Autonomous Drone Indoor Navigation Based on Virtual 3D Map Reference

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***Abstract*—Indoor drone has limitation on weight and size. This condition affects the kind of navigational sensor and computation power that can be carried by the drone. An experiment was conducted to measure the effectiveness of dead reckoning navigation method on drone. Position calculation was conducted based on IMU data. A virtual 3D map was used as a reference point for determining the real position of the drone. The experiment was conducted in 4 different flight paths. The result shown that the navigation method can be used to navigate drone in indoor environments with MSE of 0.19-0.25 m for obstacle of 2x2 m area.**

Keywords—Autonomous Drone, Inertial Navigation, Position Calculation, 3D Map, Dead Reckoning

I. Introduction

Autonomous drone (as in Unmanned Aerial Vehicle/UAV) has the capability to autonomously navigate itself around some environment. To do this, the drone must be able to determine its current position, the destination position, and then calculate a path between current position and target destination. This includes the capability to sense any obstacles around its path.

To determine the drone position, several methods can be used. Generally, a drone can utilize visual based positioning or non-visual based positioning method to do this [1]. Visual-based navigation operates mainly using light-based sensor such as camera [2], or LiDAR [3] to recognize its position based on the surrounding. Non-visual based navigation, uses various sensor such as GPS [4], IMU [5], or even RFID tag [6].

Visual based method has the capability to determine the drone's position relative to a known landmark. This method can also be used to determine obstacle around the drone. However, visual based method requires additional equipment, which add some weight. This additional weight can be detrimental to the drone flight capability [7]. Especially on smaller drone.

Non-visual based solution that uses external signal generator, such as GNSS [4] or Wi-Fi triangulation [8], depends heavily on the quality of the signal. If the signal is blocked, it will hinder the navigation capability. As such, this kind of positioning method is not suitable for indoor use.

Non-visual based method can also be used without external signal generator. The most common method is to use IMU. Using IMU means that no additional sensor needs to be equipped into the drone. As such, it is suitable for indoor navigation. It also suitable for smaller drone due to its lightweight nature.

The usage of IMU method on drone is basically a dead reckoning navigation. In dead reckoning, the current position of a drone is calculated by using previous location data, its heading, and its speed. However, this method requires the initial position to be known. So, to use dead reckoning, the drone needs to have an additional positioning calculation method. This condition becomes the base research question for this paper. How can we use dead reckoning navigation system for drone effectively, while optimizing between flight performance, payload, and computational power of the drone [7]? To do that, a dead reckoning using 3D map is proposed. This paper provides the result of experiment on dead reckoning navigation using 3D virtual map. The virtual map contains all the terrain data of an indoor environment where the drone will fly.

II. Research Problem and Related Works

Choosing the right method for autonomous drone positioning and navigation is a problem of optimalization. A flying drone is limited by total weight. The weight limitation means that the equipment that the drone can have also limited. This result in a limited choice of sensors and computing power. In short, to fly an autonomous drone, one need to optimize between flight performance, payload, and computational power.

In line with this problem, choosing the correct positioning and navigation capabilities is also part of the problem. Since, navigation capability depends on the capability to determine one position, we can focus on the positioning capabilities of the drone. Generally, positioning method of a drone can be categorized as visual based and non-visual based method [1]. Visual based positioning method work by using data gathered from light-based sensor, such as camera or LiDAR.

Camera based sensor can provide two crucial information for drone navigation: the relative position of a drone and obstacle around the drone. A drone with stereo camera can provide an accurate distance of an object from the drone [9] [10]. The information can also be used to identify any obstacles in the drone flight path. But, using this method requires the drone to carry two cameras, which can affect the drone's weight.

Using LiDAR as a positioning system can provide the drone a 3D information of its surrounding [3] [11]. Which can be used to position and navigate itself accurately. However, LiDAR sensor has considerable weight. It can only be fitted into a large drone.

