https://doi.org/10.20965/jrm.2021.p0242

Paper:

Indoor Unmanned Aerial Vehicle Navigation System Using LED Panels and QR Codes

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[Received October 12, 2020; accepted March 5, 2021]

In this study, we propose an unmanned aerial vehicle (UAV) navigation system using LED panels and QR codes as markers in an indoor environment. An LED panel can display various patterns; hence, we use it as a command presentation device for UAVs, and a QR code can embed various pieces of information, which is used as a sign to estimate the location of the UAV on the way of the flight path. In this paper, we present a navigation method from departure to destination positions in which an obstacle lies between them. In addition, we investigate the effectiveness of our proposed method using an actual UAV.

Keywords: unmanned aerial vehicle, indoor non-GPS environment, on-board camera, LED panel, QR code

1. Introduction

Indoor flight control of small unmanned aerial vehicles (UAVs) has attracted considerable attention. UAVs [1] are used not only for traditional aerial photography and pesticide spraying but also for transporting cargo, surveying disaster sites, and inspecting inaccessible areas such as bridges and highways [2, 3]. Moreover, the demand for the use of UAVs indoors is also increasing, such as the transportation of parts and products and, the inspection of buildings and machinery in large factories.

Outdoor flying UAVs can be enabled to achieve stable and unmanned flight by measuring their position using GPS. However, indoor flying UAVs cannot receive the GPS radio waves and flying stably without manual radio control system is difficult. Therefore, to realize stable and unmanned indoor flights, developing an alternative method to GPS is necessary [4].

We can see several types of indoor UAV positioning methods as follows:

Type 1. Dead reckoning by inertial measurement unit (IMU).

Type 2. Detection of markers or landmarks by on-board camera of UAV.

Type 3. Estimation of 3D map by laser or cameras on UAV.

Type 4. Use of indoor GPS or UAV tracking cameras.

Type 1 is a self-positioning method using an IMU, which is an acceleration and gyro sensor embedded in a UAV. In general, outdoor flying UAVs also equip an IMU to estimate self-position when the GPS radio wave cannot be received. However, if the self-position is calculated using only the dead reckoning method, the error of position will accumulate, and the position will be different from the actual position; hence, using a more accurate method is necessary.

Type 2 is a method to detect markers and landmarks which are registered previously by an on-board camera on a UAV to estimate the self-position. Many recent UAVs are equipped with a camera to capture aerial photographs. Landmarks are the shapes of parts of buildings and signs that have a distinct pattern. They have no costs but there are not always patterns that are easy to detect by the UAVs; therefore, placing easily detectable markers at arbitrary locations is more effective. Moreover, if the shape and size of the markers are known, the 3D position of the UAV can be determined from the image of the markers on the camera. [5] and [6] discussed UAV flight control methods using ArUco markers. In [7], a UAV navigation system using AR markers and an IMU sensor is proposed. In [8], a flight control method for multiple UAVs using a large number of markers over a wide area was investigated. In [9], a method for position and orientation estimation using three-dimensional markers and an omnidirectional camera is proposed. We also studied an indoor and outdoor UAV auto control system using LED panels and an on-board camera on a UAV. In this study, UAVs distinguish patterns displayed on an LED panel as a command that is sent to UAVs [10–12]. Recently, human-tracking UAVs that utilize machine learning systems have been proposed [13, 14]. In this method, UAVs detect human positions without markers from an on-board camera's image.

Type 3 makes 3D maps surrounding UAVs by using lasers and cameras, and estimates self-position. This technique is called as "simultaneous localization and mapping (SLAM)." Type 2 also estimates the 3D position; however, it is limited to markers, so it can obtain only sparse 3D information. However, the SLAM can obtain dense

3D information. By using this method, UAVs can detect obstacles on flight, and safety unmanned auto-flight control will be realized. Even in outdoor environments, a 3D map of ground terrain was created from UAV camera images [15]. In [16], the 3D locations of the power lines from camera images were estimated. However, these systems use lasers and multiple cameras, and a high performance computer is necessary to process 3D information. Hence, the size of the UAV becomes large if it is equipped with these systems. This may not be suitable for indoor flights. Therefore, a flight control method that communicates with an external computer is also discussed.

Type 4 uses external devices to estimate UAV location. In [17], a method to estimate the indoor 3D position of an object using radio waves, similar to GPS, is proposed. This study does not use UAVs, but this method can be applied to UAVs. In addition, UAV location estimation and tracking methods using external cameras from UAV images have been proposed [18–20]. [21] also shows UAV location estimation using an external laser scanner. By using these methods, the number of devices installed on the UAV is reduced. This is a significant advantage for UAVs. However, the cost of external devices increases. In addition, estimating the correct self-position when obstacles exist between the UAV and external devices is difficult.

In this study, we propose an indoor auto-flight control system for UAVs based on Type 2 methods. Previous studies [5–8] using the Type 2 method have the following problems:

1. Many of the patterns in markers, such as the ArUco markers, are specialized to be reliably identified as markers in the captured image, and do not contain any other information.
2. To control the flight of the UAV, it is necessary to keep capturing the image of marker, so only flight control near the marker is considered.
3. A large number of markers are required to achieve a wide range of flight control.

To solve these problems, this study proposes following methods:

a. The use of LED panels and QR code panels, not only identifies them as markers, but also sends various information and commands to the UAV.

b. By considering the "marker detectable area" described below, a wide range of flight control can be achieved with the minimum number of markers required.

As a solution to the above problem 1, we discussed an auto-flight control method using LED panels displayed on the ground or floor. In this method, the displayed patterns on an LED panel are captured by the on-board camera of the UAVs. By discriminating these patterns, UAVs can obtain various information and flight commands linked to patterns. Moreover, because the size of LED panel is known, the 3D position of the UAV from the LED panel can be estimated from images of LED panels. We have also discussed flight control methods using such information [10–12].

The position (coordinates) of the panel can be used as navigation information to be presented to the UAV. As this information does not change, displaying a fixed pattern is better. For displaying of such patterns, the use of LED panels is not effective in terms of equipment cost. We herein use a panel on which a QR code [a] is printed on paper as a marker to present information that does not change. Such panels can be realized at an extremely low cost. Therefore, in this study, we discuss the use of QR codes as markers. Since QR codes can embed a considerable amount of information, they can transmit more information at a time than LED panels.

