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A PREPARATORY RESEARCH FOR UAM COLLISION AVOIDACE USING ADSB

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Abstract

With the recent development of avionics and Unmanned Aerial Vehicle (UAV) related technology, the need for collision avoidance functions for UAVs is also expanding. Related collision avoidance equipment and system technology have been actively studied, and related standards such as the establishment of Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) of aircraft are also emerging. Among them, Automatic Dependent Surveillance Broadcast (ADSB) equipment is attracting attention as one of the key equipment for DAA because it has the feature of sending and receiving the statuses of both itself and other aircraft in the air.

A five-year project for developing a collision avoidance system had been launched for the purpose of UAVs being able to share the airspace with pilot-on-board aircraft (manned aircraft). A two-seater aircraft was converted into a UAV. A collision avoidance module using an ADSB signal and video cameras were developed in addition to a Flight Control Computer. More than one million test cases were generated based on various flight scenarios with the computer simulation for up to three incoming traffic intruders. The simulation results were successfully proven with a series of flight tests.

The technology developed in this project will be expanded for Urban Air Mobility (UAM) or Advanced Air Mobility (AAM), which are all key issues being noticed by related Korean industries and government.

Keywords: Collision Avoidance, ADSB, UAV, UAM, AAM

1. General Introduction

1.1 ADSB on General Aviation

In the USA, the ADSB has been mandatory for passenger carrying aircraft since 2020. The Civil Aviation Safety Authority (CASA) of Australia had begun to require the ADSB on aircraft flying over a certain altitude since 2013.

In Europe, the ADSB-Out has been required since Dec. 7, 2020. Aircraft certified earlier are also required to equip the ADSB-Out before 2023 [1].

1.2 Concept of Operations (CONOPS) of UAV

In recent years, UAVs or UAS (Unmanned Aircraft System) has been one of the key areas which lead the aeronautics technology and industry in both military and civilian sectors. The growth of UAVs can be beneficial for its users but raises many issues as well. One of the key issues is to share the airspace with commercial and general aviation. This in turn requires UAVs to adopt rules which manned aircraft follow. The ICAO (International Civil Aviation Organization) has set up the annex, the standards and recommendation practices for UAV expecting to fly over shared airspace. The ICAO is leading the setup of the GANP(Global Aviation Navigation Plan) including the ASBU(Aviation System Block Upgrade) for proficient usage of international and national airspace. In ASBU a roadmap was suggested for common sharing between manned aircraft and UAV hoping for smooth transition before 2030 [2][3].

The European Organization for Civil Aviation Equipment (EURO CAE) also set up committees and working groups for standard rules and recommendations. WG (Working Group)-105 has been established based on WG-73 previously. One of the sub focus teams under Steering Committee of WG-105 is Detect and Avoid [4].

The ability to share their flying status, including altitude, direction and speed of aircraft, is the key benefit of utilizing ADSB as a sensor for the DAA, which is why the MOPS (Minimum Operational Performance Standards) has been being developed based on ADSB.

1.3 Research Objectives and Goals

UAV technology development has matured for UAV to fly a predefined course or mission alone. In the military sector, the technology for swarming UAV flight has been developed, and collaboration between a UAV and a manned fighter is also relatively new in many countries.

Until recently the airspace between UAV and manned aircraft has been separated in altitudes or designated areas. Since the UAV industry has been gradually growing and is expected to grow rapidly in the near future, it will be unavoidable to share the airspace between manned aircraft and UAVs. UAM or AAM technically is considered as a UAV in many areas including its flight control and air traffic control. One key issue which should be resolved for UAVs flying into manned aircraft flying airspace is collision avoidance, since the safety of flight has been considered the most important issue in aeronautics.

The preliminary research has focused on collision avoidance between UAVs against incoming manned aircraft. The goal of the research is for the pilot of incoming aircraft (i.e., the intruder) to not be able to distinguish whether the testing aircraft is a manned aircraft or UAV when they are encountered following the rules-of-the-air based on ICAO Annex 2, Rules of the Air [5].

The testing aircraft had been converted to a UAV from two-person manned aircraft in the previous research [7]. The preliminary research of UAM has been performed utilizing the UAV to add a function of collision avoidance. The specific goals of this project are as follows.

Table 1. Performance Goals vs. Results

	Dimension	Goal	Result	Evaluation Methods
Visual Detection Distance	km	>= 6	6	Image analysis/Test Flight
Visual Detection Azimuth Angle	Deg	>= ±110	±110	Image analysis/Test Flight
Visual Detection Elevation Angle	Deg	>= ±15	±15	Image analysis/Test Flight
Processing Time for Detection	sec	< 2	0.511	Processing time in the module
Time to Calculate the Course for Collision Avoid	sec	< 0.1	0.021	Time check on simulation
Logic False Rate	/10^6Cases	< 0.5	0.0	Simulation result analysis
Number of Simulation		> $10x10^5$	$13.8x10^5$	Simulation test report
Number of Flight Tests		> 100	105	Flight logbook / Test report
Closest Distance between two Aircraft	Ft	> 500	975	Simulation result analysis
Flight Testing Aircraft		2	2	Aircraft
Camera Dynamic Range	dB	<= 120	120	Manufacturer’s specification
Camera Resolution	Pixel	1920 x1080	1920 x1080	Manufacturer’s specification

