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UAV as a Service: Providing On-Demand Access and On-The-Fly Retasking of Multi-Tenant UAVs Using Cloud Services

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EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

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UAV AS A SERVICE: PROVIDING ON-DEMAND ACCESS AND ON-THE-FLY RETASKING OF MULTI-TENANT UAVS USING CLOUD SERVICES

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By

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This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Remzi Seker, Department of Electrical, Computer, Software and Systems Engineering, and has been approved by the members of his thesis committee. It was submitted to the Electrical, Computer, Software and Systems Engineering Department and was accepted in partial fulfillment of the requirements for the degree of Masters of Cybersecurity Engineering

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EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

Abstract

UAV AS A SERVICE: PROVIDING ON-DEMAND ACCESS AND ON-THE-FLY RETASKING OF MULTI-TENANT UAVS USING CLOUD SERVICES

by Justin YAPP

As commercial roles for Unmanned Aerial Vehicles (UAVs) become more well-defined and demand for the services provided by them increases, UAVs rely more on new cloud computing services and co-opertive coordination to provide mission planning, control, tracking and data processing . We present UAV as a Service (UAVaaS) framework, which brings features commonly found in traditional cloud services, such as Infrastructure, Platform, and Software as a Service, to the domain of UAVs. Our work aims to conceptualize and design UAVaaS for commercial applications. Specifically, a cloud-provided orchestration framework that allows multi-tenant UAVs to easily serve multiple, heterogeneous clients at once and automatically re-task them to users with higher priority, mid-flight, if needed. This research utilizes a spiral model design approach to formally define the UAVaaS framework, and to identify key focus areas, protocols, data structures, network topologies, and message patterns. A safety and security analysis is performed to mitigate potential risks that are present in the system and a prototype simulation is implemented as proof of concept.

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List of Abbreviations

AUVSI **A**ssociation **O**f **U**nmanned **V**ehicle **S**ystems **I**nternational

COA **C**ertificate **O**f **A**uthorization

FAA **F**ederal **A**viation**A**dministration

NAS **N**ational **A**irspace **S**ystem

SAC **S**pecial **A**irworthiness **C**ertificate

UAV **U**nmanned **A**erial **V**ehicles

UAVaaS **UAV** as a **S**ervice

Chapter 1

Introduction

Unmanned Aerial Vehicles (UAVs) are rapidly changing the way the world does business. Technology that was once solely used as reconnaissance and attack infrastructure for military missions, has quickly become practical solutions to a wide range of commercial and industrial problems. Today, UAVs can be registered and certified to fly commercial operations involving structural inspections, wildlife protection, emergency management, land surveying, real estate, film production, border patrol, and agriculture, while simultaneously uploading and sharing visual data in the cloud.

Research and development companies, trying to stay ahead in a new competitive market, have tackled and solved major inherent issues with performance, handling, safety, management and communication, in the efforts of attracting potential customers. The Federal Aviation Administration (FAA) is now receiving pressure to develop and implement new rules and regulations to allow for safe operations of UAVs within the National Airspace System (NAS), indicating a major influx is expected in the near future.

Sadly however, as the technology and features of next generation commercial UAVs improve, their corresponding price tag increases exponentially as well. While UAVs provide immediate advantages and benefits over traditional solutions, a five digit U.S. dollar quote for just one UAV will be a deal breaker for many smaller companies. Furthermore, companies will also need to pay additionally for FAA licensing and certification, high insurance premiums to cover potential damage and liabilities, highly trained pilots and expensive maintenance fees.

Introduced in this thesis is an alternative approach to the way companies acquire and fly UAVs for commercial operations that would otherwise create a huge financial burden. By installing hubs with commercial-grade, readily flyable UAVs in areas of high commercial density and connecting them to a cloud service provider, companies can now temporarily connect to UAVs and use them as a "pay-as-you-go" utility service similar to the Infrastructure, Platform and Software as a Service business models seen today.

UAS as a Service (UAVaaS) is essentially an orchestration framework that helps to coordinate the scheduling, reservation, tasking, re-tasking and control of UAVs as needed by companies located within designated service areas. Also provided is a data consumption and billing management system that allows customers to track, monitor and pay usage charges as flight operations are flown on a daily, weekly, monthly and yearly basis. UAVaaS eliminates the long waiting times for a rental UAV to arrive in the mail, or for an outsourced UAV company to arrive at the company's location of interest. This wait time is avoided because UAVs will take off on its own to customers' points of interests and fly designated flight plans as needed. UAVaaS providers takes care of all overhead such as acquisition, maintenance, licensing and insurance of UAVs allowing customers to focus on the mission at hand.

This research aims to define, conceptualize, and design UAV as a Service to successfully realize this idea. A literature review is conducted to determine the current state of the UAV market, and the projected future impacts UAVs have on the U.S. economy. The spiral model design methodology is used to design this new system and to identify potential areas of concern.

Key objectives of this research include: (1) identification of primary actors and shareholders involved in the system, (2) identification of special requirements needed to comply with existing rules and regulations, (3) generation of high level system designs, network topologies, and data structures that can be used for future implementation of the system, (4) analysis of risk and security concerns which need to be mitigated and (5) a simulated proof of concept of how the UAVaaS system will work.

Chapter 2

Literature Review

A collection of related literature was studied and analyzed to become more familiar with current development and integration in the National Airspace System (NAS). Areas of interest include regulations and policies, economic impacts, current UAV features and capabilities and current cloud computing technologies already available for commercial UAV operations. The following sections summarize the majority of information researched and gives an up-to-date overview of commercial UAVs.

2.1 FAA Regulations and Policies for Commercial UAVs

The Federal Aviation Administration has established rules and guidelines that define how UAVs should be registered and operated within the National Airspace System[7,8]. The FAA classifies UAVs into three main categories: (1) Public (Government), (2) Civil, and (3) Hobby/Recreational. Since commercial UAV operations fall under civil policies, that is where attention will be focused.

During the second quarter of 2015, the FAA released a Small UAS Notice of Proposed Rulemaking (NPRM) which, once completed would be the primary method for companies to receive authorization to conduct non-recreational operations. The rule would limit flights to daylight and visual-line-of-sight. Until then, there are currently only two methods of gaining FAA authorization to fly commercial, non-governmental UAVs: (1) A Section 333 Exemption combined with a civil Certificate of Waiver or Authorization (COA) must be filed to allow commercial operations in low-risk, controlled environments or (2) Special Airworthiness Certificate (SAC) must be filed describing the design and construction of the UAV as well as how it is intended to be flown.

Section 333 Exemptions is usually the most popular option and is granted to operators if the Secretary of Transportation authority can determine if "an unmanned aircraft system, as a result of its size, weight, speed, operational capability, proximity to airports and populated areas, and operation within visual line of sight does not create a hazard to users of the national airspace system or the public, or pose a threat to national security and whether an airworthiness certificate or COA is required for operation. The Section 333 Exemption process provides operators who wish to pursue safe and legal entry into the NAS a competitive advantage in the US market place thus discouraging illegal operations and improving safety". As of 2/26/2016 there have been 3,615 Petitions Granted by the FAA with 399 being closed[13].

2.2 Economic Impact and Regulatory Setback of the UAV Industry

In March 2013, the Association of Unmanned Vehicle Systems International (AUVSI) disclosed an economic impact report of UAV integration in the United States[5]. Since then, this report has become a gold standard forecast for the commercial UAV market. It is predicted that the growth of the unmanned systems industry will lead to the creation of thousands of jobs and tens of billions in revenue. Furthermore, it is forecasted that out of the total 103,776 new jobs created nationally by 2025, 70% of jobs will be created as well as $13.6 billion in overall economic impact in the first three years after airspace integration is completed.

AUVSI calculated economic benefits as tax revenues to the states using three main factors: (1) the forecasted number of sales in major market categories that were identified, (2) forecasted supplies needed to manufacture UAVs and infrastructure and (3) estimated costs of labor to determine number of direct jobs created. Using these three factors, the following 10 states were predicted to see the most gains in terms of job creation and additional revenue as production of UAVs increase: (1) California, (2) Washington, (3) Texas, (4) Florida, (5) Arizona, (6) Connecticut, (7) Kansas, (8) Virginia, (9) New York and (10) Pennsylvania.

Commercial UAV applications in agriculture, accounted for $75.6 billion of total national economic impacts, public safety authorities (i.e. police, firefighters and other emergency management services) accounted for $3.2 billion, and other applications ranging from weather and environmental monitoring, aerial imaging and mapping oil and gas exploration accounted for another $3.2 billion by 2025.

AUVSI lists eight necessary conditions needed for these future predictions to be validated. Among them the most important being: (1) success of new FAA regulations that integrate UAVs into the NAS, (2) availability of significant capital for smaller manufacturing companies, (3) availability for financing for UAV purchasers, and (4) affordable insurance coverage offered by leading insurance companies.

While this paints a bright future for commercial UAVs, a lack of regulatory structure set by the Federal Aviation Administration poses as a main inhibitor for research and development[6] In 2012, the federal government tasked the FAA with determining how UAVs should be integrated into the National Airspace System. However the FAA was not able to meet their 2015 deadline and is estimated to lose more than $10 billion in potential economic impact every year, or $27.6 million for every day that this deadline is missed. Until these regulations are established and companies get the go ahead to diffuse commercial UAVs into the NAS, this economic forecast will seem nothing more than an emergent technology simply too advanced for its time.

2.3 Capabilities of UAVs and their Civil and Commercial Applications

2.3.1 Security

UAVs provide a natural birds-eye-view for security professionals to safely monitor and protect highly secured or high risk areas such as civil engineering sites, oil and gas pipelines, forestry and fishery protected areas, and border crossings. Low maintenance costs, and capabilities to rapidly set up and deploy within minutes, make UAVs the perfect option for aerial reconnaissance, aerial policing, and crowd and traffic monitoring. UAVs are multi-faceted and equipped with power subsystems that enable travelling over vast distances rather quickly and are able to respond to situations faster than traditional on-foot security. Commercial UAVs for security applications is also a lot more cost effective than traditional manned operations due to high fuel and leasing expenses. Instead of a single security personnel monitoring a location from the air, multiple UAVs can be deployed and collected data can monitored simultaneously by ground control stations, that can detect and report security breaches that may occur[10].

2.3.2 Search and Rescue

UAVs have become so sophisticated in terms of their endurance (flight time), structure (weight) and power that they can be designed to handle bulkier, technologically advanced payloads. These payloads include different optical sensors such as thermal detection, Infra-red detection, night vision sensing, making this application suitable for maritime and mountain search and rescue. Larger drones are capable of carrying weights up to 300 lbs, suitable for life raft deployment and releasing of signal flares over points of interest.

2.3.3 Disaster Management

In the event of a disaster, UAVs can be deployed in groups/swarms to collaboratively coordinate and relay feedback information to necessary Ground Control Station -personnel. This makes UAVs efficient for disaster management, in which large amounts of information need to be gathered over wide geographical areas to make strategic decisions. UAVs can assist with disaster damage estimation, rescue, and clean up supervision. UAVs can also be equipped with public announcement (PA) systems, or if tethered to an power supply cable up to 250 ft, can even be used for spotlights if necessary[4].

2.3.4 Crop Management

UAVs can be equipped with sensors to detect the moisture level of soil and crop and also detect presence of pests, bacteria, and rotting plants. This makes UAVs suitable for management of crops to monitor fields, watch crop growth, application of pesticides, water or fertilizers, and even field measurement and sizing.

2.3.5 Telecommunications Infrastructure

UAVs are also suitable for providing temporary telecommunication relays in areas that need it. They can be deployed as hot-spots to provide internet access even in the most remote areas that are not reachable by Internet Service Providers (ISPs) or Mobile Broadband Providers (MBPs). For telecommunications providers, UAVs can also be used to conduct signal coverage surveys to determine potential dead zones and where new cellular towers need to be constructed.

2.3.6 Structural Inspections

Tall structures such as bridges, buildings, cellular towers, and wind turbines would normally require sending inspection crews up on lifts, catwalks or harnesses to inspect. With UAV support, this dangerous and time consuming process can be completed much more efficiently by capturing pictures and videos instead and sending them to managers for strategic planning.

2.4 Current Cloud Based UAV Research and Solutions

Many companies and research groups have focused their attention on developing cloud-based solutions for UAV operations[3]. This research provides easy assimilation into the Internet of Things (IOT) ecosystem, allowing everything from real time data streaming to management and supervision of complete groups of UAVs remotely from anywhere in the world.

Skyward Incorporated provides powerful solutions for safe commercial drone operations in the National Airspace System (NAS) that provide regulators and insurers with need-to-know information about UAV flight operations. Operators can easily track mission specific information needed for business, insurance and regulatory requirements. Skyward's cloud-based solutions comes complete with airspace mapping and visualization, flight planning and logging, and record management systems for maintenance, personnel and inventory tracking.

Drone Deploy Inc. on the other hand, provides cloud-based software that allows automated command and control of UAVs through the cloud and enables real time uploading and analyzing of data. Essentially, Drone Deploy is a cloud based solution for aerial surveying and mapping, and provides features such as terrain modelling and crop health visualization.

Airware looks at cloud-based connectivity from a different perspective that is focused more on designing a general purpose UAV operating system for commercial drones. The platform combines custom hardware, software and cloud services to help companies safely operate drones at scale, meet aviation authority compliance requirements and integrate aerial data with business systems. Features of Airware products include, cloud connectivity, user authentication, flight simulation, real-time flight optimization, automated take-off and landing, flight planning, exporting and much more.

Eagle Eye Systems is a company that brings military-grade security to commercial markets that focuses on secure data communication in real time. Links are secured via public/private key encryption, allowing for advanced key management protocols for addition and removal of UAVs and ground control stations and controls.

Chapter 3

Methodology

3.1 Methodology Selection

The spiral model shown in Figure 3.1 is used to construct a secure, efficient and reliable orchestration and coordination framework that enables on-demand deployment and re-tasking of multi-tenant UAVs using cloud computing services. Since the concept of UAVaaS is unprecedented, a top down approach was chosen as the best process for defining the system. Through this process, a high level system design is analyzed and abstract components identified, from which more detailed, low level components can be designed to satisfy system requirements.

The spiral model combines iterative development with select aspects of the waterfall model approach[9]. This model puts a very high emphasis on risk analysis which is performed at the end of every iteration, as well as efficient incremental fine-tuning of system design without risk of “breaking” or injecting defects. Spiral Models are best used in cases where there is a budget constraint, risk identification and management is important, extensive prototyping is needed, large systems need to be divided and worked on separately, requirements are complex and need future re-evaluation to obtain clarity, and significant changes are expected throughout the life-span of the system.

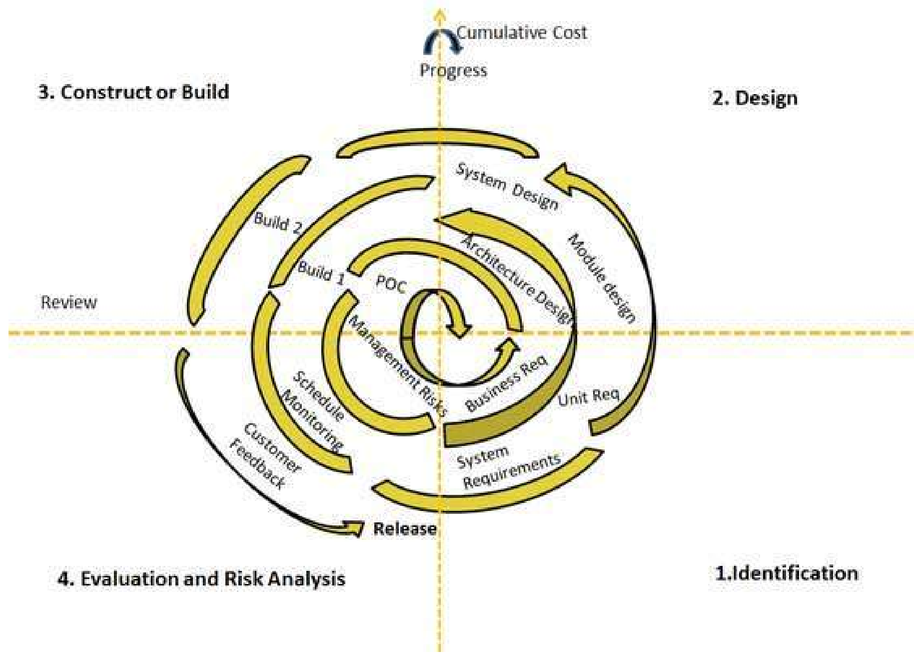

FIGURE 3.1: Spiral model design methodology

This thesis presents a total of four spiral model iterations in which the results of each are compiled and summarized into one comprehensive iteration for ease of readability and simplicity of the literature. Table 3.1 shows each iteration and the primary task to be accomplished.

