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Collision Avoidance at Intersection Using Vehicle-to-Vehicle Communication

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***Abstract*—With the emerging use of Unmanned Aircraft Systems (UAS) for applications such as transportation and logistics, there is a need for the capability for manned and unmanned aircraft to safely integrate into the National Asirspace System (NAS). As the NAS becomes progressively more populated with UAS, there is an increasing need to mitigate collisions between aircraft. The Advanced Air Mobility (AAM) campaign expresses the need for both strategic deconfliction and tactical deconfliction collision avoidance methods, of which this paper focuses on the latter. The proposed solution is an airborne Roundabout modeled after the Roundabout intersection for ground vehicles. UAS within the Roundabout use Vehicle-to-Vehicle (V2V) communications to enforce a subroutine system, allowing them to autonomously mitigate collisions in structured airspace.**

***Index Terms*—Unmanned Aerial Systems, Vehicle-to-Vehicle Communications, Advanced Air Mobility, Collision Avoidance, Tactical Deconfliction**

I. Introduction

In recent years, Unmanned Aircraft Systems (UAS), have become increasingly valuable for a wide range of applications in both public and private sectors, including the delivery of medical supplies to the surveillance of remote areas using aerial photography. This increase in the usage of UAS is expected to result in increased airspace congestion, which requires supporting technologies and infrastructure to ensure safe flight operations. To address this, the National Aeronautics and Space Administration (NASA) started the Advanced Air Mobility (AAM) campaign with the aim of developing new methods to facilitate high-density UAS traffic in urban areas. Additionally, AAM also aims to reduce travel times and minimize carbon emissions, contributing to greener and more efficient transportation [1].

This work is a collaborative effort between The University of North Texas (UNT) with Unmanned Experts (UMEX) thereby combining academic and industry professional experience as part of the grant NSF -2148178 (Resilient & Intelligent NextG Systems) and the NASA Collaborative Research Opportunity (AAM-NC 80NSSC22M0133).

NASA is currently working with the Federal Aviation Administration (FAA) as well as several other organizations to develop efficient Air Traffic Management (ATM) and Collision Avoidance Systems (CAS) to achieve these goals. One of the primary issues is that existing CAS such as Traffic Collision Avoidance System (TCAS), Airborne Collision Avoidance System (ACAS), and Detect and Avoid (DAA) systems, cannot be directly implemented on small UAS due to several factors including hardware limitations and weight constraints. NASA currently categorizes CAS into two types: Strategic Deconfliction (SD) and Tactical Deconfliction (TD), which are both responsible for safely routing UAS and to their target locations [2].Specifically, SD refers to the process of initially routing UAS on conflict-free flight paths before the flight begins, whereas TD is the process of avoiding conflicts during flight [2].

A. Main Contribution

This paper provides a detailed explanation of the airborne Roundabout system, which is based on its ground-based counterpart present throughout roadways across the world. This concept is used to demonstrate the feasibility of facilitating high-density UAS traffic in urban areas, with an emphasis on safety and efficiency. Traffic is facilitated through the Roundabout using Air Corridors, which are sections of airspace designated for UAS flight. As stated in Muna et al., Air Corridors allow for aircraft systems to follow specific procedures defined for these corridors, which are static but used in a flexible fashion [3]. The newly proposed collision avoidance strategy provides a robust solution for intersecting Air Corridors, allowing for flexible routes for UAS to utilize in the air space.

B. Paper Organization

This paper is organized as follows: Section II describes the research problem of potential collision hazards in locations of high-density UAS traffic, Section III describes how the model of the Roundabout is mathematically formulated, Section IV describes the simulations that were conducted using the Roundabout model to avoid collisions between two UAS, and Section V offers a brief conclusion.

II. Research Problem

Within the context of AAM, there is constant investigation into developing methods to safely transport people and cargo, which includes applications involving air ambulances and air taxis. In order to ensure the safety of these flights, Vehicle-to-Vehicle (V2V) communications is used as a proposed solution to avoid collisions between UAS. Roundabouts, as demonstrated in figure 1, is one use case of this airspace management that provides flight rules within air corridors to mitigate possible collisions. This image shows the Roundabout air corridor structure with two UAS. The two UAS move counters are actively communicating with V2V traverse through the intersection without collision.