For a small drone, using non-visual based positioning method might more suitable. The most common method is to use satellite navigation (GNSS/GPS) to determine a drone

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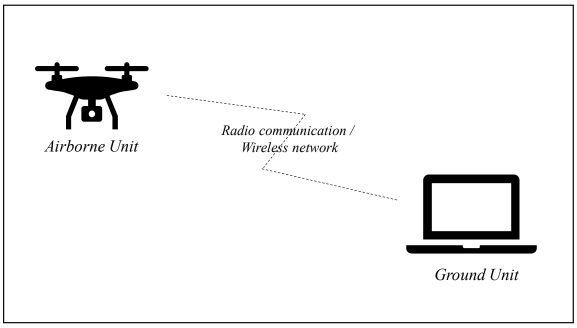

Fig. 1. The drone system for experiment

position, such as in [4]. The sensor size and weight are small enough for a small drone. It can provide an accurate position for the drone. However, to use this method, the drone needs to have a clear link with at least 3 satellites. This condition may not be available for indoor flight since the satellite's signal may be obstructed by the building material.

For indoor operation, we can use Wi-Fi trilateration as an external signal generation to calculate drone's position [8]. Marasigan et al. works show that Wi-Fi signal strength can be used to calculate a drone position in indoor operation. However, to do this, we need to know the exact location of each Wi-Fi access point. Obstructions, such as wall, can impede the Wi-Fi signal, thus increasing the calculation error.

Other method that can be used for indoor navigation is using internal sensor, such as IMU [5]. Almost every drone has its own IMU for flight control. So, the drone does not need to carry additional sensor. The current position is calculated based on the previous position and IMU reading. Bellafaire et al. [12] use this method to navigate an underwater drone, where GPS signal cannot penetrate the water. However, to use this method, the initial position of the drone needs to be known. Bellafaire et al. use GPS to get the initial position above the surface before the drone start to submerge. This would mean that the drone needs to carry an additional sensor.

We could use the original dead reckoning navigation method as an approach to navigate the drone. In the original dead reckoning navigation, current position is calculated and then compared to a map (which contain the flight path). This approach has been used in drone. Krul et al. [13] utilize a drone that can create a 3D map of its environment (using laser scanning). Then the drone can use the generated 3D map as navigation method. This method has quite a low RMSE, which mean that the accuracy of the navigation is quite high.

Based on the result of Krul et al., it is possible to navigate a drone using dead reckoning method and virtual 3D map as reference. By using this method, no additional sensor is needed (if we can generate the map before the flight). This works focuses on experimenting with the navigation capability of a drone using this kind of navigation. The drone is engineered to fly in indoor environment using IMU data as positioning method and a virtual 3D map as a reference. An experiment is conducted to achieve data about the performance of navigation method.

III. RESEARCH METHOD

This work is conducted as an experiment. Therefore, the method used for this work is based on experimental method. The drone is conditioned to fly in a controlled test area. The preparation includes the development of navigation algorithm.

A. System Set Up

The drone used in this experiment is a commercially available drone. The drone manufacturer has provided the SDK to communicate with the drone. The communication is conducted by using internet and UDP. Command data is sent to the drone, and the drone can send back the flight data parameter. In this experiment, the data is assumed to always successfully transmitted between the drone and the ground station.

To tackle the limitations on computing power on board the drone, the navigation algorithm is conducted on separate computer that act as a ground station. The ground station fully controls the flight operation of the drone based on the provided SDK. Therefore, there is no concern about the computational power needed to run the navigation algorithm. The configuration of the system used in the experiment can be seen in.

B. Experiment Set Up

The experiment is conducted in a controlled environment. The test area is a rectangular maze (made from cardboard) with size of 200 x 200 x 20 cm. A 3D map of the test area is constructed by using a 3D game engine, using a 1:1 scale. The drone starting position will always in the predetermined position.

