Tip Detection and Guidance for Automatic Inspection of Lightning Surges on Wind Turbine Blade

Shuto Homma s1270144 Supervised by Prof. Yuichi Yaguchi

Abstract

Unmanned aircraft systems (UAS) are populated for inspections and maintenance due to their smaller size and lower price. They can safely and quickly go to high places such as roads, bridges, roofs, chimneys, and other dangerous places at construction sites. The wind turbine blades are embedded with metal "receptors" to catch lightning. A conductor wire releases it to the ground through the tower (column). Since the blade's tip can rupture due to the impact of lightning, maintenance is required each time this happens. Since inspections require considerable labor and time, we wanted to solve the problem using a multi-copter type UAS to perform the inspections at that time. We propose an autonomous operation of a small UAS to touch a tip of a wind turbine propeller to guide by image processing such as GrabCut and object tracking. The recognition task of a wind turbine propeller's tip shooted onboard cameras from the ground is challenging due to similar background color and indefinite light source direction. It is also challenging to obtain sufficient background and foreground data for machine learning. Therefore, foreground extraction is performed using GrabCut, but GrabCut requires manual foreground-background hints. In order to capture dynamically changing images, this study used tracking and the previous extraction region to continuously provide foreground-background hints to recognize windmill propellers and perform tip detection. The propeller could be recognized continuously if the frame rate was sufficient. As a result, a UAS can get control from cameras that could be obtained even if the light source direction is indefinite.
Keywords: Image Processing, GrabCut, Autonomous Navigation, Wind Turbine Inspection

1 Introduction

The hot topic in using UAS for public facilities is labor-saving in periodic inspections and other inspections of high places [1]. In particular, UAS has already been demonstrated for use in inspections of bridges [2], buildings [3], and others, not only by visual inspection but also by acoustic inspection. The target of this research is the inspection of wind turbines at wind power plants. In particular, wind power plants in mountainous areas have a system in which a grounding contact is placed at the tip of a windmill blade, and electricity from lightning strikes is safely released through an internal conductor. This part had to be inspected using a crane or scaffolding for working at high elevations. For this reason, the introduction of this research was to make it possible to smoothly inspect the conductors of the ground connection by flying a UAS with conductors connected to the ground contact points, bringing an inspection device into contact with the tip of the blade, and measuring the resistance value by this means (Figure 1).

On the other hand, while there are several examples of automatic guidance of UAVs, there are few examples of guidance while accurately measuring the distance to a thin target such as this one, which is like 'looking at a blade from the front. There are examples of guidance for distant or small targets, but it is not easy to guide a UAV to the tip of the target and accurately aim the equipment at the UAV.

This study proposes a 3D butt end measurement using image processing and aims to provide control values for automatic control based on this measurement. In image processing, the target blade is recognized by three onboard cameras whose line of sight is in the apex direction, and the point farthest from

