Modeling and Simulation of Collision Avoidance Algorithm for UAV

Toto Indriyanto, Regia Dwisanti
Department of Aeronautics and Astronautics,
Faculty of Mechanical and Aerospace Engineering, ITB, Indonesia
Email: t.indriyanto@ae.itb.ac.id, regia.dwisanti@gmail.com

Abstract: Current development and operations of Unmanned Aerial Vehicles (UAVs) or drones requires their seamless integration into national airspace systems. The integration should always consider the development and utilization of the UAV's collision avoidance algorithm and logic. Therefore, concerns about command and control latency, vehicle performance, reliability of autonomous UAV functions, and interoperability of the TCAS (traffic alert and collision avoidance system) and ATC (air traffic control) roles have been subjects of many studies. Nowadays, some areas of airspace are already crowded by continuous operation of commercial aircraft. This paper describes some studies and development of a collision avoidance algorithm using Lapan Surveillance UAV LSU-05 as simulation model. Although the maneuvers are limited to horizontal plane, simulation showed that the algorithm performs very well under given case studies without any disruption to other aircraft operation controlled by the ATC,.

Key Words: collision avoidance algorithm, unmanned aerial vehicle, modeling and simulation

Nomenclature

BA	:	back angle	[deg]
DL	:	distance limit	[NM]
g	:	Earth gravity acceleration	[m/s^2]
LL	:	line-of-sight limit	[deg]
ROT	:	rate of turn	[deg/s]
V	:	velocity	[kts]
x	:	horizontal x-position	[NM]
y	:	horizontal y-position	[NM]
χ	:	heading	[deg]
ϕ	:	bank angle	[deg]
τ	:	range (distance)	[s]

1. Introduction

The demand for UAV or UAS operations continues to increase, either in civil or in military roles. The missions include border patrol, environmental observation, cargo delivery and surveillance. These missions require the UAVs to be integrated seamlessly into available civilian airspace in one or more of their flight phases. Although most UAVs are equipped with autonomous flight capabilities, they are not allowed by aviation agencies due to safety requirements. The requirement states that aircraft shall have the capability to see and avoid one another. This collision avoidance function has to be run onboard even if the connection between UAV and its control station is lost. The UAV operation has to provide an equivalent level of safety (ELOS) to manned aircraft while not negatively impacting the existing infrastructure of manned TCAS[1,2].

TCAS instructs pilots of manned aircraft how to maneuver to avoid collision with other aircraft. There are two types of sensor mode used in collision avoidance, namely cooperative and non-cooperative. Cooperative mode is used in Mode A/C transponder and ADS-B (automatic dependent surveillance-broadcast), while the non-cooperative mode can be found in optical, thermal, laser/LIDAR (light detection and ranging), radar and acoustic systems[3]. These sensors can also be utilized for UAVs to fulfill the see-and-avoid requirement. Once collision detection is detected, these systems either provide a warning to the UAV operator or take action autonomously.

In this paper a simple collision avoidance algorithm, based on data obtained from ADS-B, is proposed. ADS-B system has been mandatory in national airspaces, such as in Indonesia since 2015. The availability of ADS-B enables its expanded use for UAV as described in the following studies. Subsequent chapters present the proposed collision avoidance algorithm concept, simulation and analysis, future works and conclusions.

2. Related Studies

Two types of TCAS system are presently in operation, TCAS I and II[4]. Both systems provide **advisories** to alert pilots of a potential collision. TCAS I assist pilots in visually locating and identifying an intruder aircraft by issuing **traffic advisory** (TA) warning. TCAS II, in addition to TA, provides vertical flight maneuver guidance to pilots. This guidance is given in the form of **resolution advisory** (RA) for threat traffic. A resolution advisory will either increase or maintain existing vertical separation between aircraft.

TCAS computer connects to ATC transponder and calculates time to a potential collision known as **closest point of approach** (CPA). TCAS then creates a protected volume of airspace around its host aircraft. This airspace is based on altitude separation and calculated time to CPA. A Greek letter **tau** (τ) is chosen to denote the approximate time (in seconds) to CPA. Horizontally, the protected volume of airspace is determined as follows:

$$range\ \tau = \frac{3600 \times slant\ range\ [NM]}{closing\ speed\ [knots]} \quad (1.)$$

In a typical TCAS system range τ is programmed with varying sensitivity levels determined by altitude bands (Table 2.1). For each altitude band, there is a different sensitivity level and the value of τ for TA and RA respectively. The higher the sensitivity levels the larger the protected volume of airspace.

