Nigerian Journal of Engineering, Vol. 30, No. 2, August 2023, ISSN (print): 0794 – 4756, ISSN(online):2705-3954.

Nigerian Journal of Engineering,
Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria
journal homepage: www.njeabu.com.ng

Design and Simulation of Collision Avoidance Algorithm for an Unmanned Aerial Vehicle

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Research Article

Abstract

In a complex environment, autonomous and agile flight for an Unmanned Aerial Vehicle (UAV) is an essential problem that must be solved. This paper describes the design and simulation of an obstacle avoidance algorithm for a quadrotor UAV using low-cost ultrasonic and infrared sensors. The quadrotor operated by the control algorithm was able to fly and reach a height of 1.2 m in 5 seconds, hover for 10 seconds, then proceed towards its target obstacle, by implementing a collision avoidance strategy with an optimal input signal from the Kalman filter, avoided the target obstacle at the 50cm mark, as designed. Our research has shown that the algorithm has a low computational cost, applied data fusion technique and can be implemented using low-cost sensors and thus provides a cheap and effective navigation method for UAVs.

doi: 10.5455/nje.2023.30.02.06

Keywords
UVA; Obstacle Avoidance; Kalman Filter, Data Fusion; Ultrasonic Sensor, Infrared Sensor

Article History
Received: – November, 2022
Reviewed: – February, 2023
Accepted: – March, 2023
Published: – August,2023

1. Introduction

Multi-rotor Unmanned Aerial Vehicles (UAVs) can perform vertical take-off and landing, hovering, and other activities; they have good stability and mobility, and they can accomplish tasks in dangerous environments where people cannot approach. Because the situation is often more complicated in these environments, it is critical for drones to autonomously recognize and avoid obstacles in their path of advancement. Obstacle avoidance can be accomplished successfully when a UAV collects information about its surroundings using airborne equipment, fuses the information, creates an environment model that can be represented by symbols to serve as a reference for decision making, and achieves autonomous obstacle avoidance through high-level planning (Chen *et al.,* 2018).

Collision avoidance algorithms should guarantee the safety of UAV systems. Usually, when the UAVs are performing its mission, there exist multiple dynamic and static obstacles in the environment. Various collision avoidance algorithms have been reported in recent years (Ding et al., 2019), (Tan *et al.,* 2020), (Guo *et al.,* 2021), (Sasongko et al., 2017), (Yashin *et al.,* 2020), (Huang et al., 2021). However many of the algorithms have a drawback of high computational cost. The paper is a follow up paper to the authors' previous paper on the design and implementation of obstacle detection system for an unmanned aerial vehicle (Otsapa *et al.,* 2022) and presents the design and simulation of a collision avoidance algorithm for a UAV using low-cost ultrasonic and infrared sensor that simplifies the computation of the algorithm.

The paper is structured as follows. Section II, reviews related works on collision avoidance algorithm, section III concentrates on the system design of the algorithm, section IV focused on the results and discussion of the simulated algorithm. The conclusions are presented in section V.

2. Related Works

The following are some of the most important studies conducted by researchers on the design and implementation of collision avoidance protocols for unmanned aerial vehicles:

The paper "Collision Avoidance for Unmanned Aerial Vehicles Using Simultaneous Game Theory" by D'Apolito *et al.,* (2018) introduced a revolutionary game theoretical approach to collision avoidance for unmanned aerial vehicles. The algorithm creates a two-player simultaneous game that is then solved using game trees. The game's players are the player's car and the intruders, and they have various moves. The implications of the players' activities are described using a cost function for each combination of actions they undertake.

However, one disadvantage is that game theory cannot be used to evaluate all competitive dilemmas.

"Fusing Stereopsis & Corner Sparse Optical Flow for Real-time Obstacle Avoidance of Unmanned Aerial Vehicle," a real-time obstacle avoidance method for autonomous flight for UAV systems was presented by Ding *et al.,* (2019). A binocular stereo matching model, an improved PLKOF algorithm, and an obstacle avoidance algorithm fused with stereopsis and corner sparse optical flow sensor are employed to provide the solution. At a frequency of 5 Hz, the suggested obstacle avoidance system can detect obstacle characteristics and produce efficient motions, demonstrating that the algorithm can handle a real-time obstacle avoidance task. The huge calculation cost of the optical flow technique is, however, a disadvantage.

