Obstacle Awareness System of An Indoor UAV with Multi-Sensor Fusion Algorithm

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***Abstract*—A Flying Ad-hoc network (FANET) emerges recently due to its flexibility in terms of flying tracks and movements. As one type of Unmanned Aerial Vehicles (UAVs), a drone can be considered as the low-cost platform to implement the FANET. In a particular case, the flying tracks and movements of a drone can encounter inevitable obstacles such as building construction and any random objects. Thus, this paper focused on the obstacle issue in drone's movements and proposed the feasibility of Sensor Fusion algorithm to distinguish the obstacle in the indoor environment. Under two conditions: single and multiple obstacles scenarios, the autonomous drone implementing Kalman Filter in Sensor Fusion experienced the real time response linearly as the distance increases.**

Keywords*—flying ad-hoc network (FANET), kalman filter, sensor fusion algorithm, unmanned aerial vehicle (UAV), obstacle awareness

I. Introduction

Flying Ad-hoc Network (FANET) involves numbers of Unmanned Aerial Vehicles (UAVs) to assemble the network [1]. In assembling a FANET, the single UAV must have a good coordination among others. Beside the network assembling, the UAV offers a numerous utilization such as a data sensor aggregation inside a building, a video tapping in an indoor environment, a follow-me application, a flying coordination amongst drones and several informative and entertaining applications. The utilization of drone is usually in the outdoor environment that relies on the Global Positioning System (GPS) or other coordinate localization services to obtain the coordinate information. This coordinate information conducts the drone calibration and movements. Especially in the indoor environment, the GPS have an issue in obtaining the accurate coordinate positions [2]. The latitude, longitude and altitude coordinates are frequently misplaced or not accurate when deals with the building construction. Thus, the idea of non-GPS drone is solved by implementing the acoustic sensor or ultrasonic sensor around the drone to track and confirm the exact location. In case of tracking and confirming the location, the drone requires the exact position to detect an object that might be an obstacle. Therefore, the drone can decide the next movement to avoid the obstacle.

The obstacle is an inevitable object that exists in almost everywhere. In particular, the obstacle that has three-dimensional solid surface appeared to be a distraction in several cases i.e., a signal transmission between a transmitter and a receiver, an image capturing by a camera and a motion task of a vehicle. Several approaches of avoiding the distraction are executed by mapping the surface of the obstacle using a camera [3-5]. However, as another alternative of using a camera, an ultrasonic sensor can be applied to a quadcopter, therefore, it can fly and avoid obstacles autonomously [6, 7].

Sensor Fusion Algorithm is the algorithm that aggregates inputs from multiple sensors then calculates the parameter of objects in an unknown environment [8]. The collected data are are then constructed to perform the 'visualisation' for the drone, thus the drone can respond with the expected tread. The sensor fusion deploys the filtering method i.e., Kalman filter, [9, 10]. This work focuses on the obstacle detection and implements the sensor fusion algorithm to decide on which direction the drone will take the next movement. In order to simplify, this work uses a drone as the representation of UAV. In addition, the applied sensor fusion algorithm evaluates the response of drone including delays and expected directions as well as the calculation of data gathering in two scenarios: static and dynamic obstacles.

II. Method

Several works on sensor fusion mostly in UAV have been conducted to estimate the landing coordinate [11], altitude calculation [12], velocity estimation [13], and the fundamental of speed adaptation [14], etc. Sensor fusion implemented in the UAV combining at least two sensory data such that resulting the better sense than the individual sensor [15]. In this research, the sensor fusion is implemented and evaluated based on the indoor circumstances where the drone deals with any inevitable obstacles. The theoretical and proposed method of the obstacle awareness sensor fusion algorithm are described on the following subsections.

1. Sensor Fusion

Sensor fusion is properly implemented to encounter several issues such as the limited spatial coverage, limited temporal coverage, imprecision of physical sensors and uncertainty object [8]. Considering those issues, several sensors are integrated and through the sensor fusion where the output can be computed as illustrated in Figure 1.