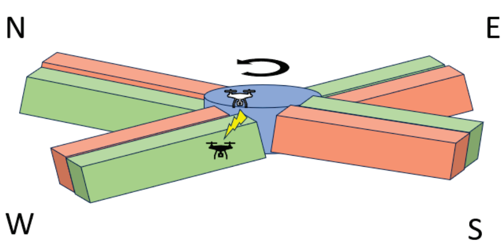

Fig. 1. Intersection of Roundabout

Roundabouts is a collision avoidance solution for cooperative vehicles in congested air spaces that utilizes V2V communications in order to appropriately mitigate potential collisions. The system requires that any vehicle in the airspace must conform to a specific set of flight rules to appropriately communicate and ensure no collisions. The Roundabout system assigns to entering UAS a flight plan to successfully traverse the intersecting Air Corridors while incorporating yielding capabilities determined by the projected trajectory of the flight plan. The collision avoidance strategy is a scalable solution offering potential changes in the system coverage, allowing the generation of more waypoints and ensuring a larger corridor for operation. The system also has the ability to be placed at any required or preferred location to allow for use in any setting. Roundabouts is a collaborative effort between academics and industry professionals demonstrating the active and continuous efforts in AAM.

III. System Model

The Roundabout system can be broken up into two vital pieces. The first part is the arithmetic and mathematical theory, which delves deeply into the use of algorithms and mathematical logic to develop the architecture and generation of way-points. The second part is the application of theoretical models with the collision avoidance principles, which uses the generated way-points in tandem with V2V, subroutine protocol, and the Designated Crossing Time (DCT).

A. Architecture of Roundabout and Generation of Way-Points

The Roundabout can be expressed mathematically using three separate equations, each working together and contributing to specific segments of its architecture. These equations consist of one circle and two equilateral hyperbolas, one with a positive and the other with a negative orientation. When superimposed on a 2D plane, these equations create a structure that mathematically resembles a real-world Roundabout. An image of how this may look on the 2D plane can be seen below in figure 2. In this image, it is easy to see two equilateral hyperbolas and a circle. The pink radius around the whole system is to represent that only this operating region is used, considering the equilateral hyperbolas will continue asymptotically on the x and y axis.

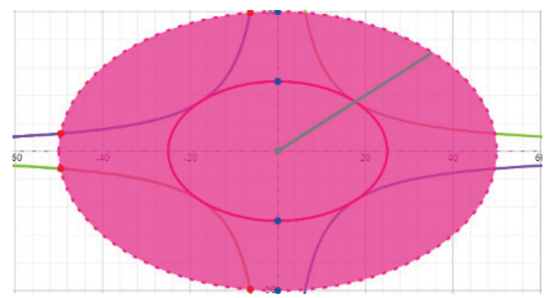

Fig. 2. 2D Superimposed Equilateral Hyperbolas and Circle

There is a specific relationship between these equations that allows for an equilateral hyperbola to be tangent to the given circle in each quadrant. The points where the hyperbolas are tangent to the circle represent the ingress and egress points of the circulatory roadway, which is where UAS enter and exit, respectively. The relationship between a given circle and an equilateral hyperbola that is tangent to that circle is based on the radius of the given circle. The exact definition of this relationship is given below in equations (1) and (2).

$$x^2 + y^2 = r^2 \tag{1}$$

$$y = \pm \frac{r^2}{2x} \tag{2}$$

The ingress points are where UAS are allowed to enter the circular roadway, while the egress points are where UAS are allowed to exit. In order to simplify the explanation, it simply refers to these as action points specifying them as entry or exit points. In total, there are four action points along the circumference of the inner circle, with one action point lying in each of the four quadrants of the circle. Mathematically speaking, the action points are the points on the circle that are tangent to the hyperbolas, all of which are conveniently located at ±45° angles from the x-axis. This allows us to easily obtain an (x,y) coordinate pair in each quadrant by making a quick reference to the trigonometric unit circle. Each equation for the action points can be seen below in equation (3).

$$
\begin{aligned}
Q_I &= \left(\frac{r\sqrt{2}}{2}, \frac{r\sqrt{2}}{2}\right) \qquad Q_{II} = \left(\frac{-r\sqrt{2}}{2}, \frac{r\sqrt{2}}{2}\right) \\
Q_{III} &= \left(\frac{-r\sqrt{2}}{2}, \frac{-r\sqrt{2}}{2}\right) \quad Q_{IV} = \left(\frac{r\sqrt{2}}{2}, \frac{-r\sqrt{2}}{2}\right)
\end{aligned} \tag{3}
$$

