Hindawi
International Journal of Aerospace Engineering
Volume 2024, Article ID 7328971, 22 pages
https://doi.org/10.1155/2024/7328971

Research Article

UAV Detect and Avoid from UTM-Dependent Surveillance

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Received 25 May 2023; Revised 21 September 2023; Accepted 4 March 2024; Published 9 April 2024

Academic Editor: Vijayanandh Raja

A hierarchical unmanned aircraft system (UAS) traffic management (UTM) system has deployed 45 ground transceiver stations (GTS) for UAS services in Taiwan. This UTM system covers most areas for UAV-dependent surveillance using ADS-B Like technology. UTM Controller can monitor all UAV flights under transparent surveillance in low airspace. Controller-initiated UAV “detect and avoid” (DAA) mechanism assists UAV separation to ensure flight safety on UTM for small multirotor UAVs. From similar concept to traffic alert and collision avoidance system (TCAS) for the manned aircraft system, the UTM software executes DAA functions to generate approach alerts to UTM Controller. Conflict is detected by heading arrow extrapolation from multiple approaching UAVs by their time to conflict (TTC) on icons. Traffic advisory (TA) and resolution advisory (RA) are pronounced on UTM console to controllers. The less priority UAV pilot will receive the controller-pilot communication (CPC) to perform avoidance resolution. In UTM, the surveillance data period is broadcasting at 5~8 seconds on LoRa (long-range wide-area network) chip. Referring to TA = 48 seconds and RA = 24 seconds, the signal delay in ADS-B Like system to UTM server is about 0.5 seconds and CPC response is measured about 3~5 seconds. From real flight tests, the RA is enough for the less priority pilot to maneuver UAV for avoidance. From real flight tests, the proposed DAA mechanism based on UTM-dependent surveillance is feasible to resolve multiple approaches. The developing UTM system using ADS-B Like technology is also examined of high availability with redundant reliability and performance stability for flight safety.

1. Introduction

The civil and commercial applications of the unmanned aircraft system (UAS) have become well accepted, such as aerial photography, search and rescue, parcel delivery, security and surveillance, precision agriculture, and infrastructure inspection [1]. The business volume of UAS application is growing rapidly, and the demand for UAS traffic management (UTM) is also increasing. According to the forecast report of Research and Market, “the Global UTM market is anticipated to reach USD 1,098 million by 2030, growing at a Compound Annual Growth Rate (CAGR) of 33.9% from USD 106 million in 2022” [1]. Facing such a rapidly growing UAV commercial market, the safety management of airspace is extremely important under UTM. Especially when UAVs are flying into the National Airspace System (NAS), harmonization from UTM to ATM will become the most concerning issue to impact flight safety.

In this paper, the detect and avoid performance is focused on the small multirotor UAVs, especially those flying under 400 feet for civilian applications. When business UAS delivery can be legally operated, low-altitude flight safety becomes hazard and threat.

Under the same flight safety requirement of the manned aircraft, when UAV can be legally flown into the National Airspace System (NAS), the adopted communication, navigation, and surveillance (CNS) technology shall fulfill the aviation system standards [2]. Just like manned aircraft in the NAS, dependent surveillance in air traffic management (ATM) [3] is the most important part for civil aviation operation after 2010. Automatic Dependent Surveillance-Broadcast (ADS-B) is the typical one of dependent surveillance to work with the secondary surveillance radar (SSR) of independent surveillance. CNS/ATM project enhances flight performance and ensures aviation safety to include satellite resources into aviation CNS. Under the same considerations, UTM for UAVs should be compatible to ATM for manned air transport aircraft in surveillance [2, 3]. UTM system deployment becomes a key technology to promote UAS services into real world [4].

The hierarchical UTM system developing in Taiwan was firstly presented in ICNS conference in 2019 [5] and more detail reports later [6, 7]. The proposed UTM system is designed and implemented with similar concept on air traffic management (ATM) [3] as shown in Figure 1.

Under UTM common concept, all UAVs are equipped with different communication channels to recognize and respond to each other's position in real time. This should be a basic requirement. From which, Murrell et al. [8] tried to construct UAV to UAV (V-V) communication for awareness of approaching UAVs by dedicated short-range communication (DSRC) radios on technology capability level four flight tests. V-V shall make effective to detect conflict approach and resolution among UAVs.

In the developing UTM [5], the ADS-B Like technologies were studied for flight data broadcast and LoRa (long-range wide-area network) was selected to establish dependent surveillance capability for UTM. The UTM project highlights the ADS-B Like technology using "Semtech" LoRa chip to design on-board unit (OBU) and deploy LoRa Gateways as ground transceiver stations (GTS). The embedded unique code in LoRa chip is marked as the remote identification (Remote ID) for UAVs [6, 9]. ADS-B Like design for UAS follows the similar concept of ADS-B in the civil aviation system [3, 5]. It adopts the dependent surveillance mechanism to be effective to air vehicles operating in low altitudes. Other definitions using Bluetooth and Wi-Fi technology were announced [10] to comply with national UAS regulations.

In 2022, NASA's ADS-B technology has licensed to Vigilant Aerospace for use the company's "FlightHorizon" DAA and airspace management product. FlightHorizon PILOT™ uses the signal from an aviation ADS-B transponder to track all other nearby aircraft in real time. It provides self-separation and maintains a well clearance in the form of waypoints to the autopilot [10]. FlightHorizon PILOT™ design meets the FAA Remote ID regulation with beyond visual line-of-sight (BVLOS) flights. DO-365B is the Minimum Operating Performance Standards (MOPS) for phase 2 of the detect and avoid (DAA) development initiative approved by RTCA. It can be used in manned aircraft and unmanned aerial vehicles to detect the intruding fling targets and generate warning signal and perform avoidance. Do-365B is cooperative with ADS-B in UAV remote operation. It is an active DAA as well as TCAS in airborne [11].

Minucci et al. analyzed the limited resources and shortage of ADS-B for air transport aircraft to open to UAVs [12]. The *ADS-B Like* technology is the most qualified candidate for its high availability, low cost, low power, and easy implementation [5, 6]. An ADS-B Like OBU can be affixed on UAVs to broadcast flight data to GTS. The ADS-B Like

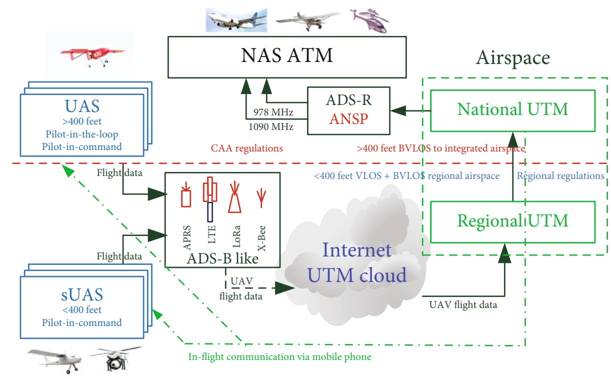


Figure 1: The developing UTM in Taiwan [5].

technology is adopted in the UTM infrastructure and deployed in Taiwan for testing in 2022 as shown in reference [6]. The LoRa-constructed UTM using ADS-B Like OBU to GTS has been verified in services with full coverage from low to high altitudes, below 400 feet to thousands of feet. However, in metropolitan areas, UAVs flying under 100 feet (10 floor building) may be blocked by tall buildings.

In low-altitude flights, such as ultralights or unmanned aerial vehicles, radar surveillance is not available and effective. In early time, when mobile 2.5G system was used, a collision detection and avoidance was studied in theoretical analysis [13] and by real-time flight test [14]. Recently, more collision avoidance algorithms were surveyed by different approaches and system structure [15]. Active detection and dependent surveillance are emphasized. Those developments successfully constructed a useful TCAS for small aircraft by dependent surveillance concept from ground control computer. He et al. [16] developed a collision avoidance approach using the sensory layer and the path planning by sense-active mapping with an idea of autonomous mental development. Similarly, Aggarwal and Kumar [17] also proposed a rule-based method to enhance pilot operation under instrument proficiency for UAV collision avoidance. To ensure UAV flight safety, regulations and rules are most concerned by a rule-based collision avoidance method by Hu et al. [18].

Similar concept for ultralight TCAS [13, 14], the dependent surveillance of 2.5G cell phone device is replaced by the OBU of the proposed UTM system with preliminary development [7]. With full deployment in Taiwan UTM system [6], various scenarios and collision avoidance algorithm are developed in this paper.

On OBU, each LoRa chip is embedded with a unique code as the *Remote ID* for UAV [19]. It is marked with icon on UTM console to show the registered pilot and UAV. In system performance, the UTM receives the first position data from UAV that can be locked and marked on the server as the *Station ID* for this flight mission [6]. On UTM, all flight data are stored for historical review.

This UTM developing project has been constructed and deployed with 45 GTSs to cover most of Taiwan territory for UAV surveillance [6].

To run this UTM system, a UTM control center is built. There are UTM consoles in front of controllers, for GIS display and real-time flight data. This design is similar to ATM control center for future UTM to ATM harmonization.

In the UTM trial tests, there is safety threat in low altitudes when multiple UAVs appear in the same airspace. Detect and avoid (DAA) becomes important in the regional UTM (RUTM) operation. The preliminary DAA solution is presented with an early idea in ICNS 2021 [7] to study flight data manipulation to generate an effective avoidance. After some improvements, the enhanced research results are presented.

In 1960s, the aircraft collision avoidance system (ACAS) was developed for passenger aircraft. The International Civil Aviation Organization (ICAO) has legislated ACAS as a flight safety equipment on airborne for all passenger aircraft since 1991. In the meantime, the FAA developed traffic alert and collision avoidance system (TCAS) to implement on airborne. TCAS II V7.1 became a standard equipment in air transportation system [20].