The physical sensors are implemented in the particular environment in order to collect the data and send the raw data to sensor fusion. The sensor fusion determines the further output using any selected mechanisms such as: competitive, complementary or cooperative fusion.

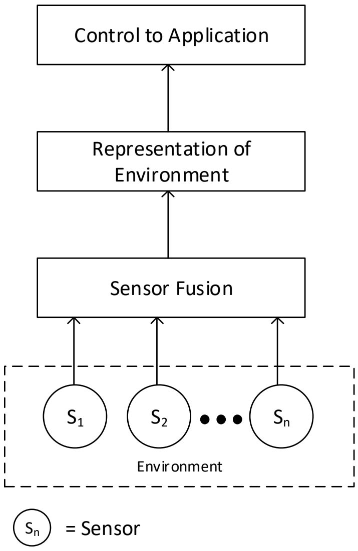

Fig. 1. Sensor Fusion Integration Block Diagram

2. Kalman Filter

In order to measure the distance between the drone and its surroundings, eight distance sensors are used as illustrated in Figure 2. The measurements are performed by using two sensors for each direction. However, measurements by the sonar sensors contain noise that makes it difficult to get reliable distance measurements. In order to tackle this issue, a linear Kalman filter is used for each sensor to reduce the noise. This method is known as direct pre-filtering scheme [9, 10]. The Kalman filter that is used is a scalar-type Kalman filter [14] since there is only one state variable in it, which is the distance.

As mentioned previously, the system model that is used for the Kalman filter implementation is a scalar model and is described as follows.

$$x_n(k+1) = x_n(k) + v_n(k) \qquad (1)$$
$$y_{n+1}(k) = x_n(k) + w_n(k)$$

where $x_n(k)$ is the measurements by the n-th sensor ($n = 1,2,\cdots,8$). While v and w describe the noise contributed by the process and measurement, respectively. The Kalman filter is then used to calculate $\tilde{x}_n(k)$, which is the estimated value of $x_n(k)$. In other words, $x_n(k)$ are the measurements given by the sonar sensors and contain noise, while $\tilde{x}_n(k)$ are the measurement with optimally removed noise.

Kalman filter is a recursive filter that runs iteratively. At each iteration, the following sets of equations executed.

$$P(k) = 1 - G(k)P(k-1) + Q(k) \qquad (2)$$

$$G(k) = \frac{P(k)}{P(k) + Q(k) + R(k)} \qquad (3)$$

$$\tilde{x}_n(k) = \tilde{x}_n(k-1) + G(k)[\tilde{x}_n(k) - \tilde{x}_n(k-1)] \qquad (4)$$

$$P(k+1) = \big(1 - G(k)\big)P(k) + Q(k) \qquad (5)$$

Before the first iteration, the initial guesses for $\tilde{x}_n(k-1)$ and $P(k-1)$ are required. The later value is the estimated error covariance which will eventually converge as more iterations occur. Q and R are the covariance matrices of v and w, respectively. The two matrices act as the tuning parameters for the Kalman filter and the values are set heuristically.

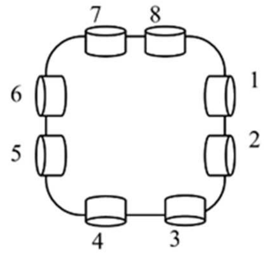

Fig. 2. The configuration of the sonar sensors mounted on the drone.

