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Research Article

Quasi-ADS-B Based UAV Conflict Detection and Resolution to Manned Aircraft

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A Conflict Detection and Resolution (CD&R) system for manned/unmanned aerial vehicle (UAV) based on Automatic Dependent Surveillance-Broadcast (ADS-B) concept is designed and verified in this paper. The 900 MHz XBee-Pro is selected as data transponder to broadcast flight information among participating aircraft in omnirange. Standard Compact Position Report (CPR) format packet data are automatically broadcasted by ID sequencing under Quasi-ADS-B mechanism. Time Division Multiple Access (TDMA) monitoring checks the designated time slot and reallocates the conflict ID. This mechanism allows the transponder to effectively share data with multiple aircraft in near airspace. The STM32f103 microprocessor is designed to handle RF, GPS, and flight data with Windows application on manned aircraft and ground control station simultaneously. Different conflict detection and collision avoidance algorithms can be implemented into the system to ensure flight safety. The proposed UAV/CD&R using Quasi-ADS-B transceiver is tested using ultralight aircraft flying at 100–120 km/hr speed in small airspace for mission simulation. The proposed hardware is also useful to additional applications to mountain hikers for emergency search and rescue. The fundamental function by the proposed UAV/CD&R using Quasi-ADS-B is verified with effective signal broadcasting for surveillance and efficient collision alert and avoidance performance to low altitude flights.

1. Introduction

Airborne support has been a critical part to disaster rescue missions. In the past, the airborne support teams were usually composed of fixed wing and rotary wing manned aircraft. While the unmanned aerial vehicles (UAVs) have been developed into mature technology, they are deployed into airborne missions for surveillance and data acquisition in civilian applications. As the airborne vehicles are increasingly evolved into the disaster area for joint operations, the irregular UAV performance threats the manned aircraft in low altitude flights. The function capability of conflict detection and collision avoidance for unmanned aircraft to manned aircraft should be paid more attention. A Conflict Detection and Resolution (CD&R) system should be developed and implemented on both unmanned and manned aircraft in a cooperative airspace.

At present, Traffic Alert and Collision Avoidance System (TCAS) is an important and independent system in commercial air transportation system for aircraft separation detection and avoidance resolution under autonomous operation. The Federal Aviation Administration (FAA) and International Civil Aviation Organization (ICAO) have enforced all commercial airliners with wider deployments and implementations with TCAS [1]. TCAS II is designed to reduce the incidence of midair collisions between aircraft by monitoring nearby aircraft which is equipped with a corresponding active transceiver. Due to more varieties of aircraft operating in the controlled airspace, different categories of aircraft also need to settle their TCAS specifications. Business jet or general aviation (GA) is the major consideration in this decade [2, 3].

Despite TCAS requirement of airborne radar, in the CNS/ATM deployment, the Automatic Dependent Surveillance-Broadcast (ADS-B) can be used not only to transmit airborne data for air traffic control (ATC) surveillance; new researches have also proposed ADS-B into CD&R mechanism for various applications [4, 5].

ADS-B consists of two different services, ADS-B OUT and ADS-B IN. ADS-B OUT periodically broadcasts information of aircraft identification (ID), current position, altitude, and velocity. It provides all vicinity aircraft with coordination information within reasonable range. ADS-B IN is the reception of flight data from nearby aircraft. This system relies on two avionics components of a high-integrity GPS and a reliable data link transceiver. The FAA certifies ADS-B data link of 1090/978 MHz communication as well as GPS receiver. ADS-B messages are encoded and decoded with the Compact Position Reporting (CPR) equations. The use of CPR is to reduce the number of bits required to transmit latitude and longitude data [6]. For terminal information service (TIS), ADS-Rebroadcast is activated to uplink the ADS-B data for vicinity aircraft in the terminal airspace [7]. ADS-R is an emerging technology for CD&R for general categories of air transportation [5].

The certified systems for general categories of aircraft are usually complicated, heavy, and expensive. The TCAS regulations do not cover below general aviation (GA) aircraft, such as private aircraft, helicopters, ultralights, and UAVs [5, 8]. It is not practical to directly implement the mature TCAS into GAs and UAVs. Since UAVs have been widely used in many respects, a suitable CD&R for UAVs to manned aircraft should be constructed to provide aviation safety in lower altitude, especially to GA in disaster rescue missions.

The proposed CD&R for UAV and GA in collision avoidance adopts the similar system concept from TCAS II to deliver traffic information in efficient airspace coverage [3, 4, 8, 9] using ADS-B data exchange mechanism. The developing system should be aimed at performing the similar specifications in both maneuverable function and data formats. The development can also be applied widely into all different types of GA aircraft, including UAVs, ultralights, and helicopters in low altitude operation. For low altitude airspace operation, horizontal separation will be more appropriate than vertical separation in flight performance [3, 10, 11].

This paper focuses on a Quasi-ADS-B transceiver development in CD&R study for UAVs to GA aircraft. The proposed Quasi-ADS-B uses 900 MHz XBee-Pro 900HP for data broadcasting, instead of 1090/978 MHz in TCAS II for air transportation systems in the developing phase. The system design will suit different CD&R algorithms in TCAS for traffic advisory (TA) and resolution advisory (RA) [3, 10, 12]. The UAV/CD&R Quasi-ADS-B transceiver is designed and implemented for flight tests using ultralight aircraft in a small confined airspace. Some simple avoidance resolution algorithms are adopted to identify its system performance. The demonstration of UAV/CD&R using Quasi-ADS-B transceiver is successfully verified with real flight tests. Further developments of useful algorithms can be followed for wider applications. The proposed UAV/CD&R can generate alert signals to pilots when TA and RA are successfully identified by the CD&R algorithms. It offers a complete solution for manned aircraft with safety information to avoid intrusion and conflict threat from UAVs.

The proposed CD&R system creates a byproduct effect to hiker safety. During the flight tests to search for the crashed UAV, an additional function is to search for the CD&R transponder on the carriers for their emergency search and rescue. The rescue team and helicopter can find the CD&R transponder signal from the missing mountain hikers. The basic functions can effectively be verified in flight tests.