The "detect and avoid" (DAA) is an important function for UAS. There are different methods using different technologies. It is classified as active and passive detections. LiDAR is a new technology to sense short-range targets and their separation in airborne. UAS introduced LiDAR to acquire 3D vision in different directions from UAV to find hazardous fields out of UAV. LiDAR offers information for the avoidance algorithm to calculate obstacle avoidance on small UAVs (sUAS) for active detection. For a stationary obstacle, this method is feasible. But UAVs are flying dynamically to cause this method with potential difficulty to detect and identify the target in time. In addition, UAV pilots may be unable to immediately respond to this conflict information by V-V (vehicle to vehicle) communication [8], to recognize the intrusion of conflict and avoid. The intrusion detection and avoidance resolution are critical issues. Regarding TCAS, the DAA can rely on UTM system software to estimate multiple approaching UAVs and pronounce an alert to UTM Controller by time to conflict (TTC) assessment. This paper proposes the dependent surveillance mechanism to monitor the flights by the third person. UTM software assists automatic conflict detection and generates different levels of alerts.

In reality, UAVs are difficult to actively detect the intruding UAVs from different directions using wireless or video technologies. Hunter and Wei [21] proposed a good concept for DAA resolution. It showed a good mathematical model and algorithm without a clear indication of target detection by flight tests. Since the incoming UAVs are relatively small compared to other obstacles in the open airspace, it is difficult to aim at the targets and identify them beyond 768 meters. This is the approaching distance of two multirotor UAVs by TA = 48 sec at 8 m/sec speed. Under the proposed UTM-dependent surveillance concept, since the UTM server receives all UAVs and displays on the monitors, the approaching objects can be clearly identified by UTM Controller when TA alert is generated from UTM software [7]. This follows the same procedures in air traffic control (ATC) under ADS-B performance in TCAS [3, 7].

When the ADS-B is launched in 2010, it is effective to enforce aircraft surveillance with real-time position reports. Similar to ADS-B [11], Zipline provided as acoustics detect and avoid method for all commercial and military aircraft, helicopters, and UAS [22]. It used a touchscreen Lynx solution to offer operators to see the flying UAV by ADS-B in airspace.

With ADS-B Like technology using Wi-Fi, Minucci et al. constructed Wi-Fi technology to detect the intrusions for avoidance [11, 12]. Hunter and Wei [21] proposed service-oriented technology for separation under UTM. Most recent researches tried to focus DAA mechanism with ADS-B Like technology.

In air traffic control, the ADS-B data rebroadcast is an enhancement to extend surveillance data of manned aircraft through different frequencies, such as 978 MHz for general aviation and 1090 MHz for air transports. Mott et al. [23] studied the detection and separation of ADS-B-equipped aircraft. When UAS is operating in the National Airspace System (NAS), UAV data from UTM should be transparent to ATM. Separation to manned aircraft should be a "must" response. A similar idea also proposed in Figure 1 to rebroadcast UAV surveillance data via Air Navigation Service Provider (ANSP) by ADS-R turned out to be a viable solution to conflict detection and resolution for different types of flying vehicles, especially for those UAVs flying into higher altitude. This is known as the harmonization of UTM to ATM in the future.

To integrate UAVs into the NAS, the FAA requires "a compatible see-and-avoid requirement for unmanned aircraft." Whitney proposed an ADS-B on-board unit to implement into sense and avoid for UAVs in [19]. This is a passive method for conflict detection. This strongly supports the concept of using ADS-B. Minucci et al. [12] developed an ADS-B Like device using 4G/LTE for sUAS under 400 feet. It meets the FAA regulation for low-altitude sUAS. 4G/LTE is the most adequate device to implement on board with link to the Internet. In the hierarchical UTM system, ADS-B Like using LoRa technology is adopted on OBU and deployed on GTS [5, 6].

Civil Aviation Authorities (CAA) worldwide have been actively creating regulatory frameworks to allow autonomous UAV to fly safely beyond visual line of sight (BVLOS) [22]. Iris DAA is cooperative manned aircraft using ADS-B to broadcast their position and other aircraft or UAVs. This DAA system is able to pick up that broadcast and maneuver around them as needed. However, the majority of manned aircraft is noncooperative, meaning they do not broadcast their position. This is especially true for the types of aircraft and missions that are commonly flown at low altitudes. Since UAVs are mostly unequipped with ADS-B to become one of the noncooperative aircraft in the National Airspace, Iris DAA solution [24] is emerging as the primary means of risk mitigation for autonomous unmanned aircraft systems (UASs). In the TCAS for air transportation aircraft, the ADS-B passive report was designed into avionics. This mechanism is termed as ADS-B-TCAS by the development [2]. For most multirotor UAVs, weight and power are critical to flight performance by adding extra payloads. Active detection method is limited to implementation due to its sensing range and target size. The developing ADS-B Like

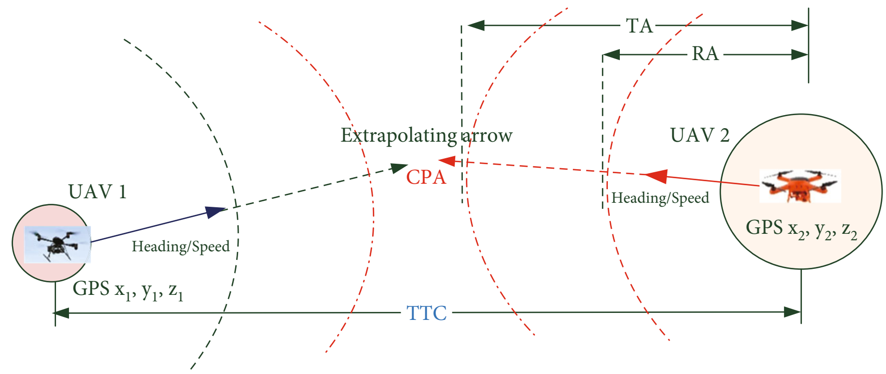


Figure 2: Definition of UAS separation bubble.

technology is optimistic to work with dependent surveillance concept for DAA. The DAA software is manipulated on the UTM platform.

In the proposed UTM system, UAVs are under dependent surveillance by the UTM Controller [5, 6]. The developing UTM system intends to extend flying vehicles into wider coverage in transparent information exchanges. Any conflict approaches among multiple UAVs in a small airspace can be effectively detected and altered. The proposed DAA resolution can promptly be activated by UTM Controller to command UAV pilot to make avoidance.

This paper develops a software DAA mechanism based on a dependent surveillance from UTM operations by controller to pilots. Real flight tests are demonstrated with different approach scenarios following TTC assessment to look into the performance of the proposed DAA by UTM-dependent surveillance. The proposed DAA accomplishes an excellent solution for UTM in approach awareness, conflict detection, and avoidance resolution.

2. UTM Deployment

Under the UTM architecture, UAVs operating in the designated airspace can be fully monitored by real-time operation. The proposed hierarchical UTM system infrastructure in Taiwan has deployed with 45 ground transceiver stations (GTSs) using LoRa Gateways. GTSs relay UAV reporting data into UTM cloud and server via the Internet [6]. The LoRa OBU broadcasts flight data to GTS for surveillance. As shown in Figure 1, the OBU design has included *Remote ID* by UAV and pilot, which was issued by FAA on December 28, 2020. In addition to UTM performance, the first data that appears on surveillance display will be logged on UTM server as *Station ID*. The Remote ID binds UAV operator with pilot license and legal registration. In the OBU design, each LoRa chip has its unique code to assign to UAV or pilot. This complies with the system operation requirement of a Remote ID and Station ID. In this way, UAVs broadcast ID and flight data to UTM. From preliminary tests, the prototype UTM has successfully demonstrated and verified reliable UAV surveillance capability with a similar operation mechanism to ATM [3, 5]. On UTM system, UAVs appear into certain airspace and will be sectioned in a small area on GIS. While UAV data are mapping onto UTM surveillance server, these position data can be checked by their TTC for conflict assessment.

The developing UTM system has produced OBUs [6], to broadcast UAV flight data down to GTS, which has deployed island-wide GTS coverage in Taiwan [5, 6]. Each GTS covers larger than 15 km in radius. The flight data can be received from more than two GTSs. The GTSs are redundant to each other to receive the same data simultaneously in better broadcast reliability and efficiency [5]. From the preliminary test results, the data communication range can reach 40 km or farther with 89% reliability with redundancy.

3. Dependent Surveillance DAA

3.1. Separation Bubble and UTM Icon. In TCAS, a separation bubble is defined as a protection circle around the aircraft [8]. Any intrusion to touch the separation bubble will be pronounced as approaching to UAVs, terrain or obstacle. The separation bubble is designed by an icon with an arrow of its heading direction and length for speed, as shown in Figure 2. Due to UAV speed and direction are varying, conflict assessment by time to conflict (TTC) of two UAVs is defined instead of their separation distance [8]. Under TTC concept, separation bubble sizes vary with respect to UAV speed. Traffic advisory (TA) and resolution advisory (RA) are defined between them. The TCC concept suits all types of aircraft in collision avoidance, for TA = 48 seconds and RA = 24 seconds [8] for TCAS of the air transport aircraft. This is also useful to DAA in UTM.

The UAV heading arrows are extrapolated to 48 seconds to intersect the closest point of approach (CPA) of two nearby UAVs. This is defined as a possible conflict point.

For all types of moving vehicles, e.g., cars, vessels, and aircraft, there are three directions to approach as shown in Figure 3 [3, 20]. Since the proposed DAA is performed on UTM console display, the controllers can easily notice their relative positions of the approaching UAVs, when TA is pronounced from DAA. The UTM Controllers can choose either one to follow up. If UAV1 is marked as the owner, a hazard line (in green color) will be created along its flying direction to get the following scenarios.

(a) From lateral conflict as UAV2, the left-hand side has low priority to avoid

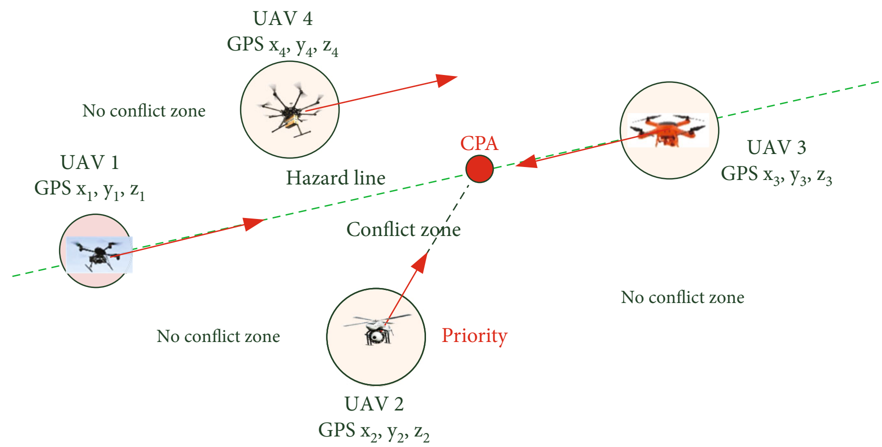


FIGURE 3: Scenarios of conflict from different directions.