The experiment is conducted on 4 flight scenarios. Each scenario has its own predetermined path. The drone is controlled based on the predetermined path. The navigation algorithm used this path to control the drone movement. The scenarios can be seen in **Error! Reference source not found.**.

C. Navigation Method

To conduct this experiment, we used two different navigation algorithms: *inertial navigation system* and *non-positioning navigation system*. The difference between two method lies in how the navigation is conducted. The difference is used to test the drone's SDK capability to navigate and see if there is any notable result. In both methods, the flight path is generated by using the game engine's path finding algorithm. The input used for this algorithm is a series of waypoint (shown in **Error! Reference source not found.**)

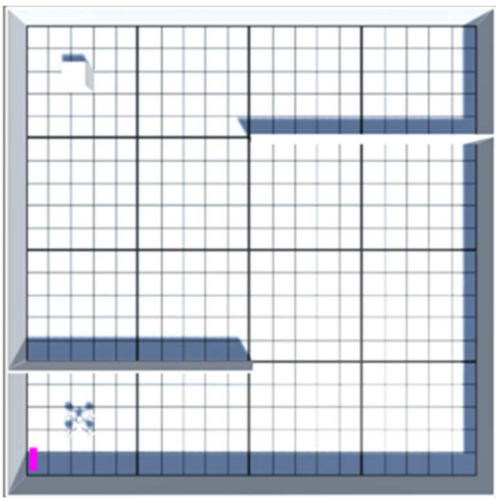

Fig. 2. 3D map of the test area

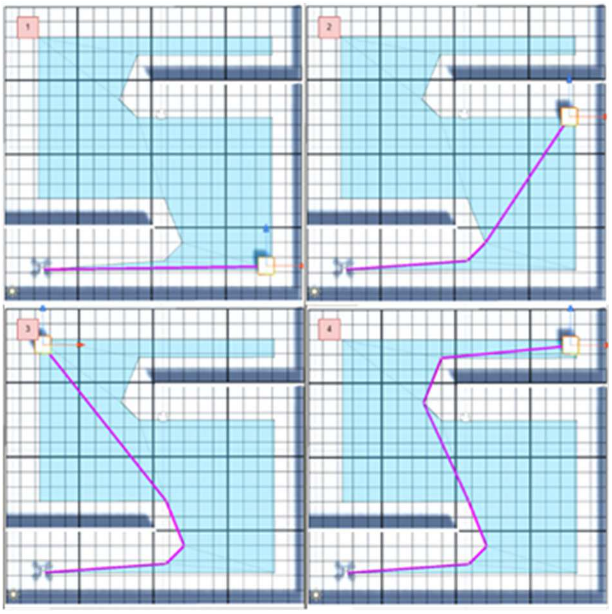

Fig. 3. Four flight path scenarios used in the experiment

The inertial navigation system algorithm calculates the drone position from IMU data received from the drone. The position calculation is conducted by using Equation (1) and (2). Displacement (s) on each axis (drone's frame of references) is calculated from the IMU data. Then, using yaw angle (θ) received from the drone, the displacement is then transformed to the universal frame of reference. Subscript i in Equation (1) show the axis used in calculation (x or y).

$$s_i = v_i . t + \frac{1}{2} . a_i . t^2 \tag{1}$$

$$x' = x.\cos(\theta) - y.\sin(\theta)$$

$$y' = y.\cos(\theta) + x.\sin(\theta) \tag{2}$$

The non-positioning navigation algorithm does not need to calculate the position of the drone. The algorithm only calculates the command trajectory needed to arrive at the next waypoint (with the assumption that the drone will execute the command correctly). This can be done by using the drone SDK capability. The SDK provide a way to send a parametric command, such as "forward 20 cm". The position calculation is conducted on board of the drone by using the drone's original firmware. In an analogy, it is like people walking with other people's directions with their eyes closed.