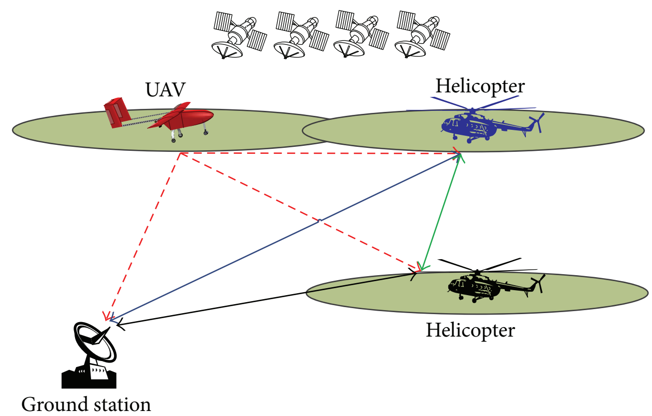


Figure 1: Architecture of UAV/CD&R using Quasi-ADS-B.

2. UAV/CD&R Quasi ADS-B Transceiver

The main function of the proposed UAV/CD&R is focused on manned aircraft to have the capability to detect and avoid all manned and unmanned aircraft within the surveillance airspace. The UAV/CD&R using Quasi-ADS-B transceiver architecture is shown in Figure 1. Manned aircraft are shown by helicopters in this figure. In the development, all the manned aircraft and UAVs are equipped with UAV/CD&R Quasi-ADS-B transceivers. In this study, helicopter is particularly specified in this application as Figure 1 in joint missions for disaster rescue. The manned aircraft is also equipped with microprocessor to handle avoidance algorithm calculation and pilot display monitor in communication setup of Quasi-ADS-B OUT/IN [7, 13]. It broadcasts and receives data packets from the vicinity aircraft in standard ADS-B CPR format including UAVs and manned aircraft. The CD&R full function of TA and RA in audio outputs keeps the pilots aware of intrusion from the nearby airspace and to perform avoidance resolution.

The UAVs are equipped with UAV/CD&R using Quasi-ADS-B transceivers to broadcast its own (UAV) CD&R data packet (Quasi-ADS-B OUT) to the vicinity aircraft, shown by dashed lines in Figure 1. 10 km coverage is restricted by XBee-Pro 900HP performance. The scheme in this research treats UAV as a moving object so the transceiver does not couple with the flight control system for UAV maneuvering. This means the UAV/CD&R will not give or receive commands to change UAV flight control. Due to the autopilot nature of civilian UAVs, waypoint navigation is the only command for flight performance. Under such circumstances, the UAVs are regarding higher priority than the manned aircraft. All the manned aircraft should perform appropriate avoidance to UAVs. Therefore, the proposed UAV/CD&R is universal to any flight control system.

Since waypoint navigation is typical in the UAV autopilot flight control, in addition, the intention of UAVs should be pronounced by themselves with next waypoints. It is the most feasible way to figure out UAV flight trajectory from the designated waypoints for avoidance resolution.

The broadcasting data packet is designed following the standard CPR format in ADS-B plus the following data with next waypoint in flight [6, 7, 14, 15]. The standard CPR (Compact Position Reporting) will be useful to be capable of merging and integrating the UAV/CD&R system with other systems using Quasi-ADS-B.

Ground control station is deployed for operation surveillance and performs ADS-Rebroadcast (ADS-R) [5] in quasi-performance. Likewise, Quasi-ADS-R repeats Quasi-ADS-B messages from one link to the other links for aircraft with Quasi-ADS-B IN, relaying data to nearby aircraft to ensure all data being successfully shared. The communication bridge is established among these airborne vehicles and ground control station to use a hybrid system between the CPR and additional part.

3. Transceiver Transmission Architecture

The FAA certified communication frequency for ADS-B data link is 1090/978 MHz. Since this frequency is currently not available in this development and to avoid frequency interference to commercial aircraft, this research uses 900 MHz radio system for preliminary design, implementation, and tests. Although the frequency of the transmissions is different, the information still follows the CPR formats, allowing future system fusion into ADS-B system easier.

3.1. Transceiver Architecture. The transceiver architecture is based on the Time Division Multiple Access (TDMA) mechanism. All participating aircraft will be carrying a transceiver for Quasi-ADS-B OUT, including UAVs and manned aircraft. The manned aircraft will have the capability of Quasi-ADS-B IN plus a situation awareness display.

Both Quasi-ADS-B OUT and IN are designed into one hardware system. This system should be booted up before every flight to run system initialization and GPS locking. After the system initialization is finished, it starts to send Quasi-ADS-B OUT once every second and listens for any Quasi-ADS-B IN data.

The transceiver Quasi-ADS-B OUT data output cycle is one second. This cycle can be split up into two major sections: (1) the slot sorting section and (2) the transmission cycle [6, 13].

The slot sorting section's main purpose is to arrange each aircraft's transmission slot number. The TDMA mechanism in this system allows as many as 10 slots (or 10 IDs), but for safety precaution a maximum of 8 IDs will be used into the airspace at one time. The slot sorting section will be split into three subsections. Each subsection is composed of 10 slots. Each aircraft will send a slot message at random time in each of the 3 subsections. It performs overall of sending three slot messages in the slot sorting section. The purpose of sending three messages at once every subsection is to ensure that each transceiver receives the messages without irregular data jam or loss. The slot message includes the aircraft ID and slot number. ID priority is assigned by the ground control station. UAV always receives higher priority than manned aircraft. Otherwise, earlier log-in aircraft will receive higher priority.

The slot number contained in each message declares the order of this aircraft and when it will send its transmission message. If any transceiver receives conflict data with the same slot number, an automatic slot change mechanism with ID priority check will be activated. All the participating transceivers will be reassigned by their IDs with priority. After ID priority check, the transceiver with lower priority ID will be reassigned to an unused slot to broadcast its data. After the slot sorting sequence ends at 300 ms mark, all aircraft's slot number has been sorted out, the next stage of Quasi-ADS-B OUT data output cycle will start. The transceiver pseudo code is shown in Algorithm 1.

The transmission cycle exchanges data between every one of the aircraft in the area. This section contains 10 slots. Each aircraft will execute its data OUT procedure at its assigned slot time to ensure no data jamming.

In this paper, considering disaster rescue missions, a reasonable number of aircraft in the surveillance airspace are assumed. It might be several rescue helicopters cooperating with a few UAVs. Figure 2 shows an example of a communication time chart for 8 different aircraft operating in the same small airspace. The slot sorting section time chart is 0~300 ms, while the latter part of 300~800 ms carries out the UAV/CD&R data as Quasi-ADS-B OUT. 800 ms~1000 ms are backup slots for emergency slots or future spare for system expansion.

