude information.

To this end, various researches have been actively studied on this topic. Even though there are various ways to measure altitude, using the relatively inexpensive commercial-off-the-shelf cameras has a benefit on a real-time application. For example, there is a method of reading surface information using a camera to measure altitude values (Digital Elevation Model(DEM)) [7], a method of training the framed size of an object by each distance with a machine learning approach [8], and a method that uses the camera's optical flow to calculate the altitude [9]. However, the above studies have limitations in that they require additional cumbersome steps in measurement and they mostly use stereo cameras for its sensor.

Therefore, this study aims to measure the altitude of UAV accurately while supplementing the limitations of previous studies. Furthermore, this study calculates the position value of a UAV through a monocular camera, which can find a UAV in the wrong location. Through this research, the corrected altitude and position are transmitted to the UAV to allow error-free flying in various mission situations.

Contributions suggested in our research is summarized as follows:

- This study measures altitude with higher accuracy than other altitude measurement methods (GPS, Barometer) that are currently applied to general UAVs. It can further estimate the relative latitude and longitude information too.
- The study can measure altitude by only using a single commercial-off-the-shelf (COTS) camera.
- This study focuses not only on estimating exact altitude value, but also on detecting the correct target. This method can determine whether the object displayed on the screen is UAV or not. Therefore, it has an additional process of initially detecting the UAV beforehand.

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- The deep learning method is applied to accurate detection and altitude estimation of UAV.

In the following article, section II will explain the limitation of previous altitude measuring methods, the FOV concept of camera used in this study, and the object detection method using machine learning. Section III will explain the method to calculate the altitude of UAV that is used in this research. Section IV will inform the condition and assumptions of experiments. Section V will indicate the results of its altitude measuring experiments. Finally, section VI wraps up the paper by suggesting the implications and future works of this study.

II. Background

A. Previous Altitude Measuring Methods and its Limits

Altitude information for UAV flight can be measured using various sensors and techniques. Among those various approaches, we now generally use Global Positioning System (GPS) and barometer to easily find out the altitude information. GPS determines the exact location of the device by using the trilateration method. The trilateration method can calculate the exact global point by using distance information between at least three satellites. This distance can be obtained by measuring the time difference between the transmitted and received signal. The upside of GPS is that it can easily obtain the position data (including latitude and longitude data) whenever it is located in the line-of-sight location with satellites. However, there is a serious downside that accurate position information cannot be obtained in non-line-of-sight conditions such as indoor and urban areas. Particularly, there is a fatal problem on GPS that has a large error on altitude measurement, even if the device is in the line-of-sight location. In fact, according to the latest report from the Official U.S Government information about GPS in September 2008, 'position accuracy standard of Global Average Position domain Accuracy' have altitude error of 15m or less [10]. Even with the latest GPS technology is applied, the average altitude error became no less than 1.46m and even worse in bad conditions to 4.16m [11]. Also, the barometer is another popular device to conveniently sense the altitude data. It measures the altitude by sensing the change of atmospheric pressure. The method through the barometer has the advantage of being relatively simple and inexpensive, but it has a leak that the altitude data is susceptible to other environmental factors such as wind, temperature, and even the movements of UAV rotors.

Furthermore, there are several other ways to measure the altitude of UAVs. Altitude can be estimated by using the RSSI from radio waves such as Wi-Fi, Beacon, Zigbee, etc [12,13]. Also, calculating the Time-of-Flight (TOF) of the reflected signal (e.g. sound waves, ultrasonic waves and so on.) can obtain the distance information from target objects [14]. Last but not least, OptiTrack can measure the altitude by tracing the LED lights [15]. However, these altitude measurement methods have limitations that each requires additional equipment which is very expensive, and some methods tend to rely heavily on environmental conditions.

B. Background Description of the Camera's FOV

In this paper, we propose a method to calculate the altitude by measuring the distance from an object using a camera. In this computational process, the field of view (FOV) of the camera is used, which means the viewing angle of the lens that can be seen at once. This viewing angle can be calculated through the following equation [16].

$$A = 2\theta = 2\tan^{-1}\left(\frac{K}{2f}\right) \tag{1}$$

In Eq. (1), f is the focal distance, K is the length of the image surface (e.g. film, sensor). This equation assumes the straight lens that does not have any spatial distortion. Furthermore, using a camera lens with a wide-angle FOV will allow seeing a wider view at once, which can detect more UAVs on one sight. However, as the FOV becomes wider, the image has more distortion, which needs the process of correcting the image should be further progressed.