Figure 1. A scene to utilize UAV for inspection of grounding of wind turbine

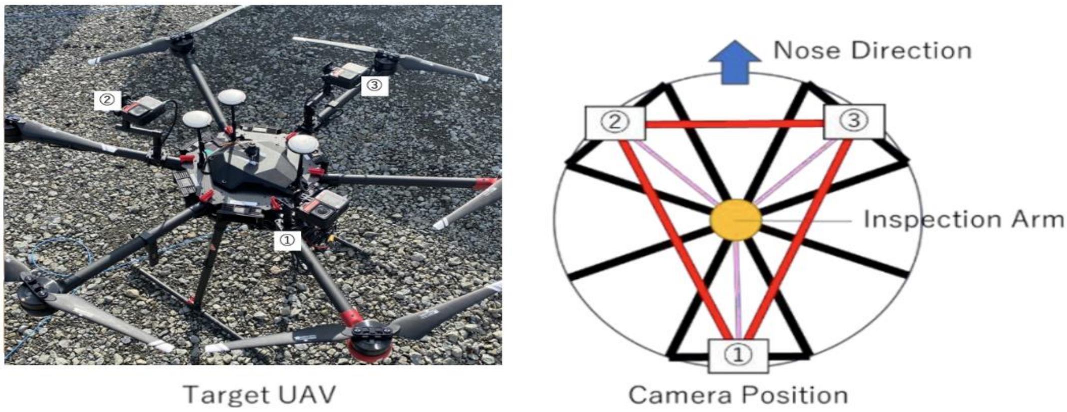

Figure 2. Experimental system and arrangement of camera position

the line of sight in the blade area is recognized as the butt end. The pixel of the inspection arm and three cameras are measured from each camera in advance. Next, using these measurements, we calculate the difference in relative height and position in the plane direction of the blade tip of the wind turbine from the center of the inspection arm put on the center of the UAV. Finally, we calculate the difference in height and position in the plane direction of the UAV.

The background is not shown in the figure above. In addition, since there are cases in which the background is not only sunny but also cloudy or directly reflected sunlight, we propose a method to apply GrabCut [4] continuously to use Grabcut for robust foreground-background extraction.

This study is as follows: in Chapter 2, the environmental conditions and the aircraft configuration are presented; in Chapter 3, the blade detection method and the relative positional information from the three cameras are presented; in Chapter 4, recognition results when using a simulated test field are presented as an experiment; in Chapter 5, we conclude our system development result.

2 System Environment

The test aircraft prepared for this study is shown in Figure 2, left panel. The test aircraft for this study is an eight-engine plane manufactured by DJI M600. The onboard camera is an Insta 360. At first, we used a fisheye camera called Kodac PIXPRO SP360 4K, but this camera did not suitable for a far position to shoot blade. Therefore, we needed to change it to Insta 360 for image stabilization and to narrow the angle of view. The image size is 1920*1080, and the frame rate is five fps. The three onboard cameras are not synchronized. The positional relationship of the onboard cameras mounted on the test aircraft is shown in Figure 2, right. All onboard cameras are oriented so that the nose direction is up. In other words, the arm visible from camera 1 appears on the top surface.

On the other hand, since the onboard camera is mounted facing upward, the arm position and camera position that the camera sees is viewed from below, so the positional relationship in right image of Figure 2 is inverted. The horizontal distance from each camera to the arm is about 30 cm. The distance between cameras 1 and 2 or 3 is about 50 cm. Also, the distance between cameras 2 and 3 is about 50 cm. In addition, the arm's height is set at about 100 cm.

3 Relative Position Calculation between Inspection Arm and a Blade Tip

3.1 Algorithm Overview

Figure 3 shows the overall system process for distance detection and flight command conversion from the UAV airframe to the tip of a wind turbine blade, including automatic navigation. In the primary process, one thread is consumed per camera to aggregate the input from each camera and the results of the wind turbine blade recognition and tip detection. Then, the relative horizontal position and vertical distance are calculated, flight commands are generated, and the overall control process is executed. In the camera class, functions for area extraction and tip detection are provided, which are called by the initialization and input value setting and by the threading process, which is always running in a separate thread in an internal loop. The threading process of the camera should be able to extract data from the primary process by memory management