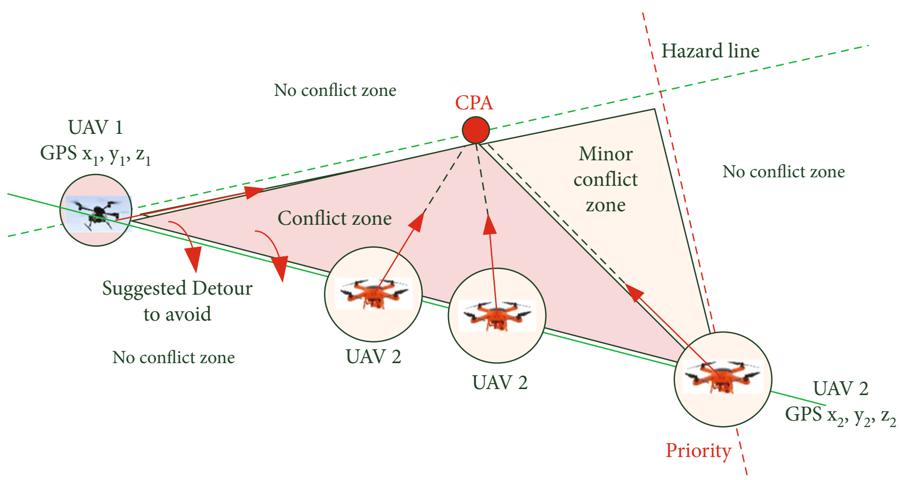


FIGURE 4: Triangular analysis for UAV approaching to conflict.

(b) Head-on conflict as UAV3, both need to make the right turn to avoid

(c) Parallel flight as UAV4, no conflict at this moment

(d) Detect the nearby UAVs for possible approaches to conflict and resolve

3.2. Triangular Analysis Method. A lateral approach conflict happens, as shown in Figure 3. In this scenario, if UAV1 is marked as the ownership, UAV2 is approaching to conflict. There is a CPA of intersection of UAV icon heading arrow extrapolations. A triangular conflict zone can easily be sketched by UAV1, UAV2 (from 3 locations), and CPA. The proposed ADS-B-DAA will check their relative position and pronounce TA and RA to alert the controllers. If either UAV changes its heading direction, the triangular conflict zone needs to be resketched. The new situation may change the conflict threat to dismiss DAA alert. This can be resulted of that UAV1 changing direction as an arrow of "suggested detour to avoid" in Figure 4.

When the UAVs keep approaching to CPA, the DAA mechanism will check their TA by TTC = 48 seconds to generate an alert to UTM Controller. When TA is pronounced, the UTM Controller should watch their movement in the next few seconds. If both UAVs proceed to CPA, RA by TTC = 24 seconds will be pronounced with a warning. The Controller initiates CPC to pilot of the less priority UAV to maneuver an avoidance. In Figure 5, UAV1 makes right turn 30 degrees for 20 seconds to diminish the high conflict zone.

When *multiple UAVs* appear in the same airspace, the UTM system will generate an alert signal to UTM Controller. For multiple UAV conflict, the solution process will start from the *shortest TTC*. Figure 6 shows a scenario of multiple conflicts. UAV1 is randomly selected as the ownership, and a hazard line is generated as green. The conflict zones are marked as CPA 1-4 with TTC = 60 seconds, CPA 1-2 with TTC = 80 seconds, and CPA 1-3 with TTC = 90 seconds. It is quite clear that UAV3 has actually no conflict to UAV1, although UAV3 appears on the console display. By elimination, only UAV2 and UAV4 need to be resolved.

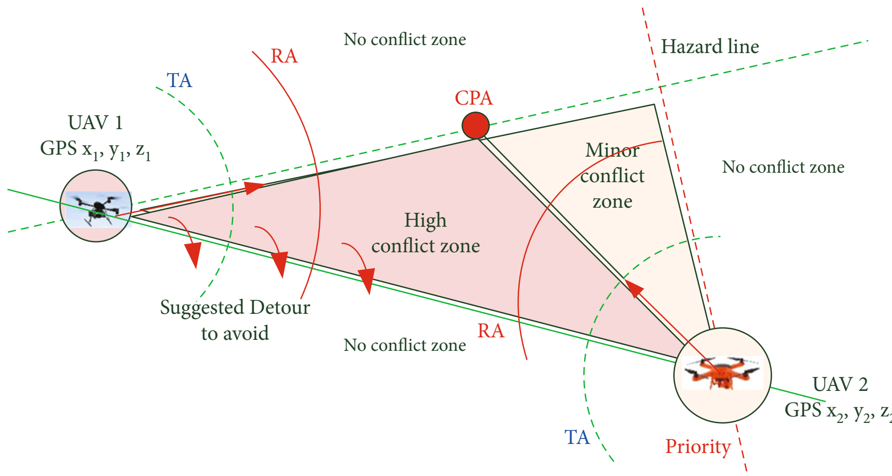


Figure 5: Approaching to CPA.

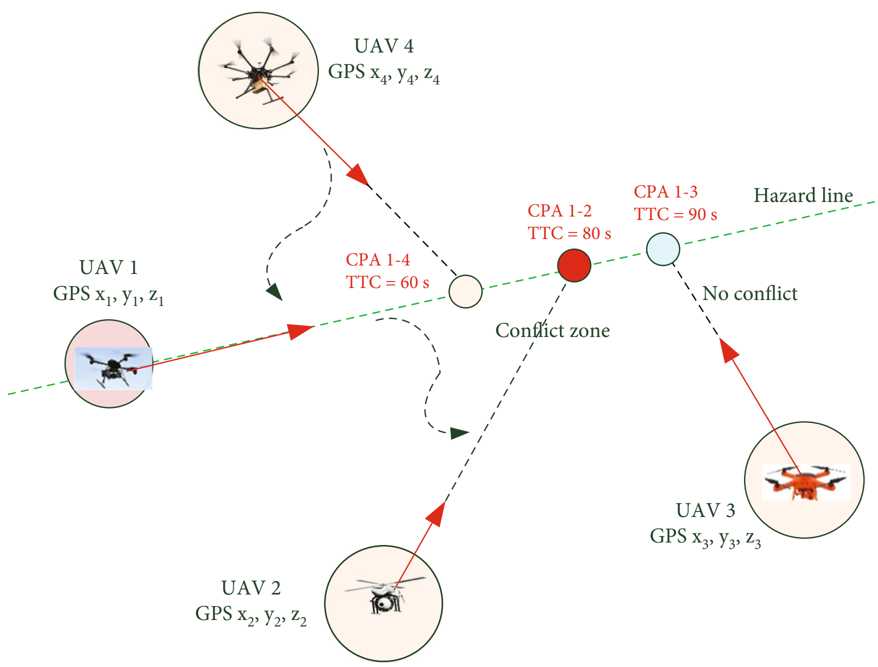


Figure 6: Multiple conflicts.

Based on the simple rule, UAV4 has the shortest TTC, and it should be resolved at first. In this scenario, the process should follow:

(a) UAV4 has less priority, and UTM Controller should ask UAV4 to make right turn for avoidance at RA. As the dash line, UAV4 should return to its original path after 20 seconds of detour avoidance

(b) Continuing to the UAV1 to UAV2 with new RA, UAV1 should make right turn to avoid. As the dash line, UAV1 should return to its original path after 20 seconds of detour avoidance

(c) Although UAV3 is on the console display, UAV3 to CPA is estimated for 90 seconds. It has passed the hazard line earlier than the others and causes no conflict in this airspace

3.3. Software Formulation. When two UAVs are flying in the same RUTM airspace, the UTM displays their relative locations with icon to show their separation. If these two UAVs are located inside the conflict range, the UTM Controller should be noticed with their relative position until:

(1) Approach continues TTC to a conflict assessment

(2) Proceed to TTC < 48 seconds, TA pronounces

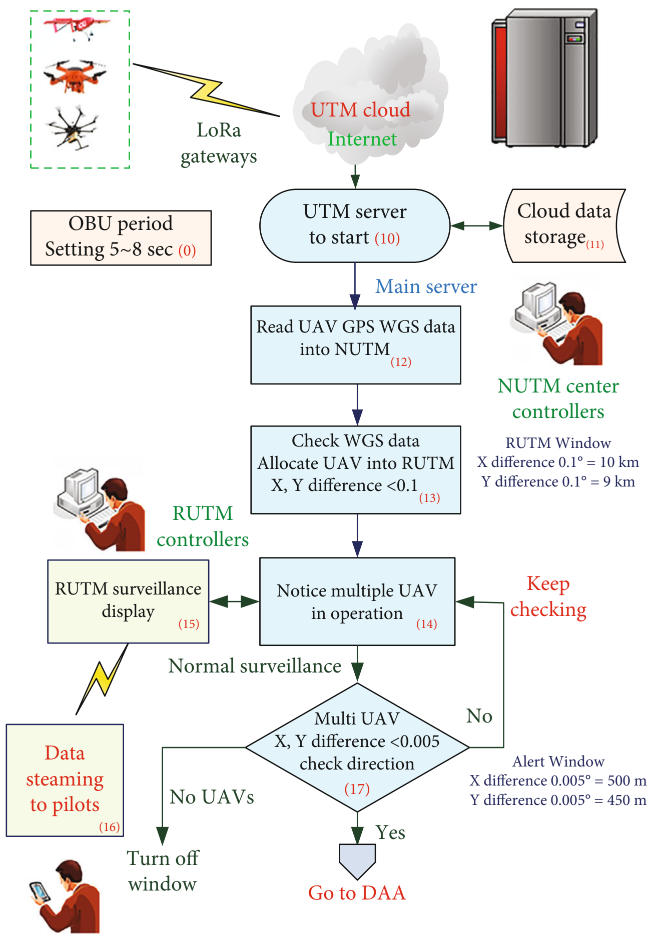


Figure 7: DAA data flow in UTM.