2. Developed Collision Avoidance Test System

2.1 Test Equipment

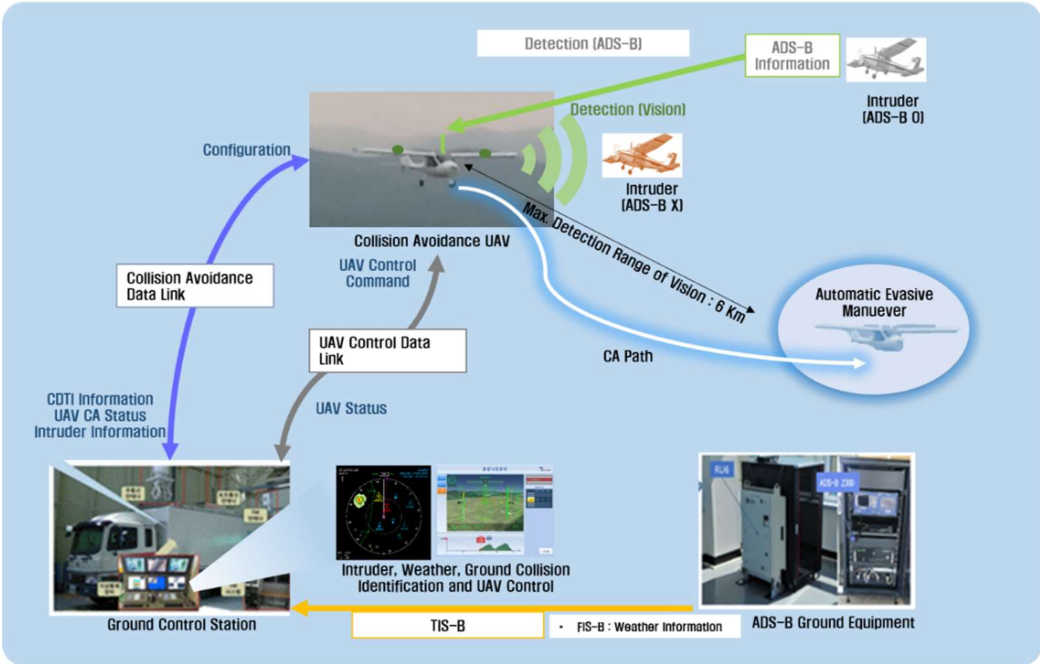

Figure 1 – Collision Avoidance Test System

The testing aircraft is an Optionally Piloted Vehicle (OPV) which can be flown by an on-board pilot or by a remotely located pilot. Devices for autonomous flight were developed on the previous project, which were slightly modified to connect with the newly developed device for the collision avoidance unit. The ground control system was also modified for this collision avoidance test. ADSB equipment were ready for FIS-B (Flight Information Services–Broadcast) and TIS-B (Traffic Information Services-Broadcast). The intruder is a manned aircraft of similar size and performance to the test aircraft. A portable GCS was developed as a backup system.

2.2 Collision Avoidance Module

A module was developed for collision avoidance and added to modules for UAV flight. An ADSB-In device with antennae was connected as a sensor. A visual system was also developed and connected as a sensor device. ADSB information was used as primary data and vision data were used as a backup in case the intruder is not equipped with an ADSB device or the ADSB device of the intruder does not perform normally. Two signals from ADSB and vision system are tested in data fusion sub-module, in which the same aircraft detected by ADSB and by vision system is eliminated from the list of tracking aircraft. Up to ten intruders are listed in the order of risk level. If a new intruder is detected and the level of risk is higher than the aircraft already in the list, the new intruder is replaced with the least risky one.

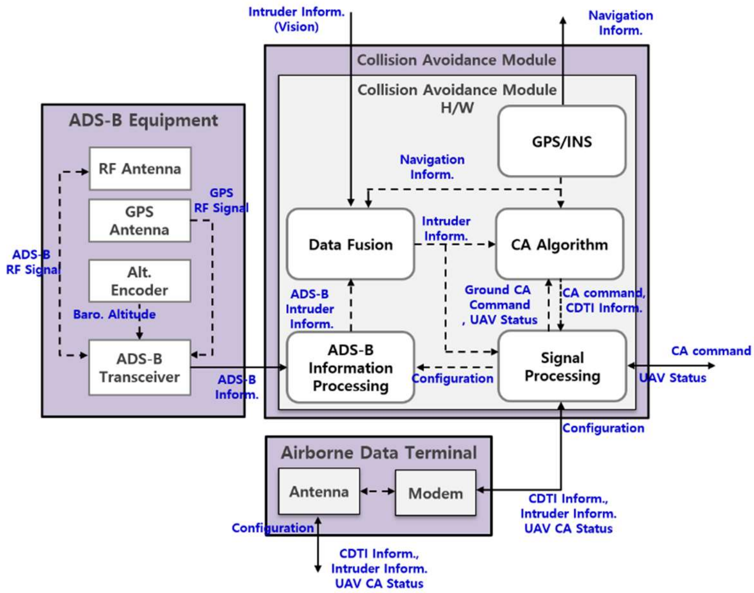

Figure 2 – Collision Avoidance Module Architecture

The information or command for collision avoidance is sent to the flight control computer (FCC). In addition to the main communication between the test aircraft and the ground control system, a separate communication channel was added for the collision avoidance module test. A set of information which includes the information of the incoming aircraft and its level of risk, which are colored yellow or red, is sent to GCS using this added communication channel.

2.3 VFR rules

The rules-of-the-air (ROA) requires pilots should follow the right of way (Figure 3). Head-on is the case the incoming aircraft (intruder) flies toward me. Converge is the case the incoming traffic comes from your right side. Since you don't do anything when the incoming traffic flies from your left, left converge is not necessarily a test case. However, in this project left converge is considered as a test case for safety reason. Overtake is the case you pass the aircraft flying in front of you. The basic rule is simply to change the course to the right.