The transmissions are synchronized with GPS clock in every second. The slot sorting sequence transmission is 11-byte data, composed of start bit (2 bytes), UAV ID (4 bytes), slot number (1 byte), checksum (2 bytes), and end bit (2 bytes). Since the slot sorting data of Quasi-ADS-B OUT transmission takes less than 10 ms, the time slot in this section is assigned by 10 ms. To ensure data reception by Quasi-ADS-B IN, each aircraft sends three sets of sorting sequence data over 300 ms. The capacity of the proposed system is bottlenecked by 10 aircraft.

The data transmission is carried out from 300 ms to 800 ms. Because the UBLOX decrypts GPS data in 280 ms, data transmission delays 300 ms for synchronization. The data transmitted for UAV in this section includes coordinates of current position and next waypoint. For the helicopter, the transmitted data will be current position and destination. These data are both encoded by the CPR. Each aircraft broadcasts its two data packets in a 50 ms slot by the sequence of ID number from the sorting section, that is, slot one at 300 ms~350 ms, until slot eight at 650 ms~700 ms.

CPR converts the data into 35 bits instead of the 45 bits, saving 10 bits per position message. It does not transmit higher-order bits in the whole period of the flight. Both even-format and odd-format are transmitted firstly to unambiguously determine the location of the aircraft. Once this process has been carried out, and the higher-order bits are known, only one kind of format can be selected to determine the position of the aircraft.

With this concept, all airborne aircraft will know the position of others in this airspace to achieve cooperative missions. After the position sharing is established the proposed conflict

```
Initialization /* System initialized and GPS lock */
REPEAT every second
    OUTPUT ID + Slot number
        IF ownership slot number = intruder slot number
            IF ownership ID priority > intruder ID priority
                Ownership slot number remains
            ELSE
                Ownership slot number shifts to an unused slot
            ENDIF
        ENDIF
    OUTPUT GPS data
    INPUT GPS data of all aircraft
UNTIL shutdown
```

Algorithm 1: Transceiver architecture.

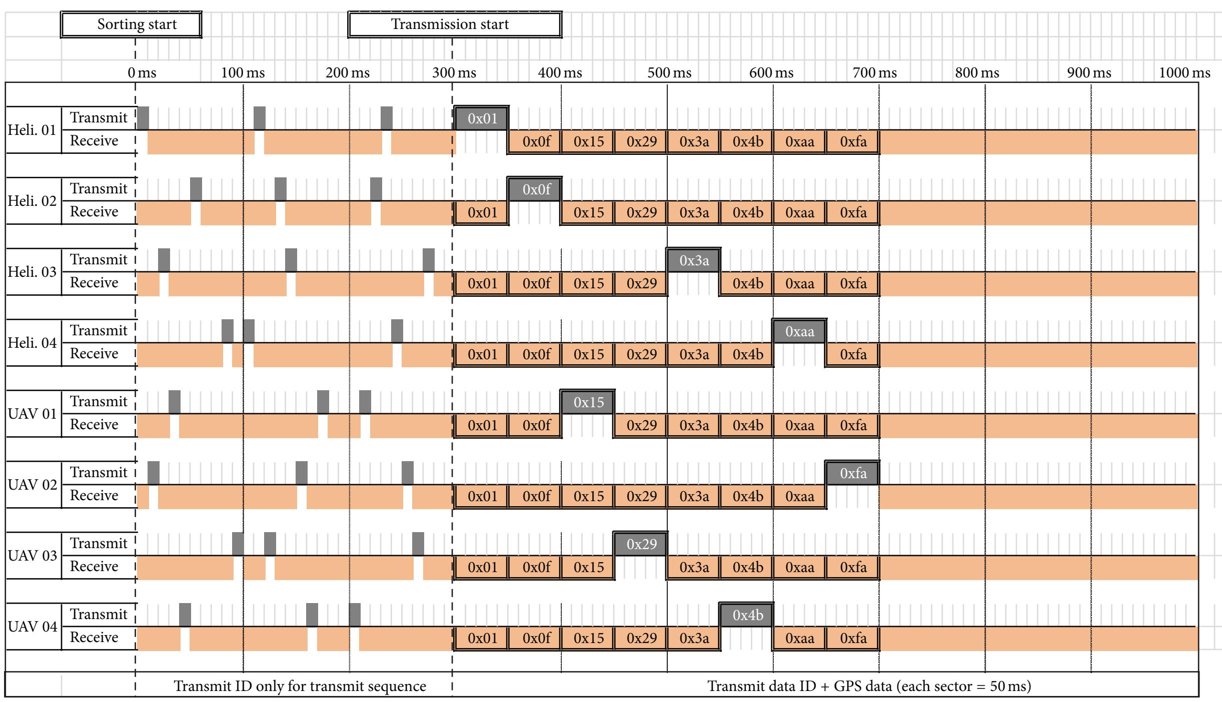


Figure 2: An example of 8-aircraft transmission time chart.

detection and collision avoidance algorithm helps to ensure the safety separation and avoidance of the manned aircraft from the intruders.

3.2. Hardware. The proposed UAV/CD&R transceiver enables cross communications among aircraft in a small airspace to exchange flight data. The proposed transceiver system is shown in Figure 3, consisting of a MCU, GPS module, and a wireless module. The adopted MCU STM32f103 is a 32-bit flash microcontroller based on the ARM Cortex processor. MCU handles GPS data input from GPS module, UBLOX Lea 6 h, and communicates to other MCU through the wireless module, XBee-Pro 900HP. The GPS has an error bubble of 5 m. GPS accuracy is acceptable for CD&R performance. GPS data reliability and stability on UAV can be maintained by using high performance antenna.

Communication platform varies for different applications. The commercial ADS-B uses 1090/978 MHz [1, 6]. Because it is a regulated frequency, it is difficult to find available 1090/978 MHz radio module in the preliminary development. An available wireless module of XBee-Pro 900HP is elected to integrate into the proposed UAV/CD&R transceiver for function capability. The XBee-Pro 900HP uses 900 MHz frequency for data transfer rate up to 200 kbps. It is similar to 1090/978 MHz system using the same CPR data coding.