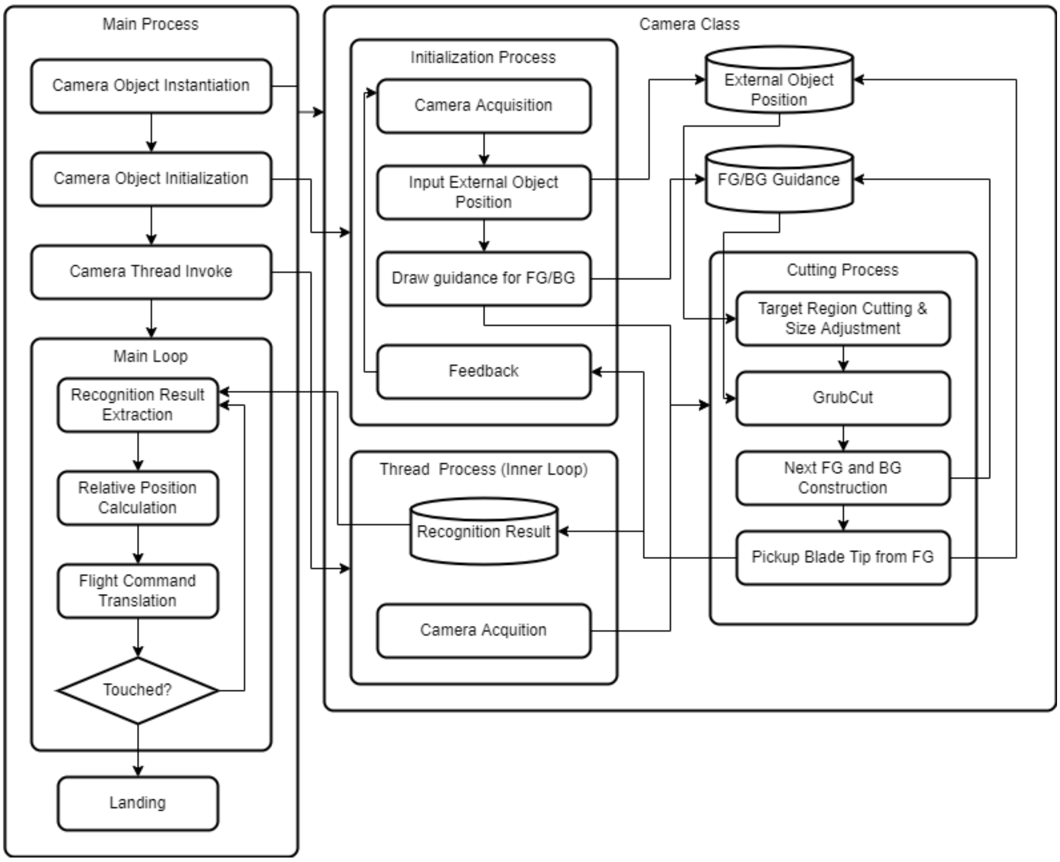

Figure 3. System process diagram of our position calculation and autonomous navigation

with Queue. However, to be able always to take the latest information, only the latest information is kept in the data area, and when writing is being done from the threading process, When a thread process is writing to the data area, the main loop is blocked by the camera thread. Since the cameras are not synchronized, the input timing shifts by about 1 second depending on the cycle, so there is a significant error in the relative position calculation information for high-speed flights. In this case, a movement speed of about 0.5 m/s is considered.

3.2 Blade Tip Detection

To detect the tip of a wind turbine blade of a wind turbine, we performed blade area recognition as the first step.

We used GrabCut for blade region extraction because there is very little texture around the wind turbine blades, and it is also difficult to extract information such as edges from the image processing due to the movement of the sky and clouds reflected in the background area (Figure 4). The disadvantage of GrabCut is manually labeling the foreground and background areas in advance, and it is challenging to perform such prior labeling for time-series images. Therefore, in this study, the blade regions extracted in the previous frame generate guidance for the next. Specifically, a thinning process is performed from the extracted blade area to describe the area in the factual foreground with a line of about 5 pixels. Similarly, a boundary line of a certain number of pixels away from the extracted blade area is described as a region that is the factual background. For the next frame, the upward-facing camera on the multi-copter causes a large viewpoint shift during control, resulting in a significant change in the position and shape of the blades in the image. Therefore, template matching uses the rectangle containing the blade area extracted in the previous frame to estimate the blade position in the next frame. The guidance extracted in the previous frame is applied to this estimated location, and the blade region is extracted similarly for the next frame.

Next, the blade tip position is calculated from the extracted blade area. The blade tip position is the furthest point of the blade region from the center of the camera's line of sight (approximately the center of the image) if the blades are extending downward,