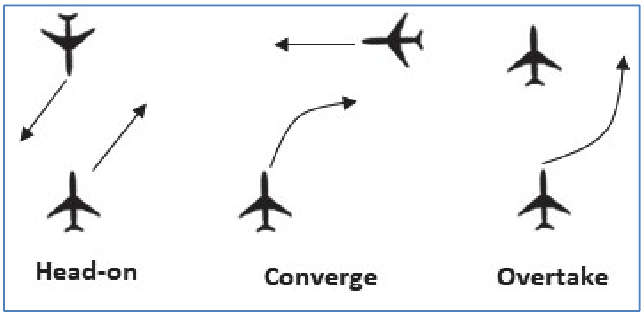

Figure 3 – Right of way

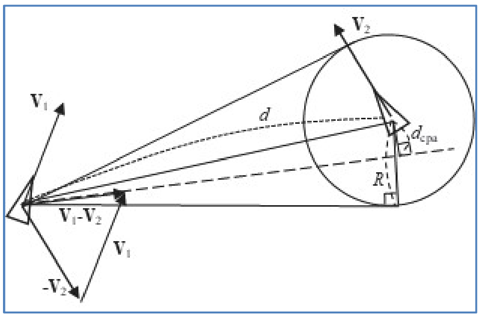

Figure 4 – Closest point geometry

3. Algorithm, Test Cases and Simulations

3.1 Algorithm

The collision avoidance algorithm was written based on the closest point geometry (Figure 4). When the relative direction $(\boldsymbol{V_1}\text{-}\boldsymbol{V_2})$ between two aircraft points within the radius R of the circle, it is considered to be collision risk area. The solution to avoid the collision is to change the direction of $\boldsymbol{V_1}$ so that $(\boldsymbol{V_1}\text{-}\boldsymbol{V_2})$ directs the outside of the circle. Following equations are used.

Time to reach the closest point : $t_{CPA} = -\left((\boldsymbol{r_1} - \boldsymbol{r_2})^T(\boldsymbol{V_1}\text{-}\boldsymbol{V_2}) \,/\, (\boldsymbol{V_1}\text{-}\boldsymbol{V_2})^T(\boldsymbol{V_1}\text{-}\boldsymbol{V_2}) \right)$

Closest point : $\boldsymbol{r}_{1(2),CPA} = \boldsymbol{r}_{1(2)} - \boldsymbol{V}_{1(2),CPA}\, t_{CPA}$

Minimum distance : $d_{CPA} = \| \boldsymbol{r}_{1,CPA} - \boldsymbol{r}_{2,CPA} \|$

A condition for collision can be

$$d_{CPA} < R_{safe} \text{ and } t_{CPA} > 0$$

A condition for excluding cases which are not cautious can be

$$t_{CPA} > t_U \quad \text{where } t_U \text{ is collision avoidance activation time}$$

The initial collision avoidance algorithm showed unsatisfactory result (Figure 5).

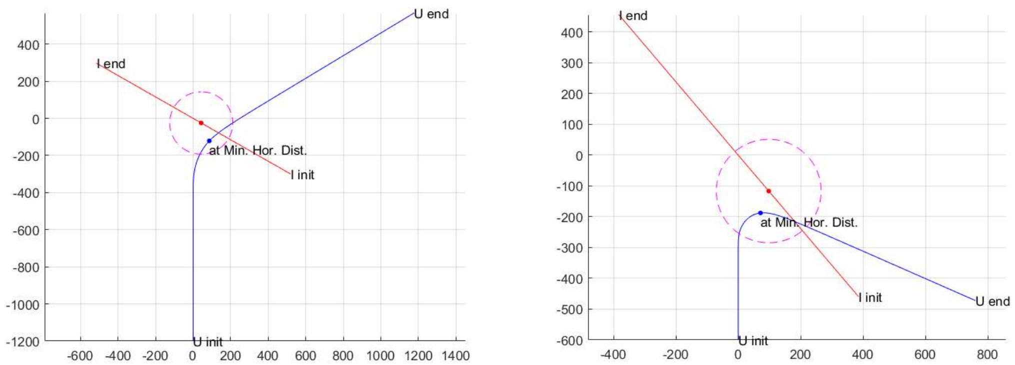

Figure 5 – Initial result

On right converge with acute angle approach had severe problem than obtuse angle approach. The cause for the result analyzed showed that approaching time increases because of a large relative velocity to the direction for avoiding.

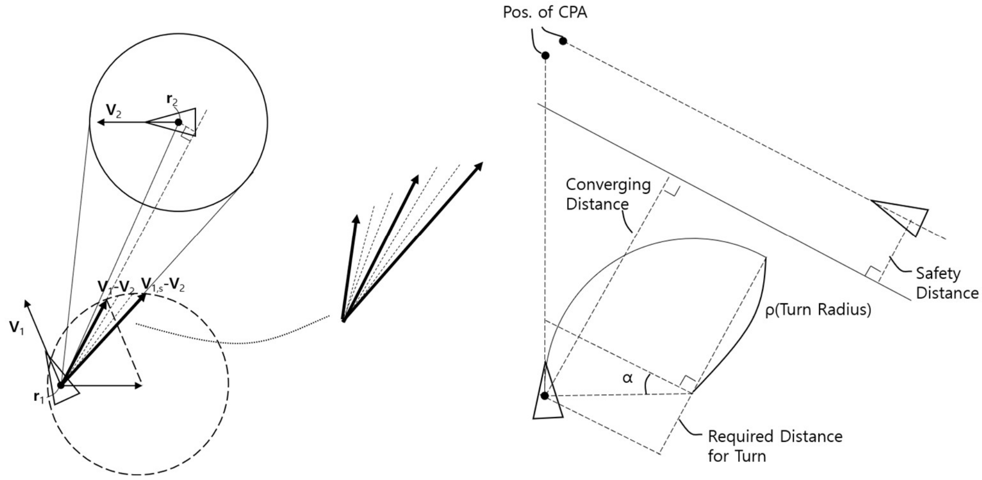

Figure 6 – Closest point calculation

In order to solve the issue, velocity vectors between the current direction and the direction to collision were sampled and the time for minimum distances were calculated for each sampled vectors. The minimum values among the time ($t_{CPA,min}$) based sampled data is considered for evaluation of collision. The original condition and the modified condition are as follows.