On the other hand, in order to achieve flight control of UAVs over a wide range, problems 2 and 3 need to be solved, that is, we must discuss how to control the UAV when marker images cannot be captured by the on-board camera. If we can produce an environment in which some type of marker can be captured at all times while the UAV is in flight, then there are no problems. However, because setting up many markers to create such an environment is necessary, flying UAVs in actual buildings will be difficult.

To realize a stable and safe indoor flight control system for UAVs using the minimum number of markers, we consider the "marker detectable area." This area can be configured by investigating the distance and direction ranges to detect the markers. In this paper, we propose a flight control method that considers this area.

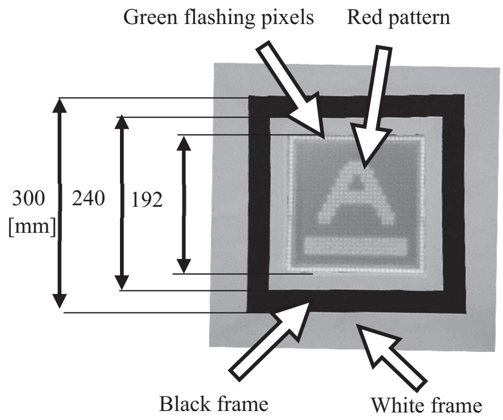
The remainder of this paper is organized as follows. In Section 2, we present the details of the devices, namely, the LED panel, QR code panel, and UAV. In Section 3, we explain the detection and discrimination methods of the LED panel and QR code panel, and we explain the flight control method using these devices. Section 4 shows the experimental results. First, we present preliminary experiment to investigate the QR code panel detection area. Subsequently, we show the UAV flight experiments in an indoor environment with LED panels and QR code panels. In Section 5, we conclude the study.

2. Configuration of Devices

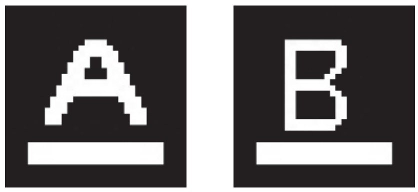
2.1. LED Panel

Figure 1(a) shows the LED panel used in this study. This panel is a square of dimensions 192 mm on each side and contains 32×32 full-color LEDs. A black and white frame is attached around the LED panel to detect its position. The inner white frame is a square dimensions of 240 mm on each side, the black frame is a square dimensions 300 mm on each side.

As shown in **Fig. 1**, 124 LEDs that are located on the four sides of the LED panel blink green at a constant frequency. The position of LED panel in captured images can be detected by estimating the blinking period of the green LED.



(a) Configuration of LED panel



(b) Displayed patterns

Fig. 1. LED panel.

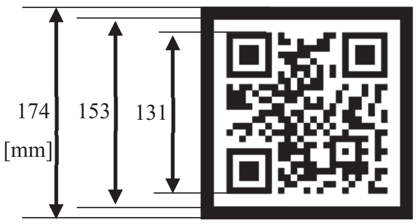


Fig. 2. QR code panel.

On the contrary, the inner 30×30 LEDs light up in any pattern with a red color. Examples of the displayed patterns are shown in **Fig. 1(b)**. These patterns correspond to the instructions of the UAV flight paths and tasks. They are displayed at the departure and destination positions.

2.2. QR Code Panel

Figure 2 shows a QR code panel. The specification of this code is 25×25 cells with an error correction level of M (approximately 15% loss restoration rate). A white frame is added around the QR code to provide a margin, and a black frame is added around the white frame to detect the position of the QR code panel.

In this QR code panel, some information are embedded, such as the ID number of the QR code panel to discriminate each other, the 2D coordinate of the QR code panel and the direction (angle) of this surface in the UAV flight area. The actual data are expressed as a string such as “Q002X000Y018R090.” By decoding this information from an image of a QR code panel and estimating the position and direction of the UAV from the QR code panel using a black frame, we can obtain the location of the UAV in the flight area. The QR code panel is printed on paper. The length of one side of the QR code is 131 mm, the white margin is 153 mm, and the black frame is 174 mm.

Fig. 3. UAV (Tello).

2.3. UAV

The functions required for the UAV used in this study are as follows:

- It is equipped with an on-board camera to capture the images of LED panels and QR code panels.
- To capture images stably, the UAV is able to hover, similar to multi-copters.

In addition, as we aim to achieve autonomous flight in poor radio wave environments in the future, implementing image processing of the captured panel images and processing of flight command instructions to the UAV based on the images in the on-board microcomputer system is desirable. However, because a UAV with on-board image processing is not yet available, the UAV is connected to a personal computer via Wi-Fi communication that performs image processing of the panel and sends navigation instructions to the UAV.

For obtaining a UAV that satisfies the above conditions, we use “Tello” [b] which is shown in **Fig. 3**. The UAV is equipped with a camera in front of the body. This camera captures images to detect the LED panel, to discriminate displayed patterns, and to read the QR code embedded in the position information. The angle of view is approximately 40° horizontally and the image resolution is 960×720 pixels.

This UAV is connected to the PC via Wi-Fi. The captured images are sent to a PC via wireless communication. The PC detects and discriminates the LED panels and reads the QR code. Subsequently, it sends motion commands to the UAV to fly to the next target. The motion commands to the UAV are the direction and distance of the straight flight, and the direction and angle of the horizontal rotation. Owing to the influence of external disturbances, the UAV does not always fly at a specified position, however, it can move to such a position with an error of a few centimeters by dead reckoning using an IMU inside the UAV.

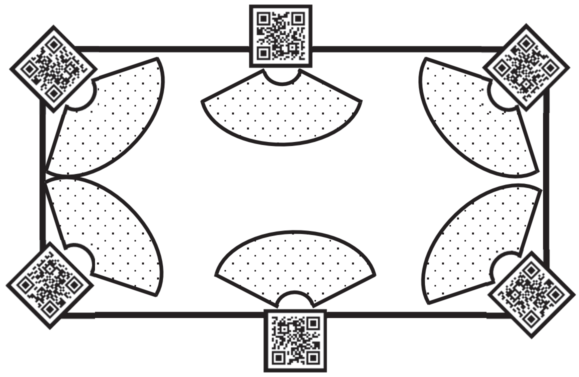


Fig. 4. Marker detectable area.

3. UAV Navigation Method

3.1. Overview of UAV Navigation Method

In this study, LED panels are used to send information about flight paths and tasks performed in the destination to UAVs. QR code panels are used as markers to estimate the UAV locations on the path of flight. This is because, even if there are many flight paths and tasks, LED panels can easily display various patterns as needed. On the contrary, the coordinates of marker positions that estimate the UAV location do not change in the flight area, and many markers are needed to flight UAVs. Hence, low-cost QR code panels are suitable for this purpose.