(3) Proceed to TTC < 24 seconds, RA pronounces; UTM Controller initiates CPC to less priority pilot for avoidance

(4) Deviate from hazard to free from a conflict

(5) Next, approach check

When conflict assessment confirms a threat, the icon arrow will stretch out to explore the heading airspace. If two arrows from approaching UAVs hit an intersection, their separation will assert TTC limit. The DAA flow chart on UTM is sketched in Figures 7 and 8.

Step 1 (check the UAVs in the surveillance airspace).

(a) From GPS receiver, the Earth coordinate data are in 8-digit decimal. Compare two UAVs with their longitude (E) and latitude (N), and calculate and assert their separation by TTC

(b) In RUTM airspace, the longitude (E axis) difference is 0.1 decimal for 10 km, and the latitude (N axis) difference is 0.1 decimal for 9 km in Taiwan. In RUTM, the multirotor UAVs are flying at speed range of 4~10 m/sec, and their surveillance range is also limited due to battery endurance for less than 40 minutes

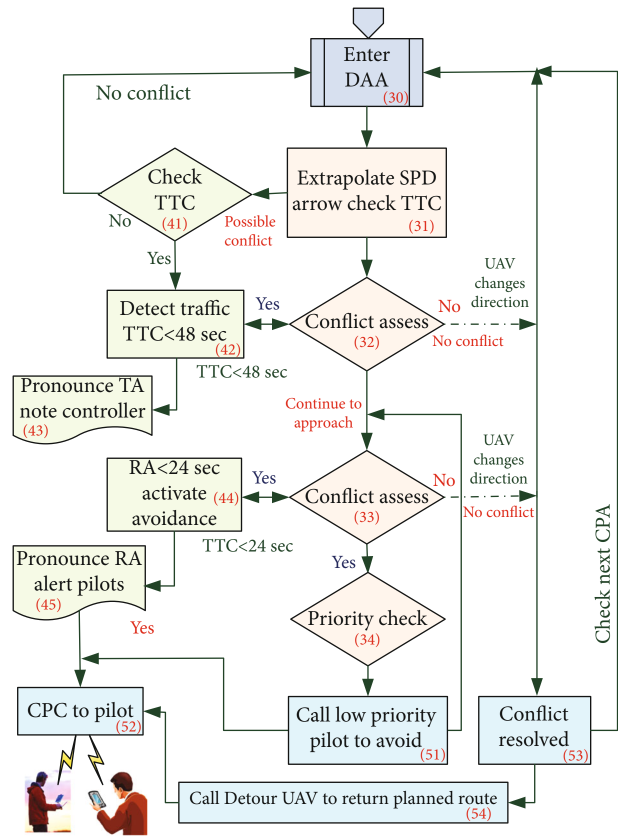


Figure 8: The UTM conflict assessment and resolution.

(c) The Taiwan UTM system defines a RUTM surveillance window of 20 km by 18 km of airspace. Inside a surveillance window, it contains alert areas and conflict sections. The definitions are (1) for an alert area, WGS data < 0.1, where $X < 10$ km and $Y < 9$ km in RUTM, and (2) for a conflict section, WGS data < 0.005, where $X < 500$ m and $Y < 450$ m in RUTM

Step 2. Once a UAV is detected in an airspace, the registered UAV with Remote ID will be marked on the UTM icons on its RUTM area. In the UTM control center, multiple displays by 1, 4, and 9 windows are designed for Controllers to watch on the UAS traffic. In front of UTM Controller, the common console displays the manipulating alert surveillance [4].

Step 3 (conflict assessment for approaches).

(a) UAVs enter RUTM, the separation check follows:

$$\text{WGS}|X_1 - X_2| < 0.1, \text{window range} < 10{,}000\ \text{m}, \quad \text{or TTC} > 1250\ \text{sec}, \tag{1}$$

$$\mathrm{WGS}|Y1 - Y2| < 0.1, \text{window range} < 9{,}000\ \mathrm{m}, \text{ or TTC} > 1125\ \text{sec.} \tag{2}$$

(b) These UAVs can be shown on the same RUTM window

Step 4 (conflict assessment for TA/RA).

(a) All UAVs under surveillance will be shown on UTM displays. UAV position is cross compared with their separation by TTC to assert the multiple approaches and conflict

(b) Under dependent surveillance, all UAVs should broadcast their position data to UTM cloud in real time. Their data will be processed to check inside their operating areas of 20 km by 18 km in RUTM airspace. Once multiple UAVs appear inside the same airspace, DAA shall activate to check the approaches and possible conflicts. They will be monitored on console display

(c) The position check algorithm follows X-Y coordinates in WGS by the following:

$$\mathrm{WGS}|X_1 - X_2| < 0.005, \text{separation} < 500\ \mathrm{m}, \text{or TTC} > 62\ \text{sec}, \tag{3}$$

$$\mathrm{WGS}|Y_1 - Y_2| < 0.005, \text{separation} < 450\ \mathrm{m}, \text{or TTC} > 56\ \text{sec}. \tag{4}$$

(d) Conflict assessment shall be activated to generate warnings to UTM Controller by TA and RA

For a quadrotor, a heading arrow shows its direction with length for its speed. The icon has a tail in dash line for the past track by 5 periods. UAV *Remote ID* of "MX1122" is following with its altitude of 45 m MSL. The arrow length represents UAV speed by m/sec. The arrow can be extended longer to check TA in 48 seconds or RA in 24 seconds. Different levels of alerts will be generated to notice the UTM Controller. When RA alerts, a resolution command shall be pronounced by UTM Controller to pilot. TTC is the baseline for conflict and avoidance for UTM Controller. Priority check is important by UTM Controller. Less priority UAV pilot should make ways for the high priority one. The conflict assessment flow chart for DAA resolution is shown in Figure 8. It will iterate until conflict is totally resolved.

In UTM, the sUASs are operating under 400 feet. There is little vertical tolerance for UAVs to perform vertical separation. Vertical separation is not recommended in the UTM. After the X-Y coordinate check, all UAVs in the same airspace must proceed with conflict assessment by heading arrow extrapolations. Referring to Figure 2, any extrapolation arrow will penetrate into another's separation bubble, or any cross-over of two arrows, a conflict will happen in the next 48 seconds. UTM Controller should take actions to command the less priority pilot to make ways.

4. Maneuver Flight Avoidance

There are different scenarios for conflict assessment and resolution. This procedure follows simple rules to assert priority. For all types of vehicle traffic, the right-hand side vehicle gets higher priority. In flight intersection, there are four possible scenarios: (1) bypass by the same direction approach, (2) head-on approach, (3) lateral approach, (4) speed to catch up the intersecting point early.

4.1. Bypass by the Same Direction. When two UAVs are flying in the same direction, the following UAV is catching up to bypass over the preceding one. On UTM, the following UAV arrow will hit the preceding separate bubble to assess an approach or a conflict. The preceding UAV has higher priority. An alert is generated by their position check to notice the UTM Controller. After immediate check, if their separation falls into TA and RA, the Controller should use CPC to command the following UAV to bypass through from the right-hand side and catch over. In UAV operation since there is not enough vertical tolerance, vertical pass through is not recommended.

4.2. Head-On Approach. When two UAVs are flying on the opposite direction along a line, head-on approach happens. UTM will calculate their TA to pronounce an alert and then RA to send avoidance command. Both UAVs have no priority. Both UAV should make ways for the upcoming UAV. The UTM Controller will call from CPC to command both pilots to turn right at 15° for 20 seconds to avoid.

4.3. Lateral Approaches. There are different conditions for lateral approaches. The scenarios count the approaching angle from sharp angle to obtuse angle. There is a strict rule to identify the priority one in traffic system suited for all vehicles [8, 14]. The DAA mechanism will follow the procedures on UTM: (i) assess TA to alert, (ii) assess RA for resolution, (iii) CPC to less priority pilot for avoidance, and (iv) command detour flight to return its original planned path. Scenarios may change if two UAVs are located in different coordinates. The following figures show the conflict resolution after approach to RA. From these scenarios, the avoidance standard operation procedure (SOP) should be simple to manipulate by the less priority pilots. Figures 9 and 10 summarize the conflict scenarios into quadrant configurations. These figures are easy for Controllers to monitor all UAVs and identify their relative relationship with the UTM. The command should be brief and precise through CPC, such as "turn right for 20 seconds and return to original path." On Zello broadcast, CPC should receive reply instantly from the pilot.

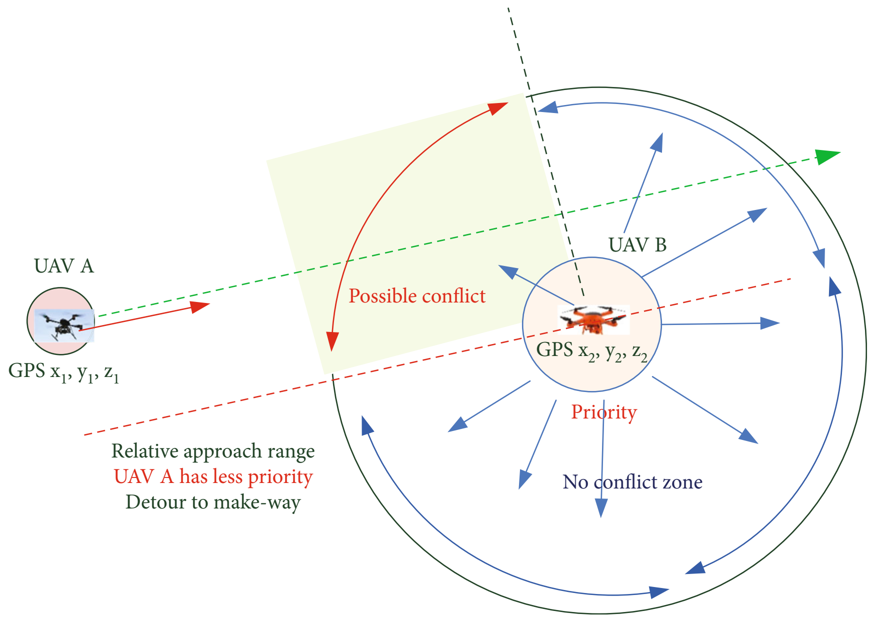


Figure 9: From UAV A, UAV B enters possible conflict zone on its fourth quadrant.