Another thing to note is that the scaling factor should be applied to the action points corresponding to the radius of the circle chosen. The scaling factors ϵ and μ are factors that represent the angular values from World Geodetic System 1984 (WGS84) coordinate system that allows for the transformation from Cartesian coordinates to WGS84 coordinates [4]. This is to say, distances are used for the Cartesian plane which are based on 1 degree of latitude being approximately equal to 111,111 meter [4]. The equation for representing this scaling factor can be seen below in equation (4). In this equation, lat is the latitude value of the intersections WGS84 coordinates, which is the center where the whole Roundabout system is agreed to be developed in space.

$$\epsilon = \frac{1}{|111111cos(lat)|}, \ \mu = \frac{1}{111111} \tag{4}$$

Trapezoidal numerical integration [5], seen in equation (6), is used to generate (x, y) points along the equilateral hyperbola. This equation uses the distance between two points (L) along the slope of the equilateral hyperbolas, and a is a quantity set to enforce the value L represented in equation (5) where r is the radius of the circle that is superimposed in the 2D plane. Using this modified trapezoidal rule, and starting at the Q_I, Q_{II}, Q_{III}, or Q_{IV} points defined above, the integral is approximated along the equilateral hyperbolas slope in order to compute the total arc length of the curve. By dividing the arc length by the desired spacing, the number of points needed along the hyperbola can be determined. Equation(6) is used in a recursive algorithm to iteratively solve for the values of b using an initial value a. The values of b correspond to x values along the curve of the equilateral hyperbola that are an equal arc length apart. After a value of b is found, the value of a is updated to the found value of b, and the next value of b is solved for. Lastly, the y values can be obtained by plugging in the x values into equation (7).

$$a = \frac{r\sqrt{2}}{2}, for\ a < Radius \tag{5}$$

$$L = (b-a) * \frac{1}{2} * \left[\sqrt{1 + (\frac{-(r^2)}{2a^2})^2} + \sqrt{1 + (\frac{-(r^2)}{2b^2})^2}\right] \tag{6}$$

$$y = \frac{r^2}{2x}, \ x = b \tag{7}$$

Geometric transformations can be applied to the points that are generated in the trapezoidal discretization. By rotating the points generated in one quadrant, the points can be populated for the other quadrants, thereby reducing the computational power. The equations to rotate these points can be seen in equation (8). These two equations rotate the (x, y) Cartesian points to a new point in the plane called (q_x, q_y) [6].

$$
\begin{aligned}
q_x &= p_x * \cos\left(\theta\left(\frac{\pi}{180}\right)\right) - p_y * \sin\left(\theta\left(\frac{\pi}{180}\right)\right) \\
q_y &= p_x * \sin\left(\theta\left(\frac{\pi}{180}\right)\right) - p_y * \cos\left(\theta\left(\frac{\pi}{180}\right)\right)
\end{aligned} \tag{8}
$$

Once the geometric rotation has occurred, the new point (q_x, q_y) is converted to the WGS84 coordinate system. The equations to convert these transformed points can be seen below in equations (9).

$$
\begin{aligned}
Latitude &= (q_x * \mu) + lat \\
Longitude &= (q_y * \epsilon) + lon
\end{aligned} \tag{9}
$$

In order to define the path through the interchange using the logic above, an expected ingress and route are used to understand the direction the UAS intends to go. The ingress may be a direction such as North, South, East, or West while the expected route may be Right, Left, Straight, or U-turn. By defining these paths, the Roundabout system is capable of generating the full path through the interchange. An example of generating the way-points can be seen below using a Matplolib plot in figure 3. In this example, the ingress is defined as west, while the route to take is a U-turn. In doing this, as can be seen below, red dots can be seen to represent the WGS84 coordinates or the way-points. The black point in the center of the system represents the initial WGS84 point that represents the center. Finally, there is a red line connecting the waypoints to show the point-to-point path of the flight plan.

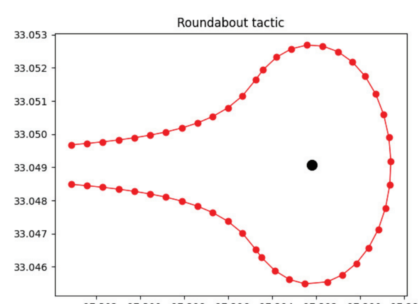

Fig. 3. Generated Way-Points through a U-turn

All directions of ingress and egress are capable of being generated in order to allow any vehicle to take any route that is designed. Another example can be seen below in figure 4 where the same ingress is defined as west while the route is defined to go left. This shows all the way-points in the path going through the Roundabout system making a left turn.

