Investigating the Use of Digital Twins in Networked Commercial UAVs

by

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Submitted to the System Design and Management Program
in Partial Fulfilment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2019

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Abstract

The Commercial UAS industry is relatively new and has significant growth potential as new technology are incorporated into it, new applications are found, and new regulations are coming in place. Digital Framework, also a relatively new concept, has found acceptance in various industry but has not yet been applied to Commercial UAS while having great potential. This thesis uses the ARIES framework to investigates how this concept can be applied to Commercial UAS, the possible applications and architecture. Towards this end, a study of the enterprise landscape and a stakeholder analysis are conducted. Next the current architecture of the Commercial UAS is identified. From this understanding, a possible future is identified and possible applications from integrating Digital Framework into Commercial UAS are identified. Finally, an architecture for the future UAS was proposed and four possible architectures that incorporated a Digital Framework into Commercial UAS were identified.

Thesis Supervisor: Dr. Donna H. Rhodes

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Acknowledgment

I would like to first and foremost thank my advisor, Dr. Donna H. Rhodes, for her immense support and guidance throughout this thesis journey. This work would not have been possible without her constant engagement and insights. Dr. Rhodes course "Systems Architecting Applied to Enterprises", has been vital in structuring my thoughts on how to approach this work.

I would also like to thank Joan Rubin, the SDM program, my cohort and members of the SEAri research group, for a rich and wonderful learning experience at MIT. The knowledge and experience I have gained during my time here have become invaluable to me. Of many more people to thank, first would be the people whom I interviewed to understand the Commercial UAS industry and the Digital Twins concept. Lastly, I would like to thank my friends who have helped me with not only the cross functional knowledge, but also for religiously reviewing this document.

To my parents, thank you for your values, guidance and support, all my life. They have helped me throughout this journey. To my sister, thank you for being a constant in my life. To my extended family, thank you for all the love, laughter and joy and for shaping me up all these years. Finally, of special importance to me, I would like to thank my wife, for being understanding and my support throughout this journey.

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List of Acronyms

ADS-B	Automatic Dependent Surveillance-Broadcast
AI	Artificial Intelligence
ATM	Air Traffic Management
B2B	Business-to-Business
BVLOS	Beyond Visual Line-of-Sight
CAGR	Compound Annual Growth Rate
CNPC	Control and Non-Payload Communications
CPU	Central Processing Unit
DroneII	Drone Industry Insights
FMDMS	Flight Management and Data Management Server
GCS	Ground Control Station
GPU	Graphics Processing Unit
GUI	Graphical User Interface
IMU	Inertial Measurement Unit
VLOS	Visual Line-of-Sight
R&D	Research and Development
ROI	Return on Investment
TCL	Technology Capability Level
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle (Also known as Drone)
UTM	Unmanned Aircraft System Traffic Management
VTOL	Vertical Take-off and Landing

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1. Introduction and Research Methods

1.1. Motivation and Background

Unmanned Aerial Vehicles (UAVs), also known to the world as drones, are aircrafts with no pilots or passengers onboard that are either automated or remotely piloted [1]. These aircrafts have been in use since the advent of radio technology in some form or other [2], [3]. The largest users of UAVs for most of this time have been the military which consisted of expensive custom-built systems designed for pilot training, surveillance and offensive capabilities [1], [2]. The first major use of UAVs was during the Vietnam war where they were used as decoys in combat, launched missiles against fixed targets, acted as "electronic listening devices" and dropped propaganda leaflets [1], [2]. In the 1980s, other countries started exploring the use of UAVs as the technology became more capable and more sophisticated.

Other smaller users of UAVs during this time were hobbyist who purchased or built foam or balsa airframes adding the avionics as needed. These systems were very inexpensive and easily available in hobby shops. Breakthroughs in transistor technology in the 1960s gave rise to miniaturized radio-controlled components at a reasonable cost resulting in a boom in hobby flying [4]. The capabilities of these systems were limited to short range visual line of sight (VLOS) flights for racing, entertainment, photography, and research and development (R&D).

In the recent decades, with the advent of low-cost miniaturized electronics and ubiquitous availability of small lightweight GPS technology, new UAV companies started catering to a new set of customers. This new group of customers are interested in Unmanned Aerial Systems (UASs). UASs are fully assembled ready to use systems which include the UAV, the UAV payload, ground control station (GCS) to control the UAV with the software and graphical user interface (GUI) needed to operate the UAV. The first set of customers in the consumer market tended to buy UAS that are easy to fly with a low learning curves and primarily used for entertainment or photography and videography. The first successful ready-to-fly consumer drone was the Parrot AR Drone released in 2010 [4]. The second set of customers are from the commercial or industry market. These customers use UASs specifically designed to augment or accelerate tasks, reduce cost and operational time in applications such as precision agriculture, construction, infrastructure management, warehouse management, disaster relief and drone delivery.

