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Unmanned aerial vehicles precision landing on a moving platform using image matrix segmentation method

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Abstract:

This paper presented the theory, planning, control and method for Unmanned Aerial Vehicles performing precision landings on a moving platform. Unmanned Aerial Vehicles performing flight mission often having issues of its retrieving due to the landing sequence inaccuracy which may lead to crash. Thus, in this paper, by using adaptive method and image processing, the H480 hexacopter, equipped with a gimbaled camera detecting the moving platform attached to a ground rover using a pattern recognition algorithm. Using AprilTag as the unique pattern, the H480 follows the moving platform and moves via pitch and roll instructions while constantly descending towards the ground. In this paper, the system proposed the degree of pitch and roll changes with regards to the position of the AprilTag i.e., the further the tag location detected from the camera center, the higher the degree of movement, such that the tag will be forced to be in the center of the camera frame. The system divides a camera frame into an 11x11 matrix in which each cell within the matrix suggests different pitch and roll degrees for the H480 movement. As a result, the system manages to assist the landing process for the H480 to reach the moving platform successfully with less than 0.5m offset from the center of the target.

Keywords: *Computer vision, Image processing, Object detection, Robot navigation, Unmanned aerial vehicle*

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1. INTRODUCTION

The wide usage of Unmanned Aerial Vehicle (UAV) in recent years, due to its various abilities has made rapid development growth in the sector. They are applied not only in the military as it was originally developed, but had been applied for other applications such as surveying, engineering, geographic mapping and even cinematography. Regardless of the application, flying a UAV can be challenging, especially without Line-of-Sight (LOS) piloting. Mostly, the UAV's pilot view can be obtained by attaching a camera to the UAV. However, it still requires manual piloting input that are prone to human error. To avoid this error, autonomous UAV is developed, which require less or no input from the human pilot. When performing autonomous flight, one of the most critical parts is to retrieve and to land the UAV accurately. This can be done using vision-sensing approach; for example, a camera that are commonly use in an UAV.

UAV navigation using a vision-based system has been a widely developed research area in recent years [1]. Usually, the UAV use GPS for navigation in its algorithm. However, GPS accuracy can be deteriorated, subject to external factor, i.e., weather, surrounding, geographical location etc., that are dynamic variables and may offset the intended retrieval point. Thus, the primary motivation of this paper is to implement the vision-based system in UAV navigation, specifically to improve its landing accuracy [2]. Few methods have been proposed to achieve such accuracy; for example, in [3], infrared imaging was used to detect the landing platform. The platform detection success rate is high in different angles and orientations; however, the average recognition time is relatively high. In [4], an optical flow method is used that suggests the UAV positioning using a few reference points within the frame. Its robust system ensure that the detection of the landing platform is continuously performed. However, it uses a monocular vision system that led to position estimation error. To improve position landing error, the author in [5] proposed that vision sensing works together with a Differential GPS (DGPS) system to give additional information on the landing platform. However, DGPS accuracy is highly dependent on external factors such as weather, location and environment to acquire accurate GPS positioning. To improve the vision-based system, [6] and [7] attached a gimbal to the camera, and use it to keep track of the landing target via the gimbal's servo control. This system added complexity to the UAV's movement stability, as it based its movement on the mechanical gimbaled feedback susceptible to mechanical failures.

Thus, this paper proposes a precision landing using a vision-based system via segmentation matrix to improve the landing accuracy on a moving platform. The next section on this paper will discuss the vision sensing mechanism in UAVs, followed by the precision landing system in section 3. Then, the simulation setup in section 4. Section 5 is the experiment results and discussion, and the final section is the conclusion.

2. VISION SENSING FOR LANDING PLATFORM

A robust and fast detection of the landing target is crucial to achieve precision landing on a moving platform. In this system, a unique marker is used in detection to ease the extraction of the target location. AprilTag marker is chosen due to its uniqueness as it provides the required fast detection. AprilTag was developed by Edwin Olson [8], focusing on robotics applications. Similar to the QR code, AprilTag objective is to provide information to the user captured by vision sensor, usually a camera. Figure 1 shows example of AprilTag marker.