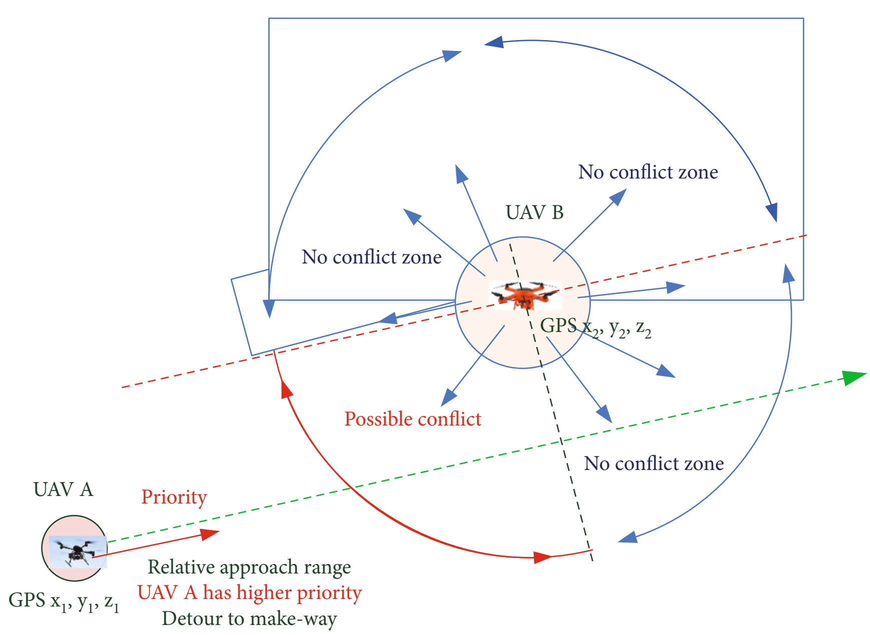


Figure 10: From UAV A, UAV B enters a possible conflict zone on its third quadrant.

4.4. Speed Up to Pass the Intersecting Point. Avoiding resolution for approaching UAVs is possible by changing either one's flight speed. The trajectory extrapolation may get an intersection point in earlier time. If TA alerts, the UTM Controller can ask the one closer to the point to speed up to pass over the intersecting point earlier for avoidance. This is the Controller's decision and makes CPC coordinate at TA. But reversely, reducing the speed from one to make way for the other is not recommended although multirotors have the capability to hover. Wake turbulence due to UAVs at crossover will not cause serious disturbance to flight performance.

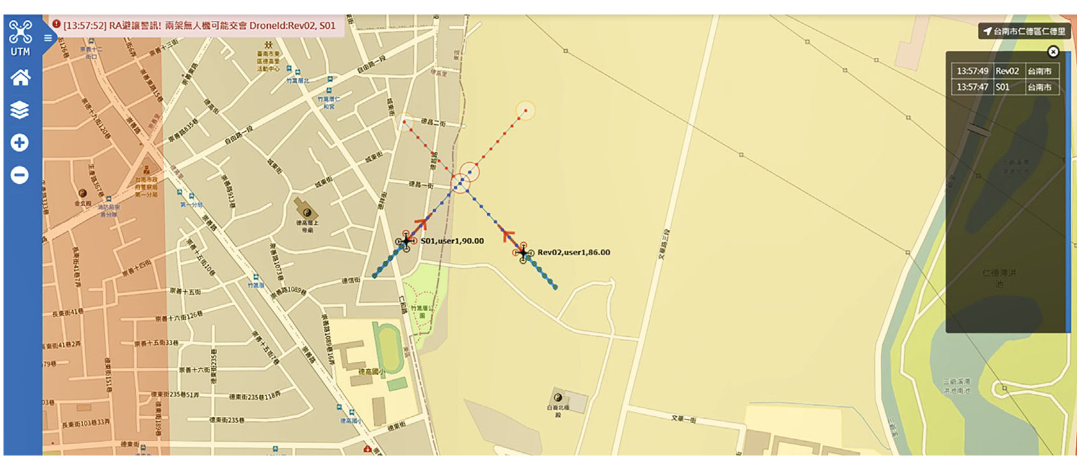
5. DAA Test Flight on UTM

The dependent surveillance in aviation system requires all participating aircraft installing dependent surveillance devices, such as ADS-B in the air transport system for manned aircraft on ATM, or ADS-B Like OBU [5] for UAVs on UTM in this paper.

Following the DAA flow chart on UTM in Figures 7 and 8, the trial flight tests are conducted to check the feasible manipulation and flight performance to UAVs. The proposed UTM system implements DAA software with the following conditions:

(a)

(b)

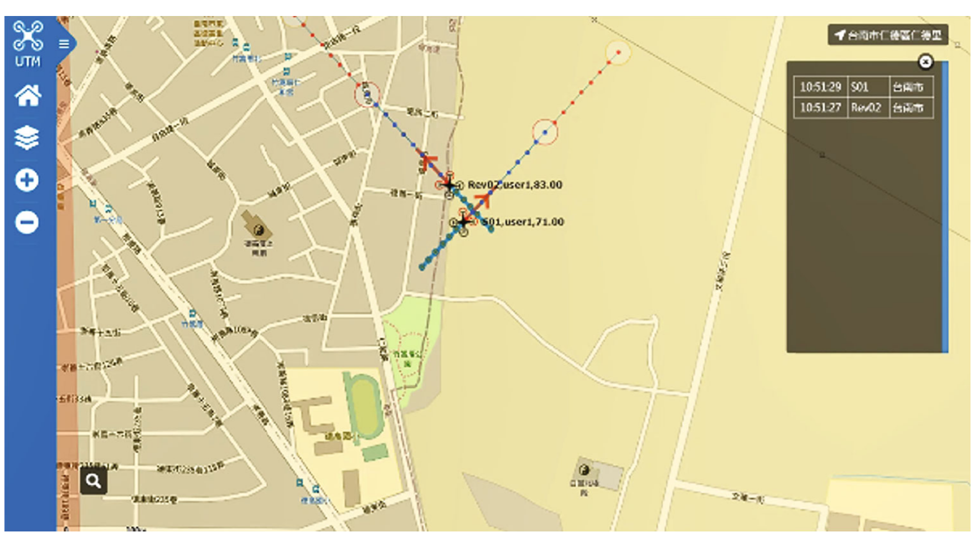


(c)

Figure 11: Continued.

(d)

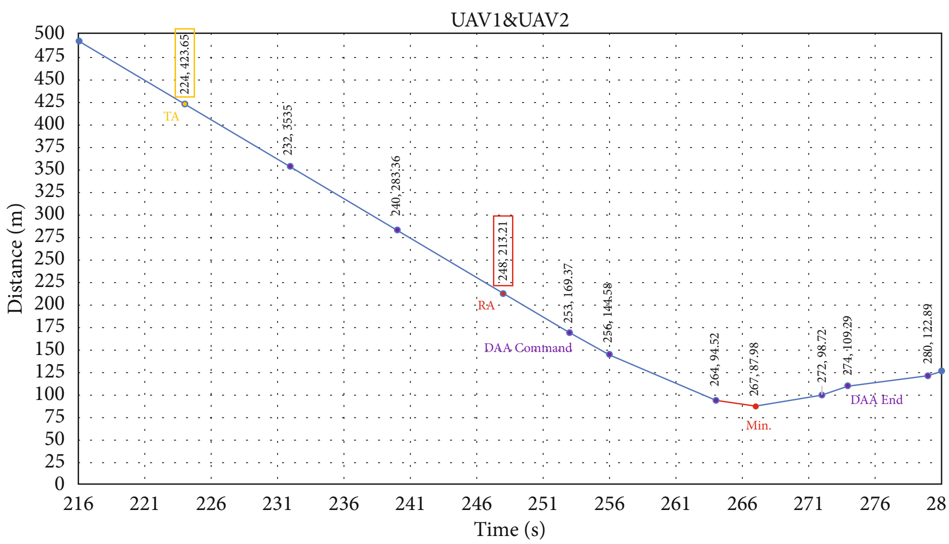
(e)



(f)

Figure 11: Continued.

(g)



(h)

Figure 11: (a) On *flight 1*, UTM display shows that two UAVs are approaching to conflict. (b) On *flight 1*, two UAVs are extrapolated to check TA and RA. (c) On *flight 1*, conflict assessment of RA < 3 data periods. (d) On *flight 1*, S01 turns heading east to make way for Rev02. (e) On *flight 1*, after 20 seconds, S01 returns to its original direction by UTM Controller command. (f) On *flight 1*, S01 proceeds to fly behind Rev02 with separation. (g) On *flight 1*, two UAVs return to their planned paths. (h) Separation from UAVs with safety margin 87 m in *flight 1*.