The first iteration analyzes the UAVaaS system at a very high level to identify key components, actors and shareholders. This identification helps to design efficient and secure data structures and network topologies that allow for future scalability and fault tolerance. At the end of this iteration, key concerns and potential issues that would pose the biggest risk to security and safety are identified and will be used as factors when making trade-off analysis between design approaches. UAVaaS functional requirements are also explored as well as UAV compatibility requirements necessary for communication with a UAVaaS cloud provider.

The second iteration analyzes the UAVaaS Coordinator subsystem, a core component

TABLE 3.1: Spiral Model Iteration Description

Iteration	Task Description
Iteration 1	High Level UAVaaS System Design
Iteration 2	UAVaaS Coordinator Subsystem Design
Iteration 3	UAVaaS Adapter Module Design
Iteration 4	UAVaaS User Facing Interfaces Design

of UAVaaS that provides secure, fault tolerant data marshalling and authentication between UAVs, operators and spectators. A custom protocol that includes specifications for message and data structures is designed and implemented to allow UAVs and users to communicate with UAVaaS. A risk and security assessment of the custom protocol is also carried out at the end of this phase.

The third iteration analyzes the UAV adapter module that will be installed on every UAV requiring communication with a UAVaaS cloud provider. This provides a standardized interface for a diverse collection of UAVs, allowing many 3rd party vendors to build and sell UAVaaS compatible UAVs. Message and data structures related to UAV synchronization, authentication, session management and communication are designed and implemented to allow UAVs and users to communicate. A risk and security assessment of these data structures is carried out at the end of this phase.

The fourth iteration analyzes the user facing interfaces that operators and spectators will use to schedule, manage and operate multi-tenant UAVs. Similar to iterations 1,2, and 3, message and data structures were designed to enable users to communicate with the UAVaaS and for software developers to write UAVaaS software for devices independent of operating system environment.A risk and security assessment of these data structures is carried out at the end of this phase.

3.2 Iteration Phase Objectives

3.2.1 Identification of System

This phase focuses mainly on defining the system to be designed and to generate lists of characteristics, benefits and advantages of the system. Once established, system requirements, important actors, participants, and key components of the system are identified. This phase can be considered a preliminary analysis that sets the stage for future development and breaks the system into manageable subsections (in many cases by subsystems) that can be worked on separately and then later integrated and tested. Also identified, are key focus areas that future developers must take into consideration that is deemed crucial for UAVaaS success.

3.2.2 System Design

This phase generates possible system design solutions, choosing the best approach from a list of alternatives that meets the requirements found in the Identification phase. A comprehensive set of data and message structures are designed to allow communication between all UAVaaS actors. The solution chosen will become the foundation/template from which other software components are designed and attached.

3.2.3 Construct or Build

This phase includes prototyping and developing a basic proof of concept design with real world, off-the-shelf technology to satisfy requirements. This area has the steepest learning curve since web server, database, networking, simulation, and other technologies will have to be installed and their respective APIs learned.

3.2.4 Evaluation and Risk Analysis

The last phase of each iteration includes identification and evaluation of possible risks in the system and developing mitigation plans to prevent or reduce impacts of these risks. It is important to note that this thesis also focuses on the cybersecurity aspects of the system design as well, and mitigation against major network attacks will be analyzed.

Chapter 4

System Identification

4.1 Characteristics of UAV as a Service (UAVaaS)

UAV as a Service is a cloud-computing architecture that provides customers with a secure, flexible, and scalable solution of scheduling, deploying and re-tasking multi-tenant UAVs from anywhere in the world. Customers can also share live data feeds with any interested parties such as clientele, news agencies, emergency management services, company supervisors and shareholders. Some of the features of UAVaaS include:

- "Pay as you go" billing for UAVs that are used.
- Transparent maintenance and replacement of UAVs by trained ground crew personnel.
- On demand scalability and dynamic assignment of UAVs based on mission parameters.
- Policy-based access to shared UAV sensor data and telemetry feedback.
- Automatic update of new UAVaaS adapter software installed on UAVs.
- Point and Click way-point navigation mechanism for customers through web browsers or smart phone devices.
- Simple scheduling and management of UAVs to be used by multiple operators.

- On-the-fly re-tasking of UAVs if needed by higher priority operators.
- User friendly management and sharing of UAV mission plans.
- Ability to view features and capabilities of UAVs to determine if mission requirements can be satisfied.

4.2 Example System Mockup

Figure 4.1 illustrates how a particular UAVaaS network might be constructed. In this diagram, three UAVaaS Hubs service a wide geographical area each assigned a designated service area radius. Hub 1 services three agricultural farms and a construction zone, Hub 2 services two agricultural farms and a construction zone and Hub 3 services one mining site, one farm, and one construction zone. If UAVaaS services are needed for these areas, the UAVaaS Coordinator will determine and return to customers, the closest UAVs that can satisfy the requirements. Both Hubs 1 and 2 service an emergency management center in the area and Hubs 2 and 3 service a mining area and construction zone.

It is important to note that spectators that have no influence in the actual mission management and control, such as CEOs and project managers, do not necessarily have to be located within a service area to view or process collected UAV data, and news companies who wish to record aerial footage do not need to be located in the service area to access UAVs.

In the event of an emergency situation, efficient re-tasking algorithms are used to determine the optimal UAVs to use for the operation based on UAV hub proximity and current UAVs in-flight that can successfully accomplish the operation and fly back to the nearest hub once the mission is completed.

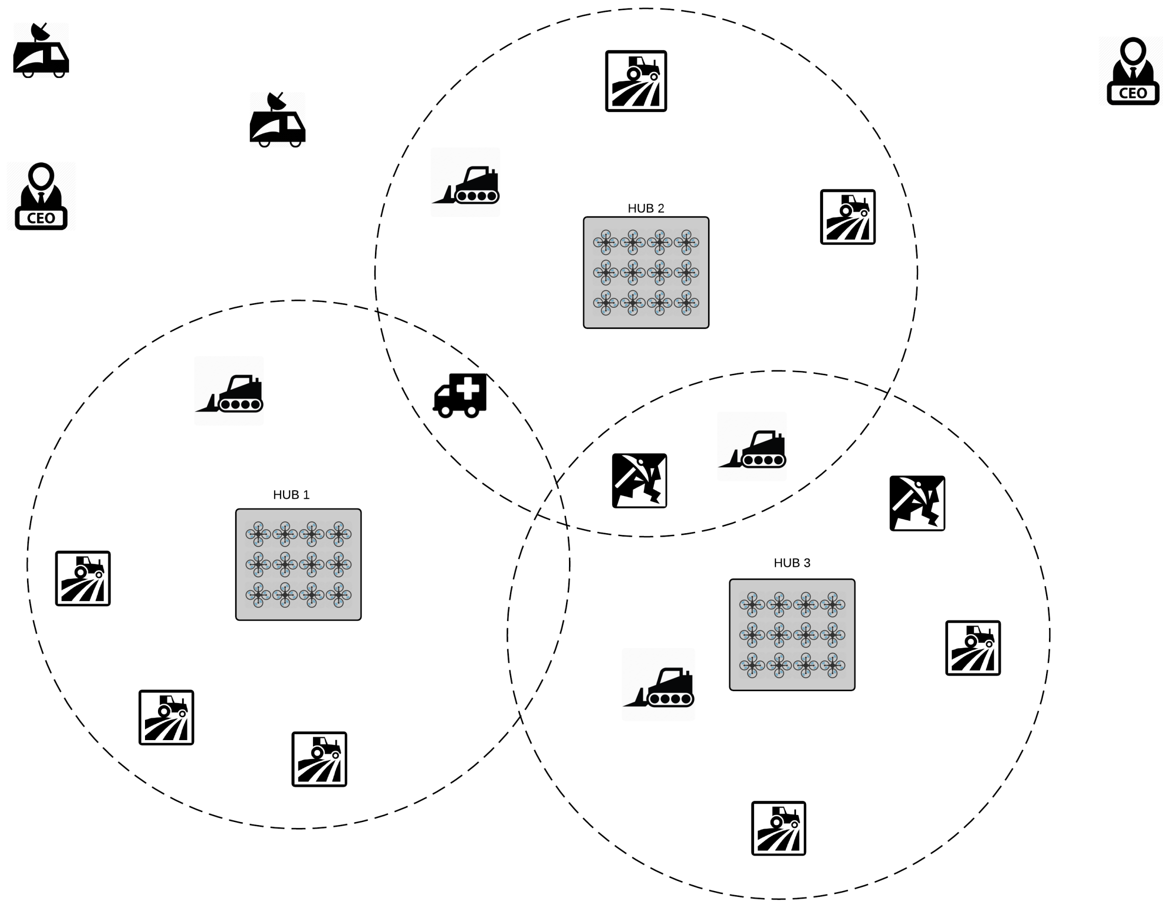

FIGURE 4.1: High level mockup of UAVaaS

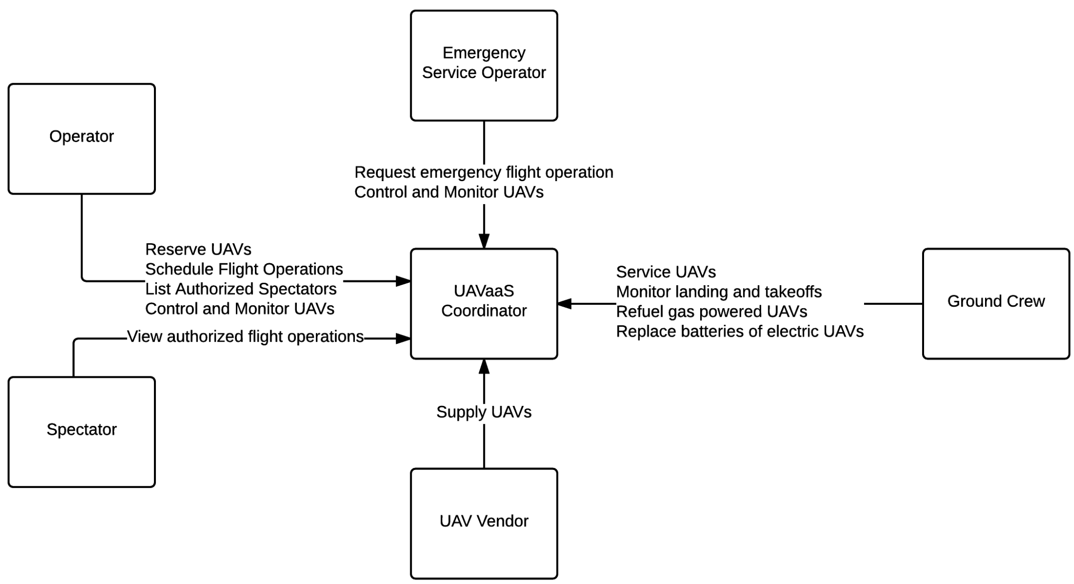

FIGURE 4.2: High level system context diagram of primary actors

4.3 Primary Actors and Shareholders

Five main actors are identified to interact with the UAVaaS system that all have a unique role to play and therefore vital to its success. These actors are operators, emergency services personnel, UAV ground crew personnel, and 3rd party UAV vendors as shown in Figure 4.2.

4.3.1 Operators and Spectators

Operators are the primary users who require access to UAVs to satisfy business requirements. Operators plan and control flight operations of one or multiple UAVs while 3rd party spectators only require the data captured from UAVs such as video and images and do not actually fly the mission. For example, agricultural farmers may need to plan and fly UAV missions to monitor the growth and health of their crops. These farmers would be classified as operators. The farming associations that control and monitor all these farms would be considered 3rd party spectators because they are only interested in the video and data captured independently and not the flight operations itself. Some of the tasks performed by operators are:

- View available UAVs near points of interest for planned mission.
- View specifications and capabilities of available UAVs.
- Schedule UAVs to be used for particular date and time.
- Configure authorized operators and spectators for scheduled UAV flight operations.
- Group UAVs into logical organization for easier management and categorization of data collection.
- Send flight commands to UAVs in flight.
- End flight operations.
- Accept or deny emergency re-tasking of customer UAVs by emergency service personnel.

4.3.2 Emergency Services Operations and Roles

Emergency Service Personnel represent privileged higher priority organizations such as fire departments, police departments, and other emergency first responders that have the ability to re-task in-flight and grounded UAVs for the purpose of using them in highly volatile, life threatening disaster situations. For example, fire fighters trying to extinguish a major forest fire may need aerial assistance of nearby UAVs for reconnaissance, planning and detection of human life within the area. Fire fighters will be able to re-task current UAVs in the area(with current customer's permission. Some emergency service operator tasks include:

- View available or in-use UAVs within a specified square mile radius of emergency scene.
- Select capabilities needed for UAV to satisfy mission requirements.
- Configure authorized operators and spectators for scheduled UAV flight.

4.3.3 UAV Ground Crew Operations and Roles

Ground crew personnel manage and operate strategically located UAV hubs that are in geographic areas identified as a high use case population. Their role is to monitor the safety of all UAVs during take-off, en-route and landing as well as to respond to any accidents or collisions that may occur. Ground crew personnel are certified UAV specialists that maintain and repair UAVs in between missions and responsible for charging, re-fueling and swapping out power supplies when necessary. Some ground crew personnel tasks include:

- Ensure safe take-off and landing of UAVs at UAV hubs.
- Monitor UAVs reporting issues of mechanical failures or low power.
- Recover fallen UAVs if necessary.
- Ensure all UAVs are fully charged and mission-ready.
- Service and maintain UAVs.
- Update UAVaaS firmware.

4.3.4 3rd Party Vendors and Roles

UAV Vendors supply UAVs to the UAVaaS system. Any 3rd party UAV company can design and manufacture UAVs installed with a UAVaaS adapter module which includes compatibility software that connect to cloud service endpoints. Vendors must also ensure that every UAV satisfies the model shown in Figure 4.3 which is explained in the next section. Some of the 3rd party vendor roles include:

- Design commercial grade UAV systems that meet UAVaaS requirements.
- Integrate on-board software to connect and communicate with the UAVaaS cloud provider.
- Certify, register and insure UAVs with FAA and insurance companies.
- Register UAV with UAVaaS cloud provider with full specifications of UAV being registered.
- Submit bank information for commission payment.

4.4 UAV Compatability Requriements for UAVaaS use

In order to guaranteed a level of standardization with all UAVs that operate with a UAVaaS provider, 3rd party vendors must satisfy a set of requirements necessary to ensure compatibility, security and safety to customers and other neighbouring UAVs. Figure 4.3 shows the components of any UAV that is compatible with UAVaaS. Some requirements generated from this model enforce that:

- UAVs shall be manufactured with appropriate commercial-grade material, i.e. motors, sensors, power supply and payloads capable of sustaining flight times of an hour or more.
- UAVs shall be fitted with a commercial-grade UAV autopilot controller capable of performing unmanned take-off, navigation and landing and basic aerial maneuvers such as loitering, turning and altitude changes.

- UAVs shall be integrated with a companion board/secondary processing device that will host the UAVaaS adapter module and is capable of connecting and communicating to a UAVaaS cloud provider. This can be thought of as a module or firmware that is supplied by the UAVaaS cloud provider to be installed on a UAV.
- UAVs shall be certified and registered to the FAA and capable of abiding by mandated altitude and speed restrictions and mandated no fly zones.
- UAVs shall include fail-safes and recovery features to detect and report failures or situations of low power and fly immediately to the nearest UAV hub.
- UAVs shall provide an interface to connect to a 4G LTE mobile broadband provider such as T-Mobile, AT&T, Verizon, etc.

4.5 UAVaaS Business Model

4.5.1 Custumer Pricing and Billing

UAV as a Service offers a utility in which customers are charged on a "pay-as-you-go basis" that eliminates the high, capital costs and overheads incurred by companies wanting to operate UAVs. This means that the only factors that affect a customer's bill is the number of UAVs, amount of flight time and amount of data consumed. Each UAV will have a predefined cost value associated that is determined by 3rd party vendors. Vendors can select base prices along with hourly, daily or weekly rates. Customers are also responsible for paying data charges that depend on types of sensors on-board that are used such as quality of pictures and length of videos taken. The equation below can be used to calculate the total estimated cost of a mission where N represents the set of all UAVs that were flown and $n \in N$.