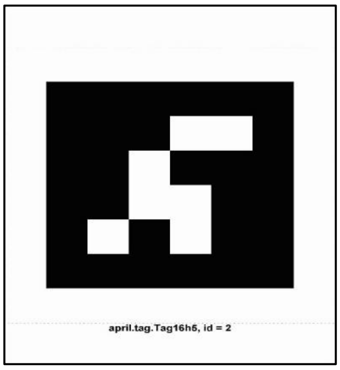

Figure 1. Example of AprilTag

AprilTag was chosen in this research due to the various crucial information it can provide from detecting a single marker. In reference to the camera frame, AprilTag can provide pitch, roll and yaw angle information towards the marker as well as the marker ID. This information can be use by UAV for reference and autonomous navigation [9]. Furthermore, the detection software is suitable towards wide viewing angle and distinct lighting condition which makes it suitable to be applied in UAVs as it is constantly moving and vibrating.

The camera setting is made with RGB type of camera to be used. The resolution is set to 640 x 480 similar to a standard digital camera. The speed of the camera must be as close to real-time as possible but at the same time able to be processed by the onboard computer given its limited capability. The optimum value is determined and then is set to 30fps. The camera is mounted onto a gimbal stabilizer as shown in Figure 2 to avoid unnecessary image blurring.

For the image processing system, a common tool is used which is the OpenCV in Python platform [9]. OpenCV is an open-source library that contains various image processing algorithms. It includes the pattern recognition algorithms such as the previously mentioned AprilTag [10]. To apply the algorithm efficiently, camera calibration is required.

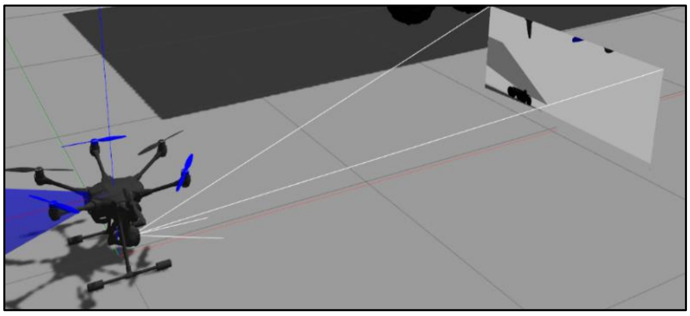

Figure 2. Camera attached to a gimbal at the bottom of UAV

Camera calibration provides 2D projection matrix that defines the relationship with its 3D points in the real world [12]. Using Euclidean transformation [13], the camera pose relative to the tag can be determined as shown in the Transformation matrix, T in equation (1):

$$T = \begin{bmatrix} R_{3\times3} & t_{3\times1} \\ 0_{1\times3} & 1 \end{bmatrix}_{4\times4} \tag{1}$$

where the $R_{3\times3}$ is a rotation matrix and $t_{3\times1}$ is a translation vector.

In order to perform an efficient image processing onto the AprilTag marker that is constantly moving, two AprilTags with different sizes are placed onto a flat surface board of 3m^2 in size. The size is relative to each other such as the more significant tag is to cater for high altitude recognition and the smaller tag is for near-descend onto the platform, whenever the more significant tag is out of the frame and cannot be detected. Then, the board is attached on the top of a 4x4 Husky rover as shown in figure 3.

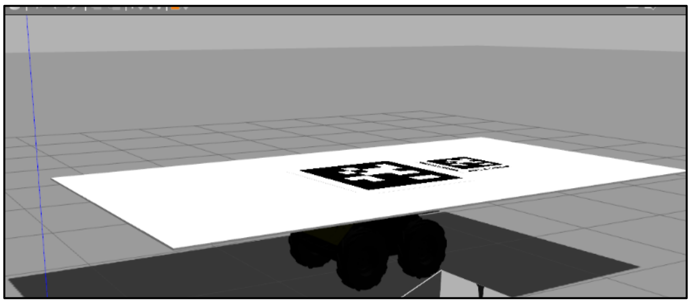

Figure 3. AprilTag setting on the Husky rover platform

To draw the lines onto the frame, the frame pixels is divided by the number of columns and rows in creating 11x11 matrix:

$$Column = \frac{pixel\ width}{11} \quad (2)$$

$$Row = \frac{pixel\ width}{11} \quad (3)$$

Then, for the boundary box for each cell (*i, j*) within the matrix to be identified, the cell's four corner points were calculated by using the following equation:

$$\begin{bmatrix} TopLeft & TopRight \\ BottomLeft & BottomRight \end{bmatrix} = \begin{bmatrix} Column * i, Row * j & Column * (i+1), Row * j \\ Column * i, Row * (j+1) & Column * (i+1), Row * (j+1) \end{bmatrix} \quad (4)$$

AprilTag detection will then be tested on each cell in the frame. Once the cell where AprilTag is presented and identified, the value of i and j which defines the position of the tag, is passed onto the precision landing control system.

3. PRECISION LANDING SYSTEM

The proposed precision landing system uses the image processing output previously to improve landing accuracy. Each cell within the 11x11 matrix were assigned with different pitch and roll instruction. This is shown in figure 4, where the camera captures, detects and highlights the AprilTag location within the frame.

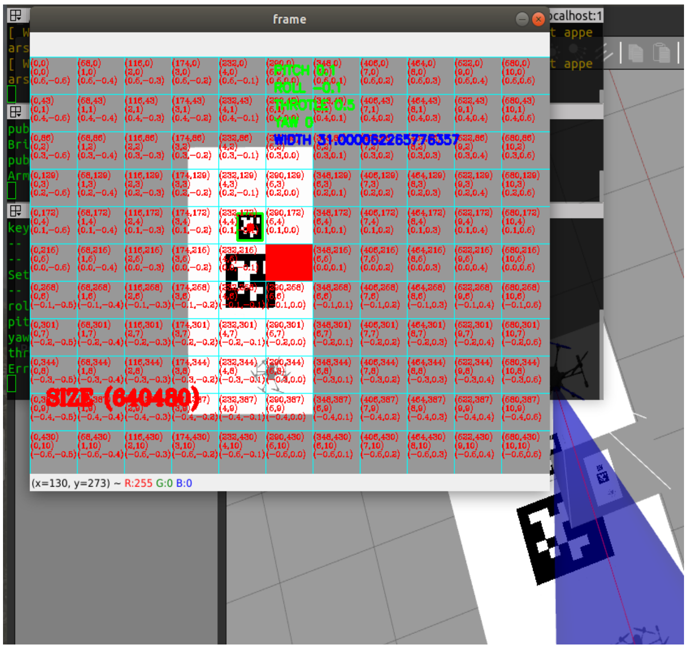

Figure 4. Proposed 11x11 matrix in a frame method

In defining the movement, in specific the rotation of a vehicle of a rigid body with 6 degrees-of-freedom(DoF) such as a quadcopter [11], Euler's angle rotation matrix can be used as reference, as shown in equation 4.

$$\Theta = [\phi \quad \theta \quad \Psi]^T \tag{5}$$

Where ϕ is the roll angle, ϴ is the pitch angle and Ψ is the yaw angle. The general rotation matrix can be written as

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^T \tag{6}$$

Where,

$$\begin{aligned}
a_{11} &= \cos\Psi \cos\phi - \cos\Theta \sin\phi \sin\Psi \\
a_{12} &= \cos\Psi \sin\phi - \cos\Theta \cos\phi \sin\Psi \\
a_{13} &= \sin\Psi \sin\Theta \\
a_{21} &= -\sin\Psi \cos\phi - \cos\Theta \sin\phi \cos\Psi \\
a_{22} &= -\sin\Psi \sin\phi - \cos\Theta \cos\phi \cos\Psi \\
a_{23} &= \cos\Psi \sin\Theta \\
a_{31} &= \sin\Theta \sin\phi \\
a_{32} &= -\sin\Theta \cos\phi \\
a_{33} &= \cos\Theta
\end{aligned}$$

The Euler's rotation matrix suggested that at any given moment, the rotation of a rigid body such as a UAV is determined by the pitch, roll and yaw degree [12].