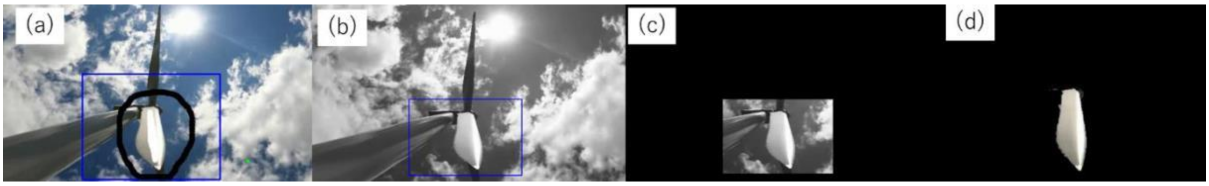

Figure 4. Find target region and GrabCut

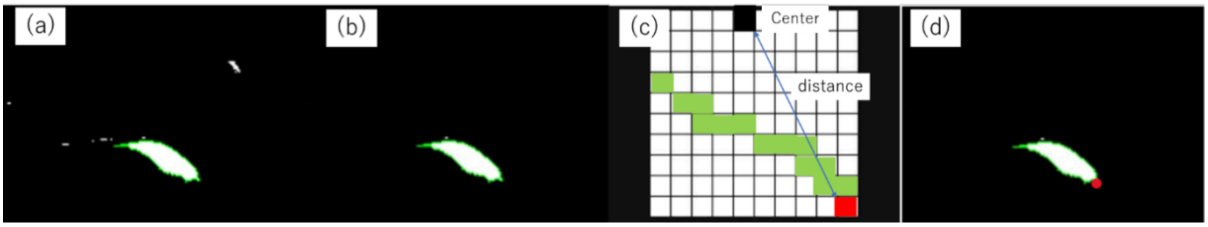

Figure 5. Find contour of blade and calculate blade tip

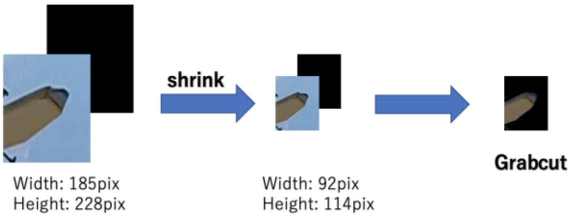

Figure 6. Shrinking process before GrabCut

considering the orientation of the wind turbine blades beforehand (Figure 5). If the blades extend diagonally downward, the furthest point of the blade area is the blade tip position from the point where the line extending in the direction of the base of the wind turbine intersects with the boundary of the image. For simplicity of calculation, Manhattan distance was used as the distance measure in this implementation.

The GrabCut algorithm has a computational complexity of O(n^3) when n pixels is on one side and requires a certain degree of iterative computation, so the computation speed becomes extremely slow when the image size is large. Therefore, the processing speed is approximately 5 Hz by extracting the blade region and further reducing the image to a pyramidal size so that the longest side is less than 200 pixels (Figure 6).

3.3 Automatic UAV Control via Three-cameras Blade Tip Recognition

The automatic control of the UAV for ground inspection is operated by generating commands based on the relationship between the triangle represented by the blade tip points measured from the three cameras and the triangle represented by the point at the center of the contact surface of the ground inspection to be contacted.

If blade tip extraction in section 3.2 is performed from three cameras, parallax can be extracted from each. Similarly, from the three cameras, the center of the contact surface of the earth inspection to be contacted is manually entered. Projecting the respective measured coordinate points from these three cameras into the same coordinate space, a triangle with the blade tip endpoint and a triangle with the grounding contact point are drawn. Now, we define the blade tip point at the i-th camera $\left(x_i^b, y_i^b\right)$, and the ground contact point (x_i^a, y_i^a). Then, the gravity difference between the blade tip and contact points as (x_i^g, y_i^g) and the area ratio δS are defined as follows:

$$\left(x_i^g, y_i^g\right) = \left(\frac{\sum_{i=1}^{3} x_i^b - \sum_{i=1}^{3} x_i^a}{3}, \frac{\sum_{i=1}^{3} y_i^b - \sum_{i=1}^{3} y_i^a}{3}\right) \quad (1)$$

$$\delta S = \frac{\begin{pmatrix} x_1^b - x_0^b \\ y_1^b - y_0^b \end{pmatrix} \times \begin{pmatrix} x_2^b - x_0^b \\ y_2^b - y_0^b \end{pmatrix}}{\begin{pmatrix} x_1^a - x_0^a \\ y_1^a - y_0^a \end{pmatrix} \times \begin{pmatrix} x_2^a - x_0^a \\ y_2^a - y_0^a \end{pmatrix}} \quad (2)$$

Using these different values x_i^g, y_i^g and area ratio δS, if they deviate from a specific range of values, the UAV is brought closer to the blade by controlling the roll, elevator, and throttle of the aircraft at a certain speed, respectively.

