The Philosophy of UAS-to-UAS Communications

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***Abstract*—With an increase in the use of Unmanned Aircraft Systems (UAS) and the inevitable integration of UAS in every imaginable industry, there is a need for enhanced situational awareness and information sharing. Traditional approaches are not sufficient for UAS as they are typically designed for human involvement in the decision-making process. Novel solutions based on variety of sensors are being developed for object detection and avoidance. This paper presents UAS-to-UAS (U2U) communication as a means to enhancing situational awareness and safety in the airspace. U2U communication is essential for enabling UAS to operate cooperatively, avoid collisions, and respond to dynamic scenarios in the airspace. As airspace is a shared resource regulated by federal agencies, such as the Federal Aviation Administration (FAA) in the United States, certain questions, such as which aircraft has the right of way, need to be addressed unambiguously. This paper focuses on the philosophy of U2U communications using the five use-case scenarios proposed by standard organizations. The outcome of this research serves as a potential input and guidance for regulatory agencies.**

***Index Terms*—UAS-to-UAS communications, Standards, Philosophy.**

I. Introduction

In the near future, Advanced Air Mobility (AAM) services, such as air taxis and air ambulances, are expected to be deployed on a large scale. AAM services use Unmanned Aircraft Systems (UAS), such as electric Vertical Takeoff and Landing (eVTOL) vehicles, to transport people and cargo over short distances within urban/rural regions. AAM platforms are expected to navigate autonomously in the airspace with minimal Ground Control Station (GCS) intervention. UAS-to-UAS (U2U) communications is one key enabler for UAS autonomy. U2U communication provides a means to exchange safety-critical information, such as location, speed, altitude, flight path, intent, and hazards, among others. It enhances situational awareness through coordination between UAS during close encounters, such as crossing an intersection or merging into traffic.

As airspace is a shared resource regulated by federal entities, such as the Federal Aviation Administration (FAA) in the United States, certain questions, such as who has the right of way, need to be addressed unambiguously; for instance, a balloon has the right of way over a glider, airship, powered parachute, airplane, or rotorcraft based on the aircraft rules [1]. Existing rules such as [2] are not sufficient for UAS as they are typically designed based on human involvement in the decision-making and execution process. It is necessary to develop rules and regulations for UAS to prevent potential accidents in the airspace. Federal aviation organizations in each country need to develop these rules and regulations to prevent accidents. In the United States, the FAA relies on standard organizations, such as the Radio Technical Commission for Aeronautics (RTCA), General Aviation Manufacturers Association (GAMA), IEEE, and the National Aeronautics and Space Administration (NASA). This paper focuses on the philosophy of U2U communications using five use-case scenarios developed by RTCA. It is to be noted that the outcome of this research serves as input to regulatory agencies.

A. Need

Existing communication technologies that are used in manned aviation, like Automatic Dependent Surveillance-Broadcast (ADS-B), cannot be implemented for UAS due to the high density in the airspace. FAA has mandated the registration of UAS using remote ID as a broadcast module for transmitting information, such as location and identity to all the other aircraft. ADS-B and remote ID modules are not sufficient for preventing collisions as they lack information about the intent of UAS. Collision avoidance systems for manned aircraft cannot be integrated into UAS as they require human intervention to avoid potential collisions. Typically, a vehicle has to go through a cell tower or satellites. Communication technologies, such as cellular and satellite communications can be used for Device to Device (D2D) communications. D2D communications can be replicated for UAS using the existing techniques but have high latency issues. U2U communications can give vehicles the capability of peer-to-peer communication, which will allow vehicles to negotiate and avoid any potential accidents autonomously using direct communications, such as mesh networks. In addition to avoiding potential collision, U2U communications can also help in sensing and rerouting in the event of bad weather.

B. Philosophy

Due to the integration of autonomous vehicles in the airspace, there is a necessity for developing rules and regulations regarding who gets the right of way; for example, when two manned aircraft approach each other head-on, the pilots need to turn the aircraft to the right [3]. These rules and regulations are developed by federal agencies in respective

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countries. The federal agencies, on the other hand, rely on standards organizations to develop protocols that account for the safety of all the vehicles in the airspace. One of these initiatives is the development of standards by IEEE P1920.2, which is working towards creating U2U protocols [**?**]. These standards are initially based on five use case scenarios proposed by RTCA, which include collision avoidance, merging, information relaying, collaborative sensing, and rerouting.