Table 2.1. TA/RA sensitivity levels[4]

Altitude [feet]	**Sensitivity levels**	**τ [seconds]**	
		TA	RA
0 to 1,000	2	20	none
1,000 to 2,350	3	25	15
2,350 to 5,000	4	30	20
5,000 to 10,000	5	40	25
10,000 to 20,000	6	45	30
20,000 to 42,000	7	48	35

Since 1991 TCAS has become a mature system mandated by ICAO for all commercial aircraft[5].

Generic process model for collision avoidance algorithm[3] involves steps as follows (Fig.2.1):

1) **Surveillance**: Accurate surveillance of potential intruders is a key initial step. Intruders that are either missed or their position erroneously identified would reduce the overall effectiveness of a collision avoidance system. Various potential sensors have been studied[6,7,8].
2) **Identification of risk**: Using surveillance data, it is determined whether a risk of collision (two aircraft are on a collision course) or a conflict (violation of safe separation) exists and avoidance maneuver is required.
3) **Determination of appropriate avoidance maneuver**: If a potential collision or conflict is identified, an appropriate avoidance maneuver is selected. In the case of an ATC providing radar separation assurance, the selection is made by controller based on his training and operational experience. In the case of TCAS, the selection is made by on-board automation system based on its programming.
4) **Maneuver**: Once an appropriate maneuver is selected, it must be executed by (auto-) pilot in control of the aircraft.
5) **Return to Course**: After risk of collision has been mitigated using maneuver, the aircraft return to its original course

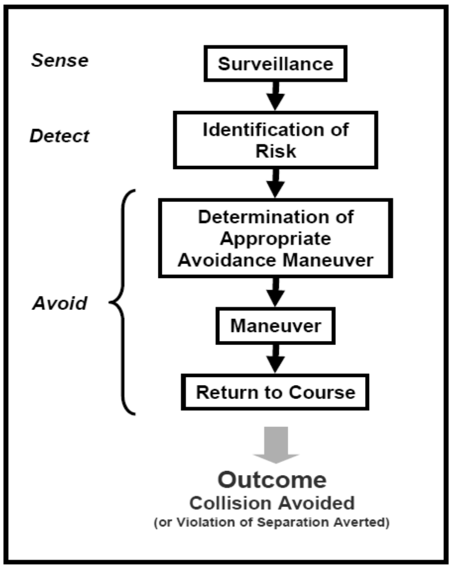

Fig. 2.1. Generic process model of collision avoidance algorithm[3)]

Hardware-in-the-loop simulation (HILS) test results of collision avoidance function implemented on surveillance UAV has been studied[9)]. The test involved a smart, tilt-rotor UAV with MTOW of 960 kg. Critical systems such as flight control, navigation sensor and actuation were provided in dual-redundancy to enhance reliability. Collision avoidance algorithm is designed based on the ADS-B as the main situational awareness sensor. The test showed that ADS-B system in airborne and ground was operated normally and HILS system became effective tools to evaluate the function of ADS-B prior to flight test. Subsequent flight tests proved that ADS-B system is effective to provide flight information to guide the UAV for collision avoidance in airspace. The resulting collision avoidance functions involve complex maneuvers in 3-D space by changing course and altitude.

Concerns about the more crowded low altitude airspace is recently raised[5)]. As a result, collision avoidance for low altitude flights become a serious problem in aviation safety. Studies on conflict detection and resolution were required under multiple maneuvering dimensions for general aviation (GA) and UAV. The paper presents collision avoidance logic for GA and UAV based on ADS-R (automatic dependent surveillance-rebroadcast). Heading change for horizontal resolution is more suitable for small GA or UAV flying in low altitude in the proposed model. The proposed system uses horizontal change instead of vertical change which might disturb the traffic flow and cause another conflict in low altitude[10)]. In addition, heading change also minimize the magnitude of the vector change. It calculates the flight distance under right turn or left turn conditions to determine which direction to change for shortest path escape. Conflict detection and resolution assessment is formulated based on the performance characteristics of aircraft. Due to waypoint navigation and autopilot, UAV gets highest priority. In the resolution algorithm, the turning angle in RA is pronounced only for lower priority in the ownership of GA. Simulations using real ultra-light flight data were performed to verify the performance of the proposed algorithm. Test verification supports the solution model in effectiveness.