In the UAV flight area of this study, we assume that there are obstacles, and flying from departure to destination in a straight line is difficult. We also assume that a map of the flight area that describes the locations of obstacles and markers is known. In such an environment, to realize automatic unmanned flight control, estimating the location of UAVs in flight and avoiding contact with obstacles are necessary. As described in Section 1, if it is always possible to detect some markers wherever the UAV is within its flight area, the UAV can always estimate its own position. However, this would require setting up markers everywhere in the flight area. This is not a practical approach to cost.

To realize practical flight control, we define a "marker detectable area" as shown in **Fig. 4**. This means that the UAV can detect and read a QR code panel in this area. This range is defined by the minimum and maximum distances and directions at which the QR code panel can be detected and identified. This also depends on the size of the panel. The larger the panel, the larger is the range. However, in this case, the area inaccessible to the panel becomes large, and the area available for flight becomes small. In addition, the cost of making and setting panels is significant. In this study, the size of the panel is determined first from the viewpoint of the production cost of the QR code panel, and then, the marker detection area is obtained. In general, however, determining the size of the panel by considering the size of the marker detection area and the cost of making and setting the panel is effective. For a safe and reliable automatic UAV flight, the entire flight area must be filled with only marker detectable areas. However, this is not practical because it requires many markers. Hence, we assume that there is no obstacle between adjacent marker detectable areas. We propose a UAV flight control method in such an environment. In Sections 3.2 and 3.3, we show the LED panel and QR code panel detection and discrimination methods. In Section 3.4, we show the flow of flight control.

3.2. Detection and Discrimination of LED Panel

This subsection describes a method for LED panel detection and discrimination from images captured by an on-board camera in a UAV. In this method, we assume that the UAV is hovering at a position far enough away to capture the LED panel.

Step 1-1. The on-board camera of the UAV continuously captures multiple LED panel images. Let the number of captured images be N_p. At this time, the capture time of each image (t_i) and the capture time of all images (T_p) are recorded. Subsequently, the green pixels in the image are extracted, and the number of green pixels $g_p(i)$ $(i = 0, \ldots, N_p - 1)$ is calculated for each image.

Step 1-2. The number of green pixels $g_p(i)$ is recalculated by linear interpolation so that the data are the number of green pixels at equal time intervals ($\Delta t = T_p/N_p$). Let the recalculated number of green pixels be $\tilde{g}_p(j)$, which can be estimated using Eq. (1):

$$\tilde{g}_p(j) = (1-p)\cdot g_p(i) + p\cdot g_p(i+1), \quad \text{(1)}$$

where j is assumed as follows:

$$t(i) \leq j\cdot\Delta t < t(i+1), \quad \text{(2)}$$

and

$$p = \frac{j\cdot\Delta t - t(i)}{t(i+1)-t(i)}. \quad \text{(3)}$$

Step 1-3. Fast Fourier transform is applied to the number of green pixels obtained in Step 1-2, and the maximum amplitude a_m and its frequency f_m are found. The green blinking frequency f is determined by the following equation:

$$f = \frac{f_m}{T_p}. \quad \text{(4)}$$

Step 1-4. Using the correct green blinking frequency f_p and a range of frequencies d_f that we consider to be correct, the LED panel can be detected when the following equation is true.

$$\left(a_m > th_a\right) \wedge \left(f_p - d_f < f\right) \wedge \left(f < f_p + d_f\right), \quad \text{(5)}$$

where th_a is the known minimum number of green pixels for this detection. If the LED panel can be

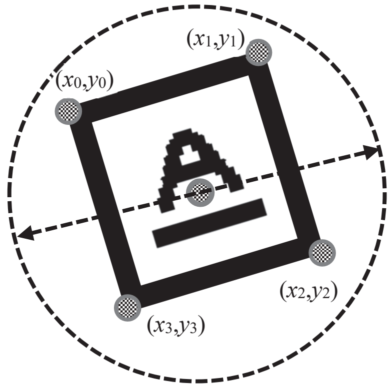


Fig. 5. Black frame extraction on LED panel image and obtain four corner points.

detected, then proceed to Step 1-5 and process the pattern discrimination. If not, the direction of the UAV is changed by rotating a few angles horizontally and repeat from Step 1-1 again.

Step 1-5. The image of the LED panel is captured again, and the red pixels in this image are extracted. If the red pixel area is not larger than the default size, return to Step 1-1 to detect the LED panel.

Step 1-6. The center of gravity of the red pixel area is obtained. To extract the pixels that constitute the black frame, only black pixels within the default range are extracted from the center of gravity of the red pixel area (**Fig. 5**).

Step 1-7. The closed space of the black pixels is filled and labeled, and the area with the maximum area is obtained.

Step 1-8. Estimating the minimum rectangle enclosing the obtained area. This gives us the four outer sides of the black frame. From this result, the coordinates of the four corners (x_i, y_i) $(i = 0, \ldots, 3)$ (**Fig. 5**) in the input image are estimated using "ARToolKit" library [c].

Step 1-9. Using the estimated coordinates of the corners, the LED panel area is extracted, and the distortions are corrected to create a rectangular image. This correction is done by the projective transformation as follows:

$$\begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} \sim \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & 1 \end{bmatrix} \begin{bmatrix} x'_i \\ y'_i \\ 1 \end{bmatrix}, \quad \ldots\ldots \quad (6)$$

where (x'_i, y'_i) denote the homogeneous coordinates in the rectangle image, (x_i, y_i) are the coordinates of the four corners in Step 1-8. They can be represented as:

$$\begin{cases} x_i = \dfrac{h_{11}x'_i + h_{12}y'_i + h_{13}}{h_{31}x'_i + h_{32}y'_i + 1}, \\ y_i = \dfrac{h_{21}x'_i + h_{22}y'_i + h_{23}}{h_{31}x'_i + h_{32}y'_i + 1}. \end{cases} \quad \ldots\ldots \quad (7)$$

The matrix elements h_{ij} are determined from the coordinates of four corners and the size of the rectangle image.

Step 1-10. The similarity between the corrected images and all images of the patterns on the LED panel rotated by 90° is calculated, and the pattern with the highest similarity is selected as the displayed pattern. Moreover, the position and angle of the UAV with respect to the LED panel are estimated from the orientation of the display pattern, the coordinates of the corners of the black frame, and the size of the LED panel using the ARToolKit library.