C. Object Detection Method with Machine Learning

In a study to detect the desired targets in vision-based data such as images and videos, machine learning has great strengths in accuracy and speed [17]. Therefore, there are various researches on object recognition using deep learning methods. Image recognition technology based on machine learning can be divided into single-shot detection (SSD) and region-based detection depending on how to extract characteristics from vision data. For object detection, accuracy is important for its performance, however, the speed to detect in real-time is also an important factor. Thus, to achieve an effective UAV detector, we need to consider and balance both performance factors.

III. Methodology

A. UAV Altitude Estimation

In this experiment, the equation used for calculating the vertical distance from an object is described as follows: As shown below in Figs. 1 and 2, the object is placed in the position of the X, Y, and Z-axis based on the camera. In addition, the horizontal size of the image in pixels is A, while the size of the object in the screen in pixels is showed as B.

To show the idea of this method, the object is set as shown in Fig. 1, and the distance between the camera and the object is calculated. Since the horizontal FOV is θ for A in Fig. 2, the angle of view (x) for the object size B can be obtained according to the relation of proportional expression. Eventually, the distance between the object and the camera can be calculated by using the object's angle of view (x) and the length of the actual object (K) as follows:

$$x(^\circ) = \frac{B \times \theta}{A}, \quad L(m) = \frac{K}{2 \times \tan\frac{x}{2}}. \tag{2}$$

The distance calculation in Eq. (2) represents the simulation in which the object changes its distance only in the Z-axis.

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The following equation represents the case where the object has a distance change in the Z and X-axis directions.

$$x'(^\circ) = \frac{B' \times \theta}{A},\ L(m) = \sqrt{\left[\frac{K}{2 \times \tan\frac{x'}{2}}\right]^2 - a^2} \quad (3)$$

Finally, the following equation shows the condition when an object changes in the distance along the Z, X, and Y axes.

$$x''(^\circ) = \frac{B'' \times \theta}{A}, L(m) = \sqrt{\left[\frac{K}{2 \times \tan\frac{x''}{2}}\right]^2 - a^2 - b^2} \quad (4)$$

Note that, K means the actual size of the object in meters, a means the distance value in the X-axis direction in meters, b means the distance value in the Y-axis direction in meters, and L means the vertical distance between the object and the camera. Accordingly, L is the final goal of the whole process, which means the altitude value of the target object.

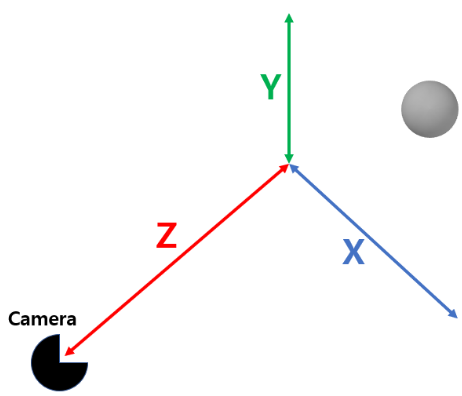

Fig. 1. Experimental Setting (In 3D)

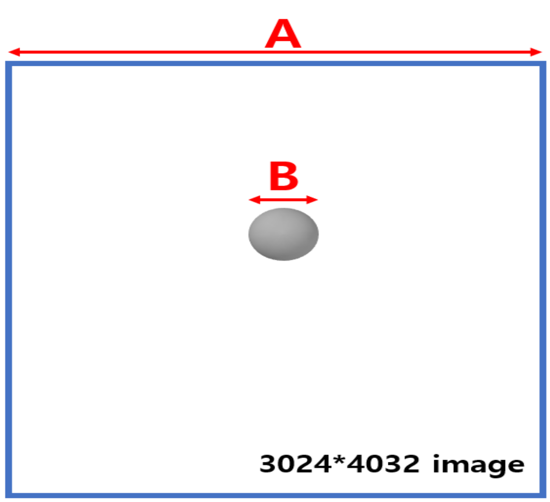

Fig. 2. Specification of experiment image data

IV. Implementation

The customized UAV with a DJI F550 frame kit was used as a prototype UAV in this research, which has a length of 0.6m end-to-end [18,19]. Also, the rear camera of Apple Inc.'s iPhone 7 was used for the single-lens camera which can be obtained easily by off-the-shelf. Our camera has a specification of 3024×4032 pixels image size with a horizontal FOV angle with 51°. We manually checked the FOV angle by simple verification. To implement the UAV detection, a machine learning based SSD object detection method is used. With the consideration of detection speed and accuracy, YOLOv3 based detection model is selected for our system [20]. YOLO is a well-made algorithm used in many other UAV-related pieces of researches. This machine learning based object detecting operation is held on a Ubuntu 16.04 LTS desktop with 3.3GHz Intel Core i5-6600 CPU, RAM with a 16GB system.