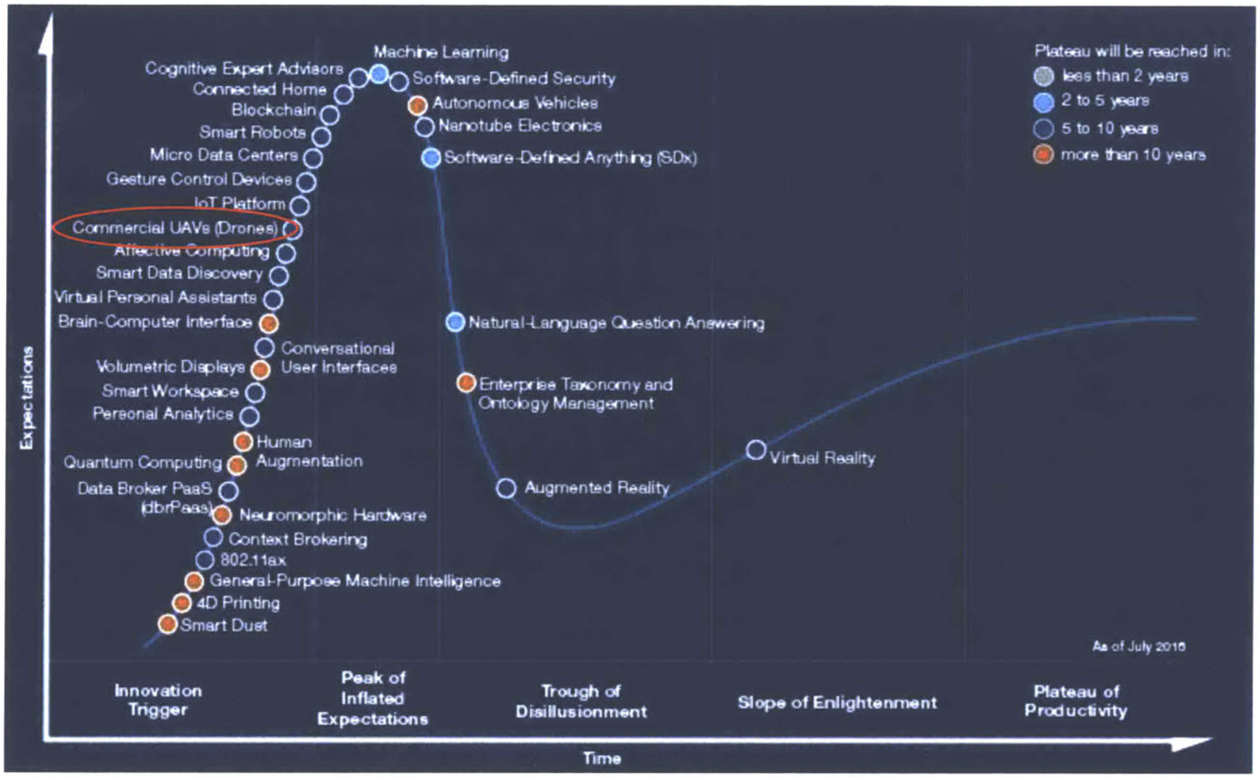

Figure 1: Gartner Hype Cycle for Emerging Technologies 2016 [5]

Gartner Hype Cycle provides a graphic representation of the maturity and adoption of technologies and applications [6]. The Hype Cycle can be broken into five key phases of a technology's life cycle as shown at the bottom of Figure 1 [6]. According to the 2016 Gartner Hype Cycle, Commercial UAS were on the front side of the curve and expected to reach the plateau in 5 to 10 years as shown in the Figure 1. By the 2017 Gartner Hype Cycle, commercial UAS were on the backside of the curve heading to the through of disillusionment and expected to reach the plateau in 2 to 5 years as shown in Figure 2. This shows that the industry is realizing that UAS technology has more work to be done than expected and the industry needs to sort itself out before reaching the plateau of productivity. Companies are also realizing the data generated from UAS and analyzed are what provides value to the customer.