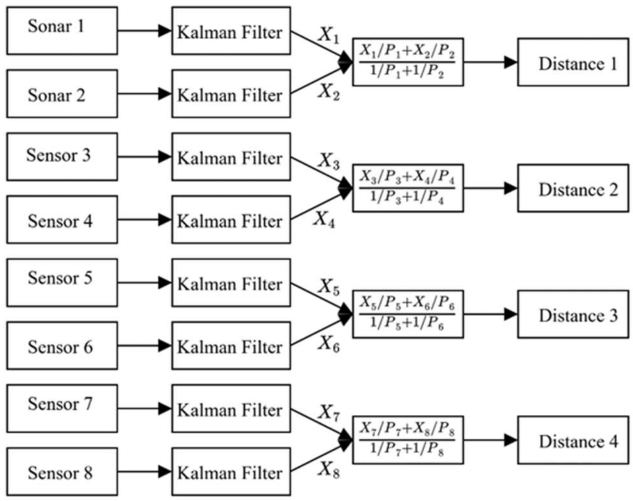

Fig. 3. Direct pre-filtering to remove noise on the measurement reading of the sonar sensors.

After the direct pre-filtering process by the Kalman filter, redundant readings by two sensors must be combined as shown in Figure 3. For example, X_1 and X_2 are redundant readings that are obtained from the output of the Kalman filter of the first and the second sonar sensor. On the other hand, Kalman filter also provides error covariances for X_1 and X_2, which are P_1 and P_2. These values give the information on how far the system should rely on the readings of the two sensors. The reading with a smaller error covariance must contribute more for the total final readings. Mathematically, it can be expressed as follows [16].

$$X = \frac{X_1/P_1 + X_2/P_2}{1/P_1 + 1/P_2} \qquad (5)$$

3. Obstacle Awareness Algorithm

The obstacle awareness concept has been developed in several fields such as in vehicle-to-vehicle network [17], robotics [18], etc.

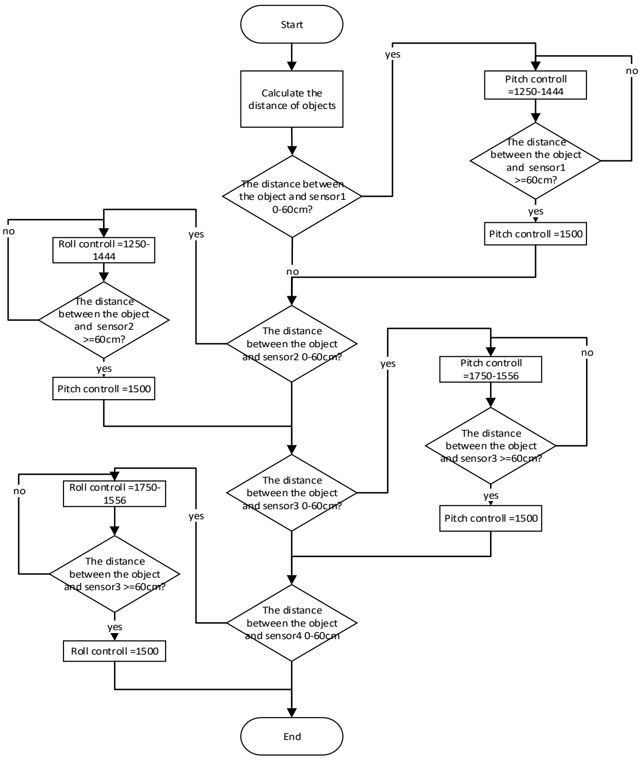

Fig. 4. Obstacle Awareness Flowchart Algorithm

This obstacle awareness concept is the core for avoiding collisions, applying auto braking systems and detecting objects [19] that leads to prediction [20] and/or further decision in more complex scenarios [21-23]. The first step of the proposed method in this work is to calculate the distance of a detected object. Each detected object is assumed to be an obstacle. The flowchart of this algorithm is illustrated in Figure 4. As the second step, this obstacle avoidance algorithm elaborates four distance calculations to execute the further decision, i.e., roll and pitch movements. Each decision performs the iteration in accordance with the input. Finally, the third step is deciding the exact direction of the drone based on the applied triggers.

In this work, the proposed method i.e., obstacle awareness sensor fusion considers the response of sensor fusion when implemented in a quadcopter drone. The sensor fusion detects the object and reacts by avoiding the detected object. The overall system design works as illustrated in Figure 5.