TABLE I. RESULT OF SCENARIO 4 TESTING

Step /Waypoint	MAE (m)	
	Inertial Nav	*Non-positioning*
1	0.17	0.01
2	0.59	0.27
3	0.27	0.25
4	0.36	0.36
5	0.34	0.34
6	0.45	0.35
7	0.29	0.44

The two methods will be compared to find out which solution has a higher level of accuracy. For measurement, an error calculation will be made using the mean absolute error formula (Equation 3). The error is calculated based on the real position of the drone (x^r) compared the waypoint (x^c) plotted pre-flight.

$$MAE = \frac{\sum_{i=1}^{n} |x_i^r - x_i^c|}{n} \tag{3}$$

IV. RESULT AND DISCUSSION

For each scenario and method, the experiment is conducted in several flights. The drone's position on each waypoint is taken and compared to the waypoint intended position as measurement. The position only taken in the x-y plane, and altitude (z-axis) is not considered in this experiment. The coordinate is presented in meter, with (0,0) is located at the bottom left of the maze (near the drone's starting point). Fig. shows one of the test result in scenario #4 (7 steps waypoints).

The results of all the flight in scenario 4 can be seen in **Error! Reference source not found.**. The result in **Error! Reference source not found.** shows the average MAE in each waypoint for each type of navigation method. The MAE is measured in meter.

From the result data, the mean average error for the inertial navigation method is around 0.29 m. While for non-positioning method, the MAE is at around 0.23 m. From the result, we can see that the drone can follow the predetermined path by using dead reckoning navigation to a degree. In a 2x2 m area, the MAE of 0.2 m is still acceptable (10% error rate).

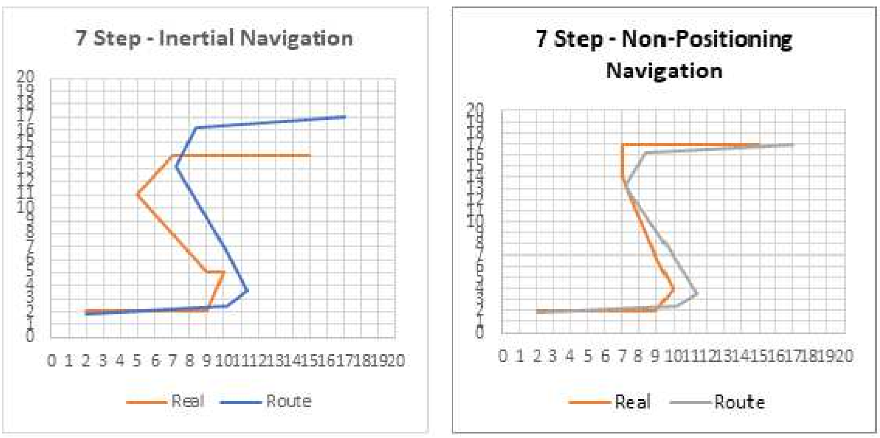

Fig. 4. Comparison between real path with planned route

TABLE II. COMPARISON OF EXPERIMENT RESULT WITH PREVIOUS WORKS

Solution	Test Area (m)	Error (m)
Inertial Navigation System	2x2	0.25
Non-Positioning Navigation System	2x2	0.19
Visual SLAM Method [13]	2x2	0.16
Wi-Fi Trilateration [8]	15x15	1.11

Compared to the inertial navigation method, the non-positioning method has better error rate. This condition is caused by the different method of calculating IMU data. In the inertial navigation method, the IMU data is calculated in the ground station using Equation (1) and (2). While in the non-positioning method, the IMU data is processed on board the drone by using the drone's firmware. What can be inferred from this that the positioning calculation of the firmware perform better than this works calculation method.

The positioning calculation in Equation (1) and (2) assumes a constant acceleration rate over a period of time. This discrepancy what caused the error in the inertial navigation method is slightly higher. However, since the interval of calculation is quite small, the error is only slightly higher than the non-positioning method.