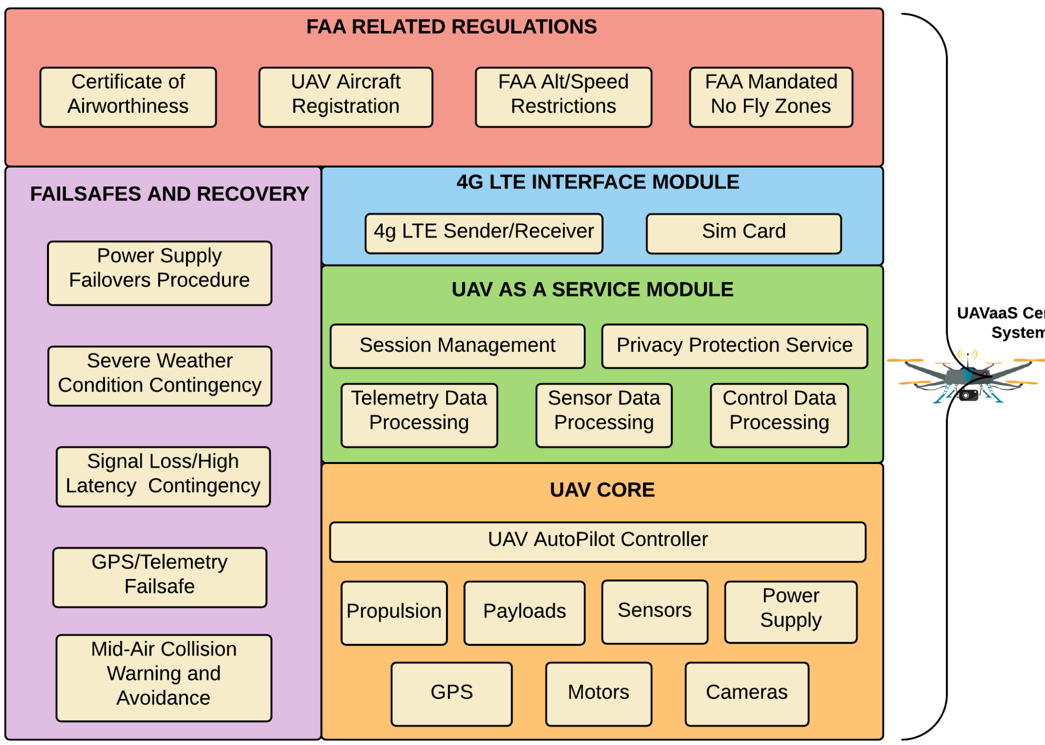

FIGURE 4.3: Model for UAVs requiring access to UAVaaS

$$missionCost = \sum_{n=1}^{N} baseCost(n) + payloadCost(n) + dataCost(n) + missionTimeCost(n) \quad (4.1)$$

4.5.2 Vendor Commission

3rd party vendors can benefit financially from a UAVaaS as well. Vendors will receive a percentage commission based on number of UAVs built by that manufacturer and will pay an upfront registration fee in order to gain access to the UAVaaS framework where it will be used by customers. Equation 4.2 below can be used to calculate the total estimated commission earned where M is a subset of all UAVs flown for the mission $M \subset N$ and $m \in M$.

$$commissionEarned = \sum_{m=1}^{M} \times commisionRate \quad (4.2)$$

4.6 Primary Concerns and Focus Areas

Before a system design can begin, an identification and analysis of key focus areas and areas of concern must be performed to ensure complete design coverage. Issues regarding security of UAVaaS data and safety of UAVs are top priority to ensure success of the system and to avoid costly redevelopment in the future if this analysis was not completed. While there are many areas to investigate, the eight most important ones are described below. Figure 4.4 shows the relationships between UAVaaS system components and some of the major concerns and focus areas that must be addressed in the design and implementation phases.

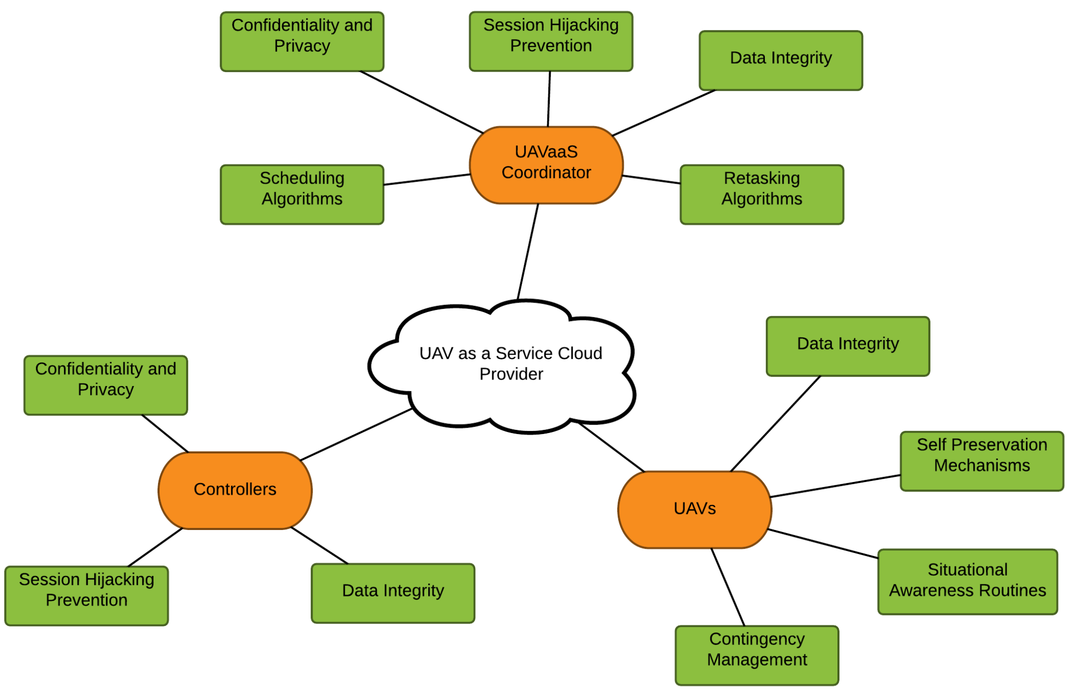

FIGURE 4.4: Relationship between UAVaaS system components and their respective concerns

4.6.1 Data Integrity

Integrity of data must be maintained with all communication in the UAVaaS network and all data that is stored on UAVaaS cloud providers must remain accurate and consistent at all times. This involves developing dynamic access control schemes that are customizable and allow only intended parties to access and modify data. Logging features must also be implemented to maintain non-repudiation, meaning that their always exists proof that a user had access and made changes to data.

4.6.2 Data Confidentiality and Privacy

Confidentiality and privacy of data must also be maintained especially in a multi-tenant system where the same storage devices and sensors are shared amongst multiple customers. Encryption schemes and key exchange protocols need to be developed and implemented to ensure security of user data and control signals sent to UAVs through the UAVaas Coordinator. A mechanism must exist that allows immediate distribution and revocation of encryption/decryption keys during instances where UAVs are re-tasked or an spectator is only allowed to view data for a specified duration.

4.6.3 Session Hijacking Prevention

The UAVaaS must prevent malicious entities from hijacking a session which can result in disastrous consequences. These consequences include complete denial of service between customers and UAVs which would cause missions to automatically terminate, or sending malicious commands to UAVs that can disrupt customer operations such as turning off sensors and flying over unauthorized areas.

4.6.4 Efficient Scheduling Algorithms

Since customers will most likely try to request access to UAVs during the same time slot, there must be an efficient scheduling algorithm to allow users to select and reserve UAVs and to notify customers when a scheduled mission is cancelled. Policies must be developed to ensure no denial of service can occur .i.e. a malicious user reserves UAVs for a period of time without the intention of flying the mission.

4.6.5 Efficient Retasking Algorithms

In the event of an emergency situation such as a natural disaster or terrorist attack, emergency management services may request the use of UAVs to assist in their operations. Once emergency management services provide the UAVaaS with a list of mission requirements, such as location of incident, estimated time of mission and sensors needed, it must compile and provide a list of the UAVs that can successfully accomplish the mission, even those that need to be re-tasked.

4.6.6 Smart Self-Preservation Mechanisms

UAVs must be equipped with mechanisms to prevent its own destruction caused by intentional or unintentional user commands. Users may for example try to fly beyond the range capable of the UAV's power supply or try to crash them into buildings or tall structures. Smart systems should detect the occurrence of these actions and automatically end the mission and fly back to the nearest UAV hub.

4.6.7 Contingency Planning Algorithms

UAVs must be continuously self aware of its current state and report any problems during or before flights. In the event of a power failure or mechanical malfunction it must try its best to navigate and return to the nearest UAV hub. If a safe return is not possible, a distress message must be sent out to all UAV hubs and its last reported location so that a ground crew recovery team can make an attempt to recover it.

4.6.8 Smart Situational Awareness Mechanisms

UAVs must also be able to detect FAA mandated no-fly zones such as airports and national parks and report to operators of impending illegal entry into those zones. Even when operators do not respond to warning messages sent by UAVs, an automatic override must be triggered to automatically avoid no-fly zones without any control inputs. UAVs must also monitor its current surroundings and check for bad weather conditions that may be too dangerous to fly in and automatically end the mission if necessary.

4.6.9 Scalability

The UAVaaS must be capable of handling a large number of connections at scale without a significant drop in service level. Too many UAVs can potentially be flown in a given service area leading overload of UAVaaS network. The UAvaaS must provide load balancing or dynamic network routing through Software Defined Networks to maintain quality of service.

Chapter 5

High Level System Design

This chapter analyses three potential system designs and network topologies suitable for UAVaaS:(1) Direct point-to-point communication between UAVs,spectators and operators, (2) virtual private networks, and (3) a marshalling and data routing service using a centralized coordinator. Each design's strengths and weaknesses are explored and ranked based on primary key concerns identified in Chapter 4 to determine the best fit for UAVaaS. A qualitative approach for each concern is taken, with a simple YES or NO response indicating whether or not the chosen design will allow for simplicity and ease of implementation. Concerns include: (1)maintaining confidentiality and privacy, (2)maintaining integrity, (3) providing authentication and authorization, (4) creating and managing communication sessions, (5)scheduling and reserving UAVs for future access, and (6) re-tasking UAVs in the event of emergency situations. From the three potential designs, the best one was chosen for development and implementation of the UAVaaS.

5.1 Direct Point-to-Point Communication

Direct Point-to-Point was chosen as a candidate because of its simplicity as illustrated in Figure 5.1, however underlying difficulties exist when trying to communicate between UAVs, spectators and controllers. Many issues are discovered which quickly made Point-to-Point

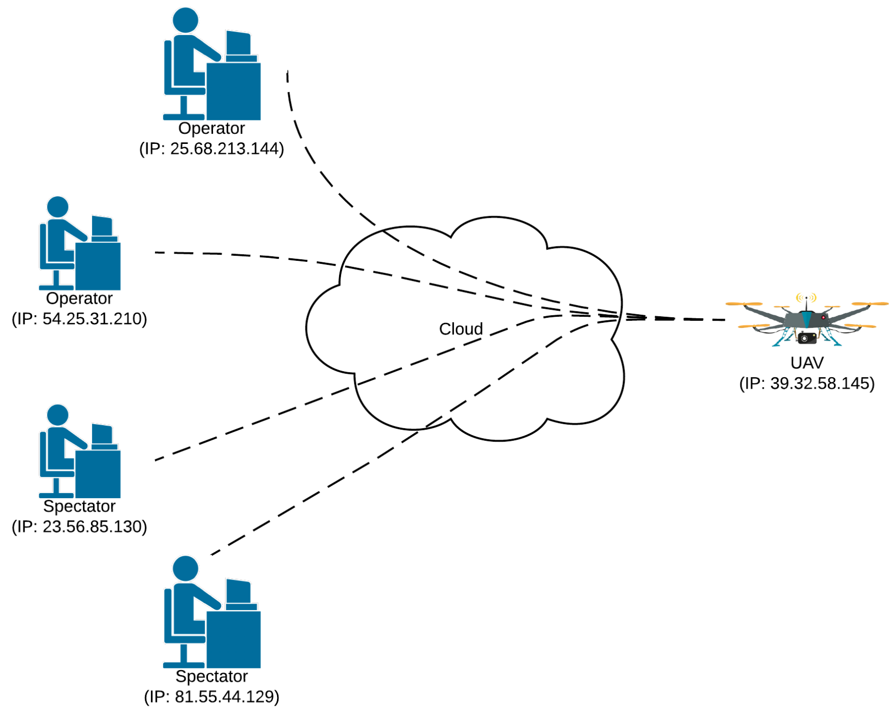

FIGURE 5.1: Point-to-Point network topology of multiple spectators and controllers communicating with a UAV

communication infeasible and insecure since it generated way too much overhead for UAVs, spectators and controllers. Table 5.1 shows the results of this analysis and illustrates why point-to-point communication would not be a good solution.

5.1.1 Confidentiality and Privacy

Since communication is point-to-point, the public addresses of all entities (Spectators, Controllers and UAVs) must be tracked in a lookup table on every device, and an efficient method of distributing new updates to these tables must be implemented. Since this information is widely accessible, it is very easy for malicious attackers to insert him/herself into the middle of communication to obtain sensitive information about a particular mission being flown. While encrypting the data may seem like a simple solution to mitigate this risk, a lot

TABLE 5.1: Analysis of properties of Point-to-Point Communication

Concern	**Offered**
Confidentiality and Privacy	NO
Integrity	NO
Authentication and Authorization	NO
Create and Manage Sessions	NO
Schedule and Reserve UAVs	NO
Retasking	NO
Scalability	NO

of overhead is placed on UAVs to perform key management and to manage authentication and authorization of individual controllers and spectators. There is also a huge computational bottleneck as well such that if a UAV wishes to distribute data to five spectators, it must encrypt each message 5 times with 5 unique encryption keys (one for each spectator).

5.1.2 Integrity

Similar to the issue of confidentiality and privacy, it is easy for a malicious attacker to insert him/herself into the middle of communication and be able to intercept and change messages in flight. While it is possible to implement hashing algorithms and digital signatures for verification, it requires setting up and maintaining public key infrastructures and certificate authorities to verify messages. Users must also go through the trouble of signing up with certificate authorities and requesting signed certificates that UAVs can use to authenticate and guarantee validity of controller data.

5.1.3 Authentication and Authorization

While authenticating and authorizing to UAVs directly is possible, it requires that each UAV store a local copy of a user database to authenticate which must constantly be kept up to date. Since this topology does not incorporate a separate password authentication server it would be very computationally expensive for UAVs to manage user accounts and permissions. Although ground crew personnel could potentially update UAVs manually, it could be a very time consuming process that could take hours, even days for a new customer to get access to UAVaaS.

5.1.4 Create and Manage Sessions

A session can be created in a Point-to-Point network topology to have all required participants networked for a specified period of time. However the implementation this topology provides would be very impractical if subjected to issues related to network latency and loss of connection. It will be a computationally expensive process for UAVs to keep track of all active controllers and spectators and to detect when a connection has been dropped.

5.1.5 Schedule and Reserve

UAVs must store a local copy of a scheduling table that is used to ensure proper access by authorized controllers and spectators. However it is difficult to implement priority functionality and reservation algorithms to properly serve multiple customers in quick succession to one another.

5.1.6 Retasking

Retasking is not possible in this network topology there prioritization algorithms are not possible as explained in section 5.2.5

TABLE 5.2: Analysis of properties of VPN Communication

Concern	**Offered**
Confidentiality and Privacy	YES
Integrity	NO
Authentication and Authorizatoin	YES
Create and Manage Sessions	NO
Schedule and Reserve UAVs	YES
Retasking	NO
Scalability	NO

5.1.7 Scalability

Since point to point relies solely on the resources of UAVs, controllers and spectators, a direct relationship can be observed between number of connections and amount bandwidth. This topology is not scalable as the number of spectators increase, the overall performance of UAVs will decrease. Similarly if the number of UAVs a controller operates increase, the overall performance of UAVs will decrease.

5.2 Virtual Private Networking

Virtual Private Networking is an isolated private network that is constructed using publicly accessible avenues such as the internet. It allows multiple devices to connect and communicate in an isolated environment without worry of outside individuals listening to communication. With this topology, it is now possible to incorporate servers that can handle administrative tasks such as authentication, key management, reservation and scheduling. While the idea of virtual private networks has many benefits there are still many weaknesses and impracticalities discussed in Section 5.1.