Currently, collision avoidance algorithm applicable for general aircraft operation is developed[11)]. The algorithm was thoroughly tested using simple setup of software in the loop simulation. Several scenarios were modeled to elaborate the possibilities of different collision courses. In the algorithm each aircraft is given two advisory circles for TA and RA, following the above table. Basically, if aircraft A detects aircraft B entering its TA circle, a change in heading angle is commanded to avoid aircraft B from entering its RA circle, therefore to avoid the collision between the two. Based on previous result[5)], to avoid collision each aircraft is given the ability to maneuver itself in horizontal plane. All maneuvers follow the right turn rule as enforced under visual flight rule (VFR)[5)]. Although the simulation is limited to three aircraft maneuvering in horizontal plane, in all scenarios the algorithm was able to successfully prevent the aircraft from entering other aircraft's RA circles.

3. Proposed Concept

However, the HILS results[9)] may not be suitable for implementation of smaller UAV. Such UAVs usually fitted with limited avionics and control devices to execute simple maneuvers. Algorithm and commands for collision avoidance should also be limited. Therefore, in this paper results from previous study[11)] are developed further. The objective of the proposed concept is to implement collision avoidance algorithm for general, multi- purpose autonomous UAV. The UAV is of fixed-wing type with heading control-only to prevent collision. It is further assumed that the UAV is capable of receiving other aircraft data using ADS-B system, either directly from other aircraft (via ADS-B out) or from its ground control station (adopting ADS-R concept). To integrate seamlessly into available airspace, the presence of the UAV must not disrupt already operated aircraft in the vicinity, so all the other aircraft can have constant airspeed and heading as directed by the ATC. The following chapters describe the modeling and simulation performed to evaluate the proposed concept.

4. Problem Formulation

To estimate aircraft trajectories, state vector representing motion of aircraft is defined as follows:

$$X_i = [x_i \quad y_i \quad \chi_i \quad V_i]^T \tag{2.}$$

where x and y are aircraft position in horizontal plane, χ is heading, V is airspeed, and subscript i denotes the UAV, aircraft A, B, C, etc. Position, heading and airspeed of the aircraft are assumed to be provided by ADS-B systems onboard each aircraft and on the ground station. Aircraft velocities in x- and y-axes can be formulated as:

$$\begin{aligned} \dot{x}_i(t) &= V_i(t) \ \cos\chi_i(t) \\ \dot{y}_i(t) &= V_i(t) \ \sin\chi_i(t) \end{aligned} \tag{3.}$$

Distance between UAV and intruder aircraft is calculated continuously using:

$$D = \sqrt{(x_{UAV} - x_i)^2 + (y_{UAV} - y_i)^2} \tag{4.}$$

Once an avoidance maneuver is commanded, the UAV is turned to the right or left using the following equation:

$$\dot{\chi} = \frac{g \tan\phi}{V} \tag{5.}$$

where g is the Earth gravity acceleration and ϕ is the bank angle.

Following description from previous studies[3, 11)] the dynamics of avoidance maneuvers for UAV can be describes as follows (Fig. 4.1):

1) the UAV monitors air traffic 360 deg around its trajectory.
2) if other aircraft is detected within its TA circle, the UAV executes avoidance maneuver by turning to the right or left.
3) after the TA circle is cleared, UAV executes return maneuvers to its original trajectory.

In order to simulate the maneuvers, some terms below need to be defined for UAV command (Fig. 4.1 for turn-right maneuver):

- ROT (rate of turn) defines the increase of UAV heading angle when performing avoidance maneuver to prevent collision, given in [deg/s]. This value will depend on the maximum turn rate of the UAV while maintaining its altitude.
- LL (line-of-sight limit) is the range angle of consideration with respect to UAV heading, in [deg]. The UAV has to monitor other aircraft from 360 deg around, so LL is set to 180 deg.

- BA (back angle) is angle between original UAV trajectory and the commanded trajectory to return to the original track, defined in [deg]. The smaller the back angle, the longer time is required to return to original trajectory.
- DL (distance limit) shows the distance between original UAV trajectory and trajectory obtained after performing avoidance maneuver. DL should be very small, typically less than 0.01 NM to ensure that the UAV return to its original trajectory.