(a) All participating UAVs shall install LoRa OBU for dependent surveillance

(b) When pilots register a flight mission on UTM, they need to join UTM Zello broadcast for CPC on personal cell phones or Zello handsets. Pilot's personal cell phone is also required for redundancy

(c) When UAVs have taken off, the initial process on UTM shall check and identify which UAVs are flying in the RUTM airspace to fit Equations (1) and (2) for surveillance

(d) All UAVs outside the RUTM airspace will not perform data cross-check

(e) UTM surveillance continues to all UAV position data to fit Equations (3) and (4) into approaching airspace in RUTM

(f) All UAV data falling into the small airspace need to carry DAA check for TA and RA

(g) Check flight direction to estimate possible conflict by intersection angle θ under different quadrants as shown in Figures 9 and 10. Confirm the priority of the approaching UAVs

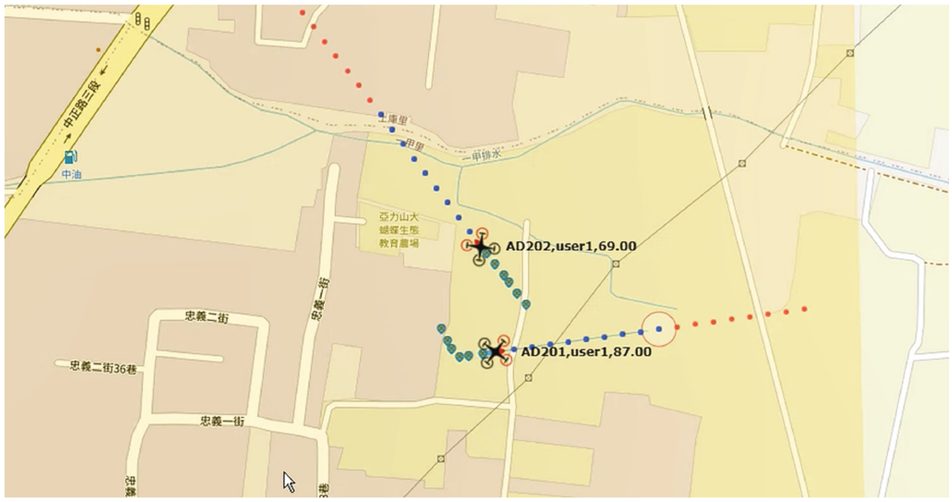
(h) Following Figures 9 and 10, less priority pilot shall turn the UAV to the right to avoid conflict. In most cases, the less priority UAV should make at least 15~20° turn or be given a new heading to fly behind

(a)

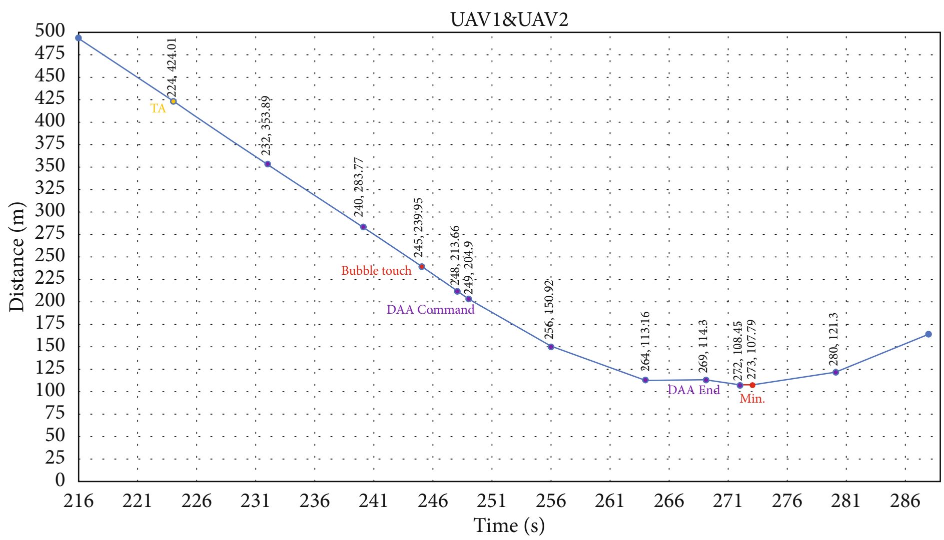
(b)

(c)

Figure 12: Continued.



(d)



(e)

Figure 12: (a) On *flight 2*, UTM detects UAVs are approaching. (b) On *flight 2*, TA and RA are pronounced on UTM. (c) On *flight 2*, AD201 turns for avoidance. (d) On *flight 2*, AD201 returns to its planned path. (e) Separation from UAVs with safety margin 107 m on *flight 2*.

the high priority UAV for 20 seconds and return to its original path

(i) The UTM Controller shall call CPC to the less priority pilot to make avoidance at the proper time

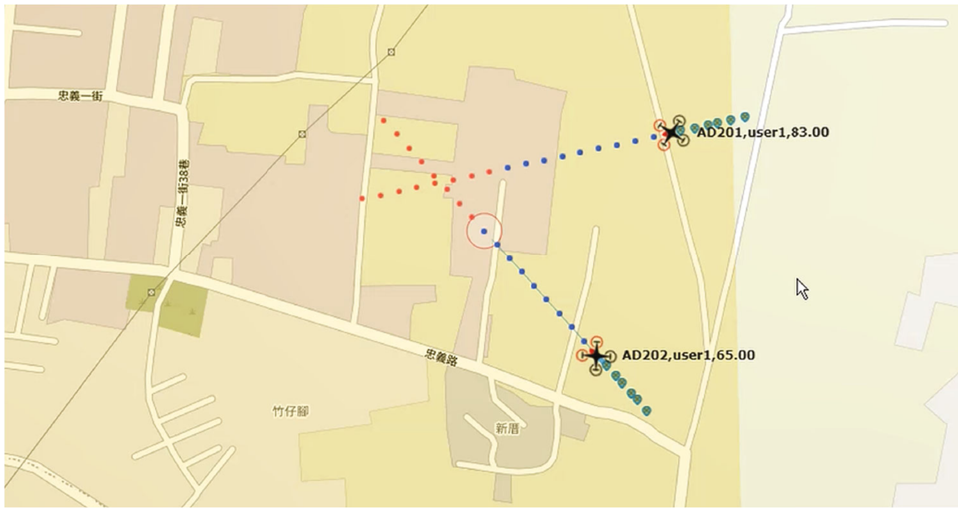
(j) Until conflict has cleared, all UAVs can return to their planned path and continue

DAA flight tests are conducted by two groups of pilots under scheduled flight routes of lateral approaches. *Flight 1* to *flight 3* are scenarios of lateral approach to conflict and follow detour resolution. *Flight 4* and *flight 5* are scenarios to command one UAV to speed up to catch over the intersecting point earlier for avoidance.

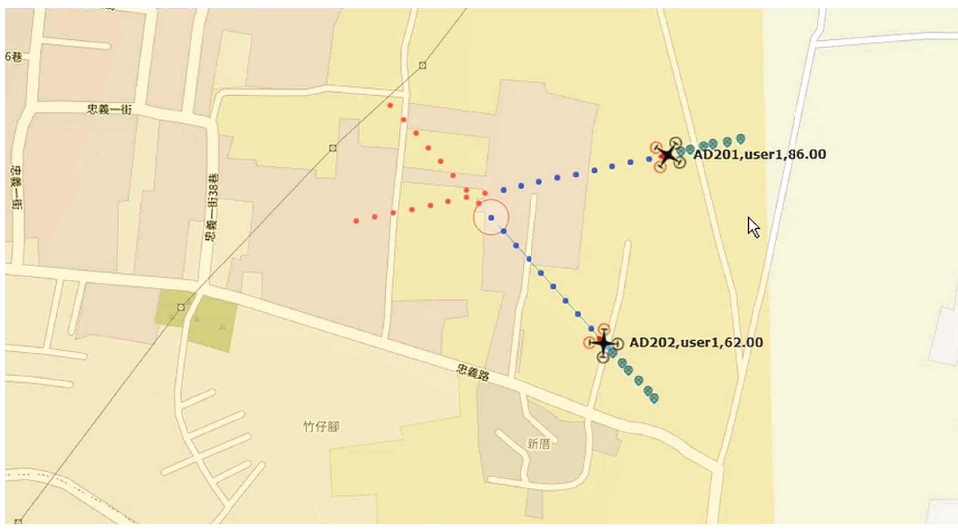
The following tests will show DAA operation on the Controller console. Remote ID and altitude for each UAV is assigned and displayed with icon on the console display. UTM parameter setting for DAA function should be determined in the RUTM performance. They are constraints of WGS *X*-*Y* coordinate difference < 0.005, data period at 8 seconds, RA = 3 data periods (24 seconds), and TA = 6 data periods (48 seconds). In most conditions, these parameters are fixed at DAA-enabled setting on UTM. The UTM software will track and check all UAVs in the RUTM airspace.

5.1. Lateral Approach to Detour. Flight 1 is an example to demonstrate on UTM for two UAVs in the same airspace as shown in Figure 11(a). UAV pilots are *S01* and *Rev02* with Remote ID on the icons. By checking UAV WGS *X*-*Y* coordinates with constraint < 0.1 to fall into the alert area and constraint < 0.005 to enter into approach section, two UAVs are approaching possible conflict with arrow extrapolation, as shown in Figure 11(b).

When conflict assesses TA < 48 seconds, in Figure 11(b), the upper left corner appears a flashing signal to alert the UTM Controller for the approaching.



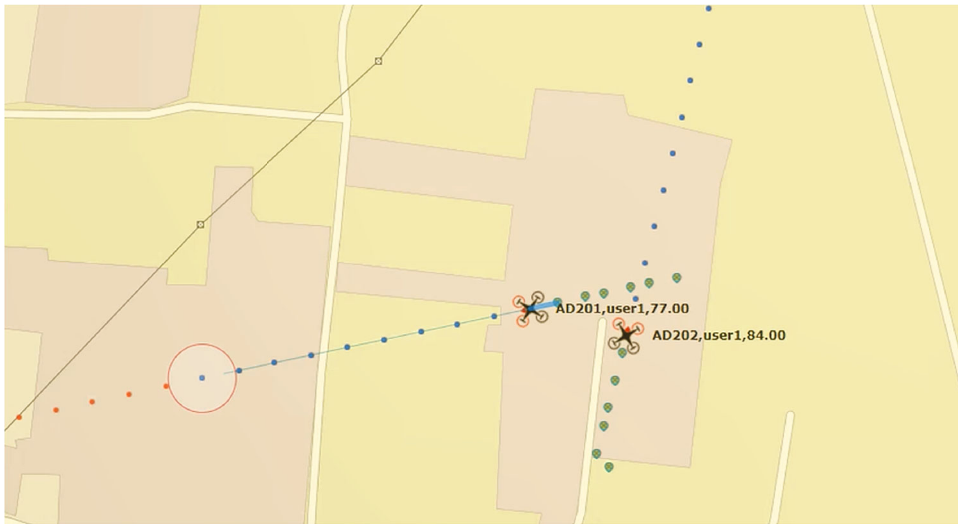
(a)