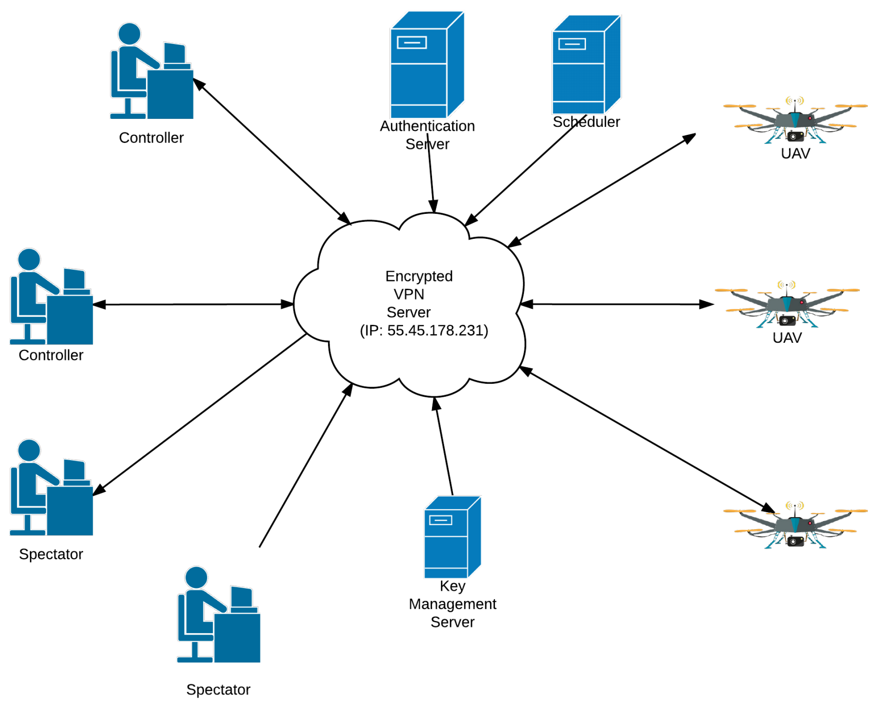

FIGURE 5.2: VPN network topology of multiple spectators and controllers communicating with a multiple UAVs

5.2.1 Confidentiality and Privacy

Confidentiality and privacy can be addressed by incorporating an authentication server on the VPN. Customers must authenticate to the VPN itself first to gain access to the UAVaaS provider and then authenticate with an internal service before access can be granted to communicate with UAVs. Encryption of data is also possible with the use of a key management service to create and distribute encryption/decryption keys.

5.2.2 Integrity

Public key infrastructures can be incorporated on a VPN to create and distribute public key certificates and to verify authenticity of messages being sent between UAVs, spectators and controllers. However since this topology still uses direct communication between participants, they must still perform their own verification which could be computationally expensive.

5.2.3 Authentication and Authorization

Authentication and authorization is resolved with the use of VPNs since only authorized personnel will have access to VPN resources. Also with VPNs it is possible to control via the use of firewalls and other systems, role-based authorized operations that depend on user roles and privileges to interact with various services.

5.2.4 Create and Manage Sessions

Creation and management of sessions still need to be handled by UAVaaS participants. In the event of high latency or loss of connection there is still no easy solution to terminate sessions cleanly or provide a method of re-connection and restart of communication.

5.2.5 Schedule and Reserve

Scheduling and reserving UAVs can now be performed using a dedicated server to create and maintain lookup tables. When a user requests access to particular UAVs, the UAVs can check these lookup tables to determine if access is allowed.

5.2.6 Retasking

Since sessions are still handled by UAVaaS participants, there is no easy mechanism to notify operators that higher priority services require use of UAVs. Even if this feature is implemented, the breakdown and creation of new sessions securely is still a major problem.

5.2.7 Scalability

Scalability using a VPN approach would require the creation of multiple VPNs that UAVs, controllers and Spectators must connect to. It will be difficult to synchronize the connection to particular VPNs.

5.3 Centralized Coordinator

A centralized coordinator solves all the concerns that have been specified in an elegant manner. All communication is done through a UAVaaS coordinator that acts as a marshalling service for all incoming and outgoing data. With this approach, communication can be broken down into 3 message types: (1) Management, (2) Data, and (3) Control. The decision to decouple communication was made to improve ease of implementation of protocols and data structures and to simplify data routing algorithms and improving efficiency. As shown in Figure 5.3. To avoid duplication, the explanations of key concerns have been omitted from this section and instead discussed throughout the following chapters.

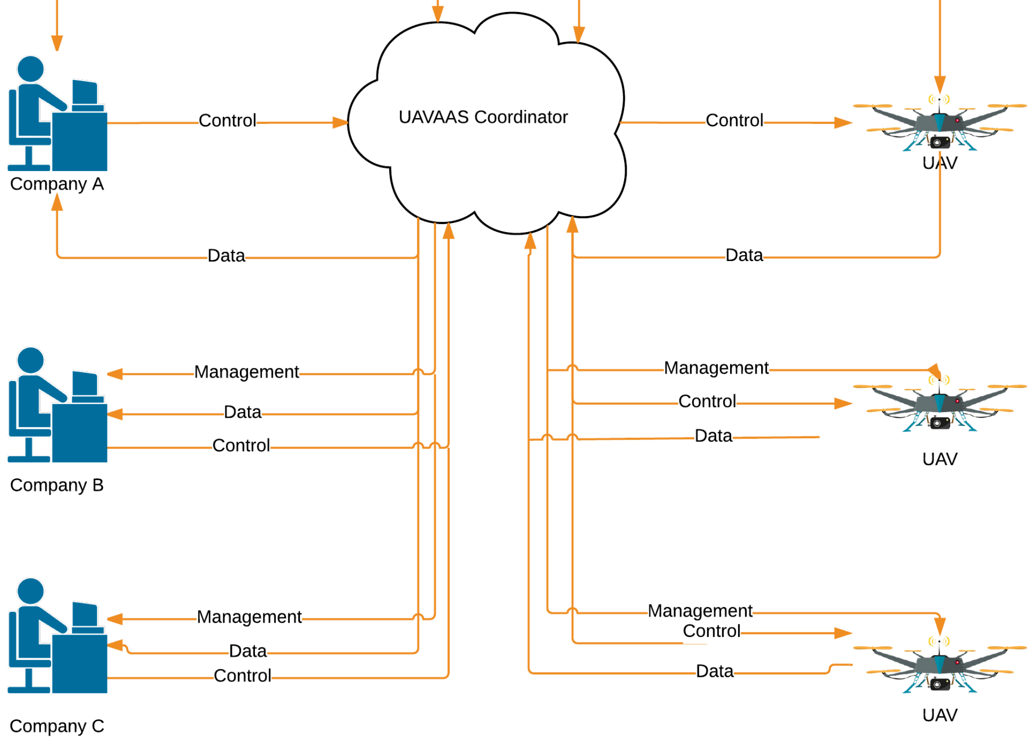

FIGURE 5.3: Communication topology between companies and UAVs that are marshalled by a UAVaaS Coordinator

TABLE 5.3: Analysis of properties of a Centralized Coordinator

Concern	**Offered**
Confidentiality and Privacy	YES
Integrity	YES
Authentication and Authorizatoin	YES
Create and Manage Sessions	YES
Schedule and Reserve UAVs	YES
Retasking	YES
Scalability	YES

5.3.1 Management messages

Management messages provide the coordination and administration properties of UAVaaS. Before any flight operation and any communication between customers and UAVs can begin, authorization and session negotiation must be handled first. Similarly, when flight operations are finished, termination of sessions, and disassociation of UAVs, controllers and spectators must be performed. Management messages are used by controllers, spectators and UAVs.

Controllers communicate via management messages to authenticate to the UAVaaS cloud provider, create mission plans, reserve and schedule UAVs and request specific session keys needed to communicate with UAVs and retrieve data when a mission has started. Spectators communicate via management messages to authenticate to the UAVaaS cloud provider and to retrieve session keys needed to retrieve UAV data collected by controllers. UAVs communicate via management messages to send status and availability updates to the UAVaaS Cloud provider for coordination purposes and to retrieve session keys needed to communicate with controllers and to send collected data back.

5.3.2 Control Messages

Control messages are relatively light-weight and provide controllers an interface to send control signals to the UAV. Since UAVs will be flying autonomously for the entire duration of the operation, these messages will be simple control commands for altitude and speed changes, uploading new way points or points of interest, or control camera and other payload features.

TABLE 5.4: Management message types sent and received to the UAVaaS

Message Types	**Description**
Authentication	Request for access to UAVaaS cloud provider
Request Available UAVs	Returns list of available UAVs in an area
Request UAV capabilties	Returns specifications for UAVs
Schedule and reserve UAVs	Creates a reservation entry for selected UAVs
Define mission plans	Create mission plans and assign UAV tasks
Group UAVs into mission templates	Group UAVs for easier control and coordination
Request access to mission logs	Returns logs of previous missions flown
Request starting of mission	Starts all UAVs and fly to starting location
Request data from ongoing mission	Returns connection information for live data
Send status	Submit status information to UAVaaS
Request flight assignment	Returns currently available flight mission by UAV
Check for retask	UAV checks if a retasking is authorized

TABLE 5.5: Control message types sent and received to the UAVaaS

Message Types	**Description**
Set waypoints	Configure flight path to include selected waypoints
Remove waypoints	Configure flight path to exclude selected waypoints
Change altitude	Change current altitude of UAVs
Change speed	Change velocity of UAVs
Take picture	Takes a picture with a UAV
End mission	End current flight operation
Accept retask request	Allows retasking of currently operated UAVs
Deny retask request	Denies retasking of currently operated UAVs

TABLE 5.6: Data message types sent and received to the UAVaaS

Message Types	Description
Send telemetry	Sends telemetry data to respective participants
Send data	Sends live data feed to respective participants
Send pictures	Send pictures taken back to cloud provider to be stored
Send warning	Send warning message to intended participants
Send error	Send error message to intended participants

5.3.3 Data Messages

Data messages contain telemetry and other data sent back to the UAVaaS Coordinator which is then distributed to appropriate controllers and spectators where applicable. These messages may include high quality photos or videos that have been taken, or real-time altitude, speed and location information needed by the controller to make decisions about a current mission.

Chapter 6

UAVaaS Coordinator System Design

A closer look at the UAVaaS Coordinator is provided and takes into account internal working components that handle inbound and outbound messages described in Chapter 5. The UAVaaS Coordinator acts as a cloud-based service that performs five main tasks: (1) authenticate operators and spectators to a UAVaaS cloud provider, (2) track and monitor UAVs connected to a UAVaaS Cloud Provider, (3) create and manage messaging sessions between UAVs, spectators and operators, (4) receive and forward control messages from operators to UAVs, and (5) receive and forward data messages from UAVs to operators and spectators.

6.1 Design

The UAVaaS Coordinator is designed with two key services that work together to satisfy all communication requirements. Two services are needed instead of just one because of the differing natures of management, control, and data messages. Management messages are sent and received as a request-response pair, meaning that when a request is received by the UAVaaS Coordinator, a response is sent directly back to the sender. Control and data messages work differently. Instead of the original sender receiving a response, the message is forwarded to its appropriate receiver(s). Management messages can therefore be processed using a simple REST service, and control and data messages can be processed

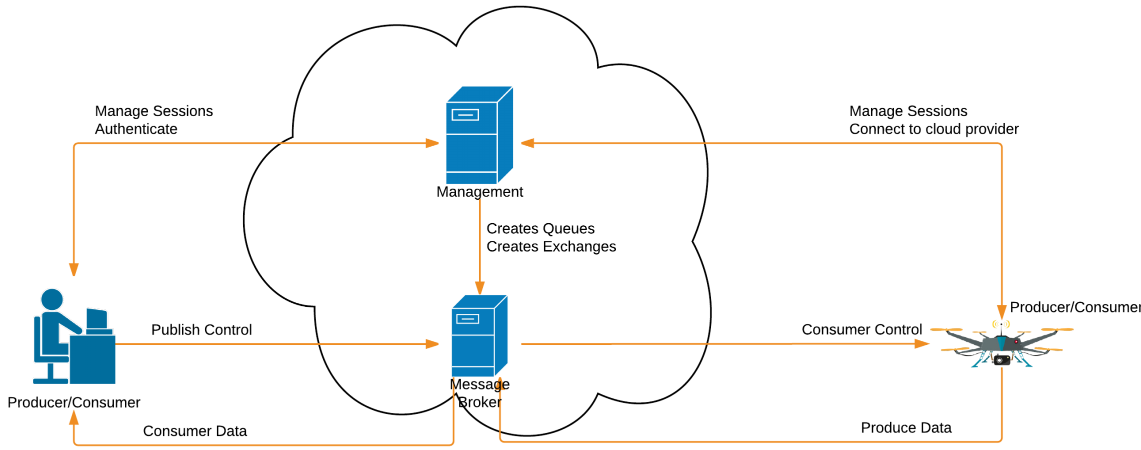

FIGURE 6.1: Internal look at a UAVaaS Coorinator exposing Management and Messaging services

using a forwarding/messaging service. Moreover, the messaging service is dynamically configured by the management service based on requests sent to it by UAVs or operators and spectators.

6.1.1 The Management Service

The management service handles the bulk of all coordination, and sets up messaging sessions between operators, spectators and UAVs. Figure 6.2 shows the entity relationship diagram of the management service. It receives and responds to requests sent by operators, spectators and UAVs, communicates with cloud storage databases to retrieve and create user account information and securely store collected data and mission logs for every flight flown. The management service also configures the messaging service based on the needs of operators and notifies ground crew of UAV issues such as warning, errors and battery status when grounded.

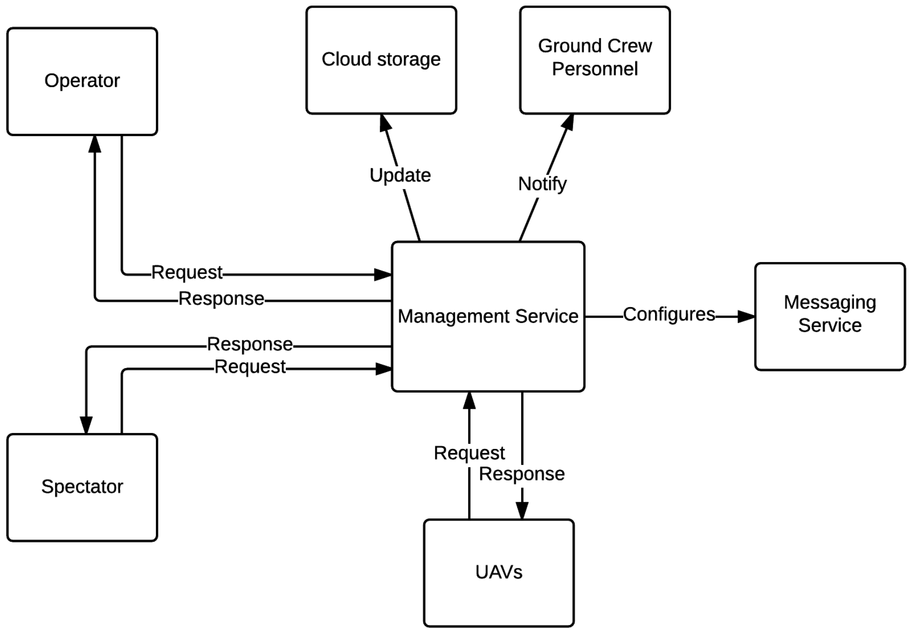

FIGURE 6.2: Context diagram of the management service

Figure 6.3 illustrates 8 exposed endpoints (highlighted in green) that UAVaaS participants can interact with via web service requests. These endpoints are identified to process requests for all available message types sent by operators, spectators, UAVs and ground crew personnel.

- Authenticator endpoint allows operators and spectators to create and login to user accounts.
- Billing endpoint keeps track of current customer bills and balances and allows them to pay for services that have been used.
- Logger endpoint retrieves different logging information including past missions flown, way points and other control commands sent, and any warning or error messages that are sent during flight operations. This endpoint is also used by ground crew personnel to monitor and respond to problems that may occur in flight.

- Connect endpoint is used by operators to request starting of a mission or by spectators to request joining an ongoing mission and request session credentials to retrieve live data from UAVs.
- Scheduler endpoint makes or cancels UAV reservations made by operators.
- UAV Inventory endpoint allows operators to create mission plans, retrieve a list of available UAVs, their corresponding specifications and flight capabilities. It is also used by UAVs when connecting to a UAVaaS Cloud Provider to send updated status information.
- Mission Planner endpoint allows operators to create various mission plans, logically group them, and assign authorized operators or spectators as needed.
- Mission updater endpoint is used by currently untasked UAVs to determine if it is assigned for a flight and while tasked checks if any re-tasking operations need to be performed. It is also used by operators to determine if higher priority services are requesting re-tasking of their UAVs.

6.1.2 The Messaging Service

The messaging service handles duplication and forwarding of control and data messages between UAVs, operators and spectators and to send error and warning log messages to the management service which ground crew personnel use to track and monitor UAVs in flight.

A messaging service uses a publisher-subscriber architecture in which exchanges and queues work together to send and receive messages. Any subscriber interested in receiving messages instantiates a queue with an interested topic and connect it to a data exchange. A publisher then simply publishes a message to the same data exchange flagged with the same topic specified by the subscriber.

