DISTRIBUTED POSITION CONTROL IN UAS NETWORKS: CHALLENGES AND REQUIREMENTS

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Abstract

Many applications of Unmanned Aircraft Systems (UASs) have been developed in the past and are commonplace today in many domains both in urban and rural areas. However, although applications for UASs in urban areas are plentiful, their realization is still limited by the lack of methods and technology that enables safe and reliable monitoring and managing of the airspace. In this context, obtaining and verifying the positions and movements of all UASs in the airspace in real-time is essential but currently not possible. In order to overcome this problem, drone-to-drone communication plays a key role. Hence, in the VEREDUS project, a solution for direct drone-to-drone communication was developed including the design of hardware, antennas and software. The performance of the network was assessed using a traffic and network simulator. In this paper, we present the core requirements and challenges identified in the project and sketch a solution that serves both current real-world UAS applications as well as future UAS networks.

Keywords

infrastructure-less networks, data link, communication, UAS, UAV, UTM

1. INTRODUCTION

Over the years, a large body of research has been conducted for Unmanned Aircraft Systems (UASs). From first concepts over military prototypes to today's commercially available drones, much has been achieved in terms of technological capabilities. Almost as old as the first Unmanned Aerial Vehicles (UAVs)[1] are the promises to fundamentally change many industries by this technology. Among them are logistics (e.g., on-demand delivery of food and parcels), surveillance (e.g., of people or traffic) as well as environmental monitoring, to name a few. Nevertheless, these promises are slow to materialize and urban skies still remain void of the large-scale UAS networks predicted. One reason for this is, that the capability to monitor and manage large amounts of UASs safely and efficiently using Unmanned Aerial Traffic Management (UTM) systems is still lacking [1]. Such systems would provide for many services to UAS operators like requesting flight permission, deconflicting and remote piloting. But most importantly, UTM systems must provide a mechanism for airspace monitoring in which the positions of UASs are reliably known at any time. Although concepts for UTM systems exist all around the world [2], the communication technology to support such concepts is still at an early stage. This does not mean, that UAS communication is a new research field. In fact, over the last decade, much has been done to develop and evaluate communication protocols for UASs, measure and analyze the performance of contemporary communication systems for the application in UAS scenarios [3, 4] or propose entirely new systems. Nevertheless, these studies either consider very specialized use cases involving only a handful of UASs, or assume high traffic scenarios, which are still to be realized. The VEREDUS project, funded by the German Federal Ministry of Economic Affairs and Climate Action (BMWK, LuFo VI, No. 20Q1939), aims to fill this gap by developing a communication system that serves the needs of current and future UAS applications, while focusing on distributed position control (DPC) for airspace management. This paper provides an overview of the objectives and

[1] UAV refers to the drone itself, the flying component, while UAS includes the UAV plus all operational support elements (e.g., ground control, communication equipment). However, these terms are often used interchangeably in the literature.

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results obtained by the VEREDUS project including challenges and requirements in developing DPC. Section 2 examines state-of-the-art technologies and commercially available UAS applications in use today. Section 3 explores emerging technologies and future UAS applications. Section 4 outlines key research challenges in creating a distributed UTM service, followed by a discussion of the methodologies employed to refine our project's goals, including an introduction to our project consortium with its unique composition of research institutes, UAS manufacturers and communication system developers.

2. STATE OF THE ART

Crucial for the adoption of any communication technology is that it delivers immediate use for its intended users. Therefore, instead of relying on future predictions of UAS applications, in the project we collected applications that are realized today in Europe. Additionally, we surveyed the current communication technologies used to identify areas of improvement.

2.1. Deployed UAS Applications in Europe

This section provides a basic overview of already deployed UAS applications in Europe.

- **Surveillance:** UAS are used to monitor industrial zones, military bases, airports and more for safety, intrusions, or illegal activities. This enables quick response to incidents even in large or difficult-to-reach areas.
- **First Responder Operations:** Fire brigades and police can deploy UAS immediately after an alarm is raised. This allows responders to assess the situation remotely and quickly, gaining valuable situational awareness before arriving on site. Additionally, UAS help in searching for missing persons as larger areas can be covered autonomously.
- **Agriculture:** UAS are used for precision spraying of pesticides, herbicides, or fertilizers over crops, reducing chemical use and labor. UAS can also be used for monitoring crop health, providing data for farmers to informed decisions on crop management and treatment.
- **Transport of Medical Supplies:** UAS are used to deliver urgent medical supplies (e.g., blood samples, vaccines). Also life-saving devices like Automated External Defibrillators (AEDs) or even life jackets for water rescues can be delivered to a victim minimizing response time.
- **Monitoring and Inspection:** UAS are used to continuously survey infrastructure (e.g. power lines, pipelines, airport perimeters) to detect damages or leaks. This reduces the need for manual inspections and enhances safety by identifying issues before they become critical.
- **3D Detection using LIDAR or Photogrammetry:** UAS are used to capture high-resolution 3D data of terrains and structures for mapping or conservation purposes. Also UAS are used for movie projects, offering high-quality aerial footage.