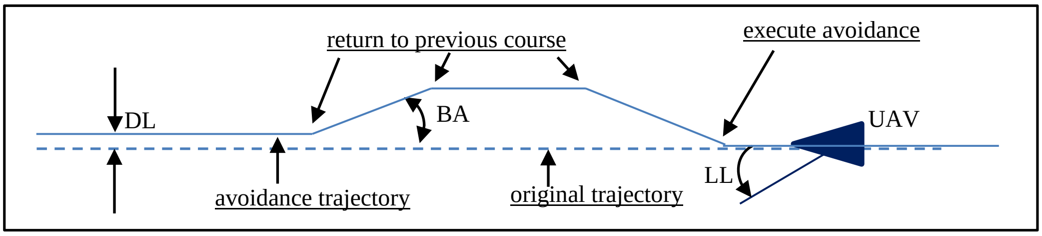

Fig. 4.1. Definitions for collision avoidance maneuver.

The above formulation is then modeled and simulated using Matlab to evaluate its effectiveness.

5. Simulation and Analysis

For simulation purpose, LSU-05 (Fig.5.1) is used as baseline UAV model.

Fig. 5.1. Lapan surveillance UAV LSU-05[12)]

Some performance characteristics of the UAV are given in the following table.

Table 5.1. LSU-05 performance Fig.s[12)]

MTOW	120	kg
Range	240	miles
Endurance	8	h
Ceiling	12,000	ft
Cruise altitude	3,000	ft
Cruise airspeed	100	km/h

In simulation the wind velocity and its effects were ignored. The UAV is treated as a point mass with constant speed and the values of ROT are varied from 6 deg/s to 50 deg/s. Intruder aircraft are given various airspeed typical for cruise altitude of 3,000 ft, ranging from 170 to 200 knots. The values of TA and RA, according to Table 2.1, are given 30 and 20 seconds, respectively. Several scenarios of collision avoidance were simulated. Turning maneuvers to the right as well as to the left were also tested and compared. The best two scenarios are presented below.

5.1. First scenario simulation

The UAV is flying to the east (heading 90 deg). The angle of encounter between the aircraft and the LSU-05 are varied: 20 deg (aircraft A), 280 deg (B), 200 deg (C) and 110 deg (D) from the UAV's heading (Fig. 5.1.1). The airspeed are also varied 170, 180, 190 and 200 kts for aircraft A, B, C and D, respectively. Paralel trajectories between intruder aircraft are set between 1.5 to 3 NM while the passing of intruder aircraft are so spaced to simulate separation controlled by ATC.

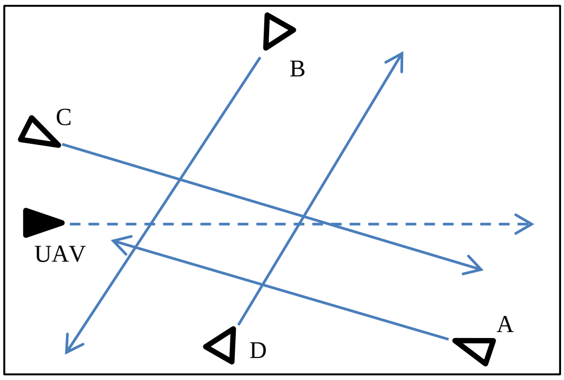

Fig. 5.1.1. Initial condition for first scenario

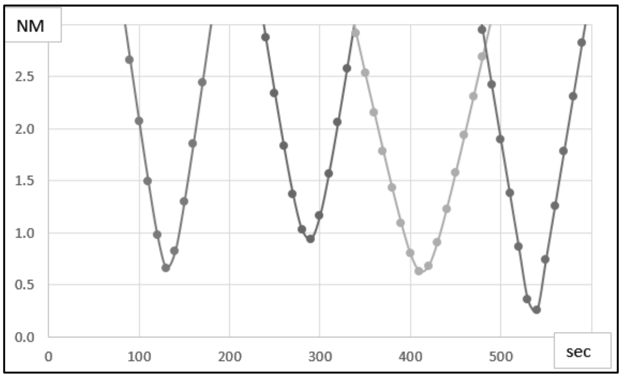

Fig. 5.1.2. Distance between UAV and intruder aircraft without maneuvers

Fig. 5.1.2 shows the distance of the approaching of intruder aircraft to the UAV, plotted every 10s for clarity. Collision parameters for first scenario is given in Table 5.1.1. Collision avoidance maneuvers are initiated after 30s TA are received to prevent the UAV from entering 20s RA circles of intruder aircraft. Comparing minimum distances and 20s RA in Table 5.1.1 clearly shows that without avoidance maneuvers the UAV will enter the RA circles.