Original condition : *(t_{CPA} > 0) And (t_{CPA} < tU) And (d_{CPA} < d_{safe})*

1st Modified condition : *(t_{CPA} > 0) And ($t_{CPA,min}$< tU) And (d_{CPA} < d_{safe})*

The next modification was added for the right converging aircraft with acute angle. For this case the turning radius of the test aircraft was considered. In overall converging distance and radius needed for turning were calculated using position, velocity and performance characteristic of incoming aircraft in general.

2nd Modified condition : *(t_{CPA} > 0) And (($t_{CPA,min}$< tU) Or (Converging distance < Turning distance)) And (d_{CPA} < d_{safe})*

The results after applying the 2nd modified condition are following. For both cases collision avoid were successful outside of collision radius (Figure 7).

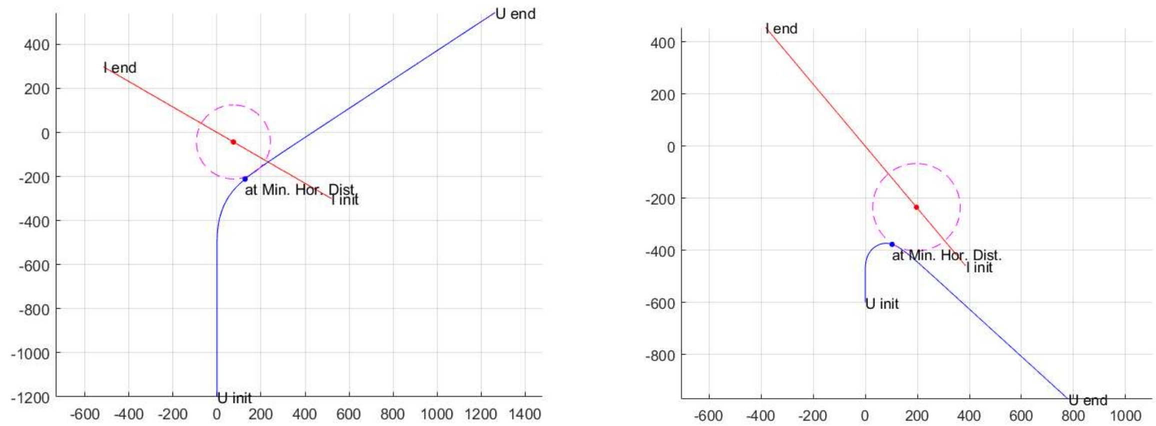

Figure 7 – The result after modification

The modified algorithm above is referred as Version 1. A Version 2 was tested for considering risk analysis against right converging aircraft (Figure 8). A Version 3 was simulated with both modifications considered for Version 1 and Version 2. A total of 9322 cased were simulated. The results of Version

3 were the best among three versions. In particular, Version 3 showed superior results against multiple intruders (Table 2).

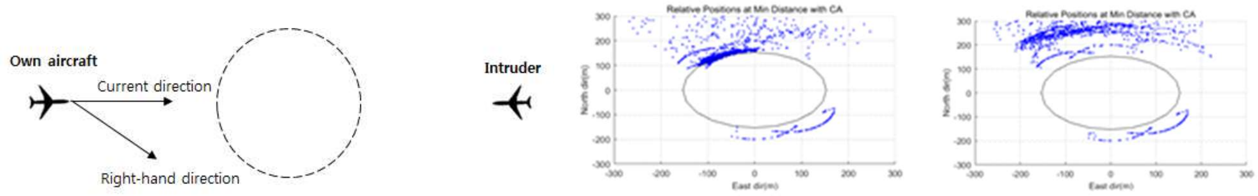

Figure 8 – The risk analysis against an incoming intruder

Table 2 – Comparison between versions

	Head-on	Overtake	Right converging	Left converging	Multiple
Ver 1	170.1541m	170.4055m	171.2734m	171.4085m	152.7683m
Ver 2 (5deg)	156.7348m	152.1035m	102.3793m	158.0994m	160.6464m
Ver 3	170.1541m	170.3796m	171.2734m	170.0180m	170.6996m

The processing time for collision avoidance algorithm consists of the acknowledging time for collision avoidance detection and the calculation time for a new flying course. The maximum acknowledging time elapsed was 22msec for ADSB signal and 502msec for visual signal. The time elapsed for a new course were between 5msec and 21msec. Time units smaller than 1.0 msec were rounded up.

3.2 Test cases generation and simulations

More than 1.38 million test cases were simulated. Test cases were generated for 90 seconds before collision and 30 seconds after collision. The speed of the test aircraft and the intruders varied from 50kts to 150kts at 5kts increments. The direction of intruders varied from 0˚ to 360˚ with 3˚ increments. The climb rate varied from -1000ft/min to 500ft/min at 50ft/min increments. When the minimum distance was not kept, the cause of the issue was analyzed and the algorithm was updated. The latest version of the algorithm showed that not a single case had failed. Also multiple intruder cases were added in the last year. The simulation considered only kinematics, which did not consider the dynamics of the aircraft.