Tan *et al.,* (2020) presented "improvement on a 3-D velocity obstacle method to attain collision avoidance with multiple dynamic and static obstacles" and developed a collision avoidance algorithm that is able to avoid static obstacles by building pyramid cone using 3-D Light Detection and Ranging (LiDAR) sensors. In the simulation a crossing encounter of ten UAVs are tested. The velocity obstacle pyramid was able to deal with 3-D obstacles and the results showed the potential of the algorithm. However, a polygonal obstacle is particularly difficult for the algorithm and it also has a high computational cost.

Guo *et al.,* (2021) developed "Three-Dimensional Autonomous Obstacle Avoidance Algorithm for UAV Based on Circular Arc Trajectory," which provides a unique and efficient three-dimensional (3D) autonomous obstacle algorithm for UAVs that avoids obstacles by producing circular arc trajectories using monocular camera. The algorithm can avoid static and dynamic obstacles by simply referring to the geometric relationship between a UAV and an obstacle. However avoidance becomes difficult when the obstacle geometry is not available or cannot be obtained directly; in such case a multistage circular trajectory correction procedure can be employed.

Sasongko *et al.,* (2017) proposed an avoidance algorithm that generates avoiding waypoints within predefined waypoints which is based on searching avoidance path on utilised ellipsoid geometry as a restriction zone containing the obstacle using 3-D camera. The algorithm was able to anticipate situation where there is complete lack of obstacle geometry information which may be due to sensor limitation. The proposed algorithm was only developed and simulated for static obstacle problems.

Yasin *et al.,* (2020) in a comparative study highlighted the two principal approach involved in various Collision Avoidance System (CAS) viz. reactive or deliberative planning. As suggested, in order to overcome the limitations of both CAS approach, a hybrid which combines both approach was developed. Also, they provided performance evaluation of the various CAS approaches used in UAV which are geometric, force-field, optimisation, and sense & avoid method. The performance metrics examined are algorithm complexity, communication dependence, static, dynamism, etc.

In efforts to enhance obstacle avoidance of a plant protection UAV in an unstructured farmland, X. Huang *et al.,* (2021) improved on the traditional A* algorithms through dynamic heuristic functions, search point optimization, and inflection point optimization using millimeter wave radar and monocular camera data fusion. This approach was quite useful in path planning and it significantly improves performance in terms of processing time, search grid and turning points.

According to the review, most existing systems have an issue with high computational cost of the algorithm, high cost of the sensors (optical flow, LiDAR, millimeter wave radar and monocular camera, etc.) without application of data fusion technique. This work used low-cost ultrasonic and infrared sensors, data fusion technique and a low computational algorithm to achieve collision avoidance for its UAV. The research has shown that the algorithm is extremely appropriate and provides a low-cost and effective navigation method for UAVs.

3. System Design

The system was designed and implemented using Matlab 2019a. It is divided into two parts. The first part deals with data fusion by using a Kalman filter algorithm to fuse sensors data from ultrasonic and infrared sensors. This is because compare to other filters in literature (for example complementary filter). Kalman filter is better able to obtain less noisy and accurate flight data for UAV by fusing the data obtained from more than one low-cost sensor (Jansen, 2014). The second part presents the software design of the collision avoidance algorithm used by the UAV in evading collision.