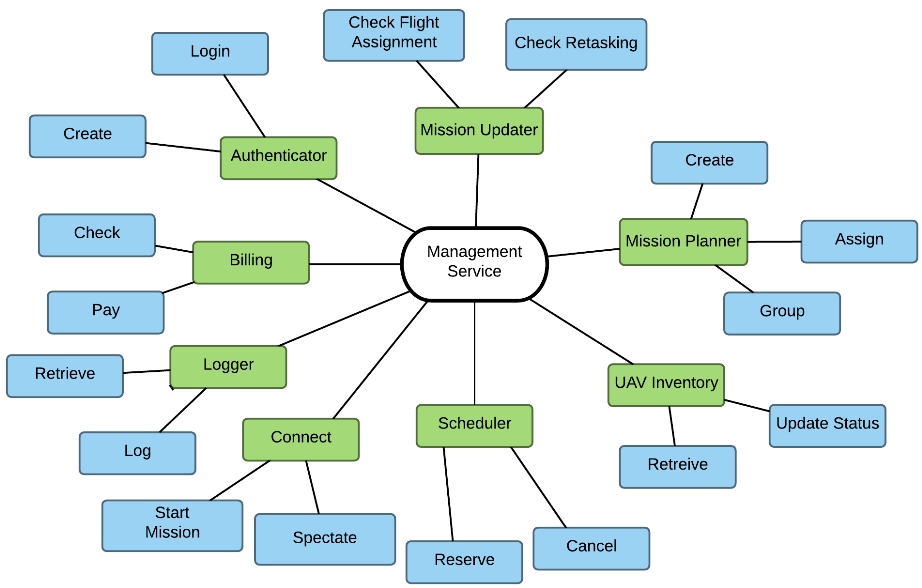

FIGURE 6.3: Endpoints exposed and available for connection by operators, spectators, UAVs and ground crew personnel

The messaging service receives its commands from the management service that tells it how to configure the messaging session. Figure 6.4 shows the design of this data exchange between 3 UAVs, 1 operator and 2 interested spectators. For this scenario, the messaging service will receive a command from the management service to setup one control exchange, one data exchange and one queue per each subscriber. Each newly created exchange and queue will be assigned a unique ID which is returned back to the management service. Upon request, the management service will then distribute these keys to the intended operators, spectators or UAVS.

As shown in the diagram, Operator A publishes a control to a control exchange Ctrl_Ex which duplicates and routes the messages to all intended UAV subscribers. UAVs in turn publish data to a data exchange Data_Ex which duplicates and routes the messages to all intended spectators and operators.

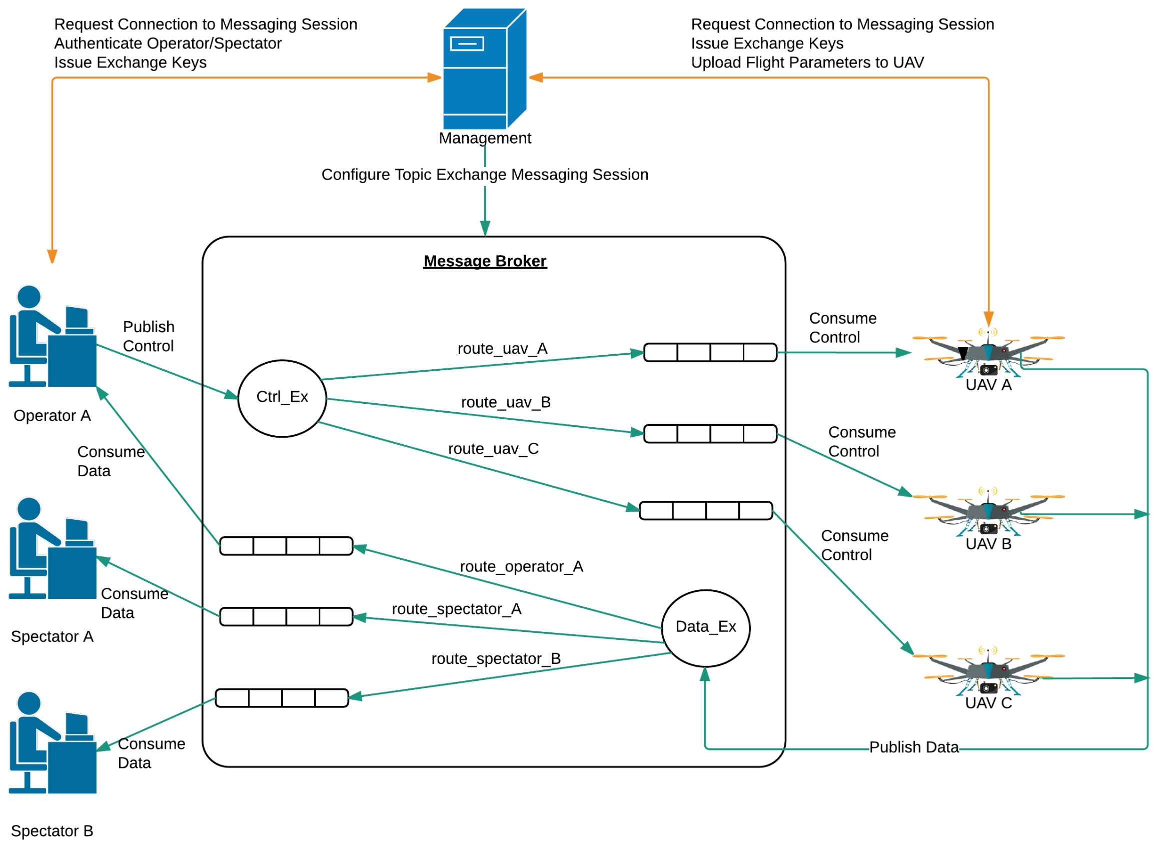

FIGURE 6.4: In depth view of the messaging service that routes messages between operators, spectators and UAVs

This architecture reduces a lot of additional overhead from UAVs that would have had to duplicate messages and send them directly to Operator A, Spectator A and Spectator B. Now, the messaging service, which is more robust and contains orders of magnitude more computational resources, will handle secure duplication and transmission of messages. Also removed is the need for public or private keys since the queue ID generated by the messaging service acts as a long, unique shared key.Guaranteed delivery of messages and maintaining privacy of data can easily be implemented. Since exchanges will only deliver messages to queues with the same topic as that labeled on the message.

6.2 Management and Messaging Service Communication

6.2.1 Access

Figure 6.5 shows typical communication between the management and messaging services. When an operator is ready to start a mission, the management service sends a session creation request to the messaging service with the IDs of the operator and UAVs. The messaging service will set up all necessary queues and exchanges and return the newly generated IDs to the management service which will then be distributed. While a mission is active, a spectator may request from the management service access to flight data being collected. The management service simply requests a queue be created for the spectator and the ID distributed.

6.2.2 Re-tasking

The re-tasking operation is similar to the access operation shown in Figure 6.6. The management service sends a re-task request with new operator and uav list information. The messaging service sets up new exchanges and queues but also looks for current queues that are in use for active UAVs and terminates them. ID distribution and spectator connection continues normally.

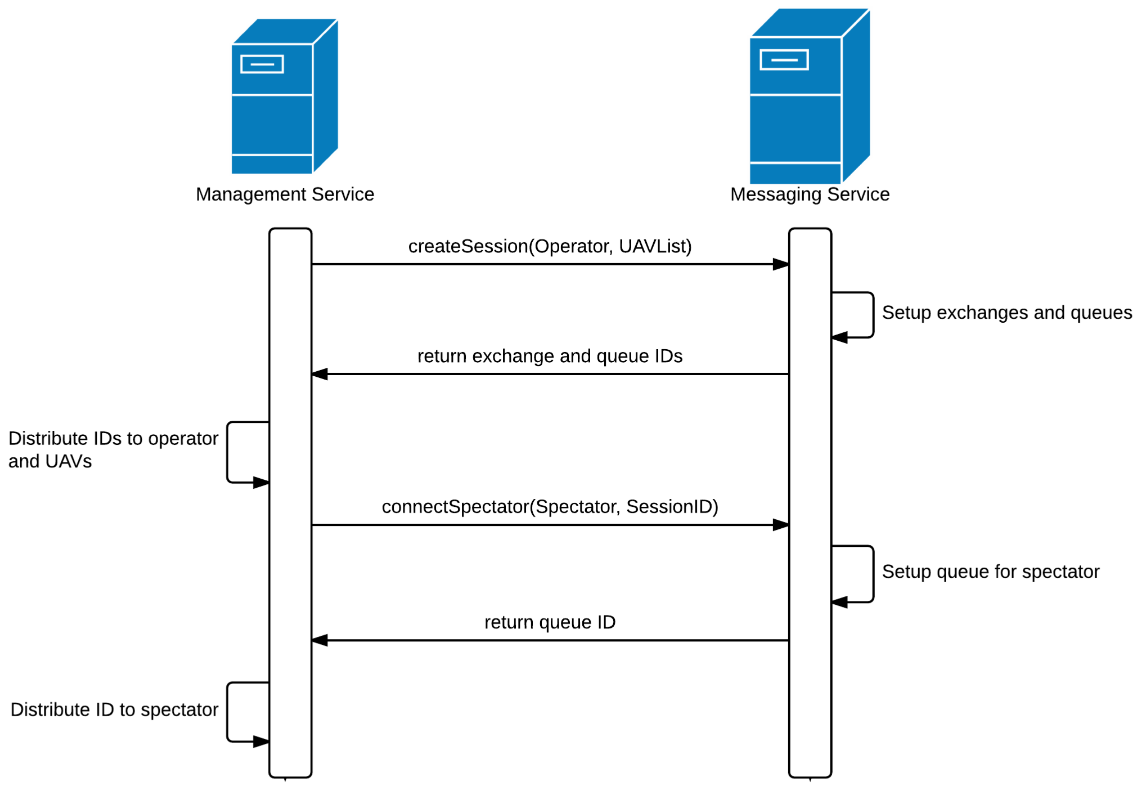

FIGURE 6.5: System sequence diagram for general access operations

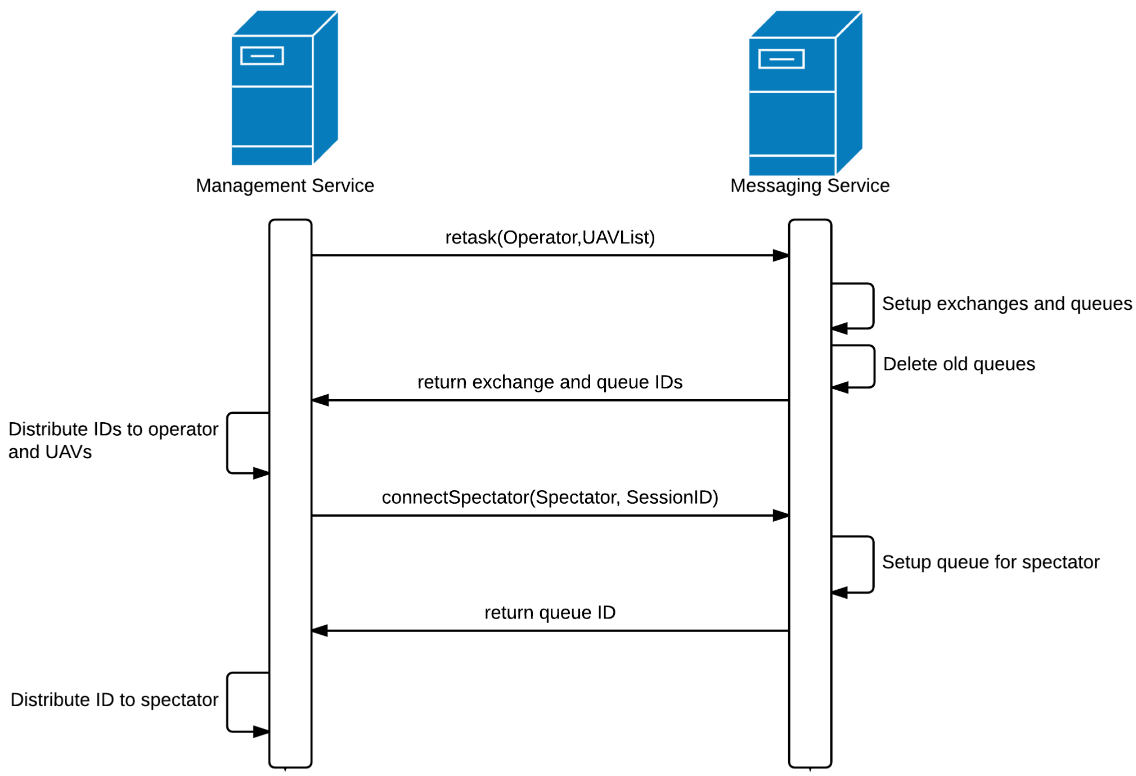

FIGURE 6.6: System sequence diagram for re-tasking operations

Chapter 7

UAV Design

The UAV Adapter Module is a piece of software installed on-board the UAV that is designed to communicate with the UAVaaS Coordinator. The software is device and operating system agnostic thereby allowing any type of UAV to connect to UAVaaS Cloud Providers. The UAV Adapter Module is responsible for: (1)Contacting and updating the UAVaaS with status and availability information, (2) respond to new flight assignments, (3) receive and interpret control commands sent by operators, (4) package and send data messages to the UAVaaS Coordinator for distribution, (5) store public certificate and private key information, and (5) authenticate to a UAVaaS Cloud Provider.

7.1 Design

Figure 7.1 illustrates a context diagram of the adapter module installed on a UAV designed to communicate with a UAVaaS Cloud Provider. Sensors, motors, GPS,batteries and other peripheral devices communicate with an on-board flight controller that is responsible for unmanned maneuvers such as landings, takeoffs and navigation to and from various waypoints. An adapter module is installed, usually on a separate on-board device, which is able capable of communicating with the controller over the mavlink protocol, getting back telemetry data from, and sending flight commands to the UAV. The adapter module is also directly

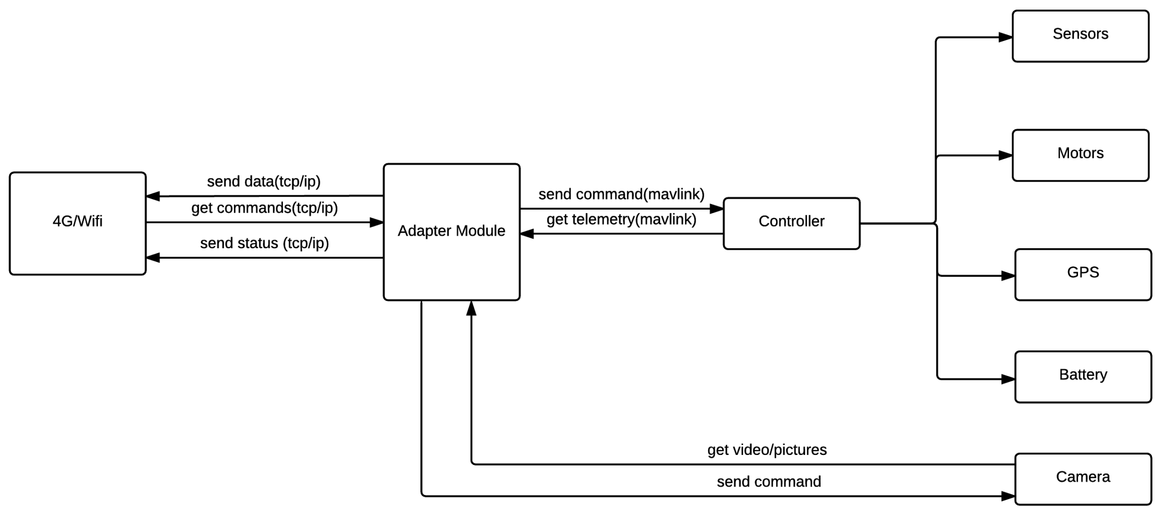

FIGURE 7.1: Context diagram for a UAVaaS adapter module

connected to the UAV's camera system where commands are sent to record video or take pictures.

The adapter module is responsible for interpreting and translating telemetry data from mavlink messages into valid TCP/IP formatted messages that can be sent to the UAVaaS Coordinator over 4G or wifi. Similarly, it is responsible for receiving UAVaaS Coordinator configuration messages and controls over 4G or wifi and translating commands back to mavlink messages that can be understood by the controller.

A total of three threads or processes are needed to design an adapter module, one for each type of message being sent or received (management, control or data). Figure 7.2 shows the system sequence diagram of communication between the adapter module and the UAVaaS Coordinator. As can be seen by the diagram, when the UAV is turned on and no flights are assigned to a particular UAV, only the management thread runs. This thread sends status and availability information to the UAVaaS Coordinator announcing its presence. Once thread one receives a new flight assignment, it creates two new threads to handle controls and the sending of UAV telemetry and sensory data. While a UAV is tasked, it constantly checks the UAVaaS Coordinator for retasking opportunities while simultaneously sending data and receiving controls.