Figure 4 shows the proposed hardware for test in a complete set for the manned aircraft in UAV/CD&R performance. The left part is a transmitter-only (Quasi-ADS-B

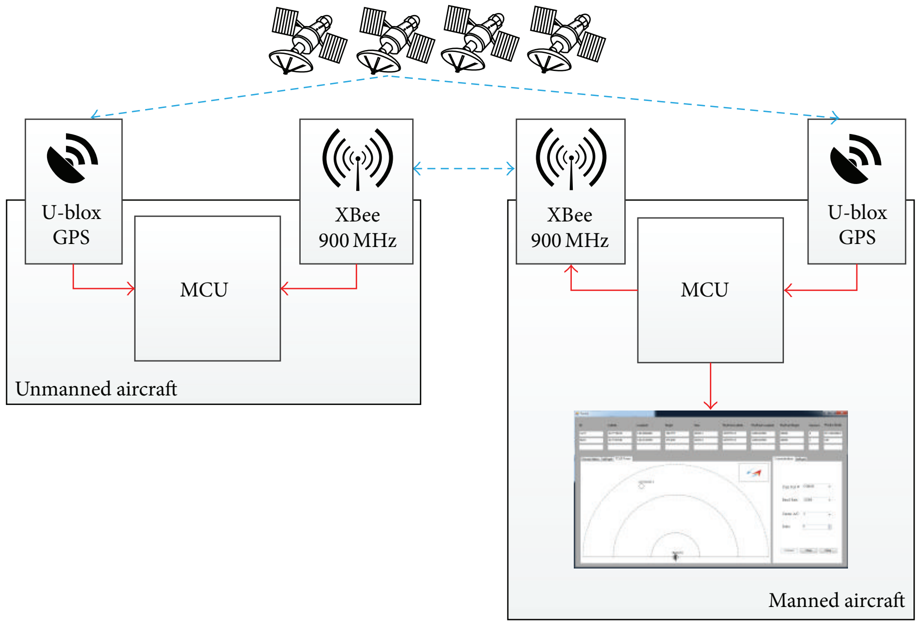
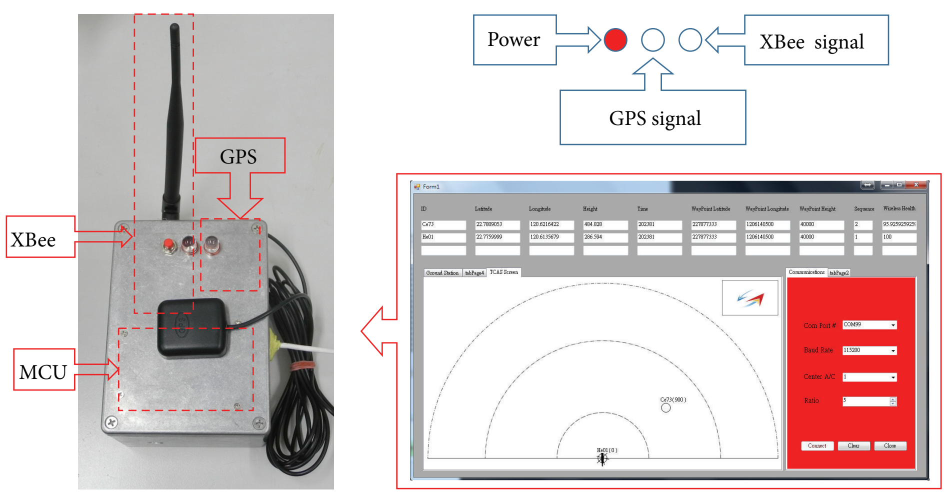


Figure 3: UAV/CD&R in ADS-B hardware.



(a) UAV/CD&R ADS-B (b) UAV/CD&R display

Figure 4: UAV/CD&R transceiver for UAV (left only) and for manned aircraft (all).

OUT) hardware for installing on UAVs, while the right part is transceiver (Quasi-ADS-B OUT/IN) and display for manned aircraft. For the manned aircraft, a microcomputer with LCD display is added with conflict detection and collision avoidance algorithm. The proposed UAV/CD&R is designed to suit different software from which proximity advisory (PA), traffic advisory (TA), and resolution advisory (RA) will be issued.

3.3. Conflict Advisories. The UAV/CD&R algorithm is installed in the microprocessor on the manned aircraft. CD&R display is shown in Figure 5 by a COM port setup

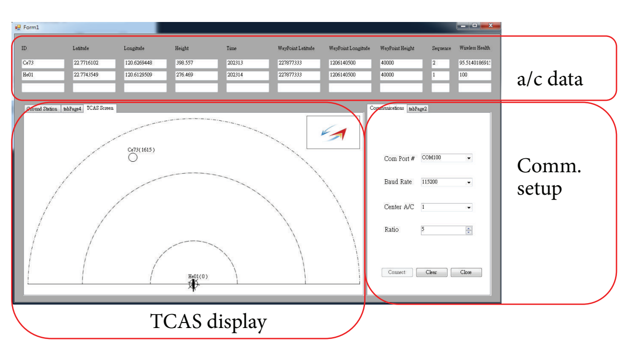


Figure 5: UAV/CD&R interface display.

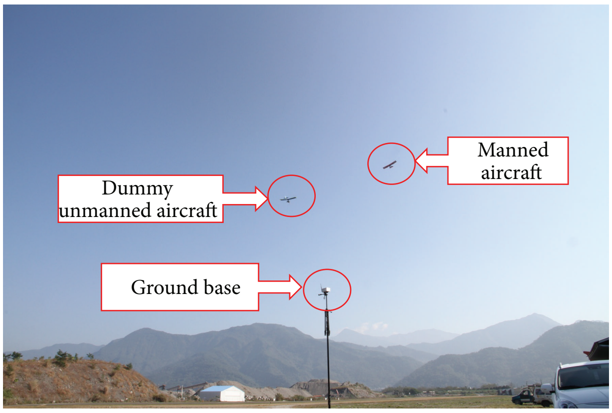


Figure 6: Two ultralight aircraft for flight test.

to show all received data on the top and traffic information of TA and RA on the screen. Both TA and RA are marked by hemisphere sector with a sense of time to conflict. The received data include vicinity aircraft GPS coordinates, UTC time, next waypoint of UAV (or destination of manned aircraft), slot ID, and the wireless transmission health of each aircraft.

The CD&R display will have three different advisories with visual and audio warnings. In PA, the screen will remain gray with audio alarm "Intrusion XXX at Y (XXX = az, Y = dis)." In TA, the screen will change into bright yellow with audio alert "Traffic, Traffic." In RA, the display will be changed into bright red with audio warning "Turn right." All alert and warning will still show every aircraft on the CD&R display.

4. Flight Experiment

To verify the operation functions of the proposed UAV/CD&R transceiver system, a series of flight tests is carried out to examine the capability of the flight data transmission. Two ultralight aircraft are used to carry the UAV/CD&R transceiver in cooperation with a ground control station as shown in Figure 6. One of the ultralight aircraft acts as a manned aircraft (or as manned helicopter) to perform conflict detection and collision avoidance, while the other plays as an UAV to fly from waypoint to waypoint.