Step 1-11. We perform the discrimination process from Steps 1-5 to 1-10 several times, and the pattern on the LED panel is determined to be the one with the highest degree of similarity.

Subsequently, the UAV executes a task assigned to the discriminated pattern. As for specific instructions, if it is a destination task, then it captures aerial photography, loads and unloads cargo, among other tasks. If it is a departure task, then it is the instruction of the flight path. After the discrimination of the flight path, the UAV estimates its location from the coordinates of the LED panel and the position and angle of the UAV in relation to the LED panel obtained in Steps 1-10, and flies to the next target of the QR code panel.

3.3. Detection and Discrimination of QR Code Panel

This subsection describes a method to detect a QR code panel and read information from it. We assume that the UAV hovers near the "marker detectable area" of a QR code panel.

Step 2-1. Capture a single image by the on-board camera of the UAV and detect the black frame around the QR code using the ARToolKit library.

Step 2-2. The image area inside the black frame is corrected to a square. Subsequently, the QR code is enlarged by linear interpolation so that one cell of the QR code is 12×12 pixels, and the total number of pixels is 396×396.

Step 2-3. Extract 4×4 pixels in the center of each cell of the QR code and calculate the histogram of these pixels. Using this histogram, we estimate the threshold and binarize the corrected image using the discriminant analysis method.

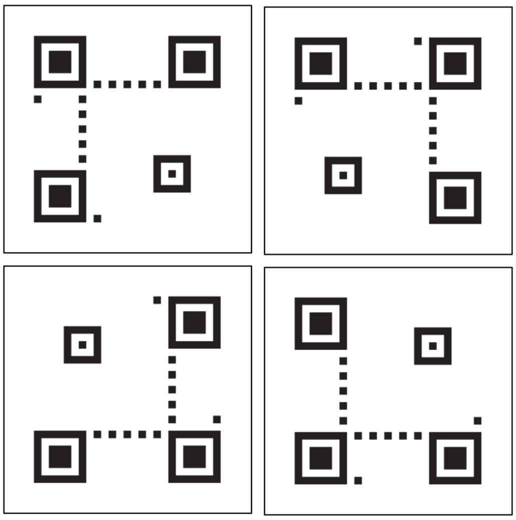


Fig. 6. Template images of common parts of the QR code.

Step 2-4. In the binarized image, the ratio of the number of black to white pixels in each cell is used to determine whether the cell is white or black, and reconstruct a QR code pattern. If the number of pixels is equal, it is assumed to be black.

Step 2-5. To check whether the QR code is rotated in a predetermined direction, we prepare template images of common parts of the QR code rotated by 90° (**Fig. 6**) and apply the template matching method to these images to determine the direction of rotation of the QR code.

Step 2-6. Rotate the QR code in a predetermined direction. The common part of the QR code is overwritten to the QR code image to correct the cells.

Step 2-7. We use "ZXing" [d], which is a 1D/2D barcode image processing library, to decode the image of the QR code and read the embedded information.

3.4. Flow of UAV Navigation

In this subsection, we show the procedure for automatic flight control of the UAV from the departure point to the destination point in an environment with LED panels at the departure and destination points and QR code panels in the flight area between them, as shown in **Fig. 7**. We assume the following conditions.

Condition 1. The flight range is assumed to comprise the marker detectable area and there is no obstacle between the adjacent marker detectable areas. In other words, the number and arrangement of the QR code panels are set up in advance to achieve this configuration.

Condition 2. The LED panel at the departure point displays a pattern that indicates a certain flight path. By recognizing this pattern, the UAV obtains the number and order of the QR code panels and the 2D coordinates of each QR code panel on its way to the LED panel at the destination point. (By considering Condition 1, when a UAV flies from one marker to the next one on the indicated path, it may fly in a straight line between the markers, and it does not come across any obstacle.)

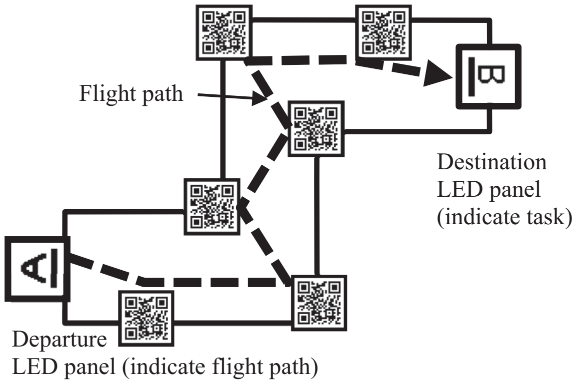


Fig. 7. Example of flight area.

Automatic flight control is completed by recognizing the pattern of the LED panel at the destination point and executing the corresponding task.

Considering the above conditions, the behavior of the UAV from the departure point to the destination point is as follows:

Step 3-1. The UAV takeoff point is located near the LED panel at the departure point. First, take off and adjust the altitude manually. In addition, the camera of the UAV should almost face the LED panel at the departure point. After these settings are completed, the system switches to automatic flight and detects and recognizes the LED panel, as described in Section 3.2.

Step 3-2. After recognizing the pattern on the panel using the method described in Section 3.2, the flight path information is obtained according to the pattern. Specifically, it is the number of QR code panel, the coordinates and the order of the QR code panels that will be passed through in sequence. If it cannot recognize the pattern on the LED panel, it makes an emergency landing and terminates the flight.

Step 3-3. The position and orientation of the UAV in relation to the LED panel are obtained from the method described in Section 3.2. The direction of flight and the flight distance are obtained from the number and coordinates of the subsequent QR code panel to be passed through. Here, the center of the marker detection area of the next QR code panel is the next target point.

Step 3-4. The UAV turns to the next target point and flies to a specified distance. While the UAV is flying, its camera is pointed forward. When it arrives at the next target point, the camera is rotated in the direction where the QR code panel or the LED panel is considered to be located.

Step 3-5. After the flight according to Step 3-4, the UAV is considered in the marker detectable area of the next QR code panel. However, because this is not certain, the UAV performs a search and approach operation on the QR code panel to read the contents of the QR code using the following procedure.

Step 3-6. The image is captured by the UAV camera, and the black frame around the QR code is detected using the ARToolKit library.

(a) If the black frame cannot be detected, rotate the UAV by 30° in the horizontal direction, and repeat Step 3-6. If the black frame cannot be detected after one round of rotation, the UAV will perform an emergency landing and finish the flight.