Since it is nearly impossible to measure the ground truth altitude value while flying the UAV, we set a static environmental condition on the ground with UAV holders shown in Fig. 3. In the following experiment for UAV detection and altitude estimation, the position of the camera lens and the position of the UAV were placed at an identical height. According to these experimental conditions, we can say that the camera is in the same environment as facing the upside of the ground vertically. Additionally, the experiment proceeds with advance information in meters of actual object size (K).

Our total process can be briefly divided into three steps: UAV Detection, Altitude Estimation, and Error Correction. First of all, through the deep learning based object detection tool, it checks if the object in the sight is a UAV. Then,

Fig. 3. Testbed for experiments

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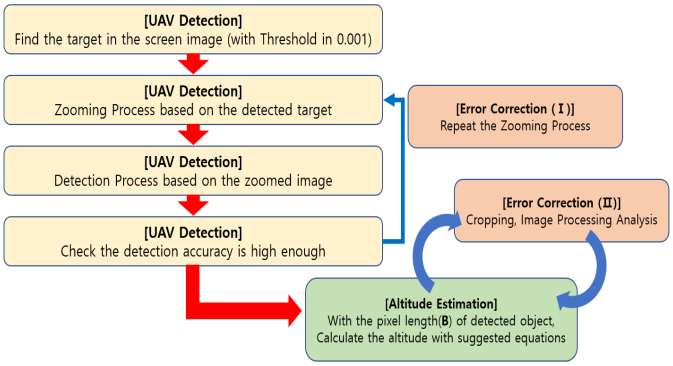

Fig. 4. Overall process of UAV Altitude Estimation.

TABLE I
UAV DETECTION ACCURACY WITH *yolov3*

Z_G(m)	Detection	Accuracy(%)
3	O	3
6	O	16
9	X	-

TABLE II
UAV DETECTION ACCURACY WITH *yolov3_drone*

Z_G(m)	Detection	Accuracy(%)
3	O	46
6	O	54
9	O	25

when it is confirmed with sufficient accuracy, the parameters required for altitude calculation is extracted from the image data. The overall process of the paper is described as the flow chart in Fig. 4.

The experiment was constructed as shown in Fig. 3, with different locations of UAV. We variate the Z and X-axis position to justify the performance of the altitude estimation. The difference in the distance (ground truth) of UAV was set as follows:

For the experiment in section 5.A.*UAV Detection*, Z-axis direction distance variates in 3*m* and 6*m*. Furthermore, in section 5.B.*Altitude Estimation*, X-axis direction distance variates in 0.6*m* and 1.2*m*, while the Z-axis direction distance is fixed at 3*m*. Besides, X-axis direction distance variates in 0.6*m*, 1.2*m*, and 1.8*m*, while the Z-axis direction distance is fixed at 6*m*. Also, X-axis direction distance variates in 1.2*m*, 2.4*m*, and 3.6*m*, while the Z-axis direction distance is fixed at 9*m*.

V. EVALUATION

The UAV positioning with a single camera is validated based on the following experimental results. For each particular process, we tried to legitimize our proposed method based on the settings previously described in section IV.

A. UAV Detection

Based on the image data obtained from the experiment, the process of determining whether the object displayed on the screen is a UAV is first performed. UAV detection was confirmed with YOLOv3, a deep learning based object detection tool. The weights applied to the UAV detection are *yolov3* and *yolov3_drone*. First weight, *yolov3* is the weight that trained with various images data provided by Darknet [21]. In addition, the second weight, *yolov3_drone* is the weight that particularly trained with 2,664 DJI drone images. The big difference between these two weights is that not only did they use different sets of training images, but *yolov3* uses 106 neural network layers (full model) and *yolov3_drone* use 24 neural network layers (lighter model). Thanks to the work of *chuanenlin* [22], we obtained the weight of *yolov3_drone* from its provided work, DroneNet.

The results of UAV detection accuracy with each weight are illustrated in TABLES I and II. The Z-axis direction distance varies as presented in previous settings.

Comparing these results from tables, we can find out that the *yolov3* weight has low accuracy due to its non-focused training dataset. Also, *yolov3* weight with full network model size has almost 20 times longer detection delay than *yolov3_drone* weight due to its thick network size. Accordingly, we conclude that the weight *yolov3_drone* is more suitable for UAV detection in the consideration of accuracy and real-time process. Thus, for the upcoming experiments, we choose to use *yolov3_drone* as a representative detection weight and model.