7.2 UAV Intake and Registration Process

An established process of acquiring and registering UAVs to a UAVaaS provider is needed for inventory, management and tracking. The UAvaaS Coordinator will also use this registration to uniquely identify and create secure sessions for subsequent communication across the entire network. Without this in place, there is no way to guarantee secure communication between operators and UAVs, and no proof that UAVs are legitimate. A successful attack on the identity of a UAV can result in major disruption of the service and loss of trust overall.

The solution suggested is to incorporate Public Key Infrastructure (PKI), in which identification of UAVs can be verified through a trusted 3rd party Certificate Authority (CA). UAVs that register with a UAVaaS cloud provider will need to request a certificate and to install corresponding private keys onto the adapter module. Communication to the UAVaaS will require a verification of each UAVs private key and a generation of unique secret session keys.

A digital certificate is a file that is generated and signed by a trusted certificate authority such as Go Daddy and VeriSign. The digital certificate contains company, or in this case UAV specific information as well as a unique public key. Figure 7.3 describe a 4 step process that is taken whenever a new UAV is obtained from a 3rd party vendor and registered to a UAVaaS provider.

The registration process involves 6 primary steps. After all steps are successfully completed, the UAV is now available for tasking.

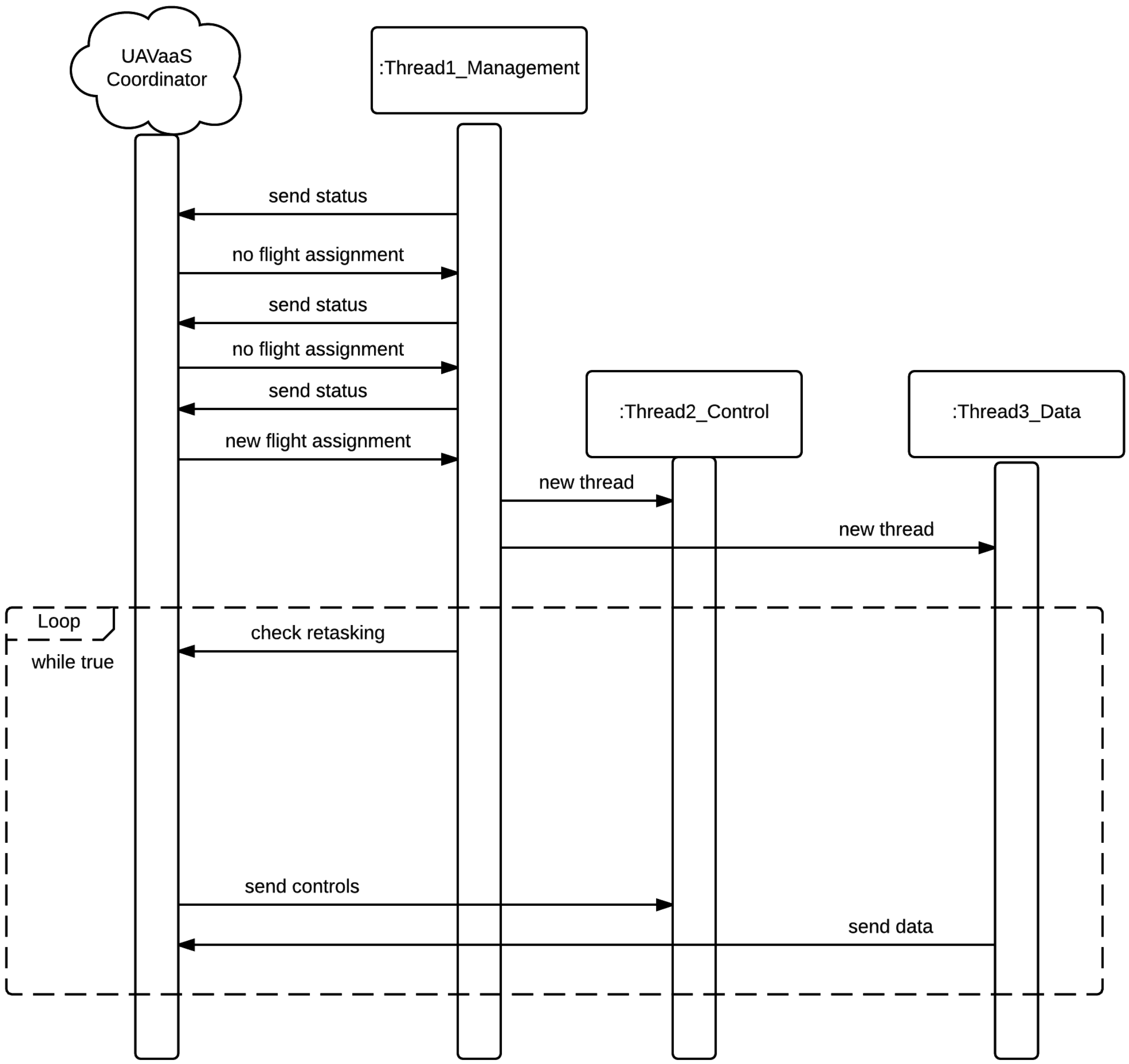

FIGURE 7.2: System sequence diagram of adapter module threads and communication to a UAVaaS Coordinator

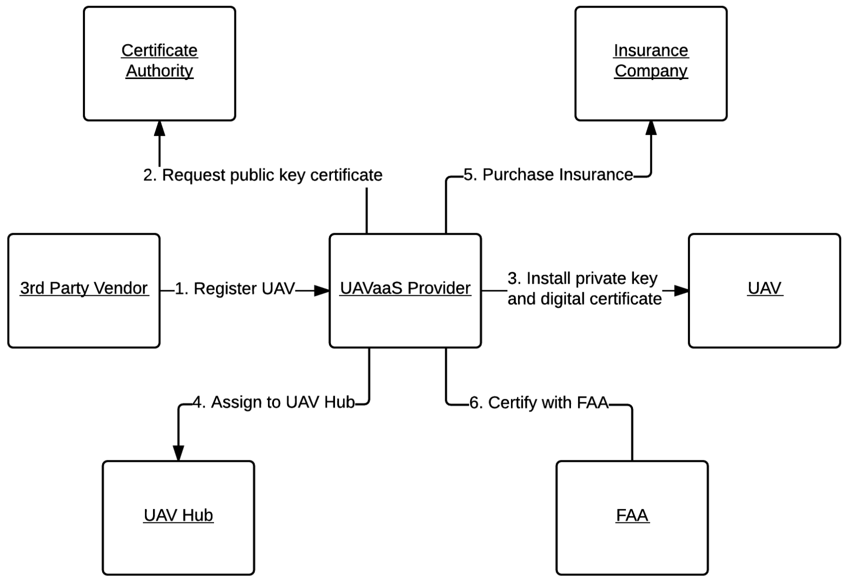

FIGURE 7.3: Registration process for newly acquired UAVs

1. 3rd Party Vendor requests registration of UAV.
   (a) Vendor supplies specifications and details of design for new UAV.
   (b) UAVaaS validates UAV to determine all requirements are met.
   (c) Vendor and UAVaaS provider negotiates on pricing and commission agreements.
2. UAVaaS Provider request new public key certificate to be installed on UAV.
3. Private key and digital certificate returned from CA installed.
4. UAV assigned to appropriate hub as needed.
5. UAVaaS provider purchases insurance for UAV.
6. UAvaaS provider certifies and registers UAV with the FAA.

7.3 Communication With UAVaaS Coordinator

7.3.1 Authentication and Session Negotiation

Before any UAV can connect to a UAVaaS Coordinator and receive new flight assignments it must first successfully complete an identification and authentication process first to prove legitimacy of the UAV in question. Figure 7.4 illustrates a sequence diagram of this process taking place. When the UAV is powered on, it first sends a management request to the UAVaaS Coordinator with the digital certificate installed on board. The coordinator then validates the certificate with a Certificate Authority. Once validated, a unique challenge is generated by the coordinator, encrypted and sent to the UAV with the public key contained in the digital certificate. The UAV decrypts the challenge with its private key and sends back a challenge response. The coordinator verifies the response proving that the UAV is legitimate and sends back an encrypted session key to be used for subsequent communication. This session key is treated as the ID for the UAV. While the UAV is powered on it will continuously send status updates and availability information to the coordinator using this session key and await for new flight assignments.

There are many important data structures the UAV adapter module must be able to parse. UAVs must send status updates to the UAVaaS Coordinator in a standard format to avoid confusion. The Status_Update message structure is illustrated in Java Script Object Notation (JSON) in Figure 7.5. Every status must include the current availability of the UAV to determine if a UAV is currently tasked or not. It must also include positional information such as its latitude, longitude, speed, altitude and battery percentage. This information is used by the UAVaaS Coordinator to eliminate and provide customers only the UAVs that are important. Initial notes and comments from vendors such as important usage information or warnings can be updated and sent with status_update messages as

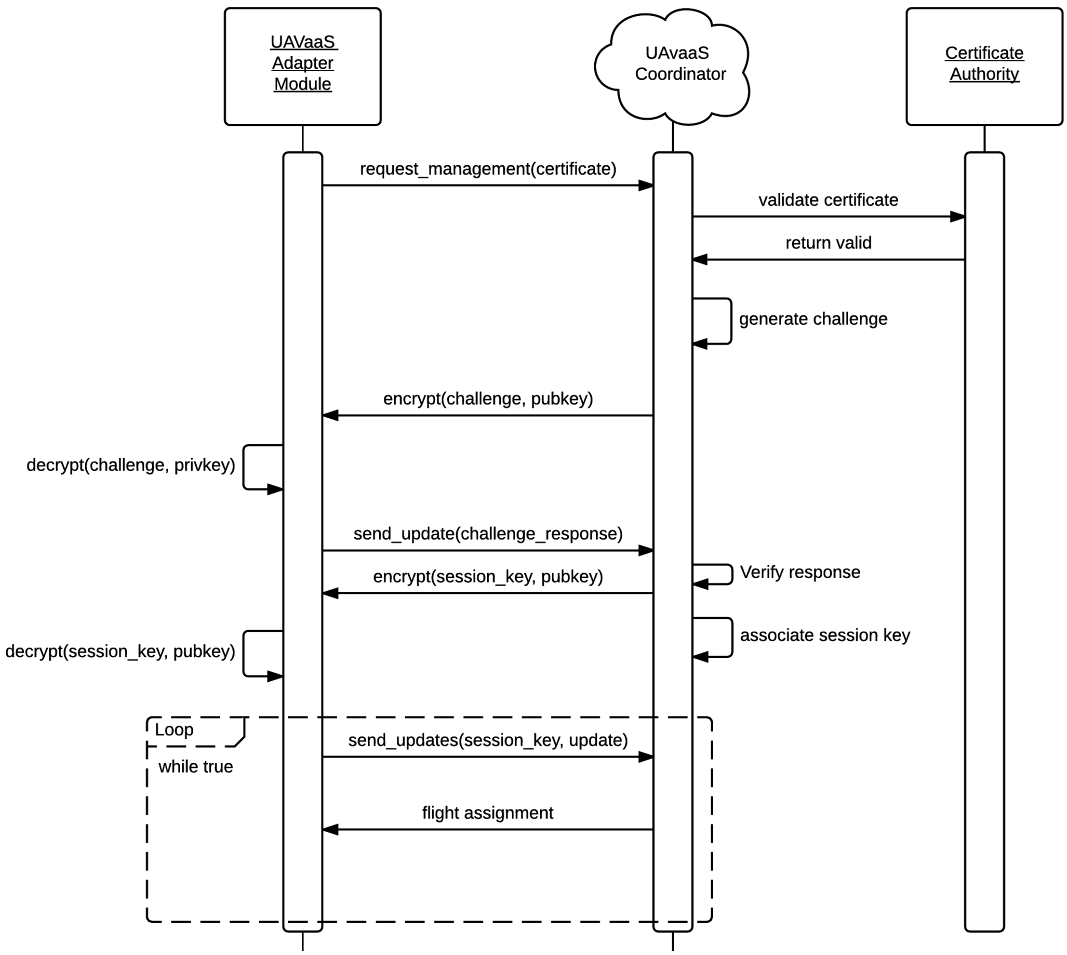

FIGURE 7.4: Session negotiation between UAV and UAVaaS Coordinator

```
{"status_update":
  {
    "status": "boolean availability",
    "latitude": "6 decimal precision",
    "longitude": "6 decimal precision",
    "speed": "speed in mph",
    "altitide": "altitude in feet",
    "battery": "as a percentage",
    "specifications":
    {
      "weight": "weight in lbs",
      "estimated_endurance": "minutes",
      "motors": "number of motors",
      "payloads": "cameras, sensors and other peripherals"
    },
    "comments":
    {
      "comment": "Notes from 3rd party vendor"
    }
  }
}
```


FIGURE 7.5: Data structure of Status Update messages

well. Note however that these comments are not the same as user comments or reviews as these will be stored by and retrieved from the UAVaaS cloud provider.

7.3.2 Flight Tasking and Retasking

UAVS will continue to send status updates to the UAVaaS Coordinator until a flight has been assigned. A flight assignment is sent when an operator has requested a scheduled mission to be started. Once a flight assignment is issued, the UAV will subscribe to relevant control exchanges on the messaging service using an assigned queue ID and topic information. The UAV will notify the management service that it is ready to begin the mission. From then on, updates will still be sent, data such as video, photos, telemetry, warning and error messages will be published and control messages fetched from the control queues until a re-tasking or mission termination operation is performed.