(b) If one or more black frames can be detected, they can be corrected to square areas and template matching is applied to the images in **Fig. 6**. If there are some corrected images with high similarities that can be identified as QR codes, we obtain the corrected image with the highest similarity among them and proceed to Step 3-7. If there are only low-similarity images, rotate the UAV horizontally by 30° and repeat Step 3-6.

Step 3-7. Estimate the position and orientation of the UAV with respect to a black frame from the coordinates of the four corners of a black frame of an image with high similarity.

Step 3-8. To read the QR code, the UAV moves to a position where the distance is approximately 1 m and the angle is within $\pm 3.0°$ from the black frame, and repeat from Step 3-6.

Step 3-9. When the UAV reaches the position shown in Step 3-8, it decodes the contents of the QR code and obtains the number and coordinates of the QR code panel using the method in Section 3.3.

Step 3-10. Repeat Steps 3-5 to 3-9 five times, and when it matches more than three times, it is taken as a result of QR code information.

(a) If the obtained number of QR code panels matches the indicated number, the position of the UAV with respect to this QR code panel is estimated, and the UAV repeats Step 3-4 to fly to the next QR code panel or LED panel at the destination point.

(b) If the number of obtained QR code panels is different from the indicated number, the UAV returns to the previous QR code panel after estimating the position of the UAV with respect to the current QR code panel (repeat from Step 3-4). This is because we can assume that there is no obstacle between the current QR code panel and the previous one.

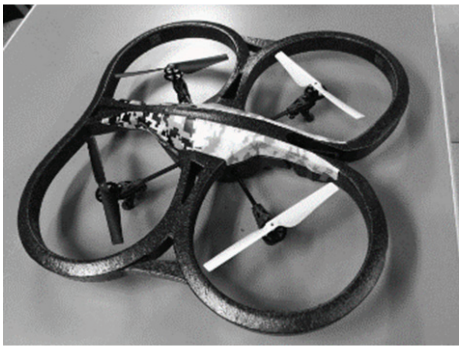


Fig. 8. AR.Drone.

Fig. 9. Logicool BRIO.

Step 3-11. In Step 3-4, if the next point is the LED panel at the destination position, when the LED panel is approached, the display pattern of the LED panel is discriminated by the method described in Section 3.2. The UAV performs the task according to this pattern. The UAV lands to complete the automatic flight.

4. Experiments

4.1. Inspection of Marker Detectable Area

In this section, we investigate the marker detectable area of an actual QR code panel and obtain the reading accuracy of the QR code by arranging cameras at various distances and directions.

Since this experiment was conducted before the introduction of Tello, we used the following devices as cameras:

- Parrot, "AR.Drone" (**Fig. 8**): It can be controlled wirelessly similar to the Tello.
- Logicool BRIO (**Fig. 9**): A general-purpose web camera.

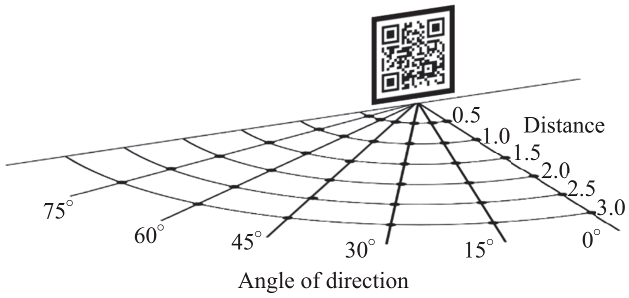


Fig. 10. Arrangement of camera for QR code panel.

Table 1. Black frame size at 1.0 m.

AR.Drone (640 × 360)	98 × 98 pixels
Logicool BRIO (1920 × 1080)	205 × 205 pixel
Logicool BRIO (640 × 480)	95 × 95 pixels

The AR.Drone is equipped with two cameras, but only the front camera is used. The resolution of this camera is 640 × 360 pixels. For the Logitech BRIO, we used a 1920 × 1080 pixel case and a 640 × 480 pixel case. This is because we think the image resolution has the greatest influence on the reading of the QR code. During the experiment, the cameras are stationary. However, the shutter speed is set to the minimum value, and the gain and contrast are set to the maximum value for each camera, because the image capturing is actually performed during the flight.

Figure 10 shows the arrangement of the camera for the QR code panel. The distance from the QR code panel is 0.5–3.0 m at 0.5 m intervals, and the direction is set at 15° intervals up to 75°, assuming that the direction is 0° when it faces to the QR code panel.

As the image is symmetrically captured when rotating to the left or right with respect to the QR code panel, in this study, only the left side was used. The height of the QR code panel is adjusted so that it is near the center of the image. The accuracy of the QR code reading was estimated by capturing 10 images at each camera location. The QR code panel is the same as that described in Section 2.2.

Table 1 shows the size of the QR code when the camera was used to capture the image at a distance of 1.0 m and at an angle of 0°. The size of the QR code varies depending on the angle of view and the focal length of the lens, but it is clear that this size is almost proportional to the resolution of the image. **Tables 2–4** present the results of the recognition rates for each camera. AR.Drone's camera in **Table 2** could not read the QR code at all at a distance of 2.0 m or more. In addition, as the angle increases, the readable distance decreases. With the low resolution of the Logicool BRIO in **Table 4**, the QR code cannot be read at a distance of 1.5 m or more. On the contrary, in the case of the high-resolution Logicool BRIO shown in **Table 3**, the frontal view was readable at a distance of up to 2.0 m. Therefore, a high resolution camera is required to read the QR code from a distance.

Table 2. Results of AR.Drone (640 × 360).

Angle [°]	Distance [m]					
	0.5	1.0	1.5	2.0	2.5	3.0
0	100%	100%	100%	0%	0%	0%
15	100%	100%	100%	0%	0%	0%
30	100%	100%	100%	0%	0%	0%
45	100%	100%	0%	0%	0%	0%
60	100%	0%	0%	0%	0%	0%
75	0%	0%	0%	0%	0%	0%

Table 3. Results of Logicool BRIO (1920 × 1080).

Angle [°]	Distance [m]					
	0.5	1.0	1.5	2.0	2.5	3.0
0	100%	100%	100%	80%	0%	0%
15	100%	100%	100%	30%	0%	0%
30	100%	100%	100%	0%	0%	0%
45	100%	100%	100%	0%	0%	0%
60	100%	100%	0%	0%	0%	0%
75	0%	0%	0%	0%	0%	0%

Table 4. Results of Logicool BRIO (640 × 480).