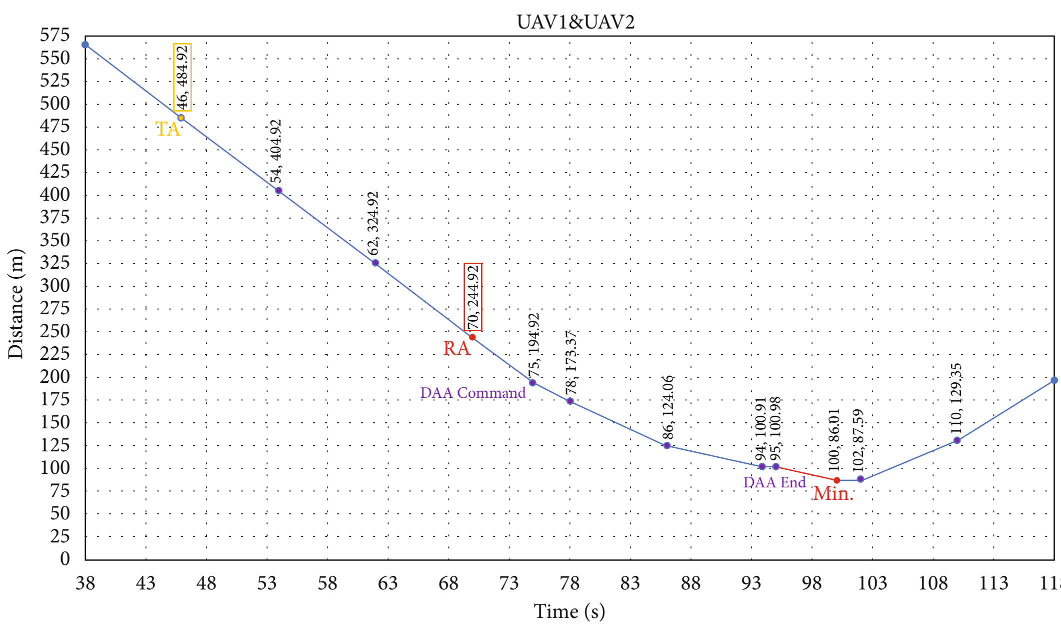
(b)

(c)

FIGURE 13: Continued.



(d)



(e)

FIGURE 13: (a) On *flight 3*, two approaching UAVs activate DAA. (b) On *flight 3*, two UAVs are approaching to TA. (c) On *flight 3*, UAV AD132 makes turn to avoid. (d) On *flight 3*, DAA completes and AD132 returns to planned path. (e) Separation from UAVs with safety margin 86 m on *flight 3*.

When both UAVs continue to fly, the conflict detection will assess RA < 3 data periods. The upper left corner of UTM console display will pronounce RA warning with flashing red as shown in Figure 11(c). The left-hand side UAV (*S01*) has less priority. The UTM Controller commands the S01 pilot to make ways to resolve the conflict. The avoidance resolution should command S01pilot to make right turn *heading east* for 20 seconds. Through CPC, the UTM Controller sends the command to the less priority pilot as shown in Figure 11(d).

By manipulating DAA, S01 UAV will detour to a new trajectory behind Rev02. S01 shall return to its original planned path to continue. Figures 11(e) and 11(f) show the DAA resolution being completed on UTM. Figure 11(g) shows that two UAVs are continuing on their planned paths.

The separation distance from two approaching UAVs is recorded from UTM as shown in Figure 11(h). In principle, the proposed DAA concerns UAV separation by TTC, and the separation record presents the safety margin from each other.

Flight 1 demonstrates a complete record of a conflict flight in the RUTM airspace. To activate DAA procedure, CPC from UTM Controller sends avoidance command to pilots. From the tests, Zello conducts reliable voice communication between the controller and pilots.

5.2. Two Scenarios of Lateral Approach. Flight 2 and *flight 3* demonstrate two scenarios for lateral approach DAA. The UTM Controller follows the SOP to communicate with

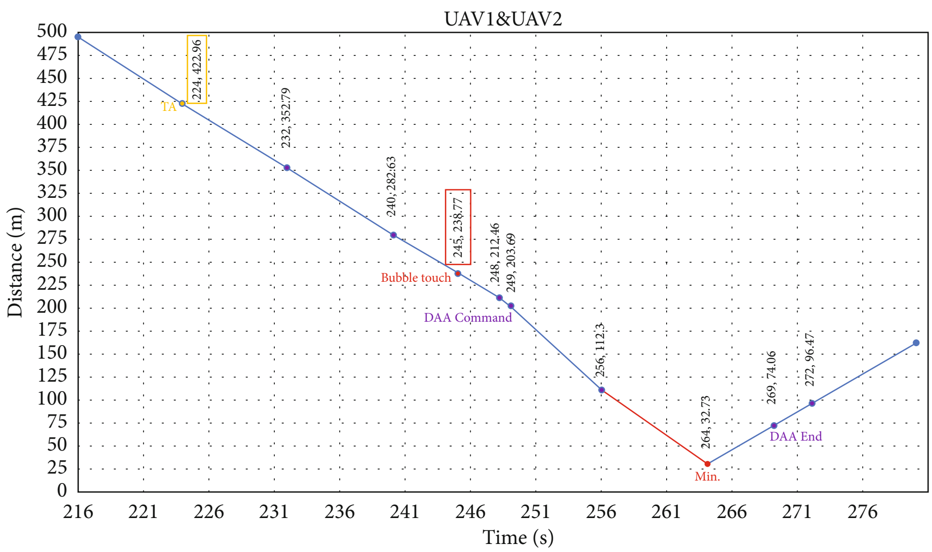
(a)

(b)

(c)

Figure 14: Continued.

(d)



(e)

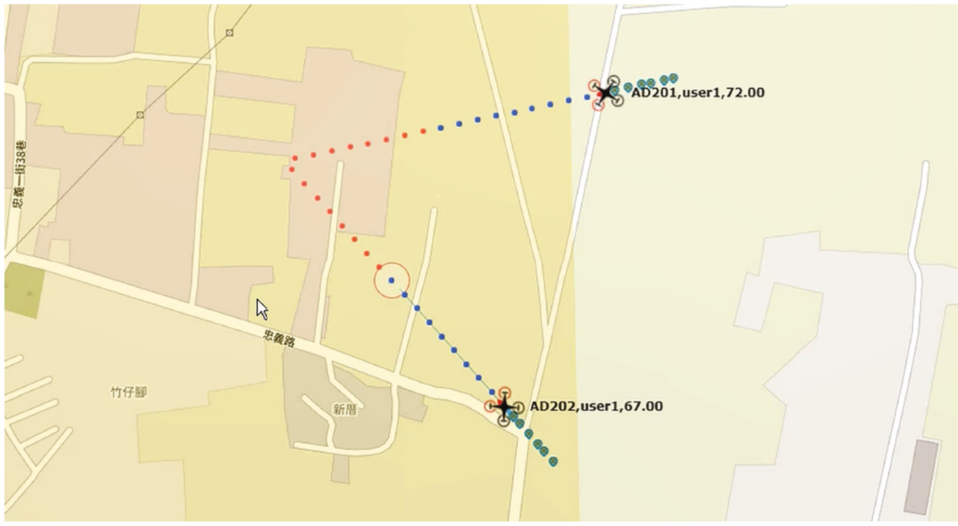
Figure 14: (a) On *flight 4*, two UAVs are approaching into RA at very close altitude of 60 m. (b) On *flight 4*, AD201 asks to speed up faster from 6 m/sec to 8 m/sec to catch over the intersecting point. (c) On *flight 4*, AD201 has already passed the intersection point to avoid. (d) On *flight 4*, DAA completes by speed-up resolution. (e) Separation from UAVs with safety margin 32 m on *flight 4*.

pilots to take avoidance. Figures 12(a)–12(d) show that two UAVs are approaching from different directions to a conflict. The proceedings of AD201 and AD202 are closing to their TA and RA to activate DAA as shown in Figure 12(b). Since AD201 has less priority, it takes a right turn to avoid as Figure 12(c). After the conflict is cleared, AD201 returns to its original direction and continues as shown in Figure 12(d). The CPA is calculated in Figure 12(e) to show that the safety margin is 107 m from each other.

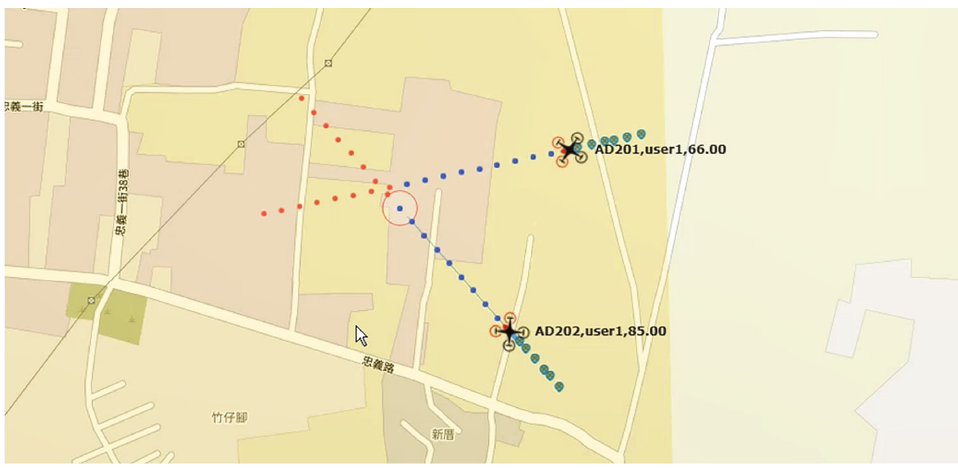
Flight 3 shows the third scenario of lateral approach from the flight test results. The figures appear similar to the previous one. Figures 13(a)–13(d) show that two UAVs are flying westbound with possible conflict direction. When they are approaching to a TA and RA, the DAA activates to command the avoidance as shown in Figure 13(b). Since AD202 has less priority, it takes a right turn to pass AD201 from behind, as shown in Figure 13(c). After the conflict is cleared, the conflict is dissolved as shown in Figure 13(d). The CPA is calculated in Figure 13(e) to show that the safety margin is 86 m from each other.

5.3. Lateral Approach by Speed-Up. Since multirotor UAVs can control flight speed easily from normal to high, the icon extrapolation shows that one UAV can catch over the intersecting point earlier. The UTM Controller can issue a "speed-up" command to resolve the conflict. The following flights demonstrate the speed-up resolution on DAA is shown in Figures 14 and 15 for *flight 4* and *flight 5*.