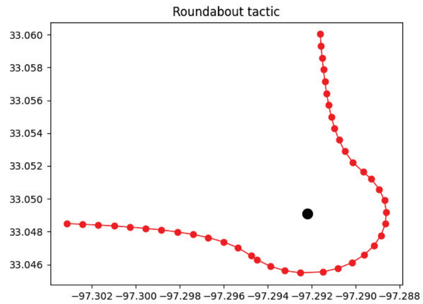

Fig. 4. Generated Way-points through a Left Turn

B. Application of Collision Avoidance Principles

After the generation of the way-points, the way-points are interjected into the UAS flight plan in order for the vehicle to traverse through the Roundabout architecture. Now that the flight through the system is known, there are a couple of other steps in order to create a working yielding or collision avoidance system. These steps include the use of V2V communications to facilitate yielding, the use of a subroutine method in order to know who yields, and DCT to know if a UAS needs to yield.

Vehicle-to-Vehicle (V2V) Communication: To develop this Roundabout use case, V2V is highly regarded since communication is required to take place at all points in the collision avoidance system. For communication, a message named the ”Discovery Message” is used, which is communication between two vehicles. This Discovery Message is a V2V communication protocol of a vehicle conversing with every other vehicle in the airspace. This communication will continue to send telemetry data such as the WGS84 coordinates, the DCT, and any other form of information, such as what the UAS is expecting to do. This is necessary in designing the Roundabout system so that vehicles can maintain a conscious state of checking if they can cross the intersection or join the Roundabout architecture.

Subroutine Protocol: The Roundabout system uses a subroutine method to divide the flight plans of the corridor into different parts. This approach breaks the generated waypoints throughout the Roundabout corridor into subroutines for the UAS to traverse. This is done by taking the ingress path, egress path, and quadrants through the interchange. The quadrants are the part of the path that are superimposed circle and can be generalized to quadrants I, II, III, and IV following the standard unit circle quadrants. This method allows for the current subroutine of the UAS, such as the specific part of the flight plan it is in, to be identified. Additionally, the next subroutine, known as the potential collision zone, is predictable due to the counterclockwise rotation around the system.

Designated Crossing Time (DCT): The DCT is the Estimated Time of Arrival (ETA) at the point that two vehicles will cross or collide [7]. For the development of the Roundabout system, the DCT difference between the two vehicles of five seconds or less is deemed a problem and requires yielding to ensure no collisions. This is to say that if a UAS is inside the quadrant subroutine of the Roundabout system, then the UAS that is entering the Roundabout via an ingress point must yield if the projected difference in DCTs is in a specified time. This follows the conventional roundabout method used for cars on a road. An image of how the next subroutine is checked can be seen below in figure 5. In this image, the route is the next subroutine in the Roundabout system for two drones. Each UAS in the Roundabout collision avoidance system must compare there routes and the DCTs to make a decision to yield or continue. Since both the routes of each UAS in this check are for the subroutine Q_{II}, and the DCT is below five seconds for the vehicles, the UAS in the ingress subroutine must yield. If there are many drones inside the quadrants subroutines of the circular part of the interchange, there is a speed limit that will ensure there are no collisions.

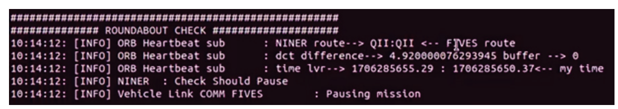

Fig. 5. Checking the Potential Collision and DCT

IV. Simulation

In order to simulate the working Roundabout use case and effectively show the V2V communication within the collision avoidance operation, a visualization environment developed by UMEX known as Air Commons is used. This allows for flights of UAS to be tracked based on receiving the telemetry data from the vehicles and a 2D visualization to be seen showing real time location of the UAS. The image of Air Commons can be seen below in figure 6. By using Air Commons, many UAS were able to be ran utilizing the Ardupilot software. The Ardupilot software is a open source unmanned autonomous controller that allows for UAS to be defined and tested to ensure no harm or expensive loss of vehicles.