3.4 ROS Implementation

For implementation in an actual UAS, implementation using ROS was performed by East Japan Computing Center, Co (Figure 7). The onboard PC acquires images from each camera and detects the blade tip position. The camera recognition results and blade tip position information are transmitted to the ground station system via a wired connection using a LAN cable, and control decisions are made on the

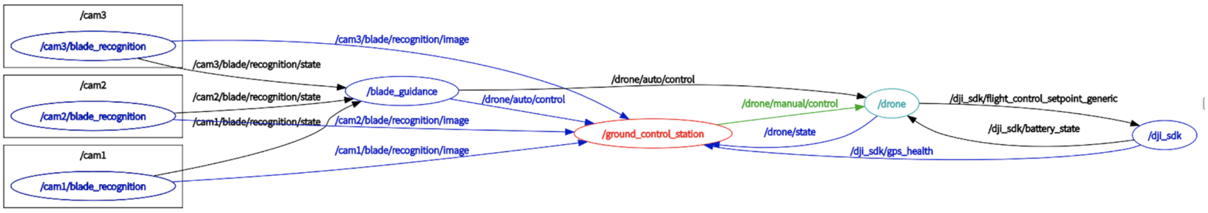

Figure 7. Connections between modules

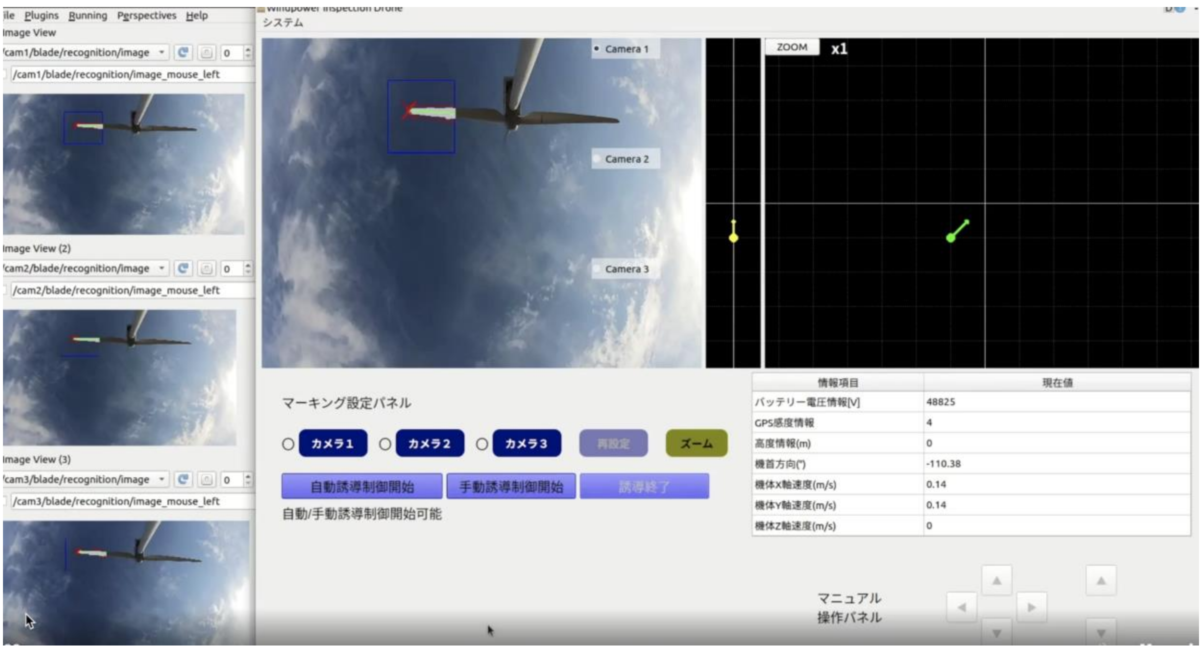

Figure 8. Control monitor of the ground control-station

ground station system. The control commands are sent to the UAS via the onboard PC. The wired connection for communication is because the UAS is equipped with a grounding contact, and the conductor extending from it is connected to the grounding inspection contact of the wind turbine, which is why the UAS is wired initially.