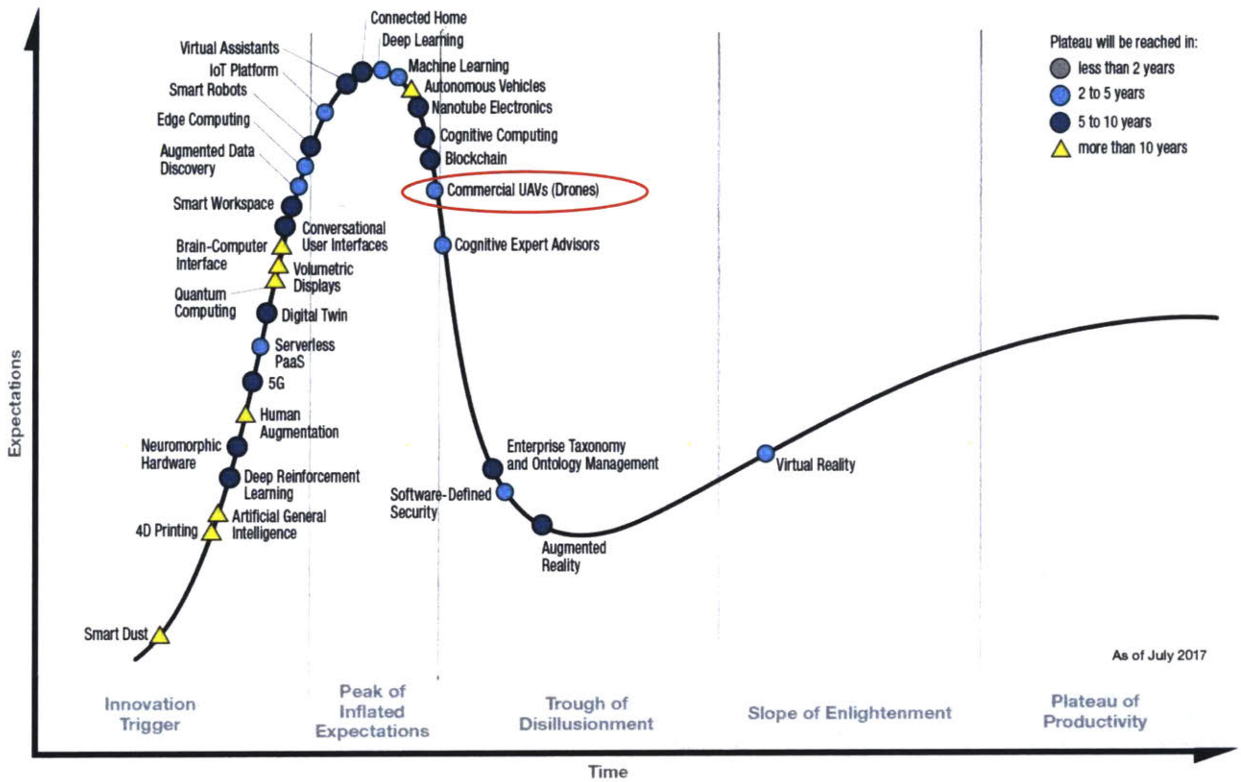

Figure 2: Gartner Hype Cycle for Emerging Technologies 2017 [7]

As commercial UAS evolve, some of the newer systems available since 2016 have integrated smart computer vision and machine learning technology. This enabled systems to avoid obstacles, intelligently track people, animals and objects – without being limited to following GPS signals [4]. As this technology continues to evolve and more powerful processing hardware are integrated into UASs, these systems will be more autonomous and able to manage and complete tasks without human interactions [8], [9].

Currently, most commercial UAS are limited to VLOS operations due to technology limitations and regulations. As new technologies such as 5G cellular communication enable UAS to operate in beyond visual line-of-sight (BVLOS) mode and new regulations and infrastructure such as Unmanned Aircraft System Traffic Management (UTM) are established for these capabilities, UAS are poised to leverage these capabilities [10]–[12].

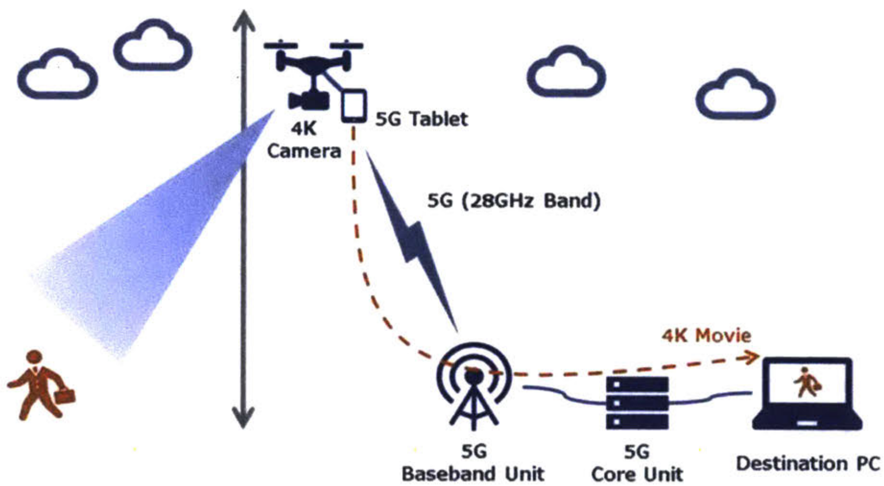

Figure 3: 5G Cellular link between GCS and UAV [11]

Data security is also becoming more and more important to UAS customers as these systems generate large amounts of data. Concerns are arising on who has access to the sensitive customer data and what is being done with it [13]–[15].