While these represent a broad spectrum of today's UAS applications, a common pattern emerges: The applications are high-value activities involving expensive equipment and the full attention of remote pilots, that in turn is requiring a high degree of communication reliability.

2.2. Existing Communication Infrastructure

As described in the section above, current applications typically utilize a very limited number of drones, often just one. Consequently, manufacturers employ infrastructure-based communication technologies, such as 3G/4G/5G and satellite (e.g., Starlink), to ensure continuous connectivity between the UAV and the operator station. However, these technologies constrain the UAS's operational range and limit the number of UASs that can be supported simultaneously. Additionally, as these systems were not designed with UASs operation in mind, there are no reliability guarantees.

3. FUTURE PERSPECTIVE

As soon as UTM systems provide for easy access to safe and reliable UAS operations, their use can be expected to become ubiquitous. This will require the employed communication system to adapt to the new applications and scale with the increasing amount of UAVs in the airspace.

3.1. Future UAS Applications

Package delivery is emerging as a key application of UAS in other parts of the world and can be expected for the near future in Europe. Here, UASs can enable efficient, same-day delivery of parcel, food, newspapers etc. and thereby reduce the dependency on ground transportation and potentially alleviating urban traffic congestion. This showcases how UAS could redefine logistics by offering speed, cost-efficiency, and even eco-friendly alternatives to conventional methods. Many already operational businesses showcase the possibilities and limitation of this application. The authors in [5] discusses the relevance for drone-based package delivery systems. As noted in [6], the volume of parcel and food deliveries in cities like Paris is expected to grow substantially. If only a fraction of the conventionally shipped packages was distributed using UAS the urban skies will become crowded. Hence, the delivery application was identified as the simulation baseline in the VEREDUS project. Beside package delivery many other applications (such as monitoring, inspection, photography etc.) will involve UAVs from different operators sharing the same airspace. Therefore, managing the airspace safely and efficiently is a critical task. Clear standards and interoperable technologies are essential to ensure, that UAS from various operators can operate seamlessly together.

3.2. Communication Technology

To enable these future UAS applications, new communication solutions are required. Due to the expected large number of UASs sharing the airspace, scalability becomes a major concern. Especially in urban areas where the cellular communication infrastructure already is highly utilized, an alternative is required. Additionally, operating UASs in close proximity of each other raises a need for direct communication between them to enable self-separation and short term conflict resolution. Finally, once UASs applications become a mass market, a much higher degree of reliability must be guaranteed.

While today, carefully planned missions also allow the operation of UASs with intermittent communication, this cannot be tolerated in city-scale deployment of UAS delivery systems with fully autonomous operating drones. To address these challenges, we expect two characteristics emerging for future UASs communication systems: First, these systems will be realized as multi-link systems, which are able to seamlessly utilize many different communication technologies at the same time. Second, while these multi-link systems will certainly integrate terrestrial and non-terrestrial communication, they will also be able to realize communication by forming an ad-hoc network where UASs directly exchange messages with other UASs in range and forward traffic on behalf of them. In combination this makes communication independent of any ground or space infrastructure while adding another layer of reliability.

4. REQUIREMENTS AND CHALLENGES

Within the VEREDUS project, we identified requirements and challenges for a communication system supporting both current and future applications, complementing today's communication technology and enabling scalable solutions for the future. The list is not exhaustive as other requirements might become applicable in the future due to standardization, legal aspects or certification.