Table 5.1.1. Collision parameters for first scenario simulation

Parameter [unit]	A	B	C	D
heading [deg]	290	200	110	20
airspeed [kts]	170	180	190	200
angle of encounter to UAV heading [deg]	20	280	200	110
closing speed [kts]	223.2	205.2	140.4	187.2
minimum distance from UAV [NM]	0.651	0.925	0.617	0.148
30s traffic advisory TA [NM]	1.839	1.705	1.166	1.569
20s resolution advisory RA [NM]	1.226	1.136	0.778	1.046

The result in Fig. 5.1.3 shows that the LSU-05 can perform the required maneuvers to avoid intruder aircraft. The UAV successfully avoid the aircraft. However, maximum turn rate up to 50 deg/s were required since the UAV fly very slowly compared to the intruder aircraft. This maneuver will make the UAV bank to 68 deg. The optimum BA is found to be about 45 deg. Maximum deviation of the resulting UAV trajectory is about 0.4 NM. From various encounter scenarios tested it was found that the best avoidance maneuver is to turn to the right when the intruder aircraft coming from quadrant 1 or 3, while turning to the left is effective for intruder coming from quadrant 2 or 4 of UAV heading.

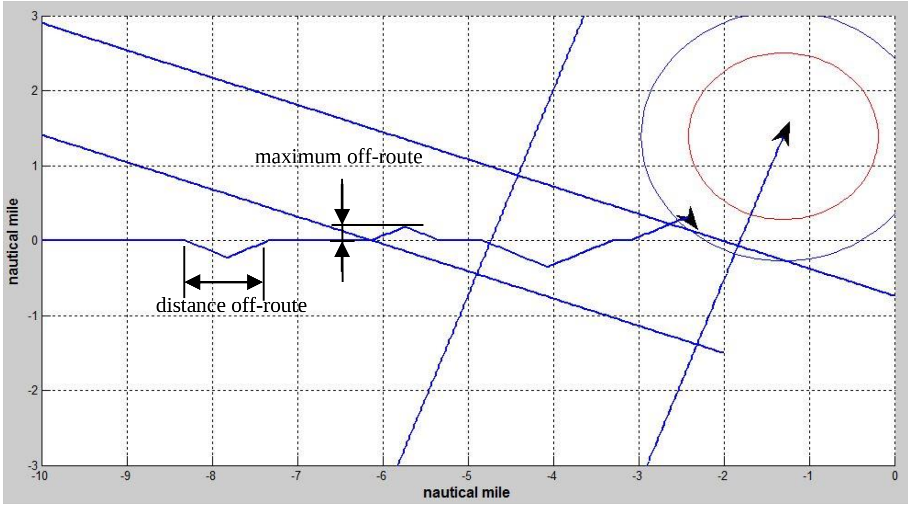

Fig. 5.1.3. Example screenshot of the UAV flight trajectory avoiding collision (first scenario)

Fig. 5.1.4 shows the distance between UAV and aircraft A, B, C and D, respectively plotted every 10s for clarity. It is clear that the minimum distances after maneuvers have increased significantly.

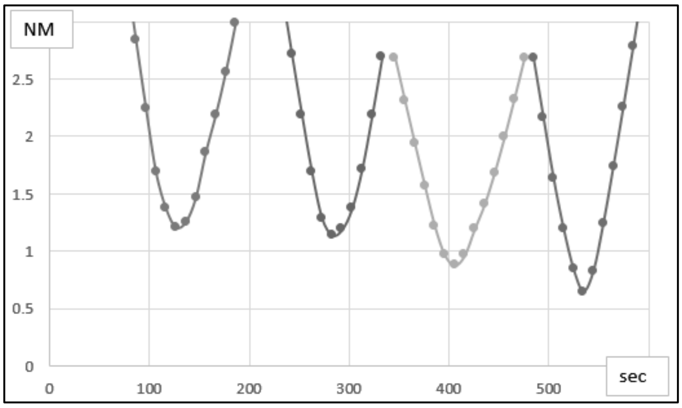

Fig. 5.1.4. Distance between UAV and intruder aircraft after avoidance maneuvers

Table 5.1.2 shows some parameters of the UAV after performing maneuvers to avoid aircraft A, B, C and D. The avoidance manuvers of the UAV result in the off-route distance from 0.8 – 1.6 NM with maximum off-route 0.4 NM.