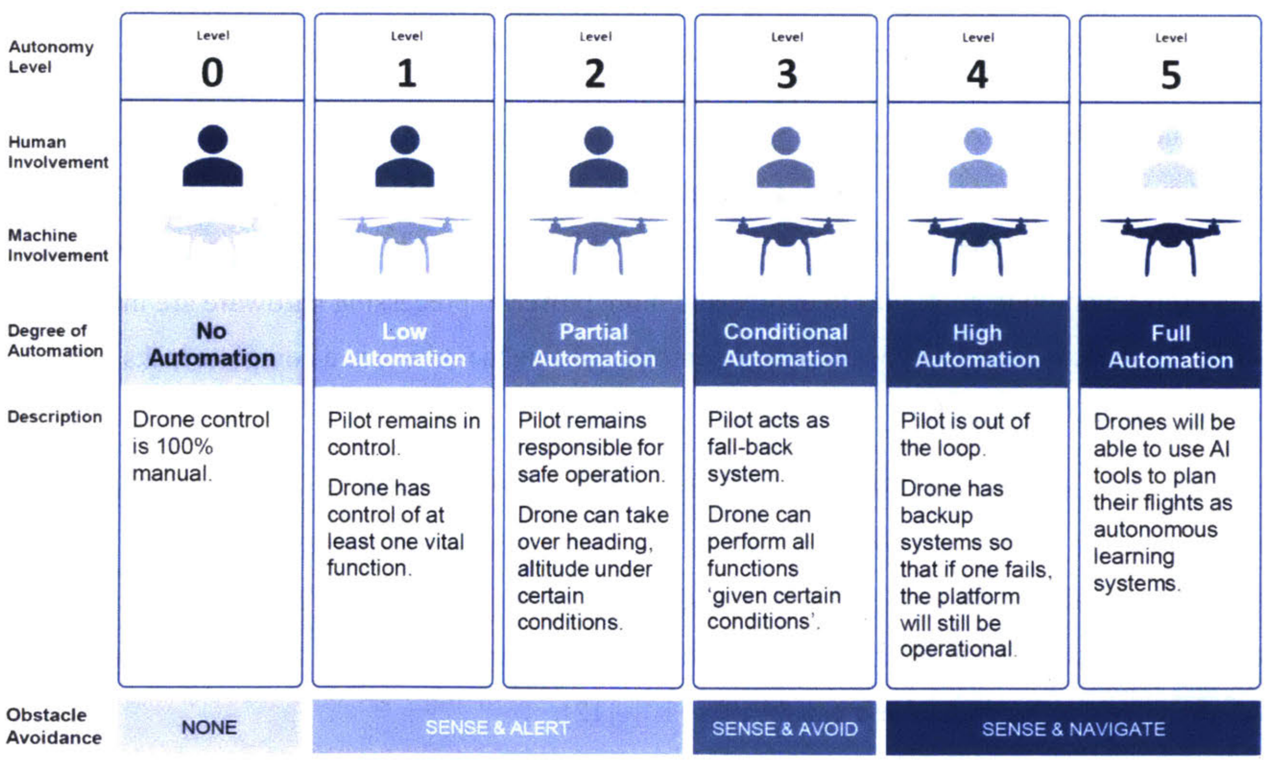

Figure 4: DroneII Five Levels of UAS Automation [16]

As drones become more autonomous, UAS Operators (pilots) will be operating and managing fleets of UAVs rather than individual ones. Figure 4 created by Drone Industry Insights (DroneII), an independent drone market intelligence organization that creates various reports on the UAS industry, organizes the various autonomy levels based on the level of human involvement, machine involvement, and degree of drone automation.

Finally, as drones become more autonomous, new autonomous methods of monitoring the health and performance of a UAS would be needed that minimize human interactions. Digital Framework, which consists of a Digital System Model (DSM), a Digital Twin and a Digital Thread, could be a technology that can be implemented in UAS.

The motivation of the author to of this thesis, is to explore how the current commercial UAS architecture could evolve when taking a holistic view of the industry. The author will also explore how a Digital Framework could be integrated into the architecture and how the architecture and the various stakeholders could benefit from this.

1.2. Research Objective

While exploring the commercial UAS industry and its current architecture, questions began to arise on the architecture's long-term feasibility and its limitations. The first question was: "What could the commercial UAS architecture evolve to?" To answer this question, an investigation of the commercial UAS industry was conducted to identify how it has evolved over the past five years.