Angle [°]	Distance [m]					
	0.5	1.0	1.5	2.0	2.5	3.0
0	100%	100%	10%	0%	0%	0%
15	100%	100%	0%	0%	0%	0%
30	100%	100%	0%	0%	0%	0%
45	100%	70%	0%	0%	0%	0%
60	100%	0%	0%	0%	0%	0%
75	0%	0%	0%	0%	0%	0%

These experimental results show that it is possible to read the QR code within an angle of approximately 45° at a distance of 1.0 m and approximately 30° at 1.5 m, even if the resolution of the camera is different. We define this area as the "marker detectable area." The camera resolution of the Tello described in the next section is 960 × 720 pixels, which is in between that of the AR.Drone and Logicool BRIO. Therefore, it is considered to have almost the same reading accuracy. In addition, we confirmed through preliminary experiments that the minimum distance at which the Tello can detect a QR code panel is 0.25 m.

4.2. Configuration of UAV Navigation Experiments

In this subsection, we describe the setup of a flight experiment using a UAV (Tello), two LED panels and six QR code panels. **Fig. 11** shows the layout of the LED

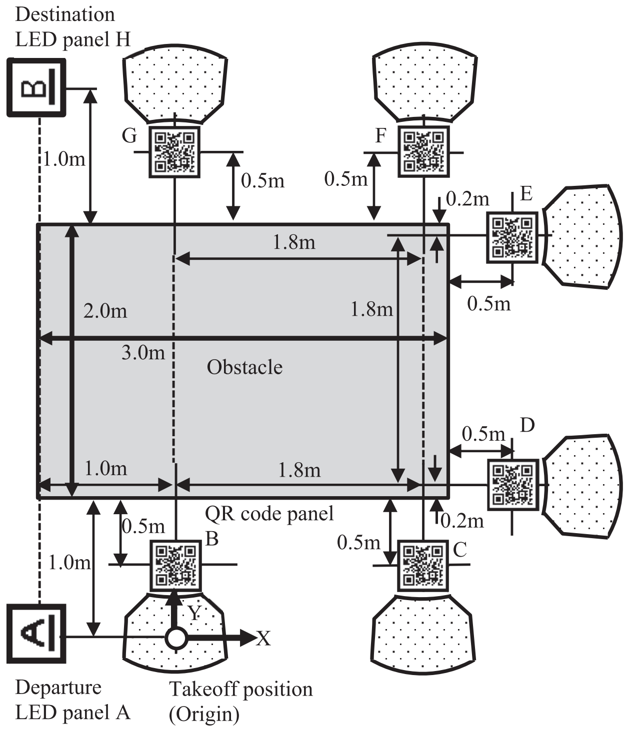


Fig. 11. Layout of LED and QR code panels for flight experiments.

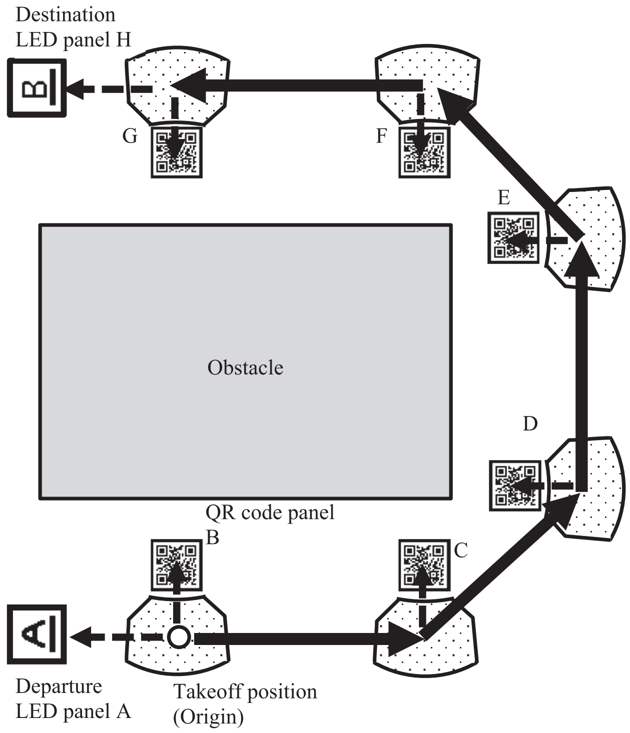


Fig. 13. Flight path in experiments.

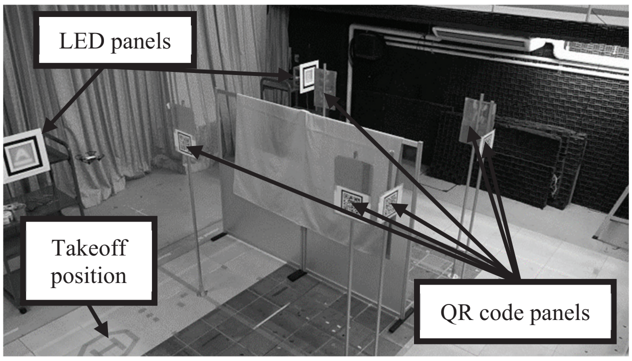


Fig. 12. A scene of flight experiment.

and QR code panels. **Fig. 12** shows a scene of the actual experimental environment. The LED panels and QR code panels are placed at a height of approximately 1.5 m above the floor. The LED panel A is the departure point and the LED panel H is the destination point. The task in LED panel H is to take photographs in the surroundings.

The center area of **Fig. 11** shows an obstacle, which cannot be flown in a straight line from LED panels A–H. For the placement of the six QR code panels B–G, we considered the "marker detectable area" described in the above sections. These are shown as dotted areas adjacent to the QR code panel. They are the union of two fan shapes (radius: 1.0 m, angle $\pm 45^\circ$ and radius: 1.5 m, angle $\pm 30^\circ$). The locations of the QR code panels were determined based on human judgment. We assume that there are no obstacles outside this flight area as shown in **Fig. 11**. However, owing to the actual walls of the room, we manually force a landing if it goes beyond this area.

4.3. Experimental Results

In this subsection, we present the experimental results of flight navigation under the conditions described in Section 4.2. **Fig. 13** shows the flight path from LED panels A–H directed to the UAV. This flight was conducted 13 times. Among them, the exact flight from LED panels A–H was 10 times. The other three flights were aborted because the radio communication between the UAV and the PC was lost during flight. The UAV did not lose sight of the QR code panel and it did not move to the wrong QR code panel on the way during flight.

Figure 14 shows images of the LED panel during a flight. These are results of detecting the green flashing of the LEDs. **Fig. 15** shows the results of detecting the red pattern on the LED panel, and **Fig. 16** shows the results of the correction by extracting the QR code part from the image of the QR code panel.