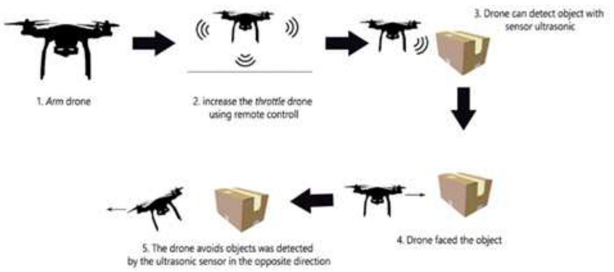

Fig. 5. The obstacle awareness design workflow

The first step of the workflow is to state the drone position 1 meter on the ground using the remote control to reach the position stability. The second step, the obstacle is applied by heading it to the drone. As mentioned earlier in subsection 2.3, when the sensor detects the obstacle, it triggers the drone to move on the opposite direction, avoiding the obstacle as illustrated on step 5 in Figure 5. Finally, the drone is operated under the specific condition i.e., applying multiple obstacles.

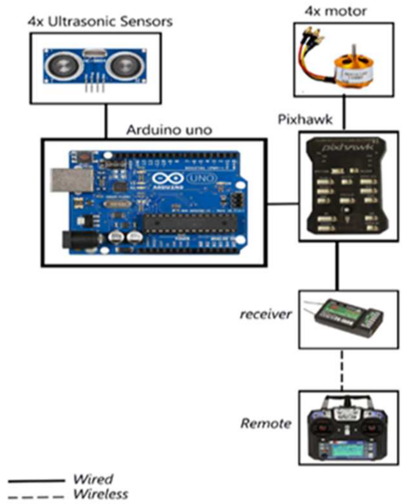

Fig. 6. Connection System Design

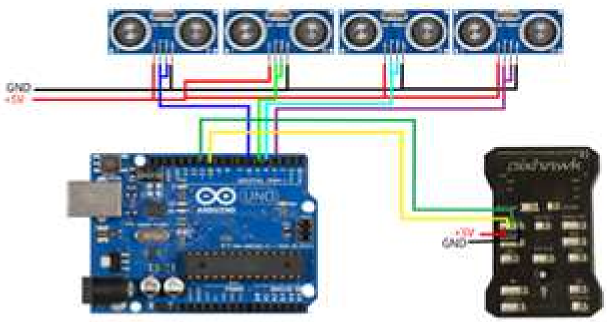

Fig. 7. Sensors, Arduino and Pixhawk Wiring Design

The connection design is illustrated in Figure 6, shows main parts of the overall system. The 4 ultrasonic sensors are connected to Arduino, carrying the input signal from the environment. The Arduino processes the input and triggers the drone's motor through the flight controller i.e., Pixhawk, [24, 25]. Furthermore, the detail wiring design amongst the sensors, Arduino and Pixhawk is illustrated in Figure 7.

III. Result and Discussion

The real experiment is conducted under the specific environment as described in Table 1. The flight controller is a programmable module where the Kalman filter concept is compiled. The HCSR04 Ultrasonic sensors are assembled on each side of the drone to observe the environment from the North, South, East and West directions as shown in Figure 8. Thus, when the object is being fed to any forementioned directions, the drone will respond efficiently and simultaneously.

TABLE I. HARDWARE COMPONENTS

No	Component Description	Type/Unit
1	Frame	F450 Frame
2	Motor	A2212/10T 1400KV
3	ESC	Simonk 30A
4	Flight Controller	Pixhawk 2.4.8 + Power Module
5	Propeller	Propeller 1045 CW CCW 10x45
6	Remote Control	Remote FlySky FS – i6 + Rx FS – iA6
7	Battery	LiPo 3300 mAH
8	Ultrasonic Sensor	HCSR04

(a) (b)