The second research question was: "How could the Digital Framework be integrated into architecture?" Digital Framework consists of three parts, a DSM, a Digital Twin and a Digital Thread. This question explores where the three parts of the Digital Framework could be integrated into the architecture and their affect.

Finally, the last question asked: "How could commercial UAS benefit from integrating a digital framework into its architecture?" This would explore the potential applications from integrating a Digital Framework into a UAS and its benefits to the various stakeholders.

1.3. Research Scope

The scope of this research has been limited to the commercial UAS industry. Due to the nature of the commercial UAS industry and the various regulations in countries around the world, the research scope was also limited to the commercial UAS environment of the United States of America.

1.4. Research Method

The ARIES (ARchitecting Innovative Enterprise Strategy) framework was used to conduct this research and structure the approach [17].

- "Architecting is the act of creating a "blueprint" for the enterprise to follow to achieve its desired transformation vision".
- "Innovation means being forward-looking so that the enterprise evolves to stay ahead of changes in its ecosystem that may impact its ability to survive and to thrive".
- "Enterprise strategy is the overarching strategy that is a determinant to success of an enterprise in delivering value to stakeholders while pulling from and contributing to its own ecosystem".

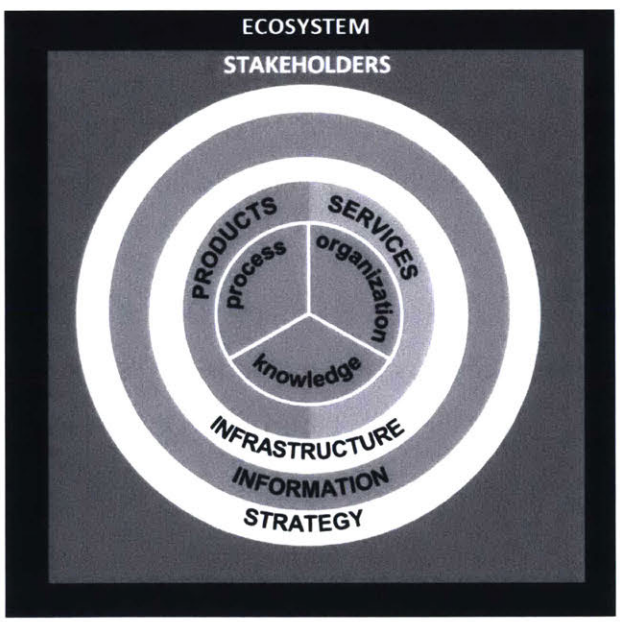

Figure 5: ARIES Unique lenses for looking at the enterprise [17]

ARIES framework provides the opportunity to look at the enterprise through up to 10 unique lenses shown in Figure 5. The framework also defines seven activities that can be performed as shown in Figure 6.

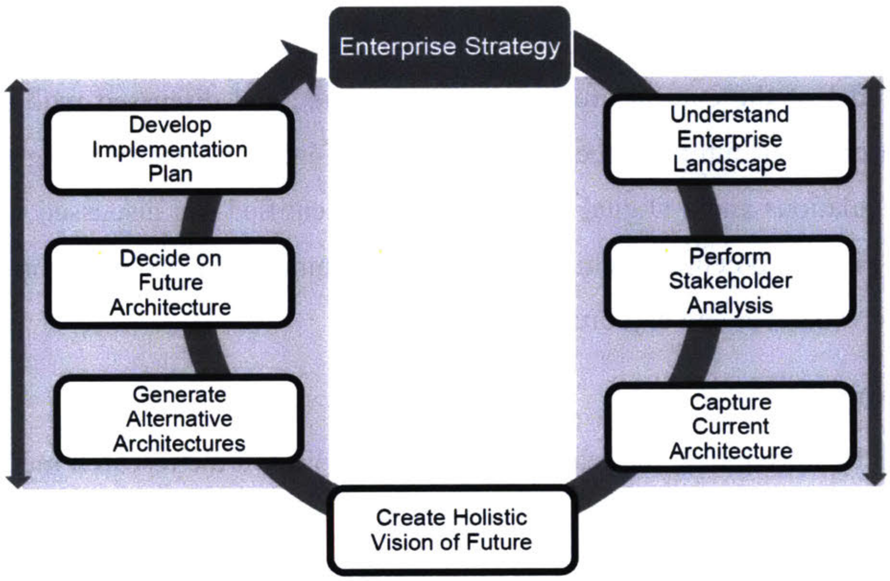

Figure 6: ARIES Framework Process [17]