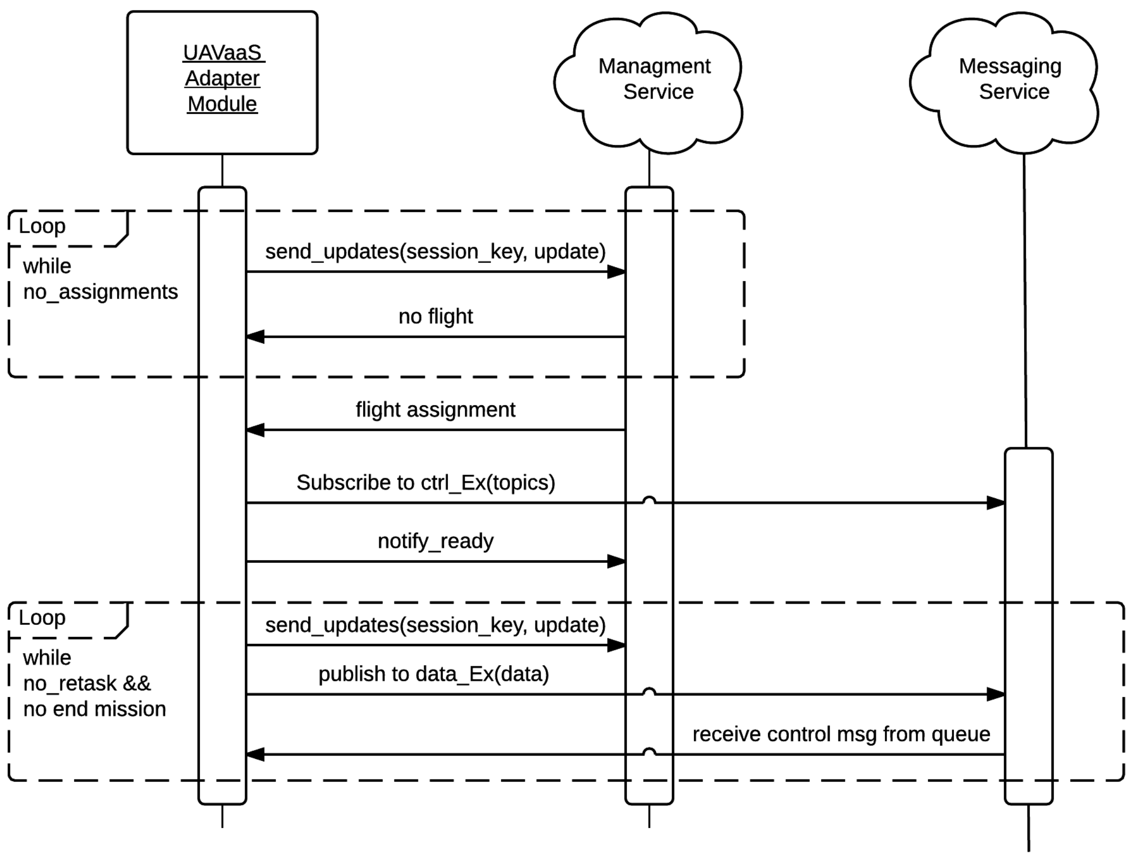

FIGURE 7.6: UAV Tasking and communication between UAV and UAVaaS Coordinator

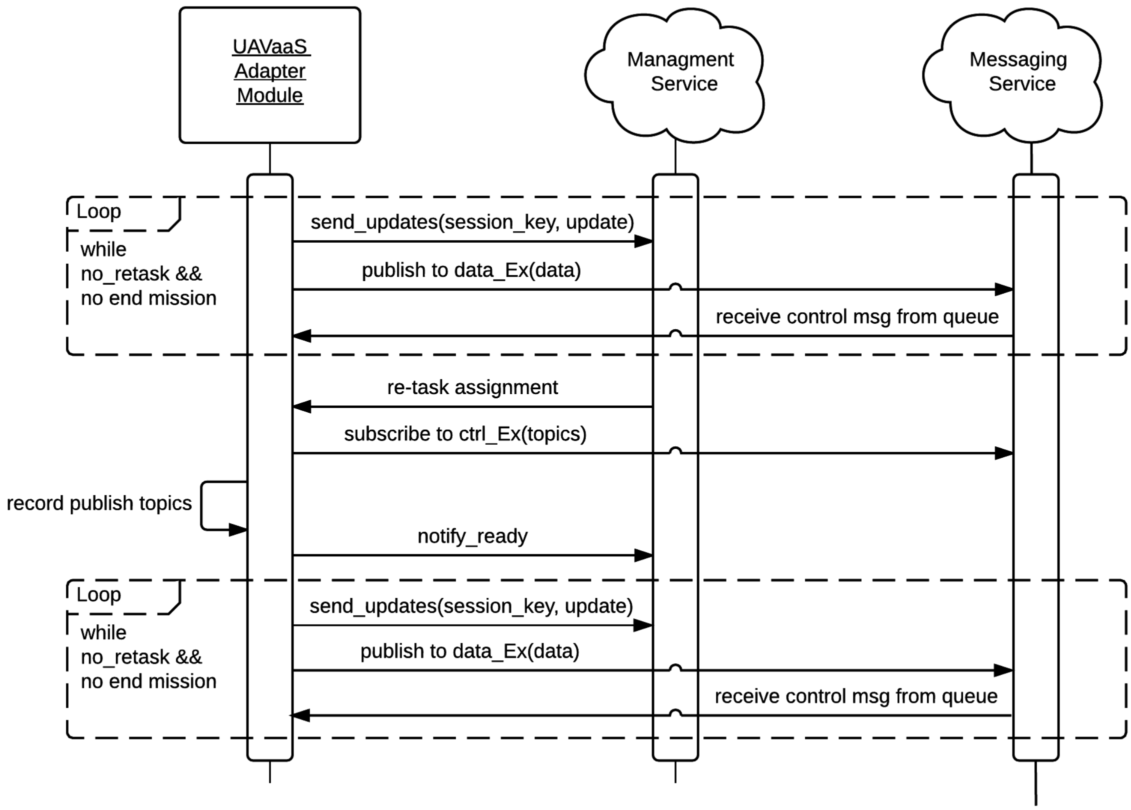

FIGURE 7.7: UAV Re-Tasking and communication between UAV and UAVaaS Coordinator

Flight re-tasking is initiated by a higher priority entity such as emergency service personnel and generally follows the same process as tasking from the UAVs perspective. Once a UAV receives a re-task assignment it simply subscribes to the new control exchanges and re-records the new topics to publish telemetry, warning/error and data messages to. The UAV notifies the Management Service that reconfiguration is complete and continues flying as normal under new operator control.

A flight assignment data structure is illustrated in Figure 7.8. Important information is contained within a flight assignment message to ensure UAVs connect to the appropriate data and control exchanges. The control and data exchange IDs are provided along with

```
{"flight_assignment":
  {
    "controlExchangeID": "long string id",
    "dataExchangeID": "long string id",
    "sbuscribeTopics": ["topic1", "topic2", "top
    "publishTelemetryTopic": "long string id",
    "publishWarnErrorTopic": "long string id",
    "publishDataTopics": "long string id",
    "flighttime": "time in minutes",
    "starting_location":
    {
      "latitude": "6 decimal precision",
      "longtiude": "6 decimal precision",
      "altitude": "in feet"
    },
    "restrictions":
    {
      "maxAltitude": "in feet",
      "maxSpeed": "in mph",
      "noflys":
      [
        {
          "latitude": "6 decminal precision",
          "longitude": "6 decimal precision",
          "radius": "in feet"
        },
        {
          "latitude": "6 decminal precision",
          "longitude": "6 decimal precision",
          "radius": "in feet"
        }
      ]
    }
  }
}
```


FIGURE 7.8: Data structure of Flight Assignment

important topics to subscribe to. Three topic IDs are assigned and used for sending telemetry, warning/error and data messages separately. Note that the UAV has no information on the actual spectators, operators or ground crew personnel involved in the communication. It is up to the UAVaaS Coordinator to route these messages accordingly. Starting location information is also provided to instruct the UAV where to fly before control is handed over to the operator. Lastly restrictions are determined by the UAvaaS coordinator based on FAA mandated no fly zones calculated and provided to the UAV. These restrictions include altitude and speed restrictions as well as no fly zones within the operating area if any exists.

7.3.3 Network Latency and Session Disconnection Issues

UAVs must make decisions and respond in the event of a loss of communication with both the UAVaaS Coordinator or operator. Prolonged network issues will result in an automatic signal to return back to the nearest UAV hub and termination of the mission. Mission criteria to terminate include absence of replies back from the Management Service from status updates or absence of data received from the control queues. If at anytime the management service detects an issue with an operator, it reserves the right to send a termination message to the UAV.

Chapter 8

User Facing Interfaces Design

User facing interfaces include all forms of communication between operators, spectators and ground crew personnel and the UAVaaS Coordinator. Discussed is the design of different message data structures that accomplish tasks discussed in Sections 5.3.2 and 5.3.3 and all tools and utilities needed for successful operation

8.1 Communication with the UAVaaS Coordinator

8.2 User Invitation and Association Process

Any user trying to communicate to a UAVaaS Coordinator must first authenticate to the UAVaaS provider after being associated with one or more companies or UAV Hubs. This means that users cannot create accounts on their own accord, but have been given permission or invited to do so by existing authorized company or organization. This proposal restricts the number of people who have access. This model follows a Discretionary Access Control format in which ones access to the system is based on the discretion of currently authorized users.

Figure 8.1 demonstrates how associations work within a UAVaaS network. As illustrated, three UAV hubs and three companies A, B, and C are directly associated to a UAVaaS

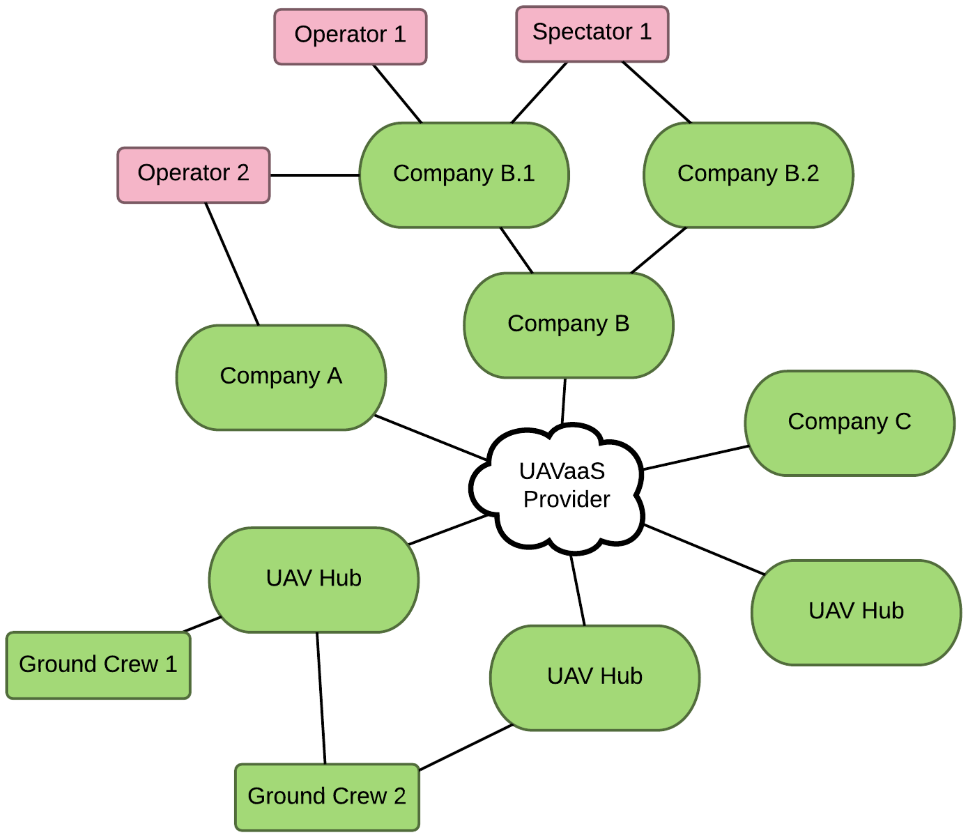

FIGURE 8.1: Association between the UAVaaS Provider and companies

Provider. This association is made by the UAVaaS provider itself in which heavy legal and technical matter is involved before giving a company access. An example of this would be a major farming association that would like to use a UAVaaS cloud provider to satisfy its business requirements. The major farming association in turn would then associate all of its farms to it labeled Company B.1 and B.2. When operators and spectators are assigned, Company B.1 and B.2 must provide permission or send out a digital invitation to join and be able to create an account.It is demonstrated that spectators and operators can belong to multiple companies and ground crew personnel can belong to multiple UAV Hubs.

Figure 8.2 demonstrated the invitation and association process between the UAVaaS Provider, a currently UAVaaS Account Holder and an Invited User. The process begins with a user authenticating with the UAVaaS Provider which then gets authenticated and returned a list of companies the user is associated with and if he/she has invite permissions. The user selects a company and sends an invitation request back to the UAVaaS Provider stating the roles and authorizations the invited user should have. The UAVaaS Provider checks if the invited user is already an account holder. If not, an invitation key will be generated and sent to the user, who will fill out an registration form and then become associated with the company. If the user is already an account holder, an association request is sent for the user to accept and then gets associated with the company.

8.2.1 Authentication and Session Negotiation

Due to the nature of UAVaaS where a user influences his/her surroundings, warrants extra care in the way authentication is performed. This design uses a two-factor authentication approach to effectively enhance its layers of security.

8.2.2 Mission Planning and Starting

Figure 8.3 illustrates a typical mission planning and startup process between the operator, spectator, and UAVaaS Coordinator. The process begins with an operator who wishes to fly a mission authenticating with the UAVaaS Coordinator. The operator submits a mission request specifying information about the type of mission that will be flown, including specified area of operation, flight time, UAV resources needed and authorized spectators allowed to view the mission. The UAVaaS Coordinator processes the request and returns a filtered list of UAVs that can be selected. The Operator chooses a set of UAVs needed and submits a flight request. The Coordinator returns a control assignment which, similar to a

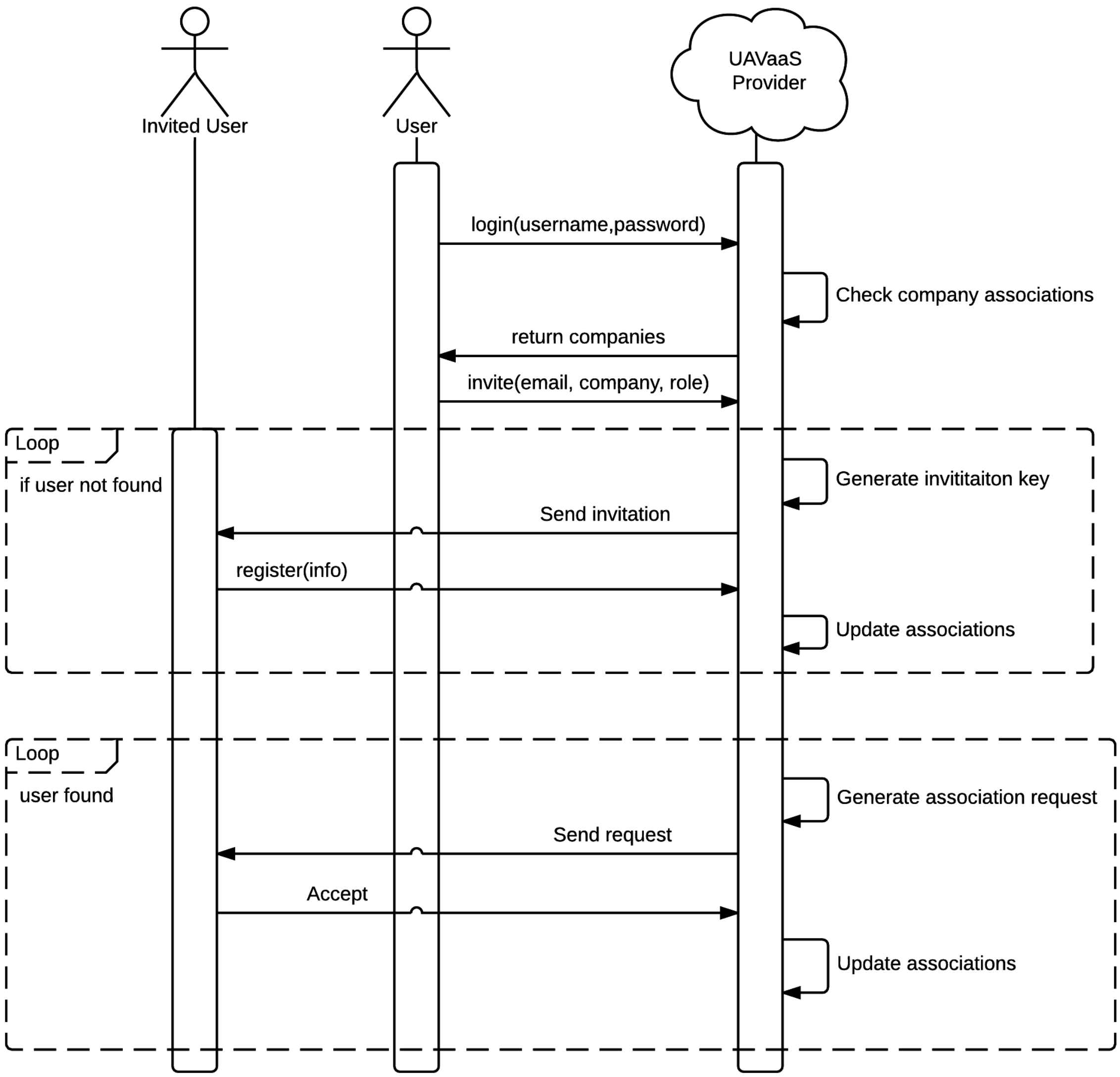

FIGURE 8.2: Invitation of user to company or UAV Hub

task assignment for UAVs contains connection information to the messaging service queues and exchanges. Once subscribed to necessary topics the operator notifies readiness and polls the coordinator until all UAVs are ready. Once ready the operator can start publishing controls and receiving data messages back.

The process for spectating a mission is more simplified and does not involve any form of mission planning. A spectator authenticates to the UAVaaS coordinator and receives a list of active missions authorized to access. The spectator selects a mission and receives a specAssignment, similar to a controlAssignement message for operators. The spectator subscribes to appropriate data exchanges with topics specified by the UAVaaS Coordinator and can begin receiving messages from the queue.

8.3 Operator Interfaces

A total of six main functionalities has been identified for the operator interface. An operator interface is any mobile app, or stand alone application or browser plugin that provides necessary utilities necessary to plan and fly a mission. These functionalities are shown in Figure 8.4 and include:

1. A control panel for mission management and controlling UAV payloads and flight parameters
2. A map panel that displays overhead view of all UAVs in flight, current waypoints set and restricted zones.
3. A telemetry panel for monitoring position speed and batter for each UAV.