In this project, the yaw degree will not be changed and will be set to zero, and equation 6 is reduced to,

$$A = \begin{bmatrix} \cos\varphi \cos\emptyset & 0 & 0 \\ 0 & 0 & 0 \\ \sin\theta \sin\emptyset & \sin\theta \cos\emptyset & \cos\theta \end{bmatrix} \tag{7}$$

The UAV rotation for precision landing can then be defined by determining only the pitch and roll degree using the previous definition. In this equation, the value 60 is the maximum pitch/roll degree use as the UAV speed multiplier.

$$\Theta = [\phi \quad \theta \quad 0]^T \times [60] \tag{8}$$

Then, pitch degree, ϴ and roll degree, Ø is defined using the following equation.

$$\theta = \left(\frac{(i-5)*-1}{10}\right)*60 \tag{9}$$

$$\emptyset = \left(\frac{(j-5)}{10}\right)*60 \tag{10}$$

For example, if the AprilTag is presented at the left top corner of the frame (i=0, j=0), then the pitch and roll degree will be,

$$\theta = \left(\frac{(0-5)*-1}{10}\right)*60 = 30\,degrees$$

$$\emptyset = \left(\frac{(0-5)}{10}\right)*60 = 30\,degrees$$

Which is the maximum movement of the UAV.

Similarly, when the AprilTag is presented at the center of the frame (i=5, j=5), which indicates that the UAV is right above the target, then the pitch and roll degree will be,

$$\theta = \left(\frac{(5-5)*-1}{10}\right)*60 = 0\,degrees$$

$$\emptyset = \left(\frac{(5-5)}{10}\right)*60 = 0\,degrees$$

indicating no pitch and roll movement to the UAV while the UAV is constantly descending using the following descend law.

Desired descent law is given as;

$$Zd = \begin{cases} 0.125m/s\,; & @\,Pw < 77 \\ 0.833m/s\,; & else \end{cases} \tag{11}$$

Where Pw is the pixel width of AprilTag marker to indicate the UAV's height from its landing target.

In general, the pitch and roll degree and speed vary. The degrees are at its maximum starting from the edge of the frame, and gradually to its minimum, when approaching the frame center. This suggested that each cell, if presented with AprilTag, have different UAV's movement to relatively pull the tag towards the center. This can be illustrated by the graph in figure 5 below.

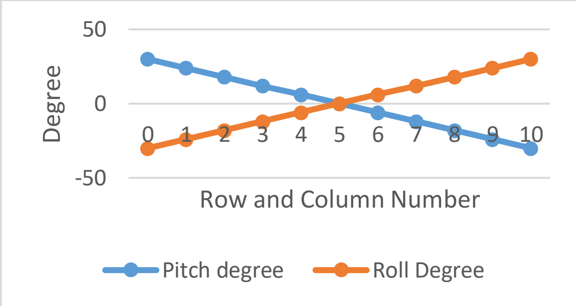

Figure 5. Pitch and Roll degree against row and column number

Meanwhile, the UAV descends by throttling down at its minimum when detecting the AprilTag over a specified threshold altitude, which is based on the tag size, Pw = 77. When the UAV's altitude] is lower than the threshold that suggests the landing platform is near, then, throttle down is set to maximum to accelerate the landing sequence to be able to reach the platform surface before the camera lost its view on the AprilTag. This can be illustrated by the graph in figure 6 below.

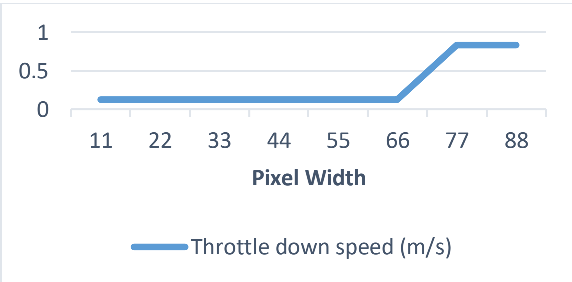

Figure 6. Descend speed against pixel width

4. SIMULATION SETUP

To validate the proposed method, a simulated experiment running in Software-in-the-Loop (SITL) mode using PX4 Flight controller. The algorithm running vision processing was built on Python3 and OpenCV platform that runs simultaneously but separately from the Flight Controller, which represents an Onboard Companion PC – as shown in figure 7.