Also, to improve the accuracy of detection, zooming can be applied to the obtained image data. This process and result will be further described in section 5.C.

B. Altitude Estimation

Under confirmation that the displayed object in the image is UAV, its altitude is estimated by using the equations in section III. The bounding box (BBOX) obtained from the UAV detection process, is used in the Altitude Estimation stage. The pixel length of the width of the BBOX is used as a parameter B in the previous equations. Other parameters needed in the equation are obtained from experimental settings.

In this research, we can further estimate the X and Y distance value only from its image data, described in Fig. 5. The parameters a and b, which are the distance value of X and Y direction can be simply calculated from the viewed image with Eqs. (5) and (6). Consequently, this research can also be tolerant of the lack of latitude and longitude data situations such as the lossy GPS condition or even non-GPS condition. Notation d_X is the horizontal distance between the center of BBOX and the center of the image. Similarly, d_Y is the vertical distance between two center points.

$$Estimated\,\mathbf{X} : a = \frac{d_X * K}{B} \tag{5}$$

$$Estimated\,\mathbf{Y} : b = \frac{d_Y * K}{B} \tag{6}$$

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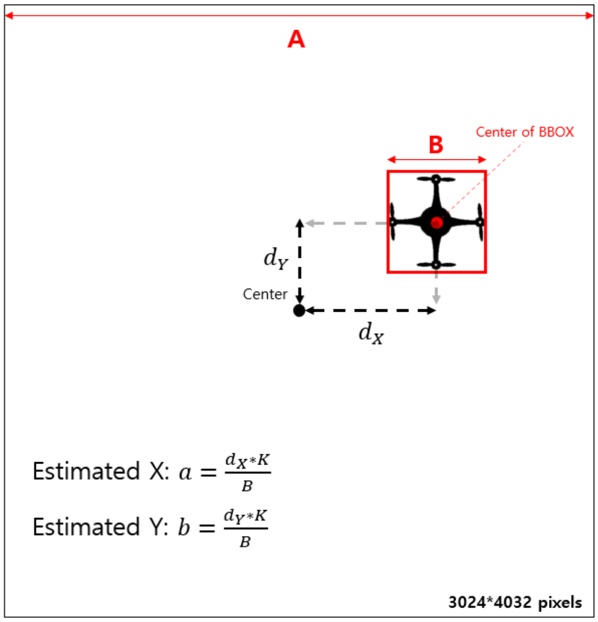

Fig. 5. X and Y-axis distance estimation

The results for UAV position at various points(stated at the beginning of section V) are plotted in TABLES III, IV, and V.

At the shown tables, Z_G, X_G, and Y_G is the ground truth distance value of Z, X, and Y-axis, respectively. And Z_E, X_E, and Y_E is the estimated distance value of Z, X, and Y-axis, respectively. The result of error compares the Z_G value and Z_E value.

TABLE III
UAV Altitude Estimation (Z=3m)

Z_G(m)	X_G(m)	X_E(m)	Y_G(m)	Y_E(m)	Z_E(m)	Error
3	0	0.0156	0	0.1668	3.06014	2.00%
3	0.6	0.591	0	0.01884	2.89116	-3.63%
3	1.2	1.1816	0	-0.294	2.48224	-17.3%

TABLE IV
UAV Altitude Estimation (Z=6m)

Z_G(m)	X_G(m)	X_E(m)	Y_G(m)	Y_E(m)	Z_E(m)	Error
6	0	-0.037	0	0.8706	5.58936	-6.84%
6	0.6	0.747	0	0.375	5.64293	-5.95%
6	1.2	1.1232	0	0.180	4.92236	-18.0%
6	1.8	1.9044	0	0.3888	5.95814	0.698%

TABLE V
UAV Altitude Estimation (Z=9m)

Z_G(m)	X_G(m)	X_E(m)	Y_G(m)	Y_E(m)	Z_E(m)	Error
9	0	-0.039	0	0.3402	6.03395	-33.0%
9	1.2	0.972	0	0.0768	6.37175	-29.2%
9	2.4	1.5702	0	0.231	6.39825	-28.9%
9	3.6	2.3802	0	0.2082	5.61045	-37.7%

C. Error Correction

The error correction process was conducted to further correct the error shown in the calculation results shown in *B. Altitude Estimation*. The UAV in the image data was enlarged to enhance the accuracy rate of detection, and it eventually confirmed that it showed better performance than before. (TABLE VI)

Results in TABLE VI confirms that the zooming process has advantages in object detection accuracy and altitude calculation. Therefore, this method is also applied to other image data that has a large error in section V.B (colored in red in TABLES IV and V). The object detection using machine learning is performed using a 348×464 image obtained through Zoom processing. Additionally, the cropping process to cut off the detected BBOX is performed separately. In other words, the process of zooming in and out of the UAV allows us to extract image data that is more focused on the UAV than the initial image data. After that, the exact pixel size of UAV, that is, B parameter can be obtained through image processing using MATLAB R2017a. The overall error correction process is represented by a simple schema through Fig. 6.