Table 5.1.2. Avoidance parameters for first scenario simulation

parameter [unit]	A	B	C	D
minimum distance from UAV [NM]	1.197	1.141	0.878	0.647
distance off-route [NM]	1.050	0.841	1.556	1.221
maximum off-route [NM]	0.251	0.236	0.437	0.267

5.2. Second scenario simulation

Again, the UAV is flying to the east. The angle of of encounter between the aircraft and the LSU-05 are also varied from 80 deg (aircraft A), 260 deg (B), 170 deg (C) to 350 deg (D) from the UAV's heading (Fig. 5.2.1). Separation of paralel trajectories between intruder aircraft are set between 1 to 2 NM. The airspeed are 170, 190, 200 and 180 kts for aircraft A, B, C and D, respectively.

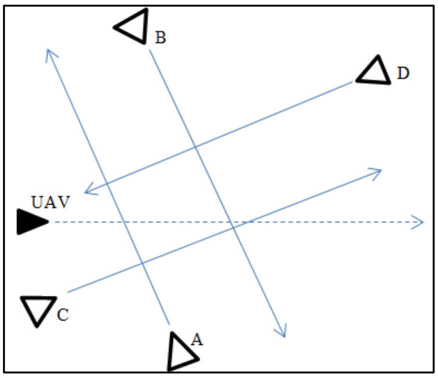

Fig. 5.2.1. Initial condition for second scenario

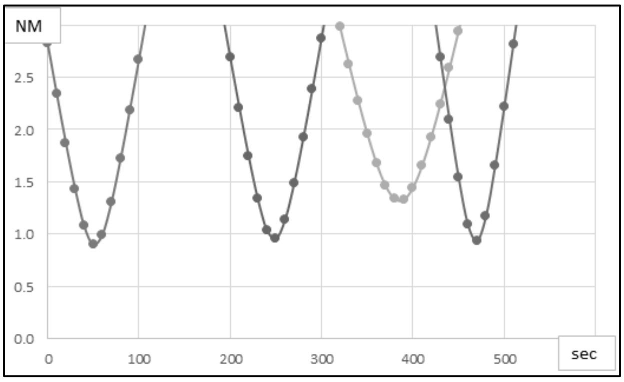

Fig. 5.2.2. Distance between UAV and intruder aircraft without maneuvers

Fig. 5.2.2 shows the distance of the approaching of intruder aircraft to the UAV, plotted every 10s. Collision parameters for second scenario is given in Table 5.2.1. Collision avoidance maneuvers are initiated after 30s TA are received to prevent the UAV from entering 20s RA circles of intruder aircraft. Comparing minimum distances and 20s RA in Table 5.2.1 clearly shows that without avoidance maneuvers the UAV will enter the RA circles.

Table 5.2.1. Collision parameters for second scenario simulation

Parameter [unit]	A	B	C	D
heading [deg]	350	170	80	260
airspeed [kts]	170	190	200	180
angle of encounter to UAV heading [deg]	80	260	170	350
closing speed [kts]	223.2	205.2	140.4	187.2
minimum distance [NM]	0.896	0.952	1.212	0.932
30s traffic advisory TA [NM]	1.443	1.567	1.318	1.933
20s resolution advisory TA [NM]	0.962	1.045	0.808	1.289

The result in Fig. 5.2.3 shows that the LSU-05 can perform the required maneuvers to avoid intruder aircraft. Again, the maximum rate of turn up to 50 deg/s were required. Maximum deviation of the resulting UAV trajectory is about 0.3 NM. Similar to previous scenario, the best maneuver is to turn to the right when the intruder aircraft coming from quadrant 1 or 3 of UAV heading, while turning to the left is effective for intruder coming from quadrant 2 or 4.