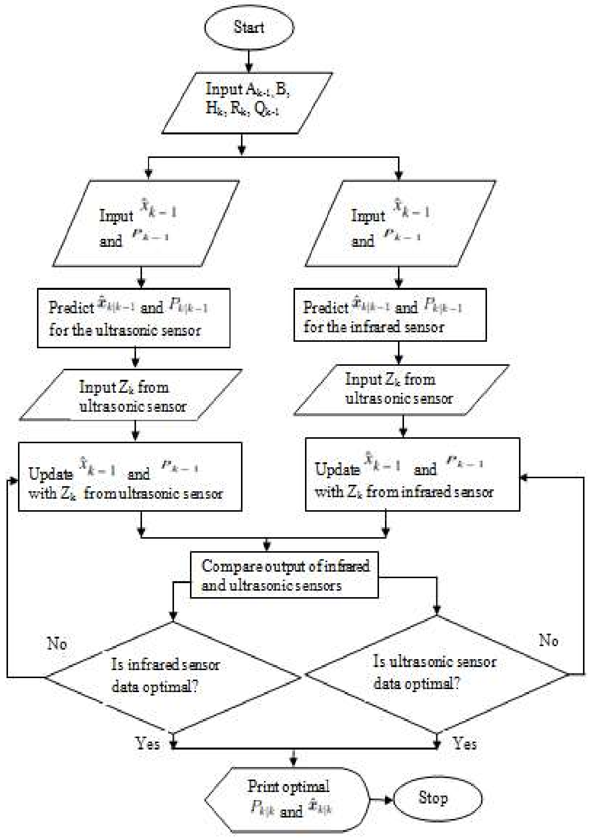


Figure 1: Data fusion (Kalman Filter Algorithm)

3.1 Data Fusion by Kalman Filter

The sensor data from the UAV's suite of sensors is fed into a Kalman filter, which uses data fusion to get the best estimate of the two at any given time. The flowchart of the data fusion algorithm (Kalman filter) is shown in Figure 1.

Where: A_{k-1}, B, H_k, R_k, Q_{k-1} =The sensor model parameters, $\hat{x}_{k-1}$ = Prior estimate,
P_{k-1} = Prior covariance, $\hat{x}_{k|k-1}$ = Posteriori estimate,
$P_{k|k-1}$ = Posteriori covariance,
Z_k = *Measurement update*, $\hat{x}_{k|k}$ = Optimal estimate,
$P_{k|k}$ = Optimal covariance.

The implementation of the Kalman filter in Matlab is shown in Figure 2.

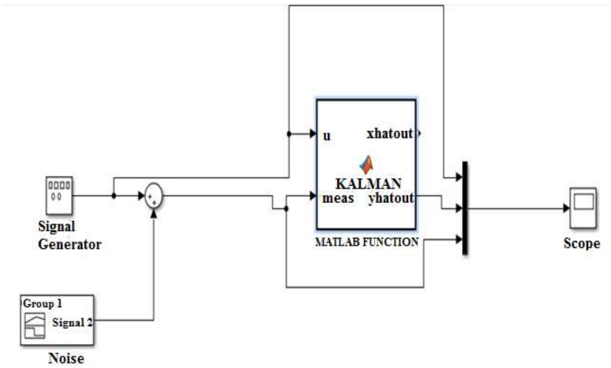


Figure 2: Kalman filter Implementation

As shown in Figure 2, MATLAB 2019a software is used to implement the data fusion algorithm using a Kalman filter. The Kalman filter estimates a process by using a feedback control: the filter estimates the process state at sometime and then obtains feedback in the form of (noisy) measurements represented by signal 1(ultrasonic signal) and signal 2 (infrared signal). The equations for the Kalman filter fall into two groups: time update equations and measurement update equations. This is shown in Figure 3.

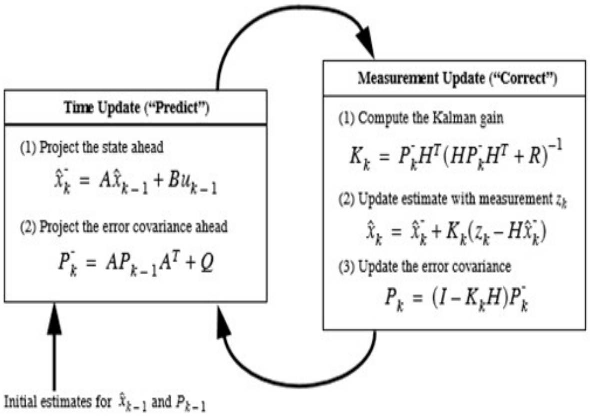


Figure 3: Operation of the Kalman filter (Greg, 2006)