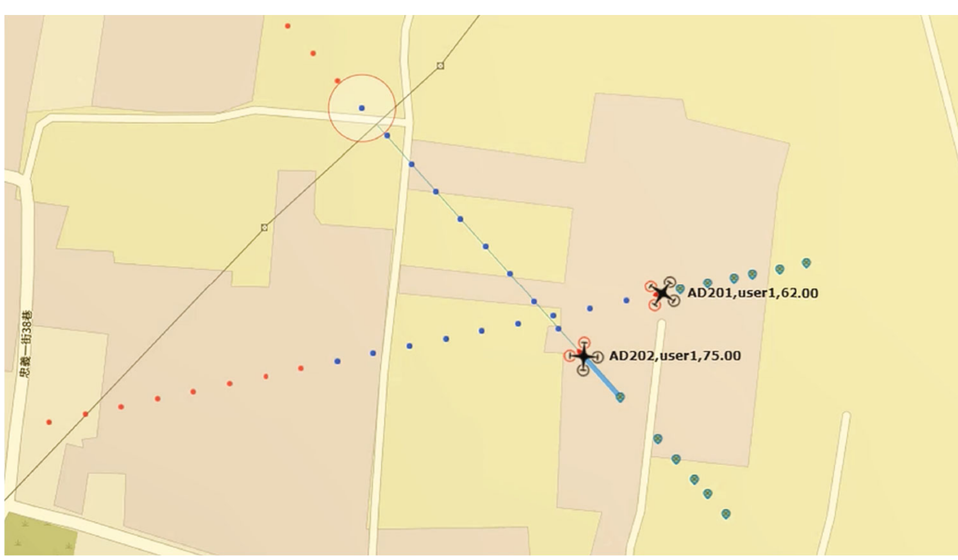
Flight 5 shows another speed-up scenario.



(a)

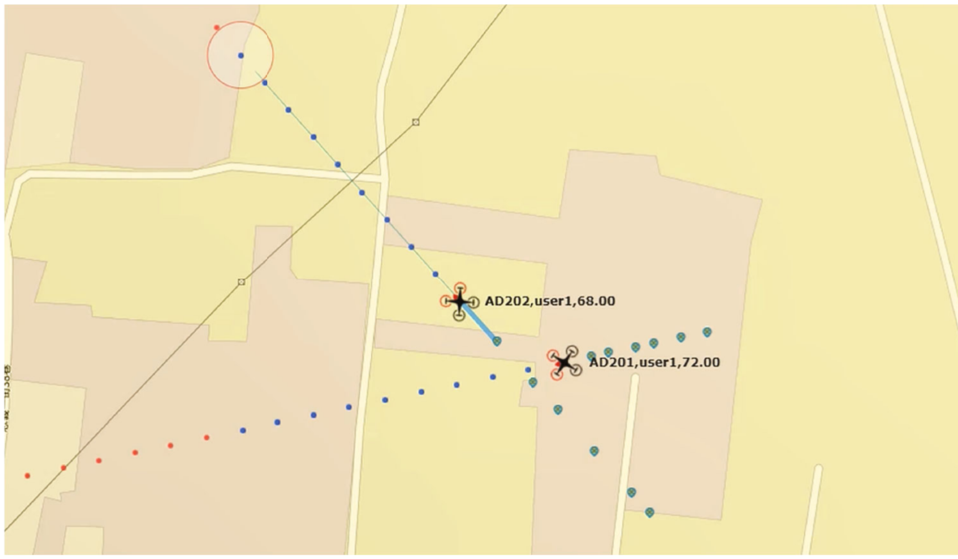


(b)

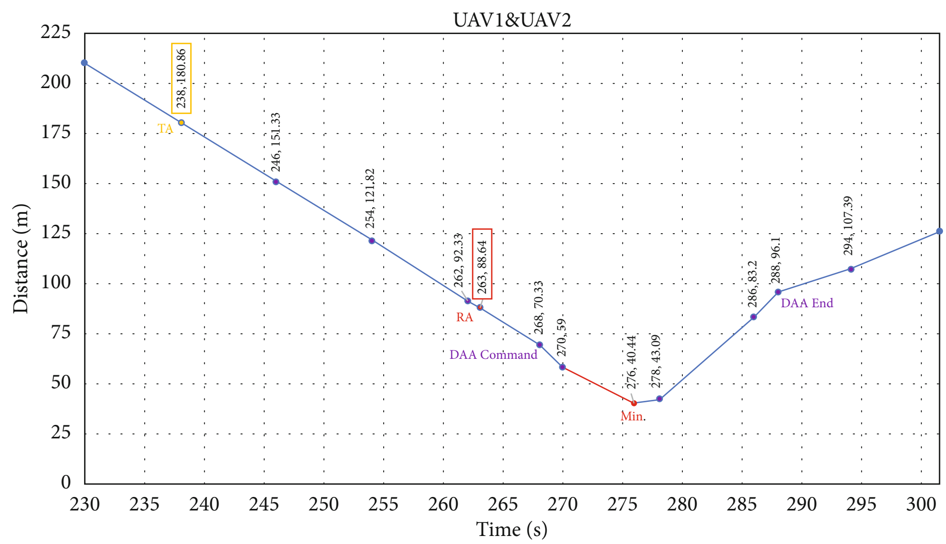


(c)

Figure 15: Continued.



(d)



(e)

Figure 15: (a) On *flight 5*, two UAVs are approach to initiate TA. (b) On *flight 5*, RA alerts UTM Controller, and AD152 speeds up to 9 m/sec. (c) On *flight 5*, AD152 speeds up to catch over the intersecting point. (d) On *flight 5*, DAA completes that AD152 has passed the intersecting point. (e) Separation from UAVs with safety margin 40 m on *flight 5*.

From the flight tests, speed-up resolution for avoidance should be very careful to perform. *Flight 4* and *flight 5* are carried on purposes to test the control feasibility and check flight safety. The UTM Controller should be precisely sure to command the one to speed up. The safety margins for *flight 4* and *flight 5* are less than 40 m, which is a little bit critical to challenge flight safety. During our flight tests, pilots are communicated in well and clear condition to follow the commands. These results demonstrate that speed-up to catch over the intersecting point earlier is possible in multirotor surveillance.

UTM system deployment can effectively monitor the UAVs in low-altitude airspace. Multiple UAVs are approaching to cause hazards to conflict or even collision. The DAA plays an important function to activate avoidance mechanism for approaching UAVs. At present, the active detection technology is not mature and reliable for small UAVs [8, 20], and the proposed ADS-B-DAA introduces a different solution strategy to perform UTM-dependent surveillance. In the UTM, all participating UAVs are transparent to UTM Controller, with the assistance of UTM software, and DAA mechanism by TTC to check TA = 48 seconds and RA = 24 seconds is conducted with no obstructions.

From the proposed DAA, UAV pilots will be coordinated with UTM Controller via CPC. There is enough tolerance to allow pilots to react to UTM commands. From the real flights, the CPA by avoidance resolution can maintain a reasonable margin to ensure flight safety under UTM control.

6. Conclusion

This paper presents the UAV detect and avoid (DAA) mechanism through UTM-dependent surveillance using ADS-B Like technology. When UAVs are flying into the same RUTM, they are approaching to become hazardous. The DAA software will manipulate the UAV approach detection and generate alert to UTM Controller from TA to RA until separation is cleared. The proposed DAA algorithm can accomplish UTM calculation for separation and assess an approach to conflict resolution. Five flights have demonstrated different scenarios for conflict approach to avoidance resolution. The controller to pilot (CPC) plays an important communication to activate the control command to pilot for avoidance. At present, only two UAVs are demonstrated in the flight tests, as present UAV operations are not so dense in airspace. The demonstrations show that TA alert to RA warning is feasible under TCAS specification for 48 seconds and 24 seconds, correspondingly. From the flight tests, the separation distance is checked from Google Maps to show the confident range for flight safety. The proposed UTM system has deployed 45 GTS to cover most of Taiwan's territory on the island. There is a medical delivery flight test in mountain area, where GTS does not cover. A mobile solar GTS is applied to augment to block area in deep mountains. It is successful to extend the UTM coverage into remote areas.

The proposed UAS DAA uses a similar concept of dependent surveillance on ADS-B-TCAS in civil air transportation. The adopted ADS-B Like key technology on UTM, such as LoRa device and its system infrastructure and server, needs to examine its system performance on surveillance efficiency and data reliability. It is expected in the future that UTM can merge with harmonization into ATM in similar system infrastructure and operation procedures. The flight test results show that the proposed ADS-B-DAA under dependent surveillance in UTM can be useful and practical. Based on UTM infrastructure, more complicate scenarios and multiple UAV approach need to perform in the future tests.

Nomenclatures

ACAS: Aircraft collision avoidance system
ADS-B: Automatic Dependent Surveillance-Broadcast
ADS-R: Automatic Dependent Surveillance-Rebroadcast
ADS-B Like: Automatic Dependent Surveillance -Broadcast Like
ADS-B-DAA: Automatic Dependent Surveillance-Broadcast-Detect and Avoid
ANSP: Air Navigation Service Provider
ATM: Air traffic management
CPA: Closest point of approach
CNS: Communication, navigation, and surveillance
CNS/ATM: CNS/air traffic management development project
CPC: Controller-pilot communication
DAA: Detect and avoid
FAA: Federal Aviation Administration
GIS: Geodetic information system
ICAO: International Civil Aviation Organization
LoRa: Long-range wide-area network
MSL: Mean sea level
NUTM: National UTM
NAS: National Airspace System
OBU: On-board unit
RUTM: Regional UTM
RA: Resolution advisory
SSR: Secondary surveillance radar
sUAV: Small UAV
TCAS: Traffic alert and collision avoidance system
TTC: Time to conflict
TA: Traffic advisory
UAS: Unmanned aircraft system
UAV: Unmanned aerial vehicle
UTM System: UAS traffic management.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work is supported by the Ministry of Science and Technology (MOST) under contract MOST 110-2622-E-309-001-CC1 (3-year project) and MOST 111-2625-M309-005 in cooperation with Chung-Hua Telecommunication.

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