In the preliminary flight experiments, the XBee omnidirectional transceiver collects around 97% of the data from the UAV and 100% from its own GPS. Although there is a 3% drop of data, these data spread throughout the whole experiment and all happened when they are separated over 1 km away, out of PA distance. In the XBee, the possible data loss happens less than 2 seconds in continuous flight test. The time delay in the Quasi-ADS-B OUT/IN and CD&R computation is examined with less than 2 seconds in overall tests. When all the test aircraft speeds are less than 120 km/hr, the possible separation shrinkage falls within 360 meters before an alert is generated to the pilots. This separation is important to TA/RA design in the CD&R algorithm. The collected data in flight experiments are used in the CD&R algorithms for further simulation and function verification.

5. CD&R Algorithm and Validation

This paper is mainly focused on UAV/CD&R transceiver hardware design and implementation using Quasi-ADS-B. The following CD&R algorithms are only adopted for flight validation in the transponding performance. The CD&R methodologies are not presented in detail.

The proposed UAV/CD&R system is designed to allow different CD&R algorithms to be validated in real flight test. Assume that each algorithm requires different sensors; the proposed UAV/CD&R transceiver hardware is also capable of integrating sensor information into dynamic resolution [2, 13, 15]. In CD&R operation, when the aircraft detects vicinity flight activities in the near airspace, intruder will be identified by proximity advisory (PA) where the minor possibility of conflict is raised. When the intrusion approaches into a near range, traffic advisory (TA) is pronounced with an alert. Afterward, the intrusion enters close range; resolution advisory (RA) is generated to give pilot a warning. In ICAO, PA, TA, and RA are defined in time to conflict (TTC), marked by τ in seconds. The sensitive level (SL) and alarm thresholds are defined by TTC according to the flight altitude. In this study, the operating altitude is around 1000 meters above ground level (AGL). The values are defined as TA = 30 sec, RA = 20 sec [1].

From CD&R algorithm, the manned aircraft (ownership) detects any aircraft within 3 km radius from itself. Once any intrusions are detected, the trajectory estimation and probabilistic grids detection (PGD) are generated. If all the time sectors probability is under the threshold, the whole process restarts. If any sector probability continues to increase into dangerous threshold, the time and sector recognition (TSR) will further generate TA alert and RA warning to pilots. PGD and TSR are explained in brief. The CD&R algorithm pseudo code is shown in Algorithm 2.

5.1. Probabilistic Grid Detection (PGD). The PGD algorithm is chosen to implant by the flight path detection for multiple aircraft in the operating airspace. The PGD is a weighted grid on the probability of the aircraft reaching the same sector at the same time. Each aircraft will generate numerous grids per second. The grids in each second describe the position prediction of the aircraft in advance. The probability grid value is based on the predicted coordinate in certain time interval. Then each grid value is calculated by applying the Gaussian Function, for μ represents the mean of expectation of the distribution (and also its median and mode) and σ and σ^2 are its standard deviation and variance:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}. \quad (1)$$

With the combination of the parameters, different probabilities can be established based on different conditions and positions of the aircraft. As the estimation progresses in time (meaning the farther ahead the prediction is), the error increases with time. By adjusting the standard deviation and variance, the correct assumptions can be met.

When the aircraft's probability grid is generated, each grid with the same time stamp will be calculated together to get

Initialization /∗ System initialized and GPS lock ∗/
REPEAT every second
  OUTPUT GPS data
    INPUT Intruders GPS data
      IF Intruder distance to ownership <3 km
          Trajectory estimation construction
          Establish PGD
          Calculate confliction probabilities
          IF conflict probability > threshold
              TSR CD&R generation
              TA alert/RA warning
          ENDIF
      ENDIF
  UNTIL shutdown

Algorithm 2: CD&R architecture.

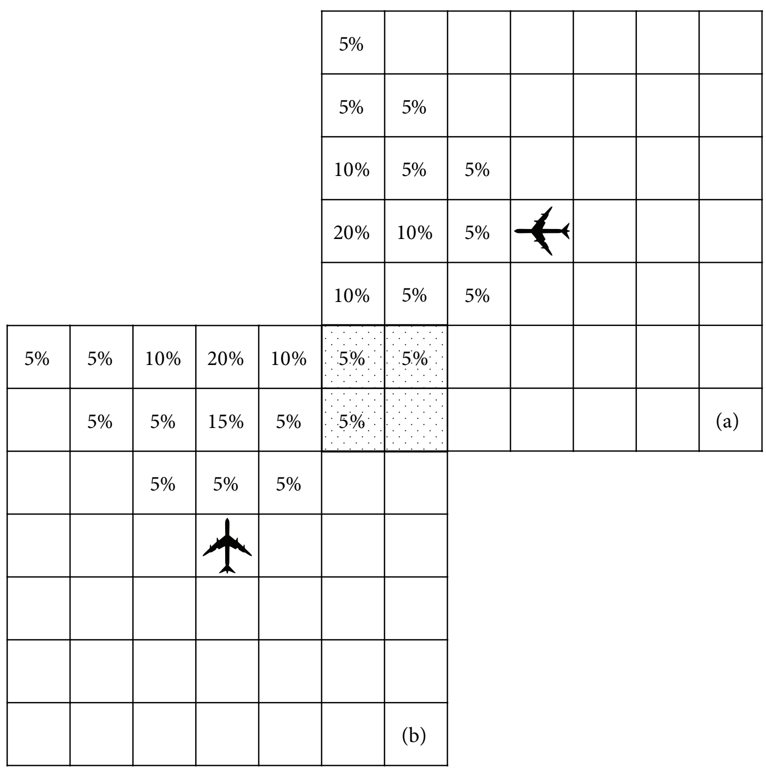


Figure 7: Probability of conflict in time N.

the weighted probability of collision at the certain time stamp. For simplicity, only time stamp N is shown in Figure 7. The PGD algorithm detects the possible intrusion to the manned aircraft, and PA will be pronounced.

Afterwards when PA is issued, a near field sector recognition algorithm is executed to calculate a safe path to avoid conflict. TSR CD&R will continue to check the separation amont intrusion aircraft after PA has been issued. The PGD algorithm pseudo code is shown in Algorithm 3.