Figure 17 shows a timing chart for the state of the UAV at one time when it has been able to fly from LED panels A–H 10 times. A video of the scene of the experiment in **Fig. 17** can be viewed at [e]. Before reading the QR code panels from B–G, the UAV repeats the motion to approach several times. For QR code panels C, D, E, and G, the UAV approached each panel during the five QR code readings because it could not read the QR code. **Fig. 18** shows the results of self-positioning of the UAV. The gray area in the figure represents the obstacle area. The flight path was almost the same as that shown in **Fig. 13**.

(a) Green pixels are OFF

(b) Green pixels are ON

Fig. 14. Detection of green flashing on LED panel.

Fig. 15. Detection of red pattern on LED panel.

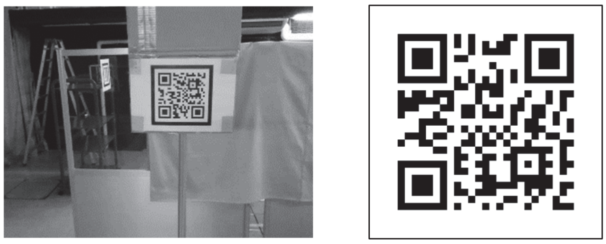


Fig. 16. Correction of QR code pattern from image.

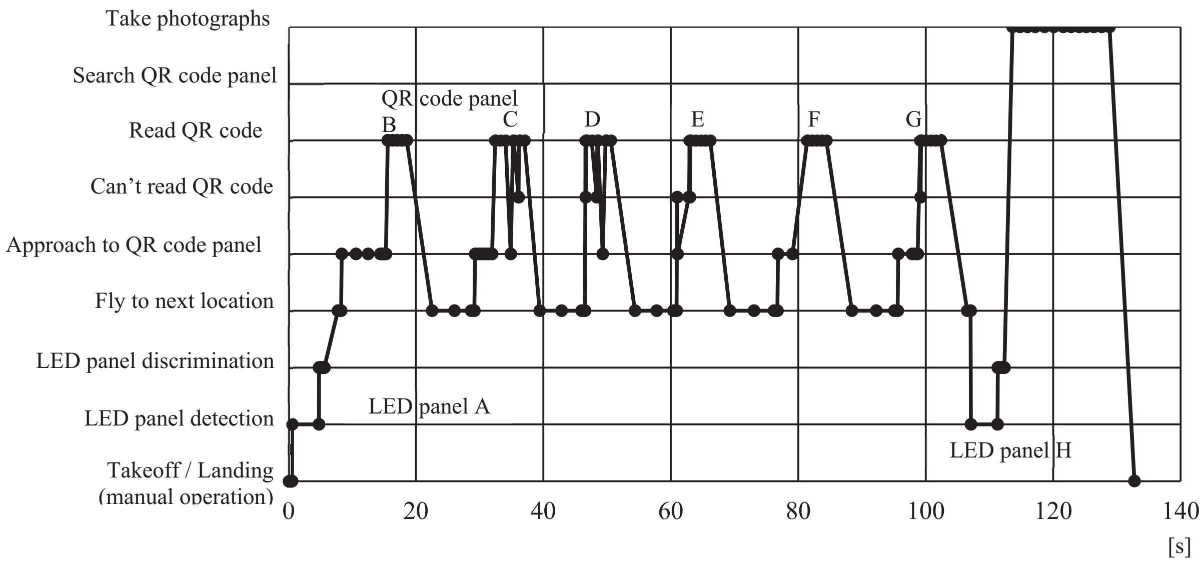


Fig. 17. Timing chart of UAV state.

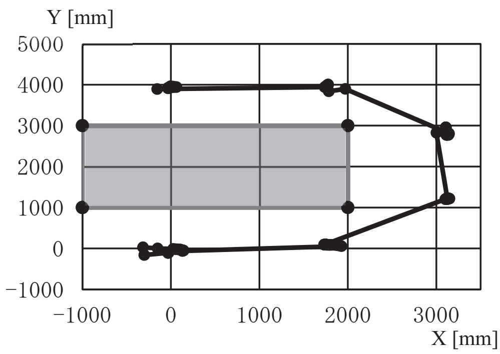


Fig. 18. Results of self-positioning of UAV.

In the experiment shown in **Fig. 17**, LED panels A and H were identified five times each, and the final identification was made by a majority vote of the results. LED panel A was identified correctly four times and incorrectly once, while LED panel H was identified correctly all five times. Therefore, the identification rate of the LED panels was 90.0%. A total of 88 QR code panel identification results were obtained for the six QR code panels. The correct identification result was 80 times. Therefore, the identification rate of the QR code panels was 90.9%.

The average processing times required for image processing were as follows:

1. LED panel detection using green LED blinking: 4.18 sec.

2. Pattern discrimination of an LED panel image: 0.0833 sec.

3. Detection and discrimination of a QR code panel image: 0.765 sec.

In **Fig. 17**, several approaching motions of the UAV may be due to the following reasons.

1. Errors are included in the self-position estimation results.

2. The UAV is not always able to fly as directed.

In the case of 1, as we had manually set up the QR code panel, there is a possibility that the location of the panel may be slightly different from the expected location. In the case of 2, although this experiment was an indoor flight experiment, it was caused by the influence of disturbance from the air conditioner wind and errors in the IMU sensor inside the UAV. However, even if the UAV flies to a position different from the indicated one, it can still detect the QR code panel and determine its own position if it is within the marker detectable area of the QR code panel. Therefore, the UAV can compensate for positional errors. In our experiments, the UAV was able to fly to the final destination (LED panel H), thereby demonstrating the effectiveness of the proposed method. In this experiment, the UAV did not lose sight of the QR code panel, so the UAV did not search for it; however verifying such an operation is necessary.

5. Conclusions

In this study, we proposed a method for automatic flight control of a UAV using LED and QR code panels in an indoor environment where GPS is not available. Here, the LED panel is used to send commands to the UAV by displayed patterns, and the QR code panel is used to detect the position of the UAV during flight. We specifically obtained the "marker detectable area" of the QR code panel and showed the flight navigation method of the UAV considering it. The effectiveness of the proposed method was confirmed through flight experiments in the area of obstacles along the flight path.

In future work, it will be necessary to study how to automatically determine the position of the QR code panel based on the position of obstacles in the flight range, taking into account the "marker detectable area." In this study, although the UAV was moved in two dimensions, examining the panel arrangement in three-dimensional space, including the movement of UAVs in the height direction is also necessary.