The camera mounted on the UAS is an Insta 360 ONE R, with an angle of view of about 112 degrees diagonal. The onboard PC is a ZOTAC ZBOX PI335-GK. The delay in image transmission from the camera to the onboard PC is about 0.1 to 0.2 seconds, the actual image processing speed is about 0.2 seconds, and the delay is within 0.5 seconds until the control decision at the ground station.

The ground control station has a control monitor to manually draw the first frame guidance for GrabCut (Figure 8). The control monitor displays the remaining battery power and the estimated position and altitude of the blade relative to the drone. The horizontal position can be seen as the green marker, and the vertical position as the yellow marker in Figure 8. The drone will hover when both overlap in the center. If the tracking is interrupted, for example, by the blade coming off the frame, the exact position of the receptor is no longer known, and the autopilot will keep hovering.

4 Experimental Result

On February 1 and 7, 2023, a hovering test was conducted at a distance of up to 1 m using an actual UAV at the Fukushima Renewable Energy Laboratory (FREA) of the National Institute of Advanced Industrial Science and Technology in Koriyama City, Fukushima Prefecture.

The wind turbine at FREA has a diameter of 33 m and an altitude of 41.5 m to the central hub. The wind turbine was fixed in an inverted Y-shape, and the UAV took off, hovered at about 10 m, and then approached from directly below using autopilot control. The UAV hovers about 1 m below the tip of the target blade and verifies to remain stationary for about 20 seconds.

In the February 1 experiment, the wind speed on the ground was 3 m from the south in the morning, and it became 5~6 m in the afternoon. At an altitude of about 30 m around the blade, the wind speed was about 8~10 m. Under such strong wind conditions, guidance to the vicinity of the blade could be performed, but the wind would shift the relative position to the blade for hovering at 1 m below the blade. A mismatch between the actual position and control occurs due to a 0.4~0.5 second response delay in controlling for the misalignment, causing precessional motion that results in off-tracking.

In the February 7 experiment, the wind speed on the ground was about 1 m easterly, and the maximum wind speed was about 3 m. There was also only moderate wind around the blades. Under these conditions, it was possible to guide the aircraft to the vicinity of the blade and hover 1 m below the blade. Furthermore, for a blade with an inverted Y-shape, after hovering to the right blade, it was successfully moved to the left blade by manual control in the air and hovered under automatic control.

As a result, the automatic control in this study was feasible, but on the other hand, the problem of control signal delay in the event of disturbance due to strong winds and the slow guidance speed of the UAV resulted in slightly poor availability. In addition, the Insta 360 ONE R has a vertical angle of view of about 80 degrees, which means that at a vertical distance of one meter, a horizontal shift of one meter from the camera would result in a deviation from the angle of view range. Because the camera on the UAV is agitated by strong winds, it will quickly shift by that much. Therefore, a camera with a broader angle of view and image stabilization is needed, like an action camera.

5 Conclusion

In this paper, we proposed an autonomous operation of a small UAV to touch a tip of a wind turbine propeller to guide by image processing such as GrabCut and object tracking. In order to capture dynamically changing images, this study used tracking and the previous extraction region to continuously provide foreground-background hints to recognize windmill propellers and perform tip detection. The propeller could be recognized continuously if the frame rate was sufficient. As a result, a UAV can get control from cameras that could be obtained even if the light source direction is indefinite. However, it was confirmed that when the frame rate is low, the amount of change in the image of the target blade increases with the amount of movement, making tracking impossible.

Figure 9. Demonstration test

As a result of this research, we have achieved accurate tip detection continuously. In the future, we would like to collect training data and challenge tip detection through machine learning to achieve fast and highly accurate tracking.

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