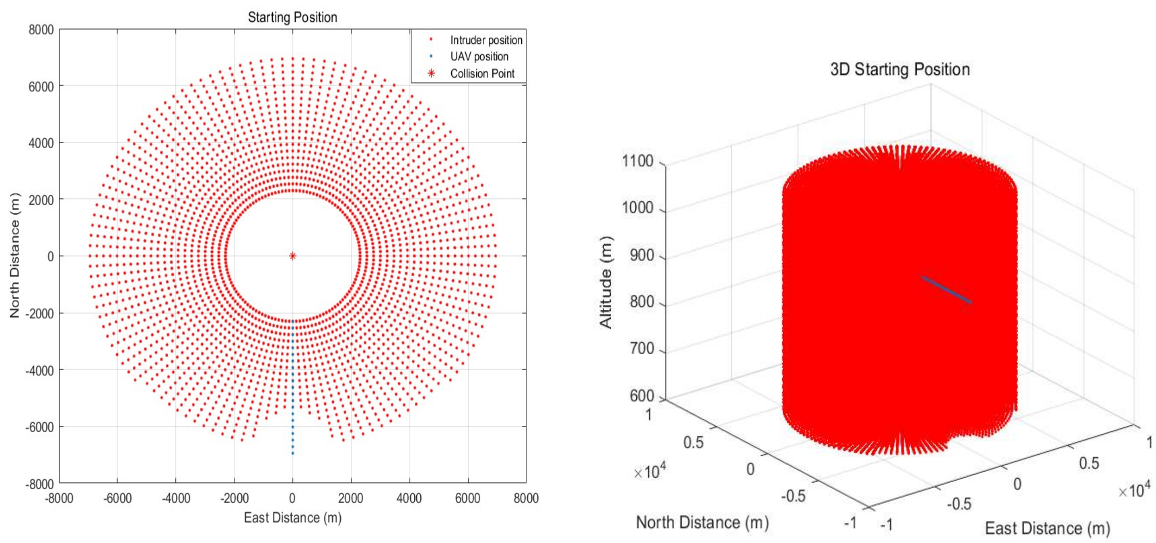

Figure 9 – Test cases for batch simulation

3.3 The results of batch simulation

Using batch type simulation, test cases generated for various relative direction and velocity were tested if the test aircraft can avoid collision against the intruder. There were 1,383,749 test cases for a single intruder, 129,864 cases for two intruders and 114,221 cases for three intruders. The minimum distances were 315.51m, 281.57m and 308.89m respectably. All of them satisfied with the minimum distance requirement. On Figure 10, the left most figure shows the minimum distance are above the green line which is the minimum distance requirement. Figures on the right show the trajectories are also satisfactory.

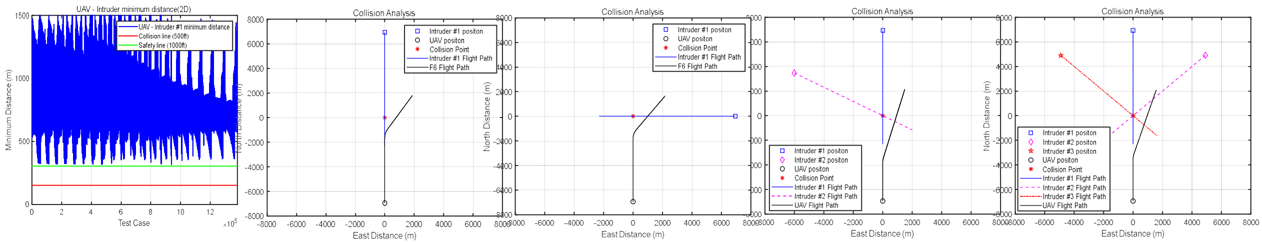

Figure 10 – The results of simulation

4. Flight test Preparation

4.1 Flight testing aircraft

Two aircraft were built to fly in autonomous mode. Since the testing runway is not capable of auto takeoff and landing because of its width and length, takeoff and landing were performed by a pilot on board. When the test aircraft is ready for flight testing in UAV mode, all the control is handed over to the external pilot located in a ground control system.

The test aircraft converted into UAV were two seat manned aircraft originally manufactured by Flight Design in Germany (Figure 11). The intruder is a model CTLS manufactured by Flight Design. The intruder has a smaller engine so it is slower and has smaller wings.

Length/Wing span/Height	6.6m / 8.6m / 2.3m
W_{TO} / W_{OE}	600kg / 480kg
Engine / Power	Rotax 912 / 100hp
Vso / Vc / Vne	40kt / 100kt / 145kt

Figure 11 - Flight testing aircraft

4.2 Optical backup system

Two sets of cameras were installed at the front most end of wing tip. Each camera set has four cameras to cover ±110 degree field of view including one camera directed towards the fuselage to a set of reference marks to compensate wobbling induced during flight. The results of flight test proved the fourth camera for compensation unnecessary since the wobbling was small enough to be compensated by a software filter. Later the fourth camera was replaced with a smaller field view camera to detect aircraft at a farther distance.