4.1. General Requirements

To realize reliable and independent communication for an UTM system, we have developed a set of general requirements the system has to adhere to:

- Provide a decentralized/infrastructureless communication network including stationary and mobile nodes
- All nodes (UASs, operators, monitoring stations, ...) are treated as equal
- All UASs using the airspace must be equipped with the communication system
- The system needs to be independent of the operator
- Gateways provide for operator access to the network from outside
- The network must be able to dynamically reconfigure/recover in case of events e.g., connecting and disconnecting nodes, relative speeds and adverse weather conditions
- In large scenarios, at least local functionality must always be guaranteed
- A high availability must be achieved independent of application
- Real-time forwarding of messages must be supported
- Scalability of the system must be given; Support of both urban (high density) and rural (low density) scenarios today and in the future
- Covering the Very Low Level Airspace (VLL) up to 150m in altitude
- Other participants (e.g., Air Taxis) should easily be integrable

Going further, we propose two core applications of the system that have to be provided to pave the way for the safe and reliable operation of UASs:

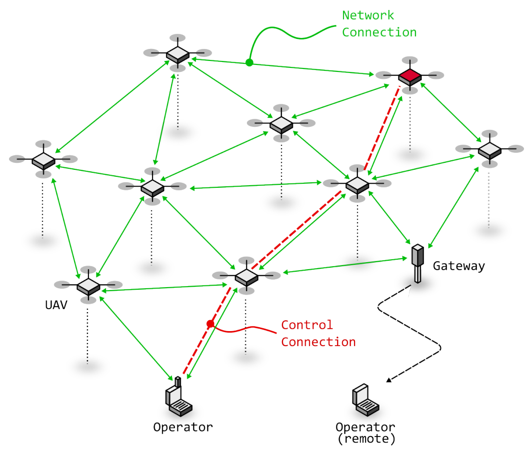

FIG 1. Schematic structure of the proposed system of providing for Situational Awareness (green) and Control Connection (red).

Situational Overview: Our first core application of the system is the provision of a situational overview (SO) using DPC. This would allow every node in the network to obtain a timely, independent and accurate view of all movements in the airspace. A schematic of this application is shown in Figure 1. Here, the network is established in between the nodes (green). To realize the SO in a decentralized way, all nodes periodically have to report their current position data similar to Automatic Dependent Surveillance - Broadcast (ADS-B) or Flight Alarm (FLARM) [7] to the network neighbors. To provide a SO of the entire network, nodes need to forward the received position reports from others through the entire network, so that every node receives the reports from all other network members. The performance of the SO can be quantified with the *refreshment rate* which is the rate at which new information from every other node is received. This is of particular importance as the age of the position information directly translates into uncertainty about the current position.

The collected information can on the one hand be used as a global SO by authorities to manage air traffic flows, deconflict or adapt single flights or on the other hand by the vehicles themselves as local SO comprising neighboring vehicles enabling collision avoidance and self-separation.

For the SO, we derived the following major requirements:

- It must be possible to construct the SO on every node independently using the available data
- The refreshment rate should be as high as possible
- The refreshment rate of the global SO (including all entities in the network) should be less than $5\,\mathrm{s}$ roughly aligned with International Civil Aviation Organization (ICAO) requirements for radar systems [8]
- A position update rate of at least $2\,\mathrm{Hz}$ should be realized similar to the ADS-B transmission rate [9]
- The network needs to enable time-synchronization
- Ground-based nodes should be able to feed the SO into other terrestrial networks (e.g., making it available on the internet or on other platforms)

Control Connection: The second core application identified in the VEREDUS project is the provision of a redundant control connection between operator station and vehicle in case of primary link loss (e.g., via terrestrial telecommunication systems) that is independent of any ground infrastructure. This has to be realized with point-to-point communications over multiple hops as shown in Figure 1 (red line). To provide for seamless connectivity, an additional satellite connection can be considered as a backup in the case that also the Air-to-Air (A/A) connection is not available. However, satellite connections come with the known drawbacks of high monetary cost and latency.

For the control connection we formulate the following requirements:

- The redundant control connection is not used for primary or direct operation of an UASs
- The priority of communication is: primary link (e.g., cellular) $\rightarrow$ VEREDUS network $\rightarrow$ satellite link
- The redundant control connection has to be established at least within $30\,\mathrm{s}$ after loss of the primary connection. For certain applications or situations this time might be reduced.

4.2. Hardware Requirements

It is self-evident, that the developed communication hardware must be compatible with the UAVs. Additionally, the same hardware must be connectable to an operator station or a gateway. To ensure this, we developed hardware requirements based on the two primary UAV types our manufacturing partners utilize (multicopter and Vertical Take-Off and Landing UAV (VTOL)), which are representative of commercial UAVs in use today. Their characteristics are summarized in Table 1. The following main requirements concerning the hardware were identified during the VEREDUS project.