Fig. 8. Ultrasonic sensors installation (a) Front view (b) Top-view

3.1. Kalman Filter Implementation

The first result shows the implementation of Kalman filter in the drone's flight operation. On one hand, the utilization the Pixhawk as the flight controller, the origin roll and pitch outputs without embedding Kalman filter is shown in Figure 9. The ripples both on roll (red line) and pitch (green line) indicate that the drone's flying mode is in the unsteady position, i.e., the captured random vibrating signal indicates the drone's coordinate position is rapidly changing, which is considered as noise. Since this experiment uses the non-GPS drone, thus, the real coordinate's position is not featured. On the other hand, the roll and pitch outputs are shown in Figure 10, appears more determined shapes compare to Figure 9. This indicates that the applied Kalman filter reduces the noise as expected. Based on this expected result, the Kalman filter is then applied on the entire scenario in this work.

3.2. Single Obstacle Scenario

The second result evaluates the roll and pitch measurement under the single object scenario. Figure 11 shows the roll output when the single obstacle is fed onto the drone. All the sensors respond toward the obstacle, which are indicated by the red pulse. This response leads the drone's movement to the opposite direction from its initial movement. In addition, the pitch measurement is also captured as shown in Figure 12.

Fig. 9. The Roll and Pitch output without Kalman Filter

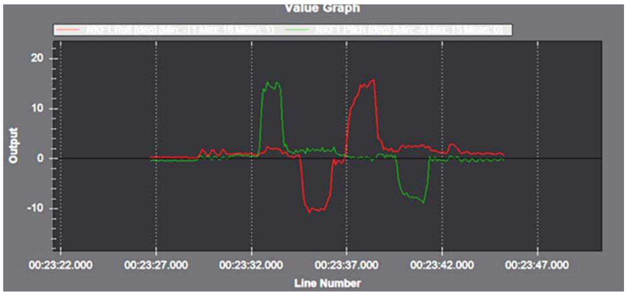

Fig. 10. The Roll and Pitch output implementing Kalman Filter

The pitch measurement indicates the real time response of sensors when they are detecting an obstacle. The complete evaluation of both pitch and roll outputs are featured in Figure 13. Each sensor's response time is evaluated as the function of distances, to perceive the pattern as the distance increases. The distance is measured from ultrasonic sensor to the obstacle, ranging from 30 cm to 60 cm. The minimum distance of 30 cm is determined since it is the minimum safety distance from the drone's propeller. The maximum distance of 60 cm is reached as it is the maximum sensor's sensing ability. All 4 sensors both for pitch and roll measurements show the response time of 2.05 seconds in 30 cm distance and gradually increase to 16.75 seconds in 60 cm distance. Although the time response increases, however, this evaluation shows sufficient response time since in the distance of 60 cm, the drone is still capable to hover to the opposite direction, avoiding the obstacle.