MAVLink protocol with TCP connection with baud rate of 115200 was established between The Flight Controller and the Companion PC. To communicate and sends trajectory command, the Companion PC were equipped with MAV-SDK, an additional API for PX4 Flight Controller that runs compatibly with Python3. Running in the background of the simulation is the QGroundControl Station to monitor and display the drone's telemetry data such as drone state, flight modes, battery etc. from the drone. Mounted to the drone is a gimbaled camera. The camera's resolution is set to 640x480 and placed at the bottom center of the drone frame. The simulation was done in Gazebo simulator software on the Robot Operating System (ROS) environment using hexacopter H480. Within the simulation environment called the World, we insert a husky ground rover, and on top of the rover is a landing platform with AprilTag marker. The platform size is 3m length and 1m wide.

In the conducted simulators, the UAV starts at its origin [0 0 0] location on the ground level, while the platform moves in a circular manner described as**;**

$$R_t(t) = [10(t)^2 \quad 10(t)^2 \quad 10] \tag{12}$$

With the ground speed of 1m/s and t is the time.

Figure 7 shows the architecture diagram of the simulation setup.

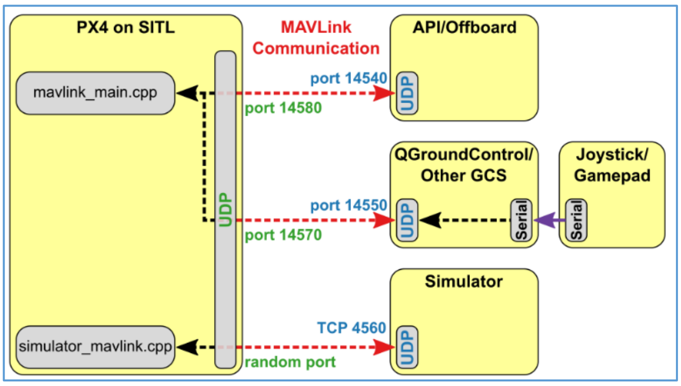

Figure 7. General architecture of the simulation setup [16].

With the above setup is established while the platform sets to move and H480 UAV has taken-off, then the algorithm for our system pre-loaded in the Companion PC is executed. Briefly, the landing sequence algorithm is carried out in the following steps:

- *The H480 climbs to the suitable height of 8m above the ground to get a wide view of the target landing platform. PX4 flight mode is changed to Loiter mode.*
- *The frame is generated and the AprilTag detection algorithm is activated.*
- *The frame generated is processed. Once AprilTag is present, an 11x11 square matrix is drawn onto the frame.*
- *The AprilTag centre location within the matrix is highlighted by identifying the cell in which the AprilTag centre was located. A bounding box showing the AprilTag marker was drawn continuously.*
- *Move instructions is sent from Companion PC to the Flight Controller. The degree of movement depends on the cell identified in the previous step. The movement consists of pitch and roll degree over a duration of every 0.1s, while the H480 descend slowly to close the height gap between itself and the rover.*
- *The system **checks** the AprilTag pixel size, to determine its proximity with the rover platform. If the pixel size is bigger than 100, then Companion PC sends land instruction at current height. Otherwise, step 2 onwards will be repeated*

The overall system flow chart of the program is as shown in figure 8.