- System is intended for UAS-Category open and specific up to 25 kg as defined in [10]
- Compatibility with VTOL and multicopter types
- System weight and volume needs to be minimized
- System can be used outside of UAS to be connected to an operator station
- Provision of interfaces to connect to UAV flight controller and operator station

4.3. Challenges

Enabling an effective DPC presents a range of technical and scientific challenges that are listed below.

4.3.1. Technical Challenges

- **Range Limitation:** Limited range of wireless technologies lead to reduced coverage. The required range depends on the vehicle density resulting in large ranges for sparse scenarios.
- **Position Falsification:** Positions emitted from UASs might be intentionally or unintentionally (e.g., through GPS malfunctions) falsified. For a trustworthy situational overview, UASs must be able to verify position reports.
- **Infrastructure Independence:** Protocols should operate independently of infrastructure, supporting U-Space without reliance on proprietary communication technologies. This enables any authority to monitor the U-space.
- **Commercial Hardware:** To create a deployable solution, standardized off-the-shelf communication technologies (e.g., IEEE 802.11bd, C-V2X) are preferred for adaptability to UAV mobility and range requirements. Scenarios range from low (i.e., to

TAB 1. Comparison of VTOL and multicopters provided by the project partners

Vehicle	**VTOL** - SONGBIRD	**Copter** - CEPTOR
Structure	Fixed-wing with vertical lift	Multi-rotor (quad, hex, octocopter)
Take-off/Landing	Vertical	Vertical
Efficiency	Efficient in long flights	Higher energy demand
Range	up to $100\,\mathrm{km}$	up to $30\,\mathrm{km}$ (one way)
Speed with lowest power consumpt.	$\sim 70\,\mathrm{km\,h^{-1}}$	$\sim 60\,\mathrm{km\,h^{-1}}$
Weight	$15\,\mathrm{kg}$	$12\,\mathrm{kg}$ with battery
Payload size	$4.4\,\mathrm{kg}$	$2\,\mathrm{kg}$ (depending on the flight time)
Hovering	Circling	Yes (higher power consumption)
Communication	3G/4G/5G - Starlink	3G/4G/5G - Starlink
Applications	Surveying, long-range delivery	Aerial photography, precise work

support current scenarios) to high (i.e., to support futuristic scenarios) UAV densities with multi-hop connectivity, making the choice of technology critical.

- **Antenna Positioning**: Optimizing antenna placement is essential for reliable communication quality, especially with the project's two UAV types.
- **Integration:** Integrating hardware and software across various UAV types presents challenges in terms of power constraints, interfacing requirements, and space limitations, which must be addressed for seamless deployment.

4.3.2. Scientific Challenges

- **Business Models:** Business models of future UAS applications strongly influence vehicle amount an positions. These are not available today.
- **Data Availability:** Analyzing large-scale UAV network performance is challenging due to a lack of empirical data. Real world trajectory data for future UAS applications are not available or are limited.
- **Coexistent Point-to-Point Communication:** For the redundant control connection a routing protocol is required that can coexist with the employed flooding protocol. This poses a challenge for existing protocols as they are sensitive to excessive amounts of background data traffic
- **Efficient Flooding Protocols:** The situational overview requires flooding of position updates, which must minimize control overhead and avoid outdated information.
- **Position Verification:** Positions need to be verified in a decentralized way.

5. MAIN PROJECT OUTCOMES

Within the VEREDUS project the software and hardware requirements presented above were addressed and prototypes of the systems were developed. The main outcomes of this research are summarized as follows:

- Based on the scenarios and the requirements outlined above, we developed a stochastic model to estimate the required range, delay and bandwidth for current, as well as future UAS networks [11]. Our results show, that today's networks require communication ranges of multiple kilometers. This value comes down for future networks to several hundred meters. Here, mainly the bandwidth required for the situational overview becomes the bottleneck.
- We reviewed state-of-the-art mobile, wireless, and satellite technologies and selected suitable technologies based on the requirements outlined above. To serve both current and future networks, a 868MHz based long-range communication technology as well as C-V2X for high data rate requirements were selected. Additionally, a Iridium satellite connection was provisioned as a backup.
- To make the situational overview scale also for larger scenarios, a special purpose flooding protocol was developed supporting more than twice the size as comparable protocols from the literature [12]. Additionally, a protocol for the multi-hop redundant control connection was developed [13]. Both protocols were extensively evaluated using simulations.
- To evaluate future traffic scenarios, an approach to simulate generic mobility traces for urban UAV networks was developed [14]. Here, urban areas with arbitrary shapes and population distribution can be

generated that are then used in a multi-step approach to derive package delivery missions and to simulate the movement of single UASs while taking into account the flight performance of different types of vehicles.