C. Objectives

The objectives of U2U communications in the context of AAM include (1) supporting autonomy in the airspace and (2) enabling coordination among multiple aircraft. This communication is essential for ensuring the safety of humans and the efficiency of operations in the airspace. U2U communications allow AAM vehicles to share information, such as the location, speed, and intent through their heartbeat. Every UAS broadcasts its heartbeat information to all other vehicles in the range using a predetermined frequency (usually 1 KHz). This subsection elaborates on the key advantages of using U2U communications: situational awareness, information sharing, and collaboration.

1) Situational Awareness: U2U communications enhance situational awareness for UAS and AAM platforms. The concept of situational awareness in the context of U2U communications allows UAS to sense the characteristics of the airspace it is occupying and share the data with other vehicles. This capability enables a comprehensive understanding of the airspace environment, leading to improved coordination, safety, and efficiency of UAS operations. Enhanced situational awareness helps in collision avoidance, information relaying, and adapting to dynamic environmental conditions.

2) Information Sharing: Information-sharing systems, such as ADS-B and remote ID are mandated by the FAA in the United States to share aircraft location and speed information with GCS and other aircraft [4]. However, ADS-B applications need authentication from existing manned aircraft collision avoidance systems, such as Traffic Collision Avoidance Systems (TCAS). ADS-B also requires human intervention to act on traffic advisory or resolution advisory from the TCAS. Additionally, ADS-B, at a given instance, can only act as either transmitter or receiver, which limits its ability to navigate in congested airways. Alternatively, the FAA uses remote ID to register the UAS, which can also share identity and location similar to ADS-B, but the information transmitted or received is not sufficient for autonomous operations as it does not have any information related to intent, heading, and speed of the aircraft. U2U communications are used to overcome these limitations by allowing direct and over-the-air communications between two vehicles coming closer to each other to prevent accidents.

3) Collaboration: A vehicle is expected to monitor its surroundings for any sudden development in weather or other obstacles, such as birds and rogue vehicles, to assess the safety of the airspace. The vehicle uses onboard sensors to collect data when a hazard is detected and transmits this information to other vehicles in its neighborhood. When multiple vehicles share their own estimated scope of hazards with the GCS, the GCS can estimate the overall scope of the airspace hazard and share it with the UAS that are affected by the hazard.

D. Contributions

This paper highlights the need for direct and over-the-air U2U communications. It explains how U2U communications facilitate autonomy in the airspace. Specific contributions are highlighted below.

- Rationale for U2U communications: U2U communications are presented as a means for enhanced situational awareness, information sharing, and collaboration among unmanned aircraft systems.
- Use Cases and Protocols: Five use cases for U2U communications, along with the relevant protocols, are discussed.
- Standardization Efforts: Ongoing efforts in various standard organizations, including RTCA, GAMA, and IEEE, are discussed.
- Messages: Two types of messages are suggested for U2U communications: broadcast and direct. An example of a broadcast message is ”heartbeat.” Each vehicle transmits a periodic heartbeat message, which includes its vehicle ID, telemetry, state, and intent. Direct messages are used for negotiations and coordination purposes.

E. Organization

The remaining paper is organized as follows: Section II explains the advantages and disadvantages of using cellular, satellite, and direct communications and their applications within U2U communications, Section III elaborates on the five use case scenarios, which are, collision avoidance, minimum separation, information relaying, collaborative sensing and airborne rerouting. Finally, Section IV gives the conclusion and the future work of the proposed technology.

II. Technologies

Communication technologies are categorized into two types: short-range and long-range communications. Short-range communications include WiFi and Bluetooth, which transmit data over 250 meters outdoors. This limited range falls short for U2U communications. Long-range solutions for U2U communications include Worldwide Interoperability for Microwave Access (WIMAX), cellular, satellite, and direct communications. In this section, the existing long-range communication technologies along the lines of U2U communications are briefly explained.