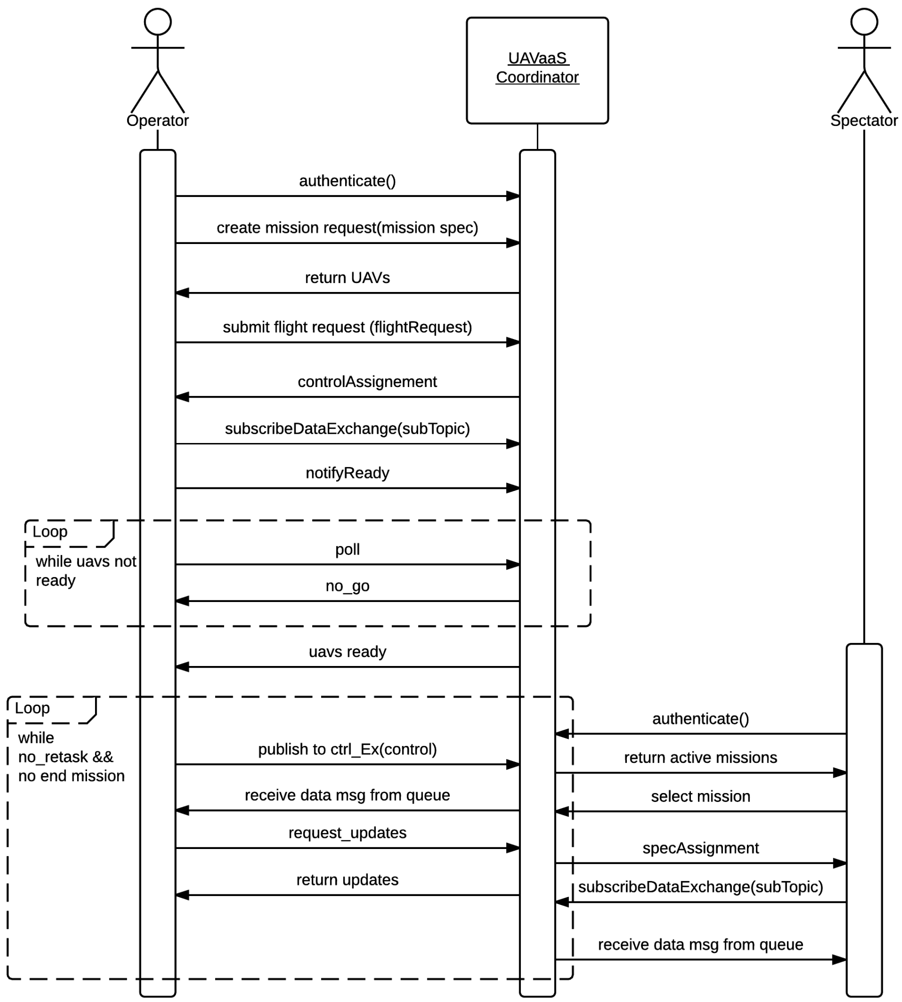

FIGURE 8.3: Mission planning and startup

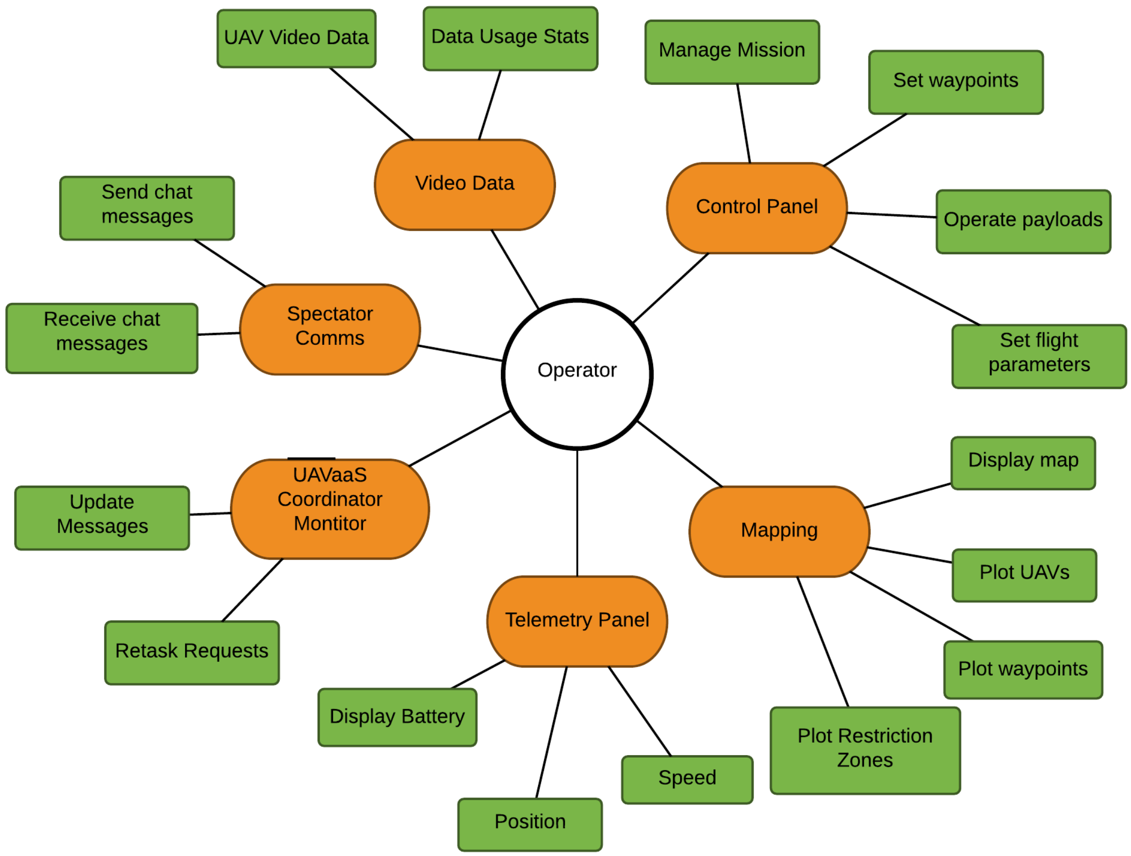

FIGURE 8.4: Required operator interface features

4. A UAVaaS Coordinator notification system for monitoring retask requests or any important updates about an ongoing mission or requests of new spectators who have joined.

5. A spectator communication chat system that allows controllers to communicate with spectators for strategic planning.

6. A video data panel that shows live data stream coming from UAVs

Chapter 9

Integrating Software Defined Networking

Software Defined Networks (SDN) is an emerging technology for network routing appliances that makes entire networks adaptable and manageable. SDN's offer the ability to update routing information on tables stored on one or multiple devices, on-the-fly from a centralized controller, making it suitable for networks required to maintain quality of service. This architecture provides network administrators full visibility of entire networks and allow easy single point configuration. Networks are managed autonomously by SDN applications installed on an SDN controller that (1) make pre-defined logical decisions and (2) distribute re-routing instructions to all routing appliances, when there is need for it.

In a UAVaaS environment, all actors(operators, spectators, UAVs, vendors and ground crew personnel) are connected over a wide geographical area in which data is transmitted through many network nodes. As more data from other sources travel through these network nodes they may become congested and require re-routing.

In order for quality of service to be maintained, SDN applications optimized for UAVaaS can be developed and distributed to internet providers to guarantee that connectivity is maintained and network latency is reduced.

9.1 Software Defined Networking Principles

Traditional networking devices as shown in Figure 9.1 are designed with two core components. A Control Plane that makes all the routing decisions for incoming and outgoing packets for each device, and a Data Plane which includes physical switching and forwarding hardware that forwards the data. Software Defined Networks works by removing individual Control Planes from networking devices and connecting them to a centralized SDN controller using Controller Agents. The SDN controller in turn acts as a network operating system that receives instructions from Business Applications that are installed. These applications include load-balancers, firewalls, intrusion detection systems among others. Business applications is given full visibility of the networking topology by the SDN controller so that strategic, optimal solutions can be generated to provide the best traffic routes. These routes are distributed and updated on local routing tables located in each network device's data plane.

When a networking device receives an unfamiliar packet, it forwards the packet to the SDN controller. The SDN controller in turn, communicates with each Business Application that determines the best route the packet should take and updates the routing tables of all necessary network devices. When networking devices fail, or becomes too congested, the SDN controller can detect and automatically reroute traffic to other, more available devices to reduce work load.

9.2 Advantages for UAVaaS

9.2.1 Prioritization

With Software Defined Networking, packets can be prioritized based on message types or operator type. For example, out of the three types of messages used in UAVaaS(management, data and control), control messages carry the highest priority. This is because operators

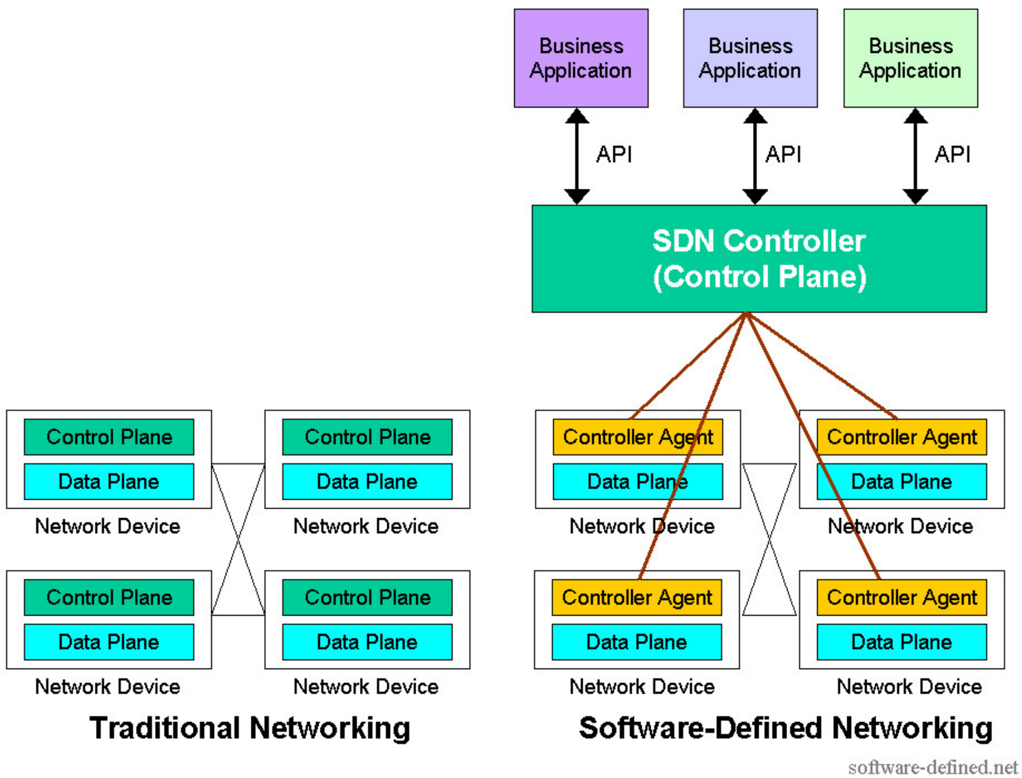

FIGURE 9.1: Software Defined Networking Architecture

need to have constant, real-time communication at all times. In the event that control messages cannot be sent to, or received by UAVs may compromise the mission. SDNs can therefore instruct networking devices on how to route control messages efficiently or place them in higher priority queues compared to data and management messages.

Sometimes higher priority operators such as emergency management services may require more bandwidth and lower latency than normal operators. In an event where multiple UAVs are needed, networks need to be configured in such a way that data messages which contain real-time video and picture feedback are routed through the network the fastest to firefighters, news crews and paramedics.

9.2.2 Standardization

In a heterogenous network, that contains devices from multiple vendors and controlled by multiple service providers, it is difficult to establish packet routing rules that are easy to implement across the entire network. With SDNs, routing logic can be developed once and distributed and installed on any routing device independent of model or ownership. This guarantees that networking devices owned for example by Brighthouse networks will perform, and make exactly the same routing decisions as networking devices owned by Comcast.

9.2.3 Failure Detection and Load Balancing

Since SDN controllers have full visibility over the entire network, it is easy to identify and determine which networking devices are failing or becomes too congested. In a UAVaaS environment, this could easily happen if multiple UAVs communicate through the same cell tower.

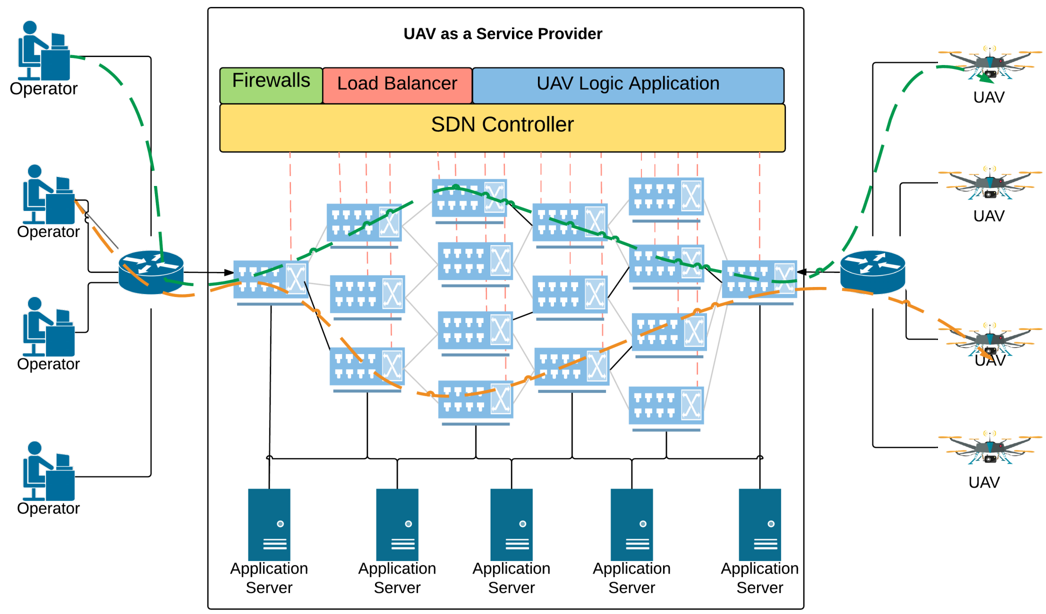

FIGURE 9.2: SDN routing between operators and UAVs

9.3 Integrating SDN into UAVaaS

Figure 9.2 shows how Software Defined Networking can be implemented on a UAVaaS provider to efficiently route messages between Operators and UAVs. The figure demonstrates how a network can be configured to forward messages through different devices thereby reducing the load experienced by each device. The SDN relies on a UAV Logic Application to provide routing instructions. In the event of device failure, routes can be dynamically reconfigured to maintain levels of service. While the figure only shows SDN implementation on one data center, controllers can be chained together to provide greater coverage and better routing decisions being made.

Chapter 10

Conclusion

10.1 General Conclusion

This research has proposed and designed a new cloud orchestration framework that provides customers with affordable, on-demand access to multi-tenant UAVs that are supplied by a UAV as a Service Cloud Provider. Once implemented, UAVs (conforming to a UAVaaS specification) can be openly shared by businesses that wish to utilize commercial UAV services, without the legal and financial overheads associated with traditional upfront capital expenditure. On the other hand, 3rd party vendors that faithfully supply the UAVaaS cloud provider with commercial grade UAVs, can make commission based profit, based on frequency and duration of UAV tasking. In order to secure UAVaaS's success, a cloud provider must prioritize and satisfy the needs of 3rd party vendors, operators, spectators, UAV hub ground crew and emergency services personnel.

The results of the system analysis explains that both direct point-to-point communication and virtual private networking topologies between UAVs, operators and spectators are not sufficient to address major concerns on areas of security, safety and privacy. Instead a central, cloud service approach must be taken in which all communication is collaborated and routed through a coordinator.

A Representational State Transfer (REST) service for standard request-response queries coupled with an Advanced Message Queuing Protocol (AMQP) for messaging routing provides the simplest and most optimal design that takes into consideration factors of scalabiltiy and fault tolerance. In order for UAVs to connect to a UAVaaS Service Provider, vendors/manufacturers must take into consideration a standard design model of all UAV builds. 4G and wifi connectivity, Micro Air Vehicle Link (MAVLink) compatible autopilot controller and dedicated TCP/IP to MAVLink adapter must be incorporated into every build just to name a few.

With the year 2016 being hailed as "the dawn of the drone age"[14], and commercial development of UAVs now in full swing, focus needs to be placed on designing efficient, cloud-friendly ecosystems that will allow UAVs to collaboratively work together for the greater good of humankind. UAV as a Service is one such ecosystem.

10.2 Recommendations

This thesis presents a general yet comprehensive description of what UAV as a Service is and how it could be designed and implemented. However before any future research and development of UAVaaS in the United States can begin, further research must be done to develop UAVs that can intrinsically abide by rules and regulations set forth by the Federal Aviation Administration. Rules such as airspace restrictions, certifiable UAV designs, no-fly zone detection and monitoring and situational awareness algorithms should be considered before any implementation begins.

Network performance and stress tests are considered outside the scope of this research. Since communication over cellular networks may be intermittent and unreliable at times, it is recommended that more research is placed on the amount of data consumption and bandwidth required for a UAVaaS system to be sustainable. If possible, Software Defined Networks should be researched and their applications assessed in a UAVaaS Cloud environment.

While UAVaaS demonstrates to reduce costs for customers and improve profit margins for UAV manufacturers, no cost-benefit analysis or detailed business models have been researched. It is recommended that more feasibility analysis is necessary on a business/marketing level, to determine optimal pricing for UAVaaS services and commissions awarded to UAVaaS vendors.

Since UAVs that operate in a UAVaaS network typically travel outside line of sight of the operator, there is no way (apart from the UAVs camera) to detect and avoid nearby UAVs and aircraft. It is recommended that more research into this area be done before any further implementation of UAVaaS is carried out.

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