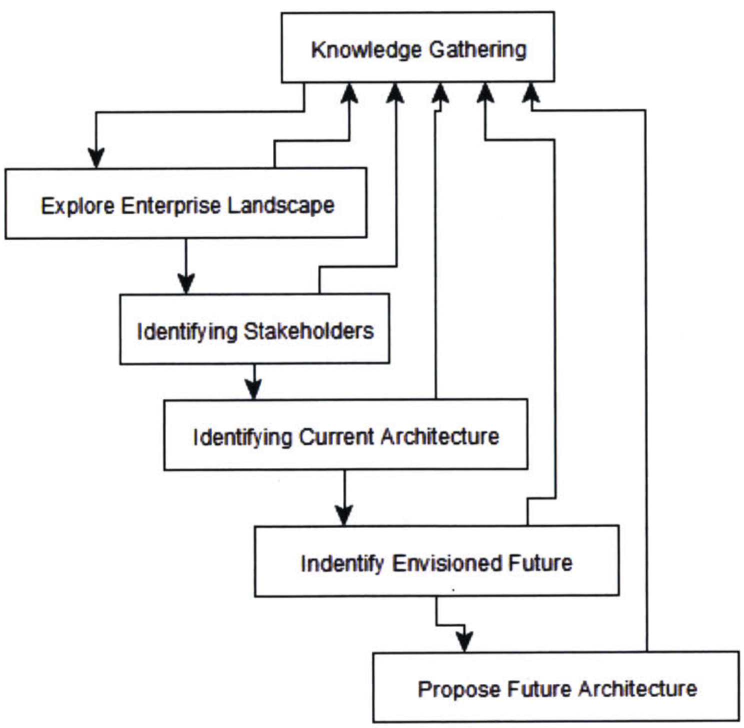

Figure 7: Research Approach

Figure 7 lays out the research approach taken to complete this thesis. A literature review (knowledge gathering) of the UAS industry and digital framework was conducted to gain an understand of the industry. This was accomplished by exploring the literature available on the industry and interviewing subject matter experts familiar with the commercial UAS industry, Digital Framework or both. From this, the enterprise landscape was explored, and stakeholders identified. A model of the current architecture was created and discussed with subject matter experts. Next, a potential future of the Commercial UAS industry incorporating the supporting technologies, regulations and a Digital Framework was identified and discussed with by subject matter experts. Finally, potential architectures of the commercial UAS incorporating a Digital Framework were generated and explored.

1.5. Thesis Outline

This thesis starts by introducing the reader to the thesis topic and the research method employed in Chapter 1. Next, the Commercial UAS enterprise landscape and Digital Framework are explored in Chapter 2. Chapter 3 conducts an analysis of the stakeholder of the Commercial UAS industry. Chapter 4 explores the current UAS architecture. Chapter 5 presents the envisioned future. Chapter 6 proposes future Commercial UAS architecture and how Digital Framework could be integrated into it. Finally, Chapter 7 summarizes the thesis.

Table 1: Thesis Structure

Chapter	Content
Chapter 1	Introduction and Research Methods
Chapter 2	Enterprise Landscape
Chapter 3	Stakeholder Analysis
Chapter 4	Current Commercial UAS Architecture
Chapter 5	Envisioned Future
Chapter 6	Proposed Architecture
Chapter 7	Conclusion

2. Enterprise Landscape

The first activity of the ARIES framework is understanding the landscape the enterprise sits in [17]. This involves understanding the factors that affect the enterprise. The first section looks at the enterprise landscape of the commercial UAS environment. The second section explores the enterprise landscape of digital framework.

2.1. Commercial UAS Environment

There are various factors that are causing changes in the Commercial UAS industry. These can be broken down into the following sections.