Figure 8 shows a section of the flight test. Solid curved lines are the real trajectory in record. The dotted straight line with asterisk symbol is a straight line estimation of the trajectory connecting the current point to the waypoint. The dotted line with circle symbol is the estimated trajectory using the algorithm discussed in this paper. From the figures, the doted circle trajectory is estimated with closer approach than the straight asterisk line. Although one section of the trajectories in Figure 8 is deviated from the recorded points by 20 m, their conflict point is still closer to the real conflict point than the straight trajectory method.

The probability grid is generated and each second probability of conflict is shown as a figure in Figure 9. In the test, the maximum single point percentage and the integer percentage are both at the 26th second. Although the absolute percentage

Initialization /∗ System initialized and GPS lock ∗/
REPEAT every second
  INPUT Intruders GPS data
   Predict future trajectory and position (next 25 seconds = 25 grids)
   Overlap of each aircraft same time stamp grids
   IF A grid block value > threshold value
    Mark block as dangerous zone
    Issue PA
    TSR CD&R execute
   ENDIF
UNTIL Shutdown

Algorithm 3: PGD CD&R architecture.

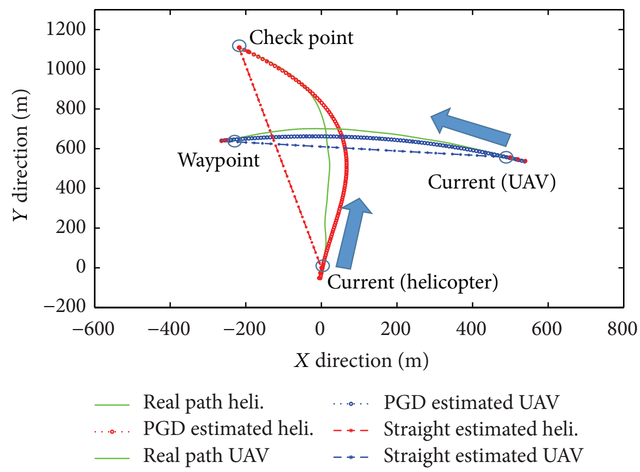
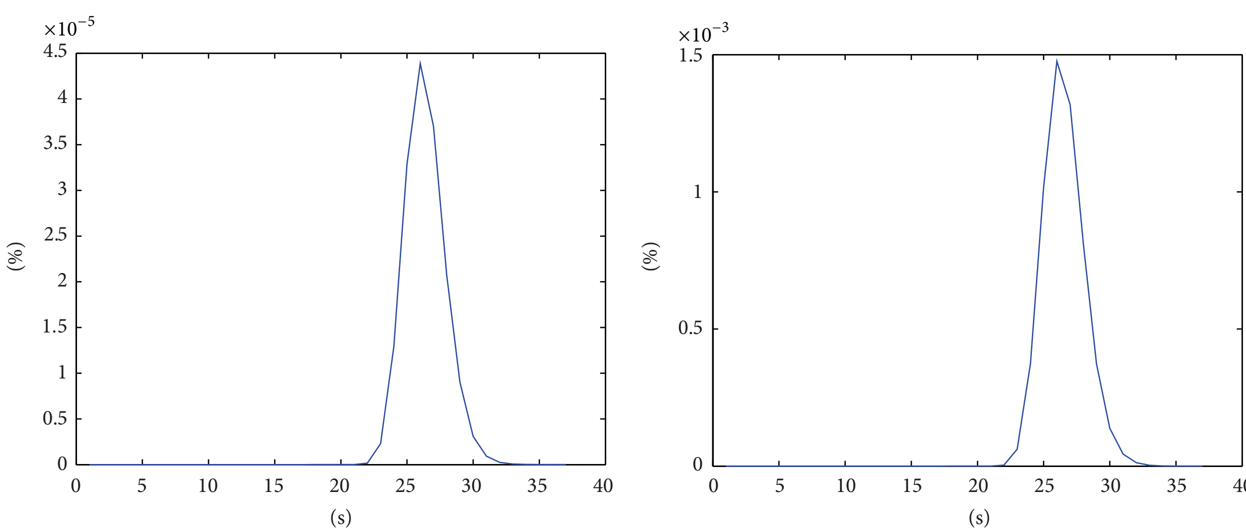


Figure 8: Test trajectory.



(a) Test max percentage

(b) Test percentage integer

Figure 9: Graph of probability of conflict.

Initialization /∗ System initialized and GPS lock ∗/
REPEAT every second
  INPUT Intruders GPS data
    IF PGD block value > threshold or intruder distance from ownership <1 km
      Generate sector of each aircraft
      Calculate overlap area of each sector
      IF Overlap area > TSR threshold
        Calculate right turn rate
        RA issue
      ENDIF
    ENDIF
UNTIL Shutdown

Algorithm 4: TSR CD&R architecture.

in Figure 9 is very small, the relative percentage increment is enough to exceed the threshold of the system and trigger and issue PA. From Figure 8, the recorded conflict point is also at the 26th~27st second. The simulation using real flight data shows that, with the combination of the trajectory estimation and probability grid, an accurate conflict prediction can be predicted.

5.2. Time and Sector Recognition (TSR). The time and sector recognition (TSR) algorithm [16] generates a sector shaped area in the tangent direction of the flight path. If any intruder's sector area overlaps the ownership sector area to a certain ratio, TA and RA will be pronounced following its resolution calculation. The avoidance path is calculated by the possible turning angle φ to decrease of overlapping ratio at most. With some restrict parameters by turning radius in constant speed, a safe right turn trajectory can be plotted to assist the pilot for conducting conflict avoidance [14, 15].

TSR is triggered in two conditions: (1) PGD exceeds threshold and (2) intruder aircraft is less than 1 km from ownership. When TSR is executed, the CD&R message will generate time and sector recognition pattern with intruders' location and heading as shown in Figure 10. The proposed TSR algorithm will identify the intruder UAVs or manned aircraft and apply appropriate separation. Conflict detection and collision avoidance from manned aircraft to other aircraft, especially the UAVs, will be shown in Figure 11.

The adopted TSR algorithm defines maneuvering angle change for UAV with 30 degrees and for the manned helicopter in 45 degrees, as shown in Figure 11. Based on this 2D spatial relation, conflict detection TA and collision avoidance RA will be published on the proposed UAV/CD&R display as shown in Figure 5.

Using the actual flight test data by ultralight aircraft, Figure 12 shows the flight path data collected from the ultralight aircraft flight tests. The red dots represent the waypoints for the UAV. The green and blue lines are the trajectory of the manned helicopter and UAV, correspondingly. The red star (⋆) marks the position to pronounce TA. The TSR algorithm pseudo code is shown in Algorithm 4.