3.2 Collision Avoidance Algorithm

The algorithm is designed to work with inputs from an ultrasonic sensor and infrared sensor, which feeds the Kalman filter with the estimates of their range data. The Kalman filter's outputs the best range estimate through data fusion. This estimate is subsequently provided to the flight controller in order to avoid the obstacle as quickly as possible. Fig. 3 is a flow chart depicting the entire obstacle detection and avoidance algorithm process.

This section discusses the ultrasonic sensor range accuracy algorithm. The algorithm is designed to improve the accuracy of range measurement for ultrasonic sensors by using a temperature sensor attached to an ultrasonic sensor, minimizing the inaccuracy of how the temperature of the surrounding environment affects distance. The algorithm was developed using Matlab version R2019a. Figure 4 depicts the flowchart of the ultrasonic range accuracy improvement algorithm.

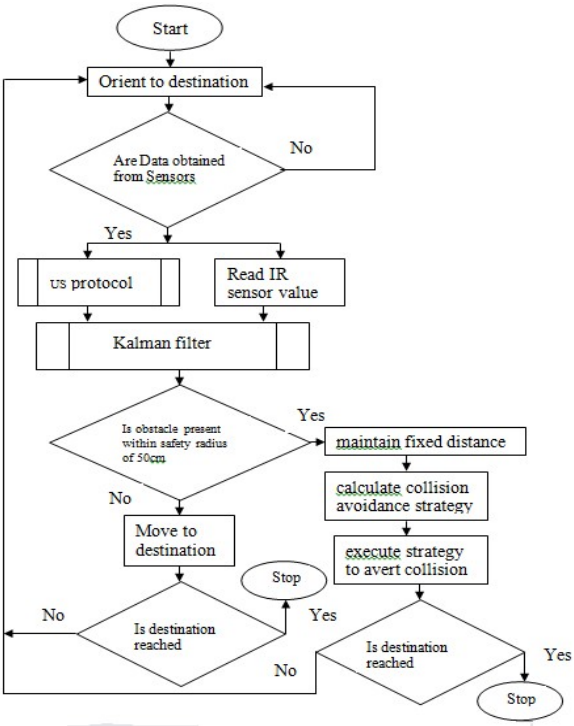


Figure 4: Flowchart of Collision Avoidance algorithm

As shown in Fig. 4 the UAV orients to its destination and obtain data signals from ultrasonic and infrared sensor which are optimized using the Kalman filter. If an obstacle is present in its direction, collision avoidance strategy which works using a maximum range of 50cm between UAV and obstacle is then implemented using the optimal estimate of the Kalman filter to avoid the collision.

4. Results and Discussions

The Kalman filter and quadrotor simulation results are presented and discussed in this section.

4.1 Result of Data Fusion Using Kalman Filter

The data estimates obtained from the ultrasonic sensor detecting an obstacle at a 50cm mark is shown in table 1.

Table 1. Data obtained from ultrasonic sensor detecting an obstacle at 50cm

Measurement Sample	Distance (cm)
1	40
2	41
3	43
4	44
5	45
6	46
7	48
8	45
9	48
10	50

The data estimates obtained from an infrared sensor operating to detect an obstacle at a 50cm mark is shown in Table 2.

Table 2. Data obtained from infrared sensor detecting an obstacle at 50cm mark

Measurement Sample	Distance (cm)
1	44
2	42
3	45
4	52
5	45
6	50
7	46
8	48
9	49
10	50

Data fusion of obstacle detection obtained from both the ultrasonic and infrared sensors readings as shown in table I and II are shown in Figure 5.

Figure 5. Shows the signal output in voltage against time obtained from the Kalman filter.