A. Cellular Communications

The 3rd Generation Partnership Project (3GPP) Release 17, published in April 2022 [5], focuses on the support of UAS in the 3GPP ecosystem, emphasizing the use of cellular connectivity to facilitate UAS operations. 3GPP is working towards developing protocols for telecommunications, including UAS 5G connectivity. The 3GPP system is designed to provide control and user plane communication services for UAS by

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enabling various UAS communication scenarios, such as direct U2U, local broadcast, transport service, and Command and Control (C2) communications [6], [7]. The 3GPP system aims to ensure ubiquitous coverage, high reliability, Quality of Service (QoS), robust security, and seamless mobility for UAS operations. The ongoing development of 3GPP specifications, including those related to 5G and UAS support, reflects the industry's efforts to address the specific communication requirements of UAS. The drawbacks of U2U communications using cellular communications include interference, spectrum congestion, and latency.

B. Satellite Communications

Satellite Communications (SATCOM) extends the reach of UAS communications, offering a method to connect drones and ground stations over long distances beyond the scope of ground networks. This technology is beneficial for UAS operations over oceans or in remote areas [8]. Satellites help with navigation and localization tasks for drones using Global Positioning Systems (GPS) and Global Navigation Satellite Systems (GNSS). The World Radio Communication Conference in 2015 (WRC-2015) marked a significant milestone by approving the conditional use of SATCOM frequencies in the Ku-/Ka-band for UAS connectivity, with companies like Inmarsat pioneering SATCOM services tailored for UAS [9]. The use of SATCOM for U2U communications is challenging due to the propagation loss, latency, size, weight, and power constraints.

C. Direct/Ad Hoc Networks

An ad hoc network is a type of network architecture in which the devices or nodes are directly connected without the need for a central server. This network topology for mobile devices is called a Mobile Ad hoc Network (MANET). A MANET can be applied to ground vehicles or drones, which are called Vehicle Ad hoc Networks (VANETS) and Flying Ad hoc Networks (FANETS), respectively. The fluid and dynamic nature of ad hoc networks allows a node to join and leave the network without affecting other components [10]. This self-forming and self-organizing network topology results in wider coverage of communication and the ability to route messages through the network based on the location and state of the other nodes. This technology is useful in U2U communications due to the nature of the heartbeat and direct messages. When a vehicle receives a broadcasted heartbeat, then those two vehicles are now directly communicating and are considered a network. More vehicles can join, and there is no set limit to the size of the network, but it is all dependent on the location of each vehicle that determines their state of network membership. In a case where the network is very large, then it is more than likely that vehicles on opposite sides will not receive each other's heartbeat, but that does not mean that they are not members; in fact, a message from one vehicle to the other can still be routed through the other vehicles in the network. In this paper, U2U communications focus on the use of direct communications for the implementation of all five use-case scenarios.

D. Key Performance Metrics

When it is time to practically implement U2U communications, the frequency of communications, the bandwidth allocated, and the hardware and software used for radios designed for U2U communications impact the performance of U2U communication protocols. The key performance metrics for U2U communications include the following:

- Round Trip Time or Latency: Latency refers to the time it takes for round-trip communication between two aircraft. For example, if a UAS sends a request for an action to another UAS, the time it takes to process the request until an acknowledgment is received by the requesting UAS, is a factor that determines the lead time needed for initiating negotiations between two aircraft.
- Data Rate: Data rate refers to the expected rate of communications during U2U negotiations.
- Communication Range: The communication range refers to the farthest distance the messages are expected to reach. This metric, in turn, is determined by the transmit power and the carrier frequency.
- Processing Time: The time an aircraft takes to process a message will add to the latency. Since transceivers typically employ software-defined radios, processing time may add to the overall latency. This, in turn, may add to the uncertainty in the estimated location of aircraft in the neighborhood.

III. Use-Cases and Standards

FAA relies on standard organizations such as RTCA, GAMA, and IEEE to develop standards for U2U communications. This section explains how U2U communications can facilitate autonomy in the airspace through the five use cases for U2U communication that are proposed by RTCA. The use cases discussed are collision avoidance, minimum separation, collaborative sensing, information relay, and airborne rerouting.