Compared to the result of previous works, the accuracy of this experiment is smaller than other solutions (**Error! Reference source not found.**). The solution using Wi-Fi Trilateration positioning [8] can be considered better because it has an error rate of 1.11 m with an obstacle of 15.24 x 15.24 m area. And followed by the SLAM [13] solution to navigate indoors with an error rate of 0.16 m with a 2 x 2 m area. Meanwhile, using the Non-Positioning Navigation System solution has an error rate of 0.19-meters and the Inertial Navigation System solution has an error rate of 0.25-meters, both for 2 x 2 m area. This experiment has closer result to the result from [13].

Another point of consideration regarding the result of this experiment is the limitation of the drone used. The drone returns speed data in decimeters. When the drone has a speed of less than 10-centimeter, the drone does not return the data due to rounding error in the firmware.

Apart from that condition, the drone has a visual positioning system (VPS) embedded in it, which is useful for stabilizing the drone when flying. VPS is sensitive to environmental light. If the light is deemed not bright enough, the drone will drift until it gets a place that is bright enough. When the drone is drifting, no speed data is sent.

In addition, because the inertial navigation method uses dead reckoning calculations, the drone position calculation has an accumulation of errors the longer the flight takes. Therefore, the more steps a route has, the higher the inaccuracy.

From the results of the average Mean Absolute Error data, it is found that the use of the Non-Positioning Navigation System solution has a higher level of accuracy than the Inertial Navigation System solution. This is because the Inertial Navigation System requires accurate positioning calculations in calculating the distance to the destination. When the positioning calculation is not accurate, the distance calculation is inaccurate too, and because the distance calculation is inaccurate, the positioning becomes even more inaccurate. This will cause the accumulation of errors to get bigger the more destinations you want to reach, this can be seen from the Mean Absolute Error which is higher the more steps that must be passed.

There are no other research results that can be compared equally because other studies use different testing environments and have different test results. However, when viewed from the research on Unmanned Aerial Vehicle Indoor Navigation using Wi-Fi Trilateration [8], the results of indoor navigation testing using Wi-Fi Trilateration, it is found that the accuracy of drone navigation has an average error rate of 1.11- meter with the best result of 0.43-meter and the worst result of 1.93-meter. These results were obtained from testing with an environment measuring 15.24-meters x 15.24-meters. The disadvantage of using Wi-Fi Trilateration as an alternative to positioning drones is that in indoor conditions, signal strength has an important effect on measuring drone position. Indoor Wi-Fi signals are also affected by signal reflection, signal refraction, and signal attenuation caused by obstructions between signal transmitters and signal receivers.

Visual SLAM research for Indoor Livestock and Farming Using a Small Drone with a Monocular Camera: A Feasibility Study [13] on indoor navigation using a mono camera to perform SLAM (Simultaneous Localization and Mapping) and run navigation routes systematically autonomous waypoints. From this research, it was found that the accuracy of navigation using the solution has a 0.16-meter error. The disadvantage of the SLAM solution for indoor navigation is that because SLAM uses a camera sensor, it needs bright light in the room evenly. The darker the light, the more it reduces the accuracy of SLAM navigation.

V. CONCLUSION

After obtaining the results from flight data and analyzing it, several conclusions were obtained regarding waypoint-based indoor drone navigation solutions. By using a waypoint-based indoor drone navigation solution, the Inertial Navigation System and Non-Positioning System methods can be a solution for drones to navigate indoors but with a high level of inaccuracy when compared to solutions from similar studies. This is because the drone used has several limitations and the algorithm is also considered to have several shortcomings. The conclusions drawn are - The two solutions offered in this study can navigate following the route with an error rate of less than 30cm. The Non-Positioning Navigation System solution has a higher level of accuracy when compared to the Inertial Navigation System solution because the drone used has various limitations so that the positioning calculation is not accurate. By using an indoor navigation solution, the drone can navigate indoors without the need for a GPS signal.

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