2.1.1. Market

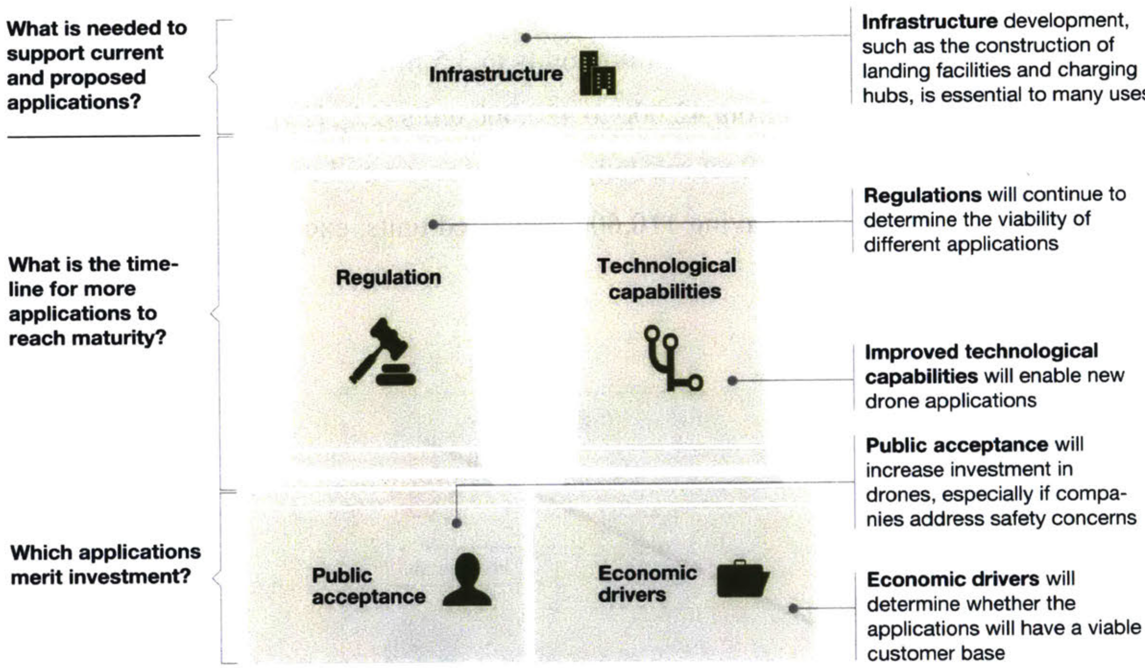

Figure 8: Factors that Affect Growth of Commercial UAS Industry [18]

According to a Goldman Sachs report, the UAS market is expected to reach $100 billion by 2020 with 70% of this market expected to be the military and 30% shared between the commercial and consumer market [19]. A report by McKinsey estimates that the commercial UAS market grew from $40 million in 2012 to $1 billion in 2017 and is expected to have an annual impact of $31 billion to $46 billion in 2026 on the GDP of United States [18]. McKinsey also broke down the factors that affect the growth of the commercial UAS industry into Infrastructure, Regulations, Technologies, Public Acceptance and Economic Drivers (Figure 8) [18].

In 2017, between the commercial and consumer UAS market share, 94% of the units sold were consumer UAS with only 6% making up the commercial market, but consumer UAS only represent 40% of the revenue share with commercial UAS taking up 60% [20]. This difference in revenue is due to the significant differences in the unit cost, where consumer UAS are priced under $10,000 with an average price of $2500, commercial UAS are priced above $10,000 with unit prices around $25,000 [21].

While the UAS market is expected to grow between 2016 and 2021 at a compound annual growth rate (CAGR) of 7.6%, The consumer market is expected to grow at a CAGR of 31.3% while the commercial market is expected to grow at a CAGR of 51% [22]. This would imply that while the consumer fleet will triple in size from 1.1 million units to 3.5 million units, the commercial fleet will become ten times its 2016 size from 42,000 to 420,000 units [22], [23]. While expectation for 2017 showed the Commercial UAS fleet reaching 108,000 registered units, actual data for 2017 showed the commercial UAS fleet having 110,604 registered units, exceeding expectations [21], [23].

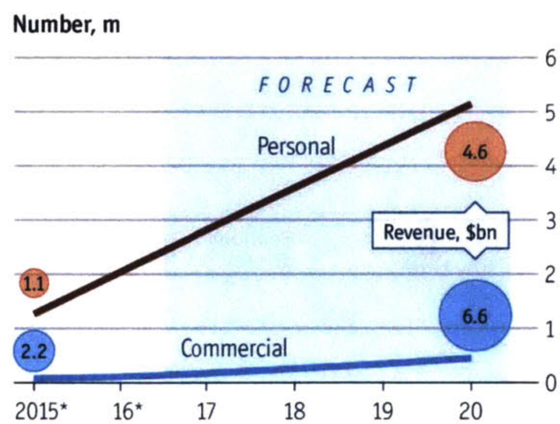

Figure 9: Drone Market Growth, Numbers vs $ [24]

With the commercial UAS segment being the fastest growing segment of the UAS industry, various organizations are already using them extensively while others are racing to integrate them into their operations. McKinsey divides the commercial UAS industry into Hardware, Operations and Services as shown in Figure 10.