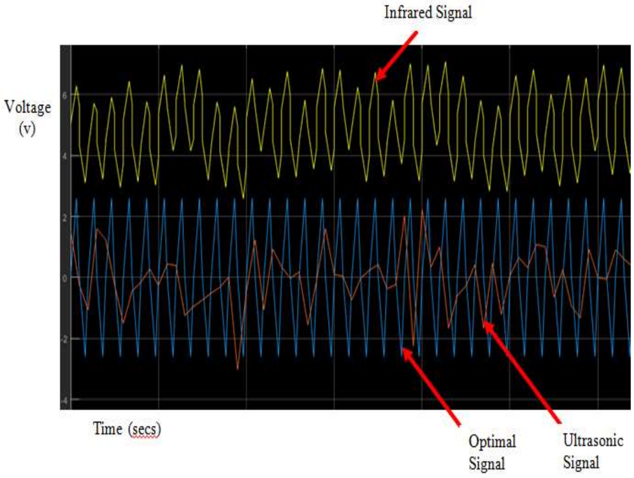


Figure 5: Data fusion using Kalman filter

4.2 Quadrotor Flight Simulation Result

Table 3 shows the input required for the quad rotor to take-off, hover, and move toward the target.

Table 3. Pitch, Roll and Yaw Values of Quad Rotor

Pitch (Deg)	Time (Secs)	Roll (Deg.)	Time (Secs.)	Yaw (Deg.)	Time (Secs.)
0	10	0	15	0	8
18	1	-3	2	20	1
0	1	3	2	0	21
-18	1	0	12	0	0
0	17	0	0	0	0

Table 4 shows a comparison of the presented work against the reviewed works in terms of the computational cost of the algorithm, cost of sensors and the use of data fusion technique.

Table 4. Comparison of Reviewed Works and Presented Work

Reviewed Works	Computational Cost of Algorithm	Cost of Sensors	Data Fusion Technique
Sasongko *et al.*, (2017)	Low	High	No
D'Apolito *et al.*, (2018)	High	High	No
Ding *et al.*, (2019)	Very high	High	Yes
Tan *et al.*, (2020)	High	High	No
Yasin *et al.*, (2020)	High	High	No
Guo *et al.*, (2021)	Low	High	No
Huang *et al.*, (2021)	Low	High	No
Presented Work	Low	Low	Yes

Figure 6 shows the graphically movement of the UAV using the required input from the UAV to take-off, hover, and move toward the target and finally evading collision.

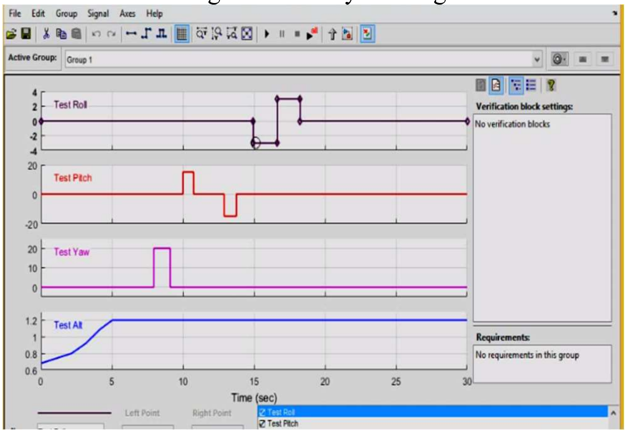
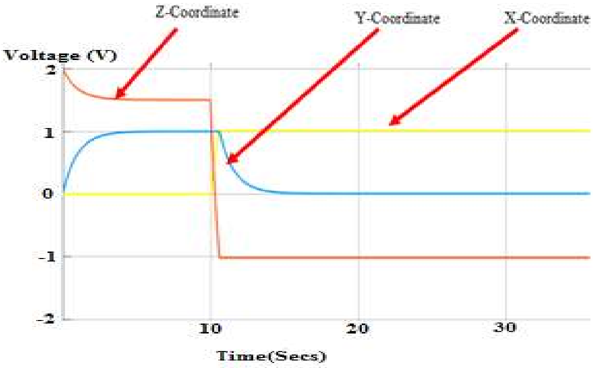


Figure 6: Graphical Representation of Input Parameters for Quadrotor Simulation

The corresponding movement produced during this whole flight from take-off, hovering, moving toward target and averting collision corresponding to the x, y and z coordinates is shown in Figure 7, while the simulation showing the quadrotor evading collision is shown in Figure 8.