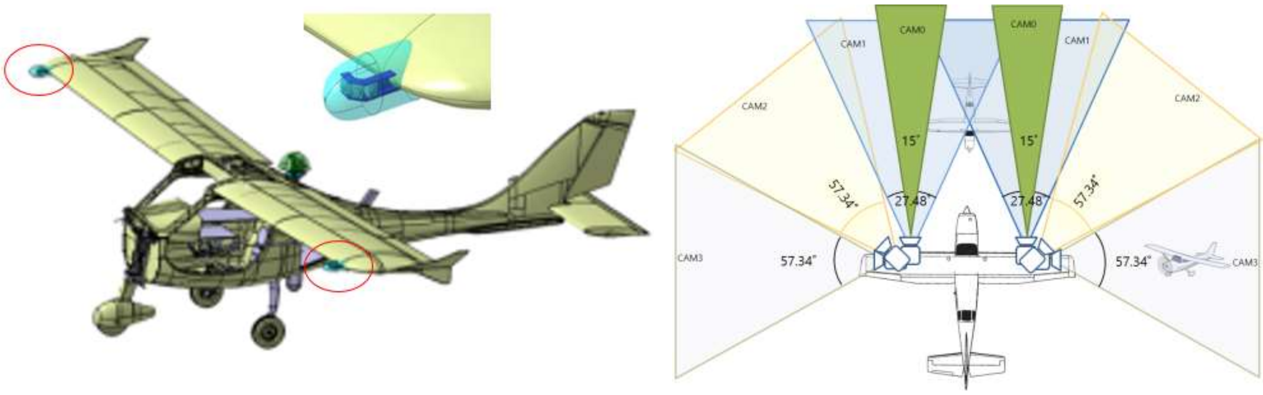

Figure 12 - Video cameras installed

4.3 Ground Control System

A ground control system had been used which was mostly built in the previous project. A set of new equipment were added which are CDTI (Cockpit Display for Traffic Information), ADSB-In, and ADSB-out. The CDTI is the same device built in the test aircraft (Figure 13, Figure 14).

Figure 13 – Ground test devices, ground control system vehicle, testing aircraft

Figure 14 – HILS test, GCS - inside, GCS - monitors

4.4 Flight test environment

The Goheung flight test center is located on the southern shore of Korean peninsula (Figure 15). The runway is adequate for small general aviation aircraft. A new runway is being built for larger size aircraft or auto landing and takeoff UAVs.

Figure 15 – Flight testing facility

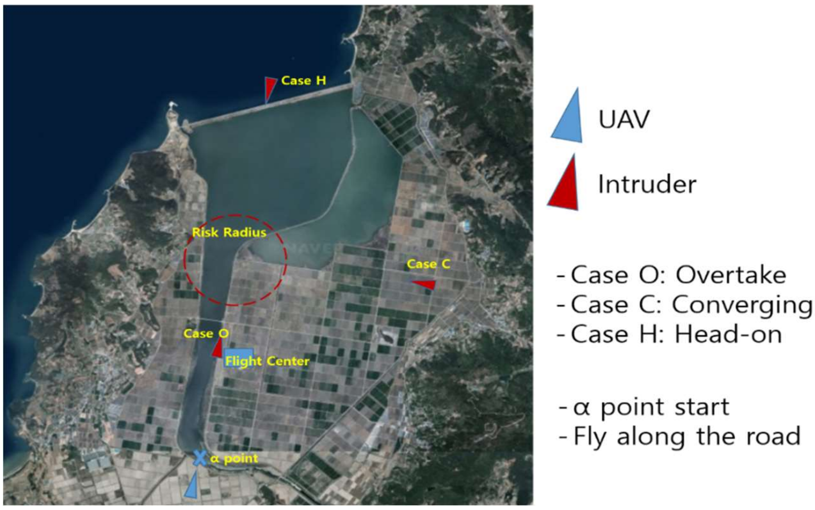

Figure 16 – Top view of flight testing center and aircraft locations for test

On the head-on test, two aircraft are separated vertically and laterally for safety. On the converge test only the altitude separation was applied. There was no separation on overtake case. The test cases were generated against intruder flying to a designed collision point with relative angles of 0˚, 30˚, 60˚, 90˚, 120˚, -30˚, -90˚, 180˚. All these cases were tested with virtual intruders and a limited number of the above cases were tested using a real intruder (Figure 16). For multiple intruders, one of them was a real intruder and remaining aircraft were virtual.

There are two steps for collision avoidance. On self-separation condition the remote pilot located in GCS can change the direction of the test aircraft to the direction displayed in yellow on the monitor. If the pilot does not adjust the direction, the directional arrow changes its color to red and the flight control computer takes over the flight control and does the maneuver.

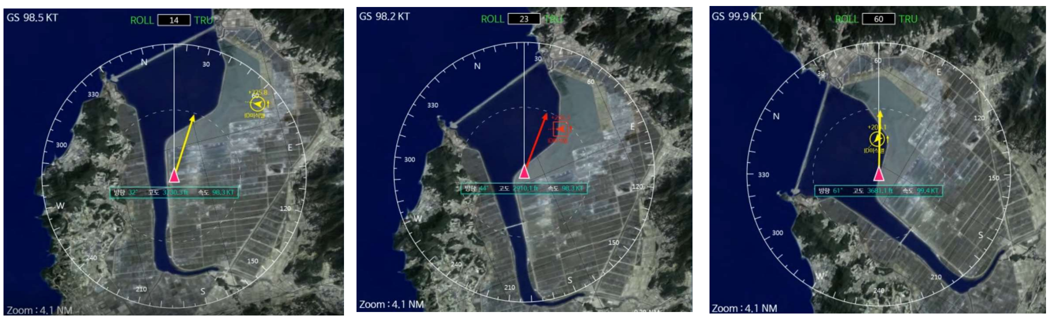

Figure 17 – Warning levels and recommend avoiding direction

5. Flight Test Results

A total of 105 sorties of flights had been flown and each sortie included at least two test cases. Before the aircraft was ready for autonomous flight, most flights were used to acquire images for visual cameras and devices. Not all flights included the real intruder or intruders. Virtual intruder or intruders are a set of data which is broadcasted by the ADSB-Out device located on the test ground facility. Since the ADSB type used in Korea is 1090ES and the ADSB used in the flight test was 978 UAT, the virtual intruders were invisible to other aircraft flying over the Korean peninsula. Otherwise it may have caused a serious risk to other aircraft.