A. Collision Avoidance

Collision avoidance is the first use-case scenario in U2U communications. This use case was developed to avoid potential accidents in airspace by leveraging the data exchange among vehicles to enhance situational awareness. This data exchange comes in the form of a heartbeat, which is a message that is broadcast every second from the vehicle. The data contained within the heartbeat is general information on the vehicle, like its telemetry, intent, status, and more, as shown in Figure 1. While this heartbeat only contains general information, other vehicles in the area that receive this broadcast can process this information and act accordingly if needed to avoid collisions. The nature of the heartbeat allows for the automation of air traffic conflict management, where independent vehicles are responsible for monitoring their surroundings. With this, a vehicle can act per collision avoidance protocols when the probability of a collision is high. The collision avoidance protocols consist of two cases: the first is merging, used when a UAS wants to merge from one direction to another, and the second is when two vehicles are on the verge of a collision. The case where a vehicle is merging into a lane utilizes both broadcast and direct messages to facilitate a safe merging process. When a vehicle initiates the merging process, its heartbeat reflects this by changing the state of the vehicle so that neighboring vehicles will know its intent. Depending on the traffic of the lanes and the position of the surrounding vehicle, the vehicle attempting to merge, through a process, will select a vehicle and ask it to yield. This is accomplished by creating a session with the vehicle and exchanging direct messages until the yielding request is accepted or denied. A high-level diagram of this process can be seen in Figure 2. The merging vehicle will modify its heartbeat message to reflect the merging status and begin direct communication with a vehicle to request and negotiate to merge. If the negotiation proves successful, the vehicle will begin to merge while the second vehicle yields.

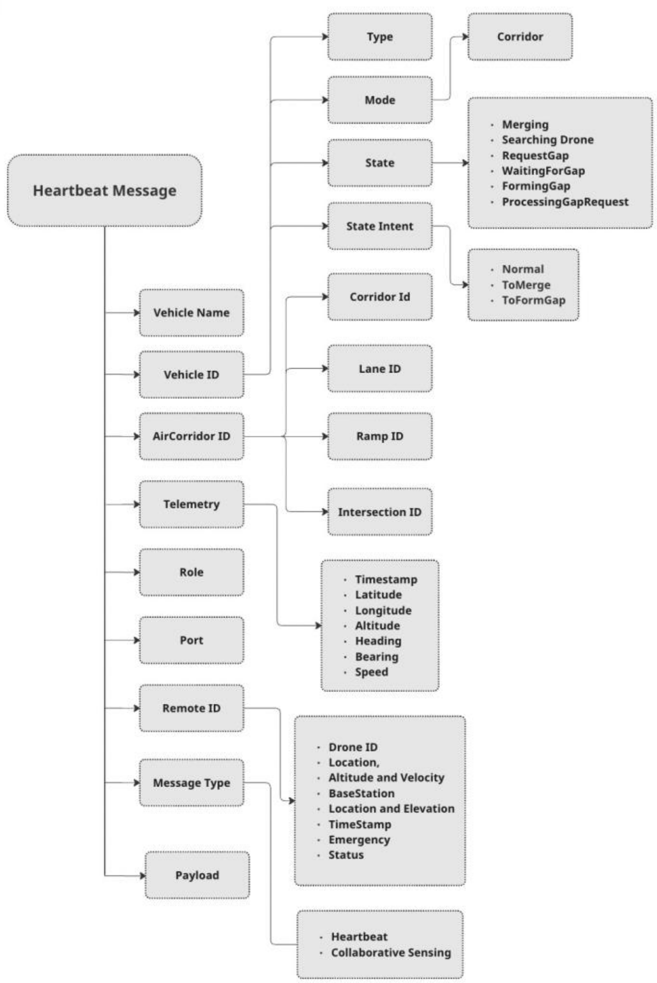

Fig. 1. Format of a Heartbeat Message.