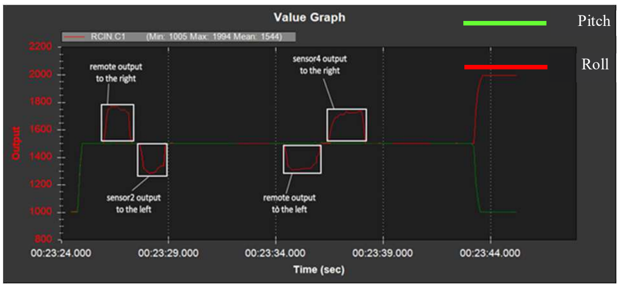

Fig. 11. The Measurement of Roll Output Under the Single Obstacle Scenario

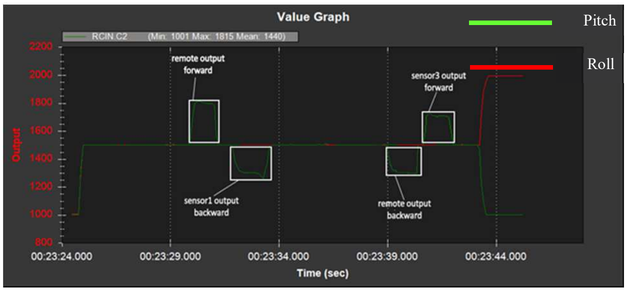

Fig. 12. The Measurement of Pitch Output Under the Single Obstacle Scenario

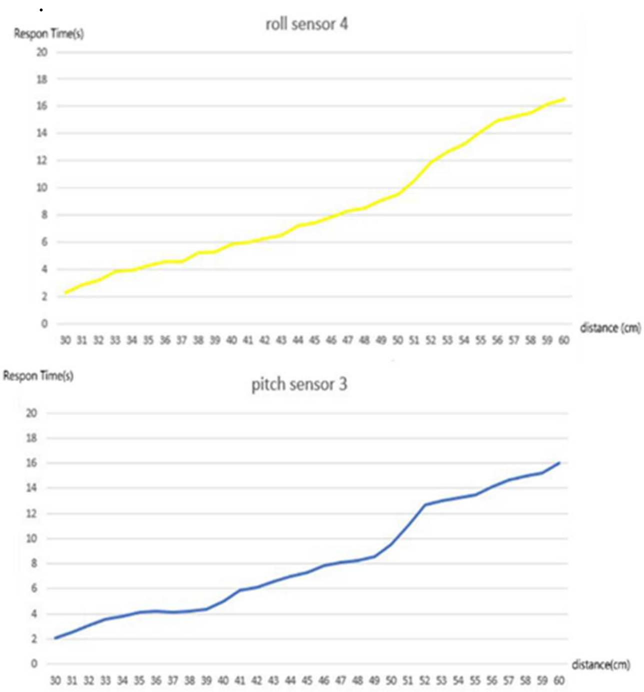

Fig. 13. Evaluation of Sensors as the Response of Various Distances

3.3. Multiple Obstacles Scenario

The third measurement is captured, in order to evaluate the main purpose of the sensor fusion method. By locating multiple obstacles in front of each side of the drone, two sensors are detecting the same obstacles simultaneously as shown in Figure 14. The drone's maneuver is indicated by the pitch and roll output which appear simultaneously. The main distinction is the direction of the drone when it detects single obstacle and two obstacles.

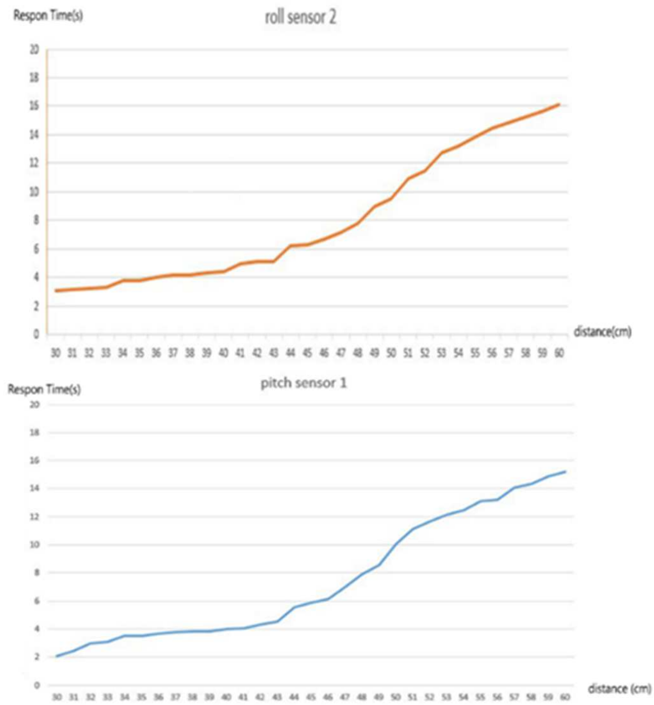

Fig. 13. Evaluation of Sensors as the Response of Various Distances (Cont.)