- To provide for verification of received position updates, approaches from literature have been applied to our scenario [15]. A new approach based on comparing independently measured GNSS positions and node distances in the projected network was developed [16] and evaluated using simulations.
- To provide for omni-directional communication, special antennas were developed to be used with the provisioned C-V2X module.
- The entire communication module was realized in hardware providing all necessary interfaces. Additionally, software was developed implementing communication between UAV and communication module as well as the developed protocols.
- The communication system was integrated into 4 UAVs (two of each type as listed in Table 1). An exemplary integration is shown in Figure 2.
- Extensive flight tests and measurement campaigns were conducted to proof the functionality of the system and to obtain performance data in real life scenarios.

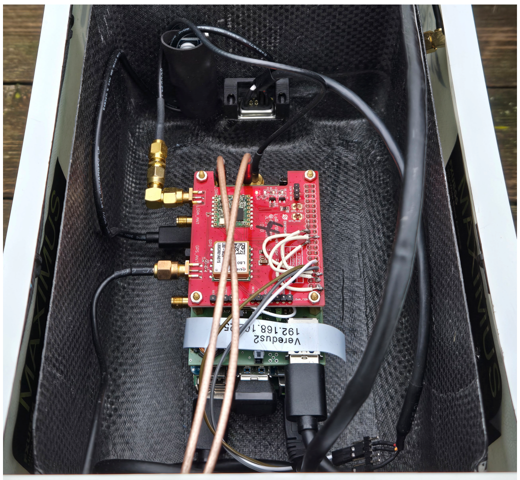

FIG 2. VEREDUS communication system integrated in a Songbird

6. VEREDUS CONSORTIUM

To achieve these outcomes, a wide variety of skills in different disciplines are required by the diverse VEREDUS consortium consisting of 2 academic and 5 industry partners.

6.1. Academic partners:

- The **DLR-Institute of Air Transport (DLR)**[2] conducts research in the area of air mobility with a strong focus on flight operations concepts, economics and scenarios. In the VEREDUS project, DLR lead the development of scenarios and requirements for the project. Based on these, a simulation framework was developed allowing for the generation of arbitrary city structures, flight demand and realistic 4D trajectories for individual UASs.
- The **Institute of Communication Networks at Hamburg University of Technology (TUHH)**[3] is a research institution specialized in design, validation and modeling of communication networks. Correspondingly, their contribution in the VEREDUS project, is centered around developing tailor-made communication protocols for the distribution of data in UAS networks, system-level evaluation via simulation as well as analytically modeling the performance.

6.2. Industrial partners:

- **IMST GmbH**[4] has an extensive research program in the field of RF systems and RF and millimeter wave components, which has been built up since 1992 and has been involved in many projects in the field of FE co-operation as well as on the level of industrial product development. In VEREDUS IMST is responsible for the design, realization,characterization and integration of the C-V2X circular polarized antennas.
- **MediaMobil**[5] is a telecommunications network operator and service provider. VEREDUS was a strategic activity to develop the architecture and critical software components of a heterogeneous communications network providing ubiquitous and seamless connectivity for UAS networks.
- **f.u.n.k.e AVIONICS**[6] is a developer and a producer of avionics solutions for communication, navigation and display. Their contribution is on developing an radio module, which is integrated with the antenna front end in the provided drones, considering the specification of the requirements for the VEREDUS modem.
- **Germandrones**[7] develops flight control software, hardware, and communication solutions. They provide test vehicles, such as the SONGBIRD model, for the final demonstration of VTOL UAVs and are responsible for defining project requirements and preparing the demonstrators for flight testing.

[2] https://www.dlr.de/de/lv
[3] https://www.tuhh.de/et6/homepage
[4] https://imst.com
[5] https://www.mediamobil.de/en/
[6] https://www.funkeavionics.de
[7] https://www.germandrones.com/en/

- **Globe UAV**[8] develops intelligent drone systems based on cellular solutions for Beyond Visible Line of Sight (BVLOS) operations in 5G and 4G networks. They provide vehicles (CEPTOR model) and are responsible for defining project requirements, preparing the demonstrators and providing their test field for flight testing.

7. ACKNOWLEDGMENTS

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