When RA is issued in Figure 13, the display turns to red with audio warning. Sector recognition algorithm will

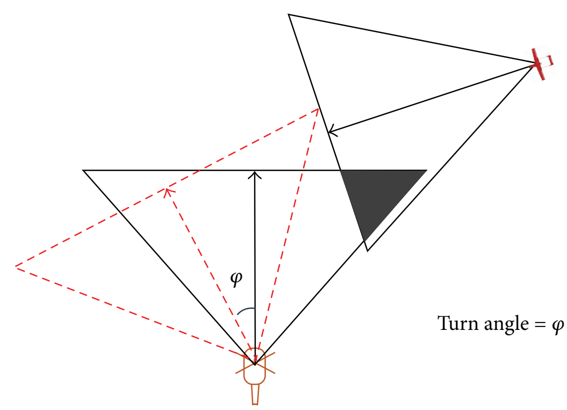


Figure 10: The time and sector recognition algorithm.

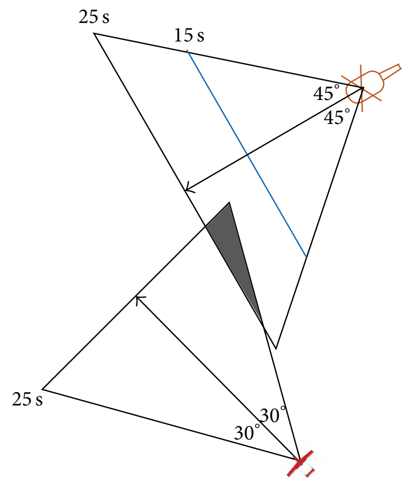
then calculate the best right turn trajectory to escape in Figure 14(a). The conflict resolution suggests the manned helicopter to increase the distance from the intruder and avoid conflict by making right turn. The separation of two aircraft is calculated in Figure 14(b).

The flight tests demonstrate the effectiveness of the proposed UAV/CD&R transceiver working with two different algorithms for conflict detection and collision avoidance among UAVs to GA.

5.3. UAV Crash Search and Mountain Hiker Search. The proposed UAV/CD&R hardware can also be applied to missing UAS search once crashed. Since the 900 MHz XBee-Pro 900HP is independent from autopilot system, it continues to broadcast position data once crashed.

Likewise, the proposed UAV/CD&R hardware carried an additional test from mountain hikers. It can be used to send their SOS by the proposed CD&R transponder. Since the mountain hikers are staying at a fixed position, the CD&R ADS-IN in the rescue helicopter can easily locate the transponder signals and call for rescue. Two CD&R transponders are used at the same time during flight tests. Its application to mountain hiker can be verified in byproduct.

The hiker SOS transponder will be broadcasting randomly at the emergency slot of the whole second



(a) (b)

FIGURE 11: Advisories (a) TA and (b) RA by TSR algorithm.

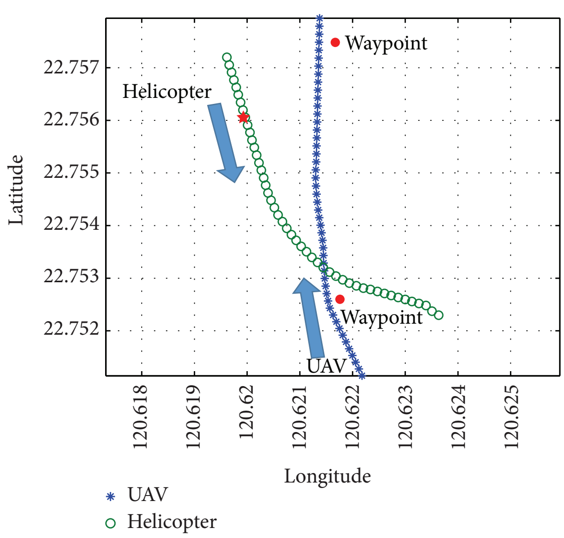


FIGURE 12: Flight test path of two conflicting aircraft.

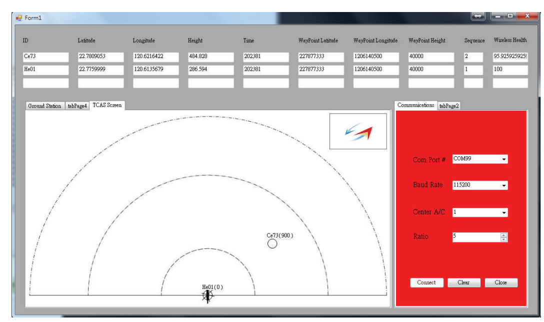


FIGURE 13: Display of intrusion on the manned helicopter when RA is issued.

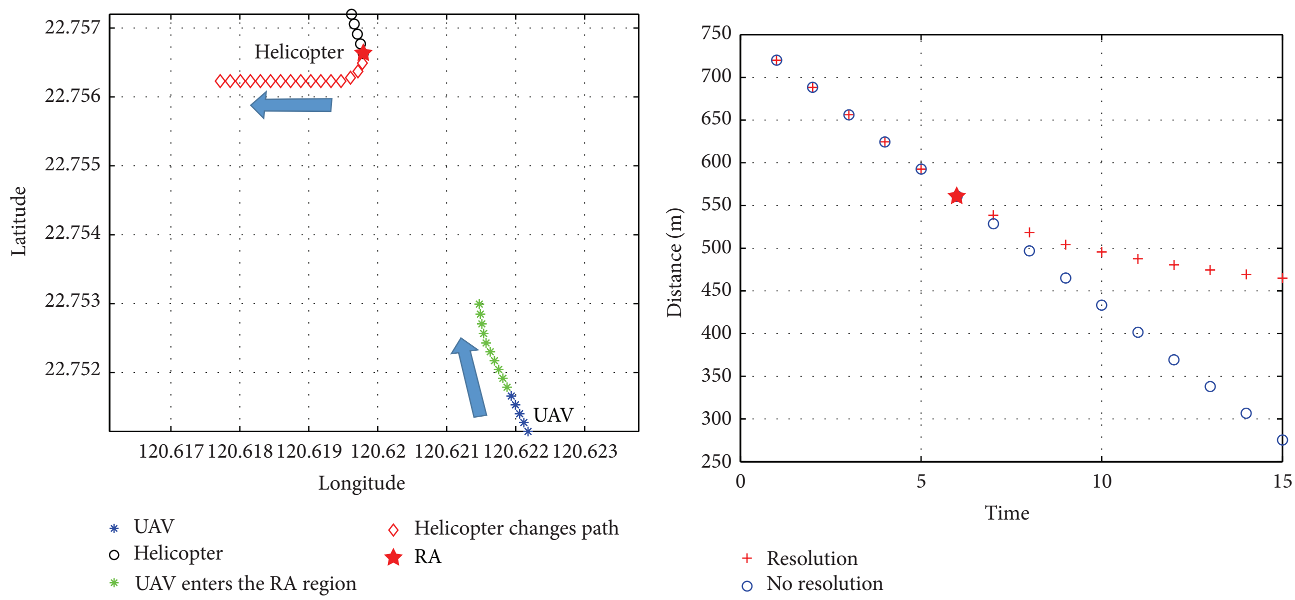
(800 ms~1000 ms). These slots are unused message slots used for emergency and future expansion usage. Because these slots are originally free with no message flow, no slot sorting is required.