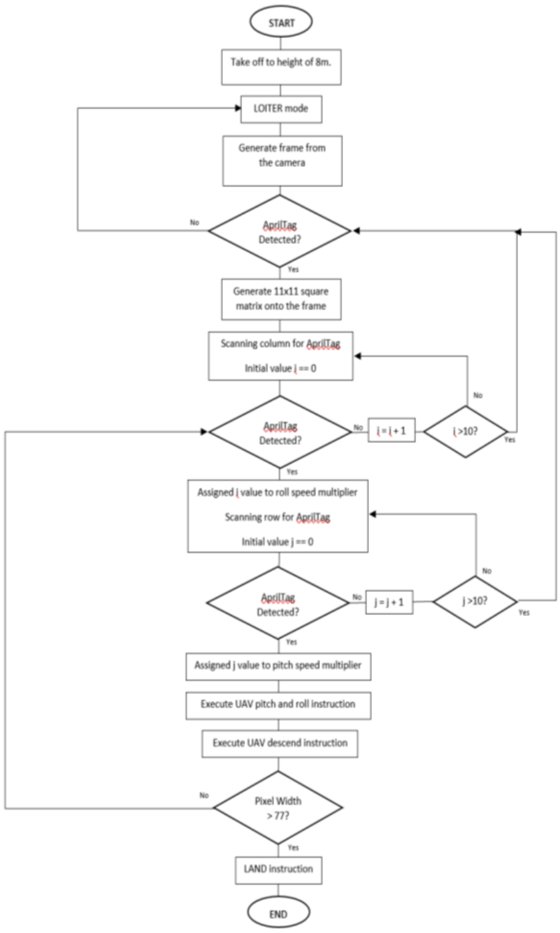

Figure 8. Flowchart of the vision-based system for precision landing.

4. EXPERIMENT RESULTS

In order to validate the proposed system and algorithm, an H480 UAV and a ground rover are generated in a ROS and Gazebo environment to capture both objects' status and movement. The movement of H480 is defined by its pitch, roll, yaw and throttle while the ground rover is defined by its linear and angular movement. In this setup, H480 will only change its roll and pitch movement and the throttle will be decreased according to the descend law in equation (11) to achieve platform landing when it is near, while yaw remains constant, thus will not be captured.

Figure 9 illustrates the trajectory of the H480 and the ground rover. As shown, the ground rover continuously moves in a circular manner with a radius of 5m, while the H480 hovers at almost the origin with an initial height of 8 meters. Then, it moves following the ground rover trajectory, once the AprilTag marker is presented and captured by the algorithm in the camera frame. With the target locked onto the marker, the H480 slowly descends until it reaches the platform and performs landing instruction, which then results in less than 0.5m offset error for each trial.

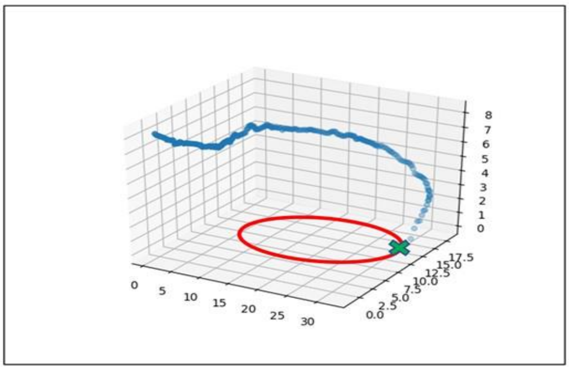

Figure 9. Trajectory movement of the UAV (blue) and landing platform (red).

Figure 10 shows the time taken for the H480 to reach the target on the ground, with regards to its altitude. As shown, the initial H480 altitude is just above 8m so as to get a wide view of the ground rover and the tag. Next, the algorithm sends throttle down instruction with a rate of descend between 0.3m/s to 0.5m/s. As the H480 draws close to the platform, the descend rate increase to 2m/s. This is to ensure that the landing is safely secured onto the platform, which if otherwise, the H480 will not be able to catch the ground rover's speed, and misses the landing platform. Once the vertical distance between the rover and the H480 is between 0.5m to 1m, indicating the approaches, the H480 perform the lands and closed the vertical distance to zero.

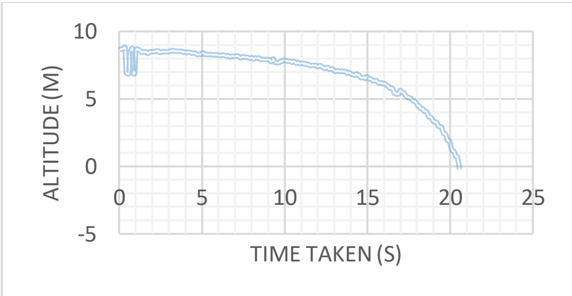

Figure 10. UAV Height against the time taken to reach ground level

The UAV Attitude over time is shown in Figure 11 below. As shown in the figure, the H480 moves at its maximum with the roll degree at 30 degrees, suggesting that the tag's distance is furthest from the camera center. Then, it gradually reduces to 0 degrees, showing that the H480 has locked the target in its center. The H480 inertia causes the UAV to drift from the target, thus giving the negative value after it reaches 0 degrees (tag in the center), and similar processes continue until it lands. This is similar to pitch value as shown.