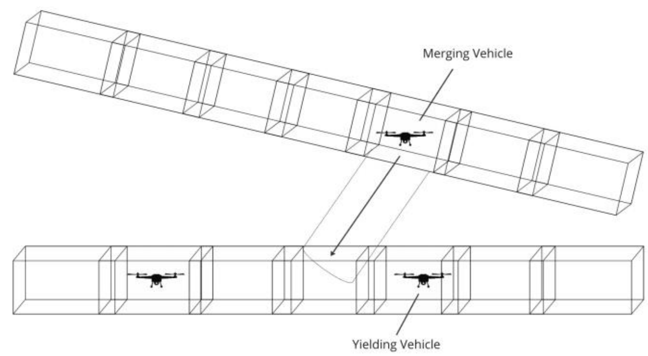

Fig. 2. Merging.

The second scenario, regarding two vehicles on the verge of collision, relies only on the heartbeat messages [11]. When a vehicle is in flight and receiving heartbeat messages, it is constantly comparing the telemetry in the message and calculating the distance between itself and the other vehicles. If the distance between two vehicles is less than the predefined threshold radius, then the possibility of collision is high. To ensure their safety and avoid a collision, vehicle use the information contained within the heartbeat to determine their action, which is either to yield or proceed. The role a vehicle plays is based on the priority. In this case, the vehicle with higher priority will proceed, while the vehicle with lower priority will yield.

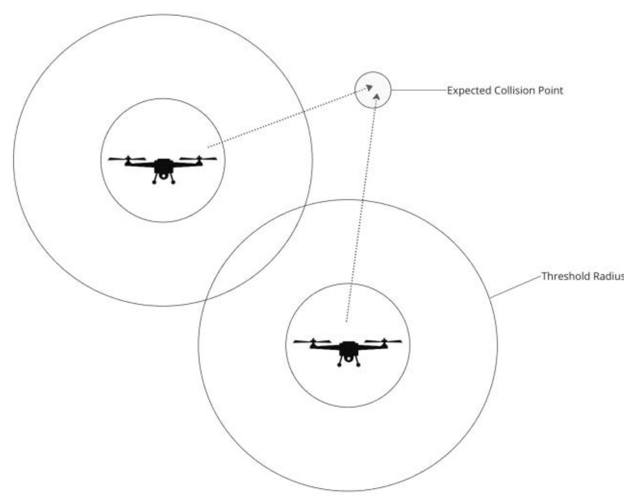

Fig. 3. Collision Avoidance.

This can be observed in Figure 3, where two vehicles have broken their threshold radius for safe flight. The expected collision point is determined, and based on the priority information within the heartbeat, one vehicle will yield while the other proceeds.

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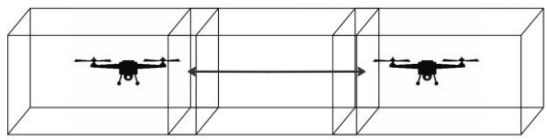

Fig. 4. Minimum Separation.

B. Minimum Separation

To truly preserve the safety of the airways, every vehicle must conduct operations within a safe distance from one another. This minimum separation distance is a predefined distance that all vehicles must maintain at all times. This use case relies entirely on the heartbeats received from neighboring vehicles, more specifically, the telemetry information contained within the heartbeat. The telemetry of the nearby drones is pulled, and the distance from Vehicle A to Vehicle X is calculated. If it is determined that the minimum separation distance threshold has been broken, then it is the responsibility of the two or more parties involved to negotiate and determine a solution to regain the minimum separation distance. An example of this can be seen in Figure 4, where, while in flight, two vehicles are constantly monitoring one another to keep their minimum separation distance.