The actual flight tests performed for collision avoidance was 34 sorties which included 86 test cases. The near miss distance referenced is 154.4 meters (500ft) which may be interpreted as an incident or semi-accident. For safety reasons, a larger margin of distance between test aircraft was secured for the actual flight tests. Among the simulation test, the minimum distance between the intruder and the test aircraft was 315.5 meters for a single intruder cases and 281.5 meters for two intruders, and 308.8 meters for three intruders. On the actual flight tests, the minimum distance measured was 295.5 meters, which was well over the goal of the requirement of the project.

5.1 Virtual intruder cases

For safety reason, test cases for virtual intruders were executed before executing test cases against the real intruders. The minimum distance among the test cases was 295.5m on the left converging case, which is well above the required distance

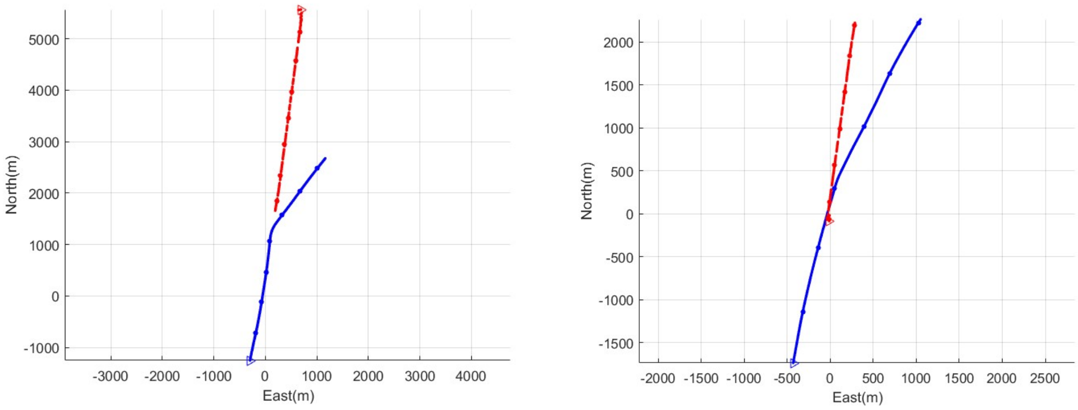

Figure 17 - Minimum distance against the virtual intruder (head-on : 467m, take over : 455m)

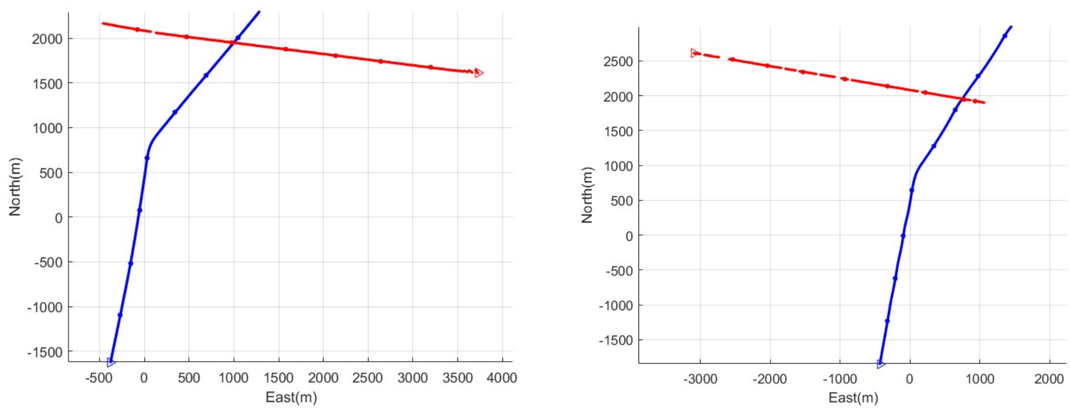

Figure 18 - Minimum distance against the virtual intruder (right & left converging : 482m, 295.5m)

For multiple intruder cases, three virtual intruders were applied. Figure 19 shows test case results against three intruders including right and left converge and head on cases. The result shows larger minimum distance compared to single intruder cases. It was as expected since it is necessary to avoid all incoming intruders early enough to avoid collision

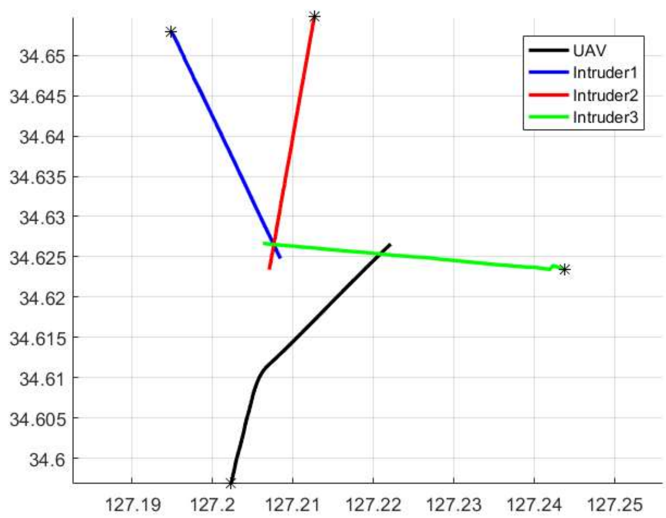

Figure 19 – Minimum distance against the virtual intruders (616m)

5.2 Real intruder cases

On tests for real intruders, for safety reason altitude separation was applied. The minimum distance case was 358m on right converging case. Overall, the trajectories between virtual intruder and real intruder cases were very similar. It was as expected considering the test aircraft does not distinguish a real intruder or a virtual intruder.