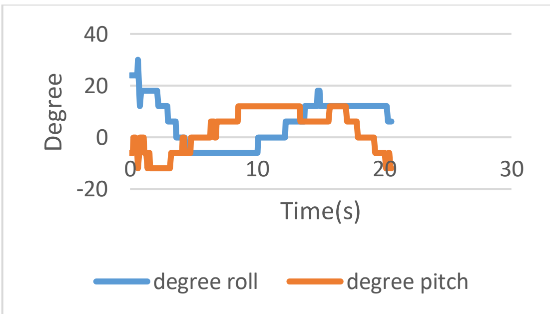

Figure 11. UAV attitude against time during precision landing.

Upon reaching its stability, the algorithm sends attitude commands periodically so that the H480 adjusts itself, correcting its position error towards the target, with its roll and pitch movement at minimal, until it eventually lands on the target platform, as shown in figure 12.

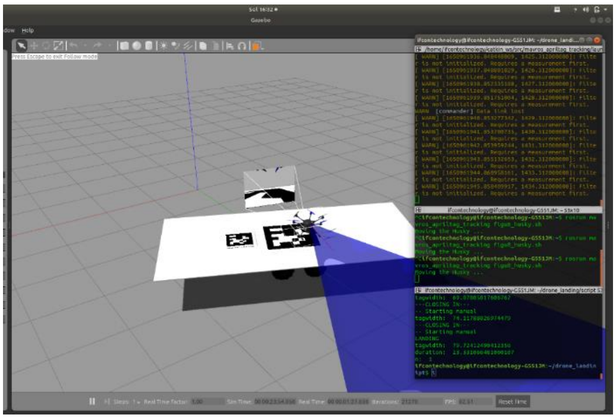

Figure 12. UAV lands on the center of the moving platform

Table 1: Marker Detection in UAV applications

Description	Problem Statement	Method	Advantages	Limitation
Marker Detection	UAV Geolocation Estimation[17]	AprilTag Feature Detection	3D positioning on the subject can be determined	No movement of the target subject (static target)
	Precision Landing[18]	Infrared images of cooperative object	High detection success rate in different angle and orientation	High average recognition time from affine invariant moment result

Table 1 shows the comparison from different literatures that use marker detection in their flight mission, the objective, method use, advantages and its limitation. In [17], similar AprilTag marker has been used for reference to estimate its positioning in the 3D space. While in [18], a custom unique marker has been used to perform precision landing in addition of thermal imaging to increase the detection accuracy towards the marker.

4. CONCLUSION

This paper presented a method based on only camera vision and image processing algorithm, precisely pattern recognition, to perform UAV precision landing on a moving platform. Using the AprilTag marker as a target, the system proposed achieved real-time detection. Upon detection, the system divides the camera frame into 11x11 matrix, whereby each cell signals and commands the UAV to specific pitch and roll movement to get the marker in the center, while continuously descending towards the platform. Simulation in ROS and Gazebo environment results show that the system succeeded in precision landing on a moving platform with an offset error of less than 0.5m. Furthermore, the landing sequence duration takes an average of 20s from the moment the tag is detected while maintaining the UAV stability, showed by the minimal roll and pitch degree, reducing the vibration and oscillation that may lead to critical instability if implemented on an actual UAV.

Future work includes the integration of vision-based navigation with GPS to achieve more precise landing and provide a failsafe when image processing is denied. For example, when the distance of the UAV to the target exceeds the frame area, bad lighting exposure, blurring images, and the marker is out of focus. With the above integration, a total autonomous UAV system can be developed to reduce human error, which may cause a crash during landing.

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