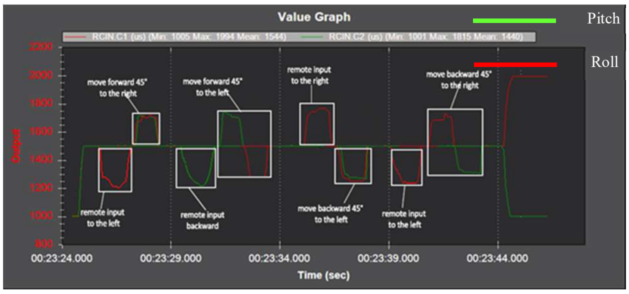

Fig. 14. Sensors' Response of 2 Obstacles Simultaneously

Compare to Figure 11 and Figure 12, the pitch and roll output in Figure 14 and Figure 15 tend to occur simultaneously, thus, it indicates the movement of the drone is in 45° opposite direction. The 45° movement is yielded as the response of sensor fusion method in the obstacle avoidance algorithm. The movement is expected to avoid the obstacle that comes from two directions. Figure 15 shows the output of pitch and roll when it is applied multiple obstacles in the dynamic scenario. The dynamic scenario is evaluated to ensure that the ultrasonic sensors are operating as expected when it detects any moving object.

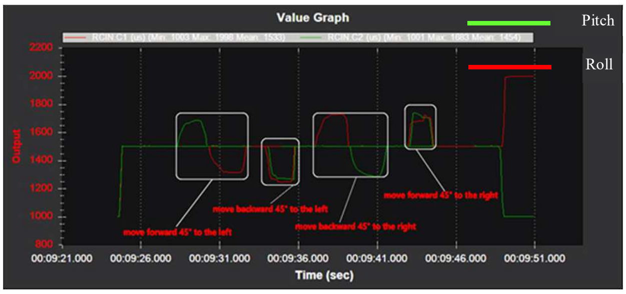

Fig. 15. Sensor Response 2 Objects Simultaneously in a Dynamic Scenario

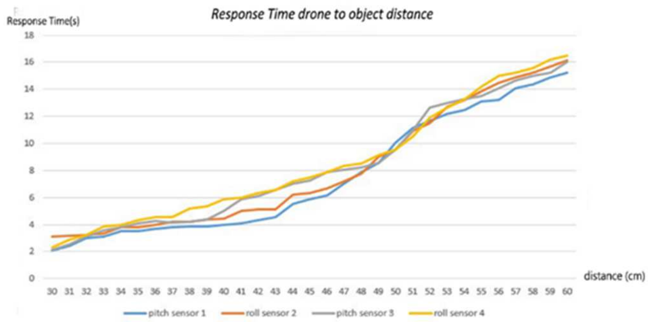

Fig. 16. Sensor Response Towards Multiple Objects in a Dynamic Scenario

The result in Figure 16 shows that each sensor behaves as similar as it is applied in a static object. The sensor's response shows the incremental pattern of response time as the distance increases, obviously. The response time ranges from 2 seconds to 16 seconds that increases linearly as the distance increases. Thus, the sensor's responses are also valid in a dynamic obstacle scenario. For both scenarios, the proposed method of obstacle awareness with Kalman Filter was rigorously evaluated, therefore yielded the expected results i.e., smoothing the oscillating result and directing to the proper decision to avoid obstacles. However, the limitation of this experiment is the relatively low speed of drone movement.

IV. CONCLUSION

This work proved that implementing Kalman Filter in the non-GPS drone operation reduces the noise. The output signals tend to be smoother, therefore, the drone's flight tends to be in the stable movement. The oscillating outcomes in drone's movement was damped as expected. In addition, the sensor fusion implementation appears to be the good solution for avoiding obstacle in the specific condition. This is proved by evaluating multiple obstacles and showing the opposite movement when the drone found obstacles in range. This solution becomes the alternative method to avoid drone crashing when it is operating in indoor scenario. Thus, this obstacle awareness method can be further developed to obtain the assembling network in FANET.

For further works, it is recommended to evaluate several extreme conditions such as the higher speed of drone and multiple-drones scenario.

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