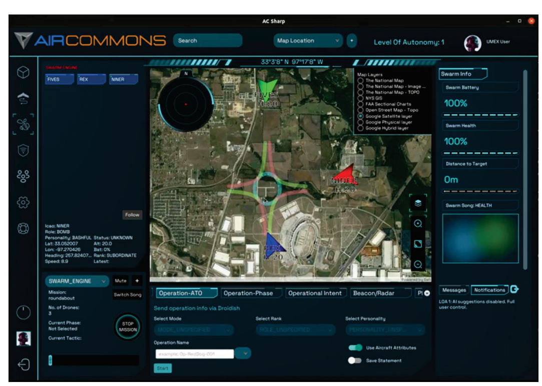

Fig. 6. The Environment Air Commons

For simulation purposes, three UAS called Fives, Niners, and Rex are created and flown through the Roundabout corridor system. Each UAS is given an initial position to start and the expected path to take. As each UAS is in the air space and about to enter the Roundabout, they check for potential collisions with the other UAS in the Roundabout using what is formally called the discovery message. This message allows for the UAS to communicate and exchange their subroutines as well as the potential collision zones and their DCT between the two vehicles. If their is a potential collision, yielding will take place. In figure 7 the output of "PAUSING" is displaced since the routes of each UAS is QII and the DCT is below 5 seconds, therefore, concluding there is a potential collision found forcing the UAS in the ingress subroutine of its flight to yield.

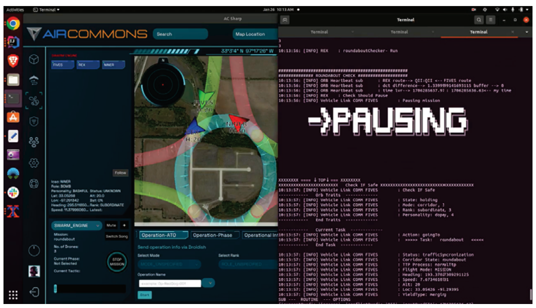

Fig. 7. The UAS "Fives" Pausing

After the UAS in the subroutine of ingress yields and the UAS in the Roundabout systems subroutines of the quadrants passes, there may or may not be any potential collisions with other UAS. Once the UAS makes the correct decision that their is no potential collisions, then it will begin to flight the remainder of its mission. In figure 8 it can be seen that Fives begins to "RESUME" or continue its flight and enter the Roundabout corridor with the speed limit.

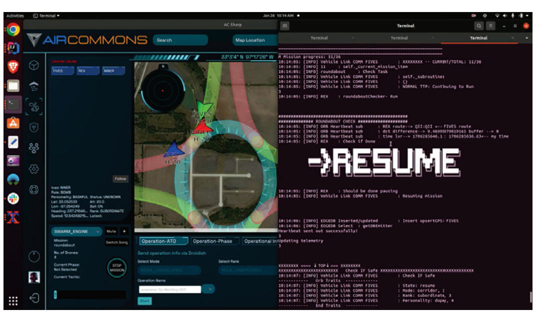

Fig. 8. The UAS "Fives" Resuming

After each UAS has successfully finished all yielding protocols in the Roundabout, the UAS continue to maintain communication in order to always monitor the other UAS in the system. However, since all UAS in the system have already entered and yielded accordingly each UAS will continue its initial flight plan and finish by exiting in the respective egress subroutine that was initially specified. In figure 9 each UAS can be seen going into the direction that they have been assigned, and no collisions have been made. This shows that V2V communication for UAS has successfully been accomplished and the Roundabout collision avoidance use case was successful at mitigating potential collision for AAM.

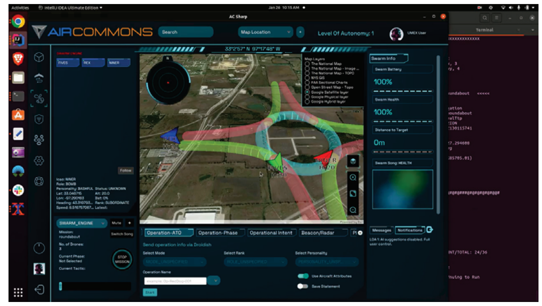

Fig. 9. Each UAS Finishes its Mission with No Collisions

V. Conclusion

This paper presented the Roundabout system, which uses V2V communication to facilitate UAS traffic in the airspace. V2V communications is a developing protocol that allows this use case to mitigate potential collisions. Future works will include extending the Roundabout's functionality into three dimensions, offering the capability to route traffic upwards and downwards in addition to the typical directions. This would allow for the Roundabout to be the medium through which altitude-differing layers of the airways could be accessed. Ultimately, the Roundabout has the potential to serve as a great benefactor to assist in wide-spread UAS integration into the NAS. The development of this model will continue into the future with this goal in mind.

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