Scale: Voltage: 1 unit to represent 1V and Time: 10 unit to represent 10 Seconds

Figure 7: 3D Motion Movement Coordinates of the Quadrotor.

Figure 8 shows the implementation of the visual reality operation of the quadrotor receiving optimal input signal from the Kalman filter and implementing the collision avoidance strategy to avert collision.

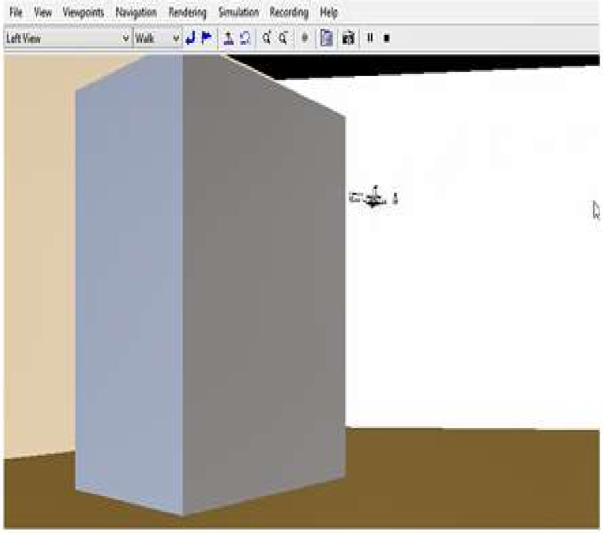


Figure 8: Quadrotor evading collision

4.3 Discussion

Table I and II shows the readings obtained using using ultrasonic and infrared sensors at 50cm distance to the obstacle. The data fusion of obstacle detection data obtained from both the ultrasonic and infrared sensors readings are shown in Figure 5. It is observed from Figure 5 that the output of the Kalman filter as seen from the scope after the application of the data fusion algorithm is able to improve obstacle detection estimates by producing optimal signal from the noisy inputs of ultrasonic and infrared signals. The optimal signal when compared to the ultrasonic and infrared signal is shown to possess an improvement in amplitude.

Table 3 shows the input required for the quad rotor to take-off, hover, and move toward the target. It is observed that the combinations of the input pitch, roll and yaw generated from the flight controller as seen in Figure 6 results in the movement of the UAV as seen in Figure 7 towards its destination and its ability to evade collision using the collision avoidance algorithm as depicted in Figure 8.

Table 4 shows an analysis of the reviewed works compared with the presented work in terms of computional cost of the algorithm, cost of the sensor and application of sensor fusion technique to the flight data.

The comparison as shown in Table 4 shows that the collision avoidance algorithm employed in this work has low computational cost, used cheap sensors (ultrasonic and infrared) and utilizes sensor fusion that makes the obtained data less noisy and reliable. The presented work is thus better in comparison to the reviewed works.

5. Conclusion

This work focuses on the development of an obstacle avoidance algorithm for a UAV that has been validated in a simulated environment. The simulation illustrated how a quadrotor with a set pitch, roll, and yaw can acquire a 1.2m height and hover at this height for 10 seconds before descending to the target and avoiding collision at the defined 50cm mark.

The presented work proves that the method is very feasible and provides a cheap and effective form of navigation for UAV's.

The following recommendations are suggested for further improvement on the designed project:

i. The data fusion process can be made better by using an extended Kalman filter instead of a Kalman filter. Kalman filter is optimal as a linear filter but not as a non-linear filter.

ii. The scope could be extended, in the future, to observe the performance of swarms of robots in both, simulation platforms and experimentation. Such experimentation could be used to validate the use of the system in other intensive missions.

Future work will analyze the performance of the proposed algorithm by applying it to actual flight tests on a real quad rotor unmanned aerial vehicle.

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