In the experiments, the flight was aborted because radio communication between the UAV and the PC was lost. Equipping the UAV with an on-board computer that performs image processing of LED panels and QR code panels is also necessary. In the future, we will study these points and realize a UAV navigation system that can fly indoors safely and accurately.

Acknowledgements

This work was supported by Pacific Consultants Co., Ltd. and Spiral Inc. I would like to thank Mr. Daiki Miyamoto and Mr. Kai Hattori, graduate students of Tokushima University, for their cooperation in this study.

References:

[1] K. Nonami et al., "Drones Making Great Strides," NTS Inc., 2016 (in Japanese).
[2] Y. Fujino et al., "Large Structure Health Monitoring," NTS Inc., 2015 (in Japanese).
[3] Y. Hada et al., "Development of a Bridge Inspection Support System Using Two-Wheeled Multicopter and 3D Modeling Technology," J. Disaster Res., Vol.12, No.3, pp. 593-606, 2017.
[4] S. Abiko, "Significance of Indoor Drone and Introduction of Its Research Topics," J. Japan Society of Photogrammetry and Remote Sensing, Vol.55, No.4, pp. 250-253, doi: 10.4287/jsprs.55.250, 2016 (in Japanese).
[5] Y. Hane and A.Takeda, "Attitude Control for AR.Drone based on Camera Images," Information Processing Society of Japan (IPSJ) Tohoku Branch SIG Technical Report, Vol.2014, pp. 1-3, 2015 (in Japanese).
[6] M. F. Sani and G. Karimian, "Automatic Navigation and Landing of an Indoor AR.Drone Quadrotor Using ArUco Marker and Inertial Sensors," 2017 Int. Conf. on Computer and Drone Applications (IConDA), pp. 102-107, doi: 10.1109/ICONDA.2017.8270408, 2017.
[7] H. Nakanishi and H. Hashimoto, "AR-Marker/IMU Hybrid Navigation System for Tether-Powered UAV," J. Robot. Mecharoton., Vol.30, No.1, pp. 76-85, 2018.
[8] S. T. Moon, D. H. Cho, S. Han, D. Y. Rew, and E.-S. Sim, "Development of Multiple AR.Drone Control System for Indoor Aerial Choreography," Trans. of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan, Vol.12, No.APISAT-2013, pp. a59-a67, 2014.
[9] N. Hatakeyama, T. Sasaki, K. Terabayashi, M. Funato, and M. Jindai, "Position and Posture Measurement Method of the Omnidirectional Camera Using Identification Markers," J. Robot. Mechatron., Vol.30, No.3, pp. 354-362, 2018.
[10] H. Ukida and M. Miwa, "Development of Information Communication System Using LED Panel and Video Camera," IEEJ Trans. on Electronics, Information and Systems, Vol.133, No.1, pp. 8-17, 2013.
[11] H. Ukida and M. Miwa, "LED Panel Detection and Pattern Discrimination Using UAV's On-Board Camera for Autoflight Control," J. Robot. Mecharoton., Vol.28, No.3, pp. 295-303, 2016.
[12] H. Ukida, "Flight Control of UAV Using Panels and Onboard Camera," J. Japan Society for Design Engineering, Vol.54, No.10, pp. 635-640, 2019 (in Japanese).
[13] A. Rohan, M. Rabah, and S.-H. Kim, "Convolutional Neural Network-Based Real-Time Object Detection and Tracking for Parrot AR Drone 2," IEEE Access, Vol.7, pp. 69575-69584, doi: 10.1109/ACCESS.2019.2919332, 2019.
[14] H. Yamashita and I. Mitsugami, "Automatic Tracking Drone for Video Analysis of Moving People in Wide Area," Information Processing Society of Japan (IPSJ) SIG Technical Report, Vol.2020-CVIM-222, No.38, 2020 (in Japanese).
[15] T. Suzuki et al., "3D Terrain Reconstruction by Small Unmanned Aerial Vehicle Using SIFT-Based Monocular SLAM," J. Robot. Mecharoton., Vol.23, No.2, pp. 292-301, 2011.
[16] K. Nakaya, "Separation assessment between power-line and trees using small drone for maintenance of transmission facility," 2019 Annual Meeting Record I.E.E. Japan, pp. S21(16)-S21(19), 2019.
[17] D. He et al., "3-D Spatial Spectrum Fusion Indoor Localization Algorithm Based on CSI-UCA Smoothing Technique," IEEE Access, Vol.6, pp. 59575-59588, doi: 10.1109/ACCESS.2018.2873686, 2018.
[18] T. Kasahara and K. Sato, "An autonomous hovering control of multicopter using only USB camera," Proc. of the 6th Int. Conf. on Positioning Technology (ICPT2014), pp. 355-357, 2014.
[19] K. Hidaka, D. Fujimoto, and K. Sato, "Autonomous Adaptive Flight Control of a UAV for Practical Bridge Inspection Using Multiple-Camera Image Coupling Method," J. Robot. Mechatoron., Vol.31, No.6, pp. 845-854, 2019.
[20] H. Deng et al., "Indoor Multi-Camera-Based Testbed for 3-D Tracking and Control of UAVs," IEEE Trans. on Instrumentation and Measurement, Vol.69, No.6, pp. 3139-3156, 2020.
[21] R. A. Pratama and A. Ohya, "State Estimation and Control of an Unmanned Air Vehicle from a Ground-Based 3D Laser Scanner," J. Robot. Mechatoron., Vol.28, No.6, pp. 878-886, 2016.

Supporting Online Materials:

[a] DENSO WAVE Incorporated, "DENSO WAVE, the Inventor of QR Code," (in Japanese). https://www.qrcode.com/ [Accessed March 10, 2021]

[b] Ryze Tech, "Tello." https://www.ryzerobotics.com/ [Accessed March 10, 2021]

[c] M·SOFT, "ARToolKit," (in Japanese). https://www.msoft.co.jp/service/artoolkit.html [Accessed March 10, 2021]

[d] ZXing-C++. https://github.com/nu-book/zxing-cpp/ [Accessed March 10, 2021]

[e] Computer Vision Laboratory, Mechanical Science Course, Department of Science and Technology, Faculty of Science and Technology, Tokushima University, "Video of Experimental Results," (in Japanese). https://www-cv.me.tokushima-u.ac.jp/research/AR_QR_UAV/ [Accessed March 10, 2021]

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