C. Collaborative Sensing

The collaborative sensing use case is one that was proposed to provide vehicles with spatial awareness of hazards in the airways, as shown in Figure 5. Once a vehicle observes a hazard in the air through onboard sensors, it broadcasts a message decorated with information on the observations and sensor data. These hazards can either be weather, non-conforming vehicles, or non-conforming object hazard types. The weather hazard type encompasses all scenarios of bad weather through wind data. In the event of a heavy storm, tornado, or snowstorm, heavy winds are all present. By simply collecting wind data through onboard sensors, vehicles can account for all scenarios of hazardous weather. If the hazard type is a non-conforming object, like a bird or a hobbyist drone, vehicles use other onboard sensors to collect data on the unauthorized object in the airway and broadcast the collaborative sensing message to neighboring vehicles and ground control stations. The same logic applies to non-conforming vehicles, which are vehicles that do not follow mission protocols, whether it be a loss of communication or a divergence from the assigned flight path. Until the vehicle begins to conform to standard mission protocols, it is considered a non-conforming vehicle for others to observe and be cautious of. With multiple vehicles broadcasting the observed hazards, the local ground control station can more accurately assess the situation and act accordingly. The preceding action is the creation of what is known as a constraint, which is a three-dimensional volume that encloses an area that is observed to be a hazard to vehicles. This constraint is then broadcasted to all local vehicles for them to process and avoid. The creation of these constraints in the airways and giving vehicles dynamic no-fly zones allows for safe flights and near autonomy using U2U communications.

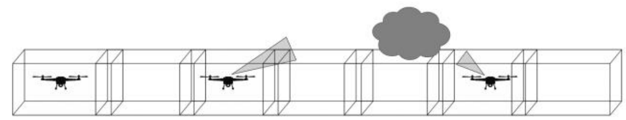

Fig. 5. Collabrative Sensing.

D. Information Relay

Information relay is a use case that utilizes U2U communication to use nearby vehicles as nodes from which a message can be relayed to the desired UAV. The communication in this scenario comes in the form of a direct message, which is a peer-to-peer communication protocol. Multiple different types of messages can be relayed, like constraints and new routing, but only the ground control station can utilize the information relay protocol.

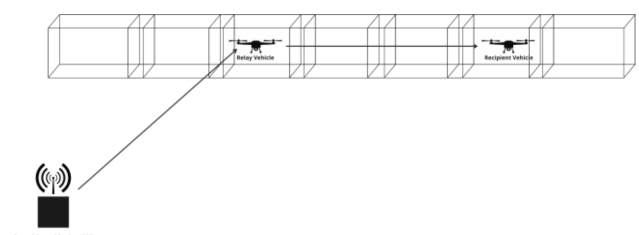

Fig. 6. Information Relay.

Figure 6 shows a ground control station sending the recipient vehicle a message by relaying it through the relay vehicle.

E. Airborne Rerouting

Airborne rerouting is a proposed use case that allows for a UAV to have a dynamic flight plan. This dynamic flight plan is beneficial in the case of emergent-hazardous weather or other unexpected hazards in the airways. The rerouting system also utilizes the direct peer-to-peer messaging protocol. In this scenario, when a constraint is formed, and a ground control station becomes aware of a vehicle on a path towards the constraint, it attempts to assist the vehicle in effectively avoiding the constraint by sending it a new route that avoids the constraint. The ground control station, if needed, can use the information relay to send a vehicle out of the UAS range to a new route by routing it through a nearby vehicle.

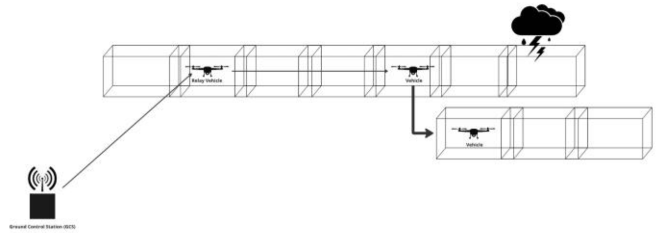

Fig. 7. Airborne Rerouting.

This scenario can be seen in Figure 7, where a vehicle is on the verge of passing through a hazardous thunderstorm, so the ground control station sends a new route to the vehicle by using the nearest vehicle as a relay node.

IV. CONCLUSIONS AND FUTURE WORK

This paper highlighted the need for U2U communications through use cases. Several scenarios, including collision avoidance, airborne separation, information relay, and rerouting, are described to justify the significance of U2U communications. The key performance metrics relevant to the practical implementation of U2U communications are presented, but not directly addressed. The concepts presented here will serve as a foundation for developing standards for U2U communications. The key performance metrics including data rate, processing time, round trip time, and communication range will be further investigated in future work.

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