The process of obtaining the exact pixel size of the target UAV through image processing of MATLAB is as follows. First, the UAV and the background are separated through edge detection. This can be completed by using the fact that the background color like the sky is usually monochromic which can easily be distinguished from the UAV. Since what we want is the length of the pixel in the horizontal direction of the UAV, we convert the entire edge-detected image into a matrix. That is, the black pixel, which is the part shown as the edge in the whole image data, is set to 1, and the other background part is set to 0 and converted to a matrix represented by the setting.

TABLE VI
UAV Altitude Estimation with Error Correction(Zoom)

Z_G(m)	Detection	Accuracy	Z_E(m)	Error
6	**O**	87%	5.4426	-9.29%
9	**O**	84%	8.7304	-3.00%

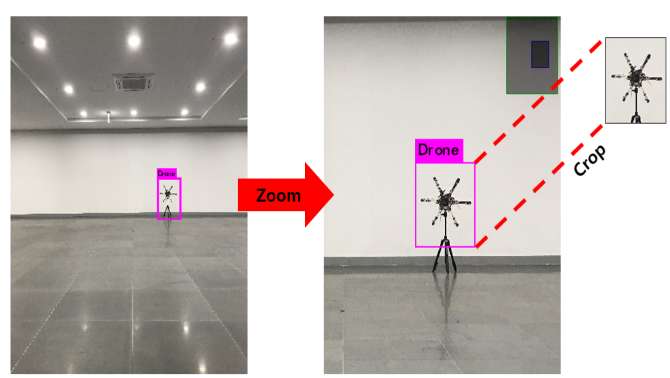

Fig. 6. Error Correction process (Zooming, Cropping)

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TABLE VII
PARAMETER B ESTIMATION (WITH ZOOMING AND CROPPING)

Z_G(m)	X_G(m)	Y_G(m)	B(Zooming)	B(Cropping)
6	1.2	0	89	74
9	1.2	0	88	75
9	2.4	0	92	77
9	3.6	0	88	76

TABLE VIII
UAV ALTITUDE ESTIMATION WITH ERROR CORRECTION

Z_G(m)	X_G(m)	X_E(m)	Y_G(m)	Y_E(m)	Z_E(m)	Error
6	1.2	1.1232	0	0.180	5.86345	-2.28%
9	1.2	0.972	0	0.0768	9.13206	1.47%
9	2.4	1.5702	0	0.231	9.04518	0.502%
9	3.6	2.3802	0	0.2082	8.47317	-5.85%

Since parameter B required in this calculation is the horizontal size of the UAV image, the sum is calculated for all terms of each row, and the number of the largest term from the first non-zero value to the last non-zero value is calculated as the pixel width length B. After the above process, the results of the improved altitude measurement were obtained significantly. (TABLES VII and VIII)

Through the above experiment process, the effectiveness of the altitude measurement method using a single camera presented in this study was confirmed. First, it was confirmed that the detection of UAV using a machine learning based object detection tool is detected with considerable accuracy. Next, the accuracy of estimated altitude was generally located within 10% of the error, but tends to increase as the distance to the object became relatively far. Therefore, it was confirmed that the error can be reduced through the zooming process, cropping and image processing process for the image data of the camera. This has an error of within 5% on average, and even with a maximum error, the actual error length is quite small within 60cm. This is not a visible error considering the size of the actual UAV.

VI. CONCLUSION

In this paper, we investigate the importance of accuracy of altitude information on UAV and the principle of UAV's altitude measurement. Understanding the error of the altitude measurement sensor requires additional UAV altitude measurement. The method of measuring the altitude from the object using the field of view of *"Single Monocular Camera"* was used, and the validity of this method was confirmed by constructing the actual experimental environment. After the object detection by machine learning, the distance is calculated with the parameters obtained from its image and equations. Besides, it was confirmed that the altitude error was reduced by enlarging, cropping, and image processing. Through the proposed process, the method of measuring the altitude from the object using the FOV was justified. This UAV elevation correction system will help us find and fix malfunctioning nodes in the UAV-aided mission environments.

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