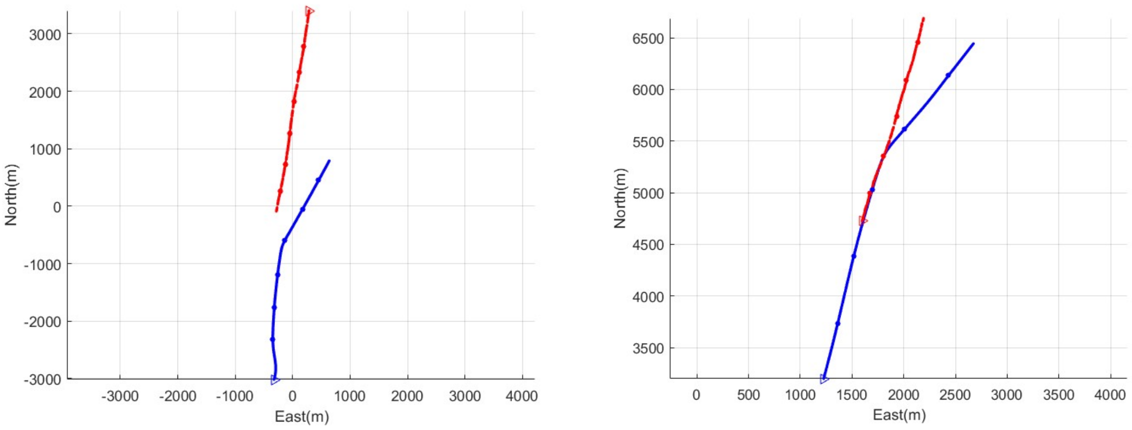

Figure 20 – Minimum distance against the real intruder (head-on : 561m, take over : 414m)

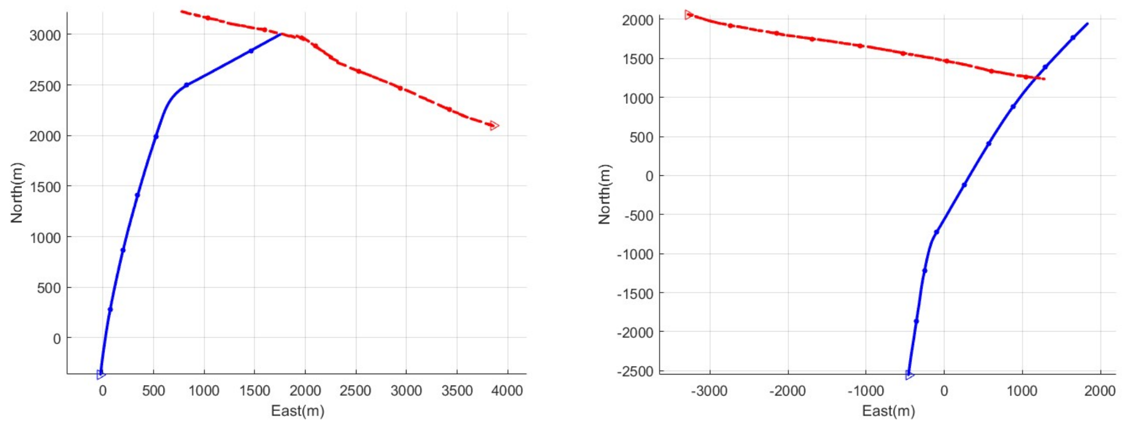

Figure 21 – Minimum distance against the real intruder (right & left converging : 358m, 681m)

For multiple intruder cases, one real intruder and two virtual intruders were applied. The trajectory shows similar results with three virtual intruders.

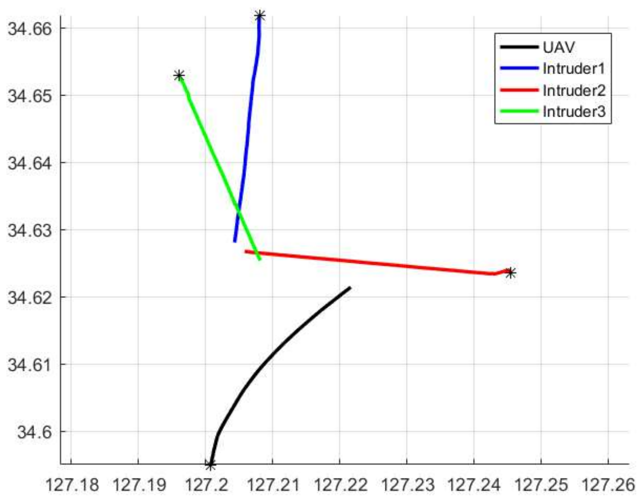

Figure 22 – Minimum distance against the real intruders (857m)

6. Conclusion

For five years, two UAVs had been converted from manned aircraft and 105 sorties of flight tests had been executed. More than a million test cases were simulated for various conditions and showed no failure on algorithms. The most important minimum distance between the intruder and the test aircraft had met the preset criterion, and all the required calculations had been finished within the required time limit.

The results of this preparatory research will be adapted into UAM development with the capability of adapting collision avoiding rules which will be a key issue while developing UAM.

7. Acknowledgement

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9. Copyright Statement

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