6. Conclusion

In this paper, a UAV/CD&R transceiver hardware using Quasi-ADS-B is designed and fabricated for tests. Based on the FAA CD&R specifications, 1090/978 MHz frequency is defined [1]. In the proposed system, 900 MHz XBee wireless module is adopted for implementation and preliminary verification. The transceiver carries ADS-B format in CD&R operation into 10 km coverage range. By careful arrangement, the selected TDMA performance can avoid time conflict and resolve automatic time slot adjustment to split out data overlapping. The designed transceiver hardware of 500 g of weight with 6-hour battery lasting in Figure 4(a) is quite suitable for any kind of UAVs. The same design for manned aircraft including a man-machine interface to display the TA/RA situation awareness is adequate for practical applications.

The proposed wireless transceiver for UAV/CD&R has been successfully verified by a series of flight tests using multiple ultralight aircraft. Actual airborne flight data are collected from the participating ultralight aircraft as well as the ground control station. The manned aircraft receives effective intrusion message to activate its embedded algorithm for conflict detection and collision avoidance. Several flight test data have successfully supported the proposed mechanism for UAV/CD&R using Quasi-ADS-B communication.

The proposed UAV/CD&R transceiver is an open hardware system suitable for different CD&R algorithms. In the tests, two CD&R algorithms are adopted into CD&R performance verification. The results strongly validate the effectiveness of the proposed UAV/CD&R transceiver design. The XBee transceiver within reasonable data loss plays an efficient media for ADS-B performance in high efficiency, high reliability, and low cost in real world implementation.



(a) Trajectory of UAV and manned aircraft

(b) Separation between two aircraft

Figure 14: Avoidance trajectory of manned aircraft to UAV.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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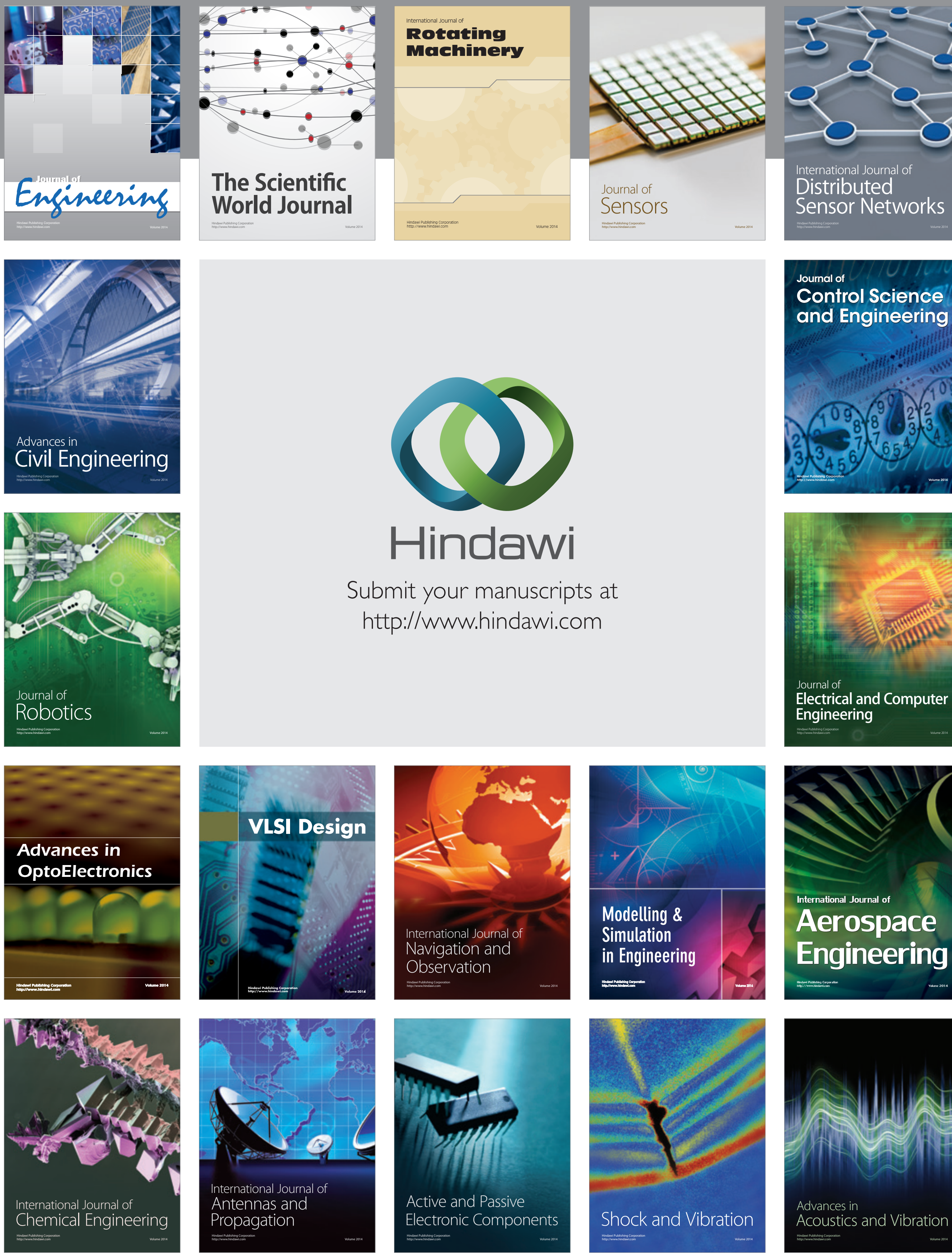
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