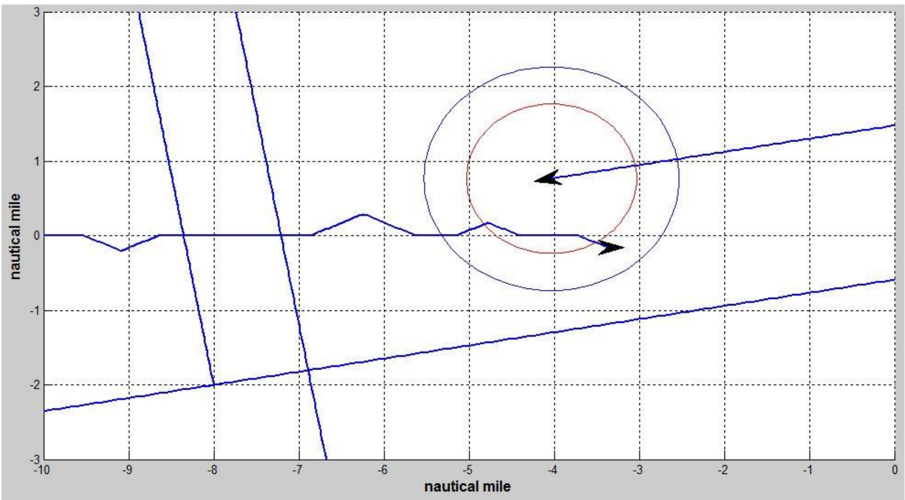

Fig. 5.2.3. Example screenshot of UAV flight trajectory avoiding collision (second scenario)

Fig. 5.2.4 shows the distance between UAV and aircraft A, B, C and D, respectively plotted every 10s. It is clear that the minimum distances after maneuvers increase significantly.

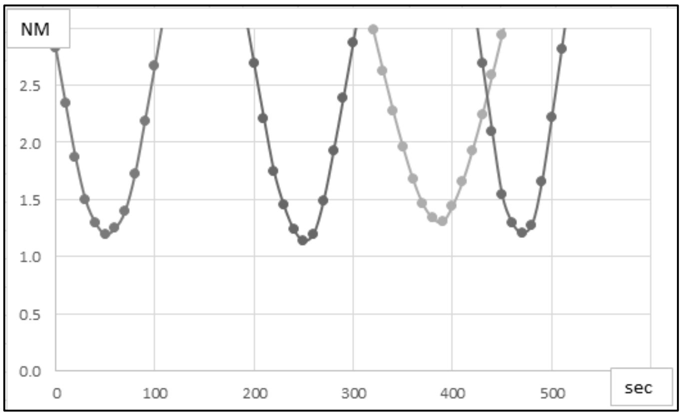

Fig. 5.2.4. Distance between UAV and intruder aircraft after avoidance maneuvers

Table 5.2.2 shows some parameters of the UAV after performing maneuvers to avoid aircraft A, B, C and D. The avoidance manuvers of the UAV result in the off-route distance from 0.3 – 1.2 NM with maximum off-route 0.5 NM.

Table 5.2.2. Avoidance parameters for second scenario simulation

parameter [unit]	A	B	C	D
minimum distance from UAV [NM]	1.059	1.105	1.304	1.209
distance off-route [NM]	0.343	1.161	0.710	0.645
maximum off-route [NM]	0.195	0.293	0.487	0.406

From scenarios that have been tested, it is found that the avoidance maneuver only effective when the UAV is entering TA circle within ± 90 deg of intruder aircraft's heading. The UAV design should also include the high G requirements resulting from the avoidance maneuvers that need to be performed. Although it is suggested that the maneuver should only turn to the right[5)], it will be more effective if the turning is flexible, depending on the geometry of encounter between the UAV and intruder aircraft.

6. Future Works

It is realized that the scenarios being tested could not describe all the possibilities that would occur in actual cases of collision avoidance. When the UAV enters the TA circle at an angle of more than ± 90 deg, evasive maneuvers are not effective to perform since the UAV will soon be well behind the aircraft. Other factors that need to be considered are the velocity of UAV with respect to intruder aircraft. These parameters require more detailed simulation scenarios to be developed. The next concern is how to avoid the wake vortices generated by the passing aircraft effectively. This vortices will depend on aircraft's size, altitude, airspeed, and flight direction. These considerations require a more detailed follow-up analysis.

7. Conclusions

The proposed collision avoidance maneuver has been modeled and simulated successfully with the existing constraints. LSU-05 as the simulated model can be maneuvered out of RA circles of intruding aircraft without disrupting the aircraft's traffic. In some cases, the UAV has to be maneuvered up to its maximum turning capability. Although the maneuver is limited to heading change, several cases of encounter have been tested and the results are promising. The results will be used for more detailed studies on aircraft traffic avoidance maneuvers, either before or after close-encounters.

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