	Aircraft hardware		Operations				Services		
	Components	Original equipment manufacture	Physical infrastructure	Navigation/ traffic/ UTM[1]	Operators	UAV[3] mitigation	Support services	Data management	Multi-segment
Description	Components used on a UAS[1] platform	Full UAS platform manufacturing or integration	Physical infrastructure for UAS takeoff, landing, recharging	Systems designed to navigate airspace	Professional operation of UAS	Threat prevention and mitigation	Services supporting the UAS ecosystem	Software and analytics to digitize the information collected by UAS	Organizations with multiple value-chain offerings
What's included	• Batteries • Gimbals • Payloads • Sensors • Motors	• Consumer UAS • Commercial UAS	• Landing pads • UAS stations • Vertiports • Chargers	• Artificial intelligence software • Route planning • GPS devices • UTM	• Photography • Mapping • Inspections	• UAS guns • Shields • Nets • Lasers	• Pilot marketplaces • UAS law • Insurance • Retail and distributors • Consulting • Training	• UAS mapping software • Image-processing software	• Manufacturers with a data-analysis platform

Figure 10: Start-ups active across the UAS value chain [18]

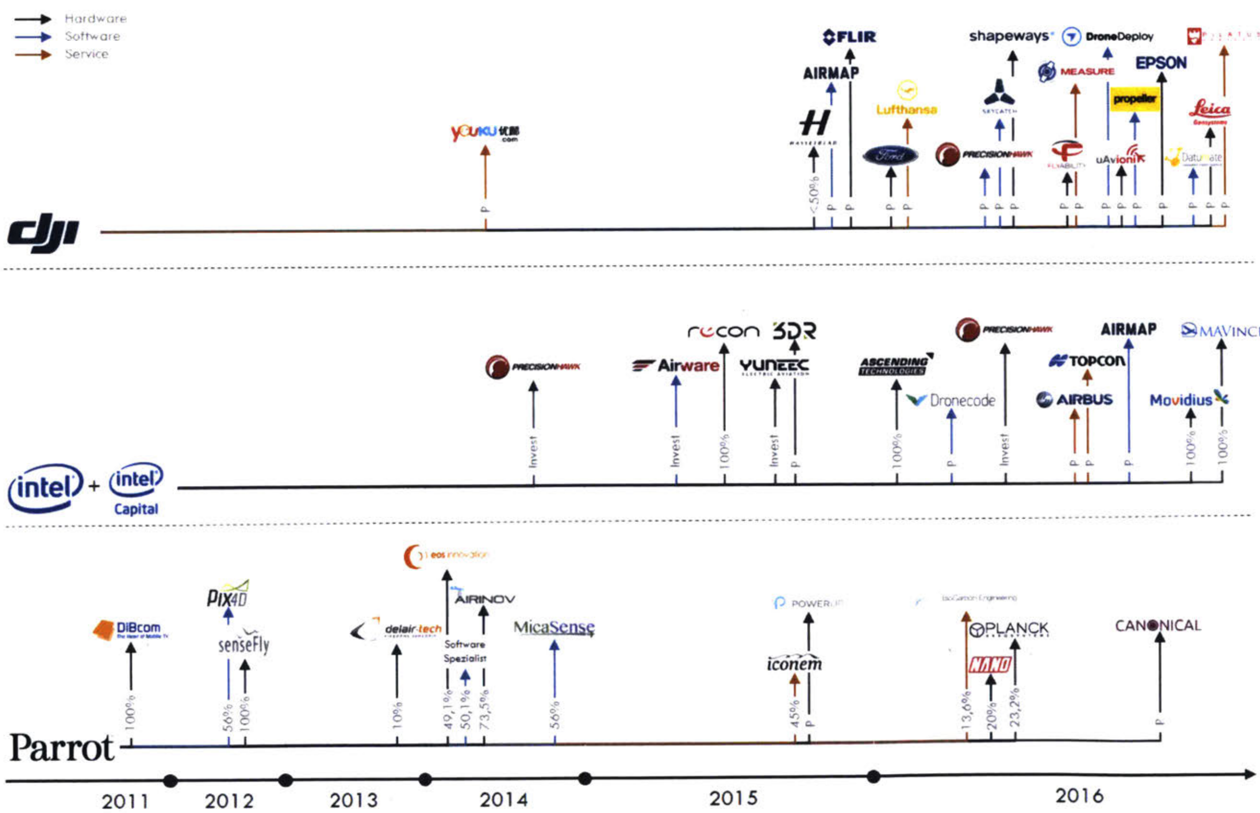

Figure 11: DJI, Intel & Parrot Partnerships, Investments & Acquisitions [25]

Meanwhile, DroneII breaks the commercial UAS industry into three sectors, hardware manufacturers, software developers and service providers. Hardware manufacturers such as Microdrones, Kespry, DJI and Aeryon build the UAS and develop the software needed for the operations of the system. Software developers such as Pix4D, DroneDeploy and 3DR developed software to analyze the data generated or manage the drone operations. Finally, service providers operate the systems for customers or supply these systems to customers. Until recently, organizations have been developing their offerings independently, but customers are now more interested in end to end solutions. New data suggests that there has been an increase in partnerships, investments and acquisitions between the different groups with the industry consolidating to provide more integrated services as shown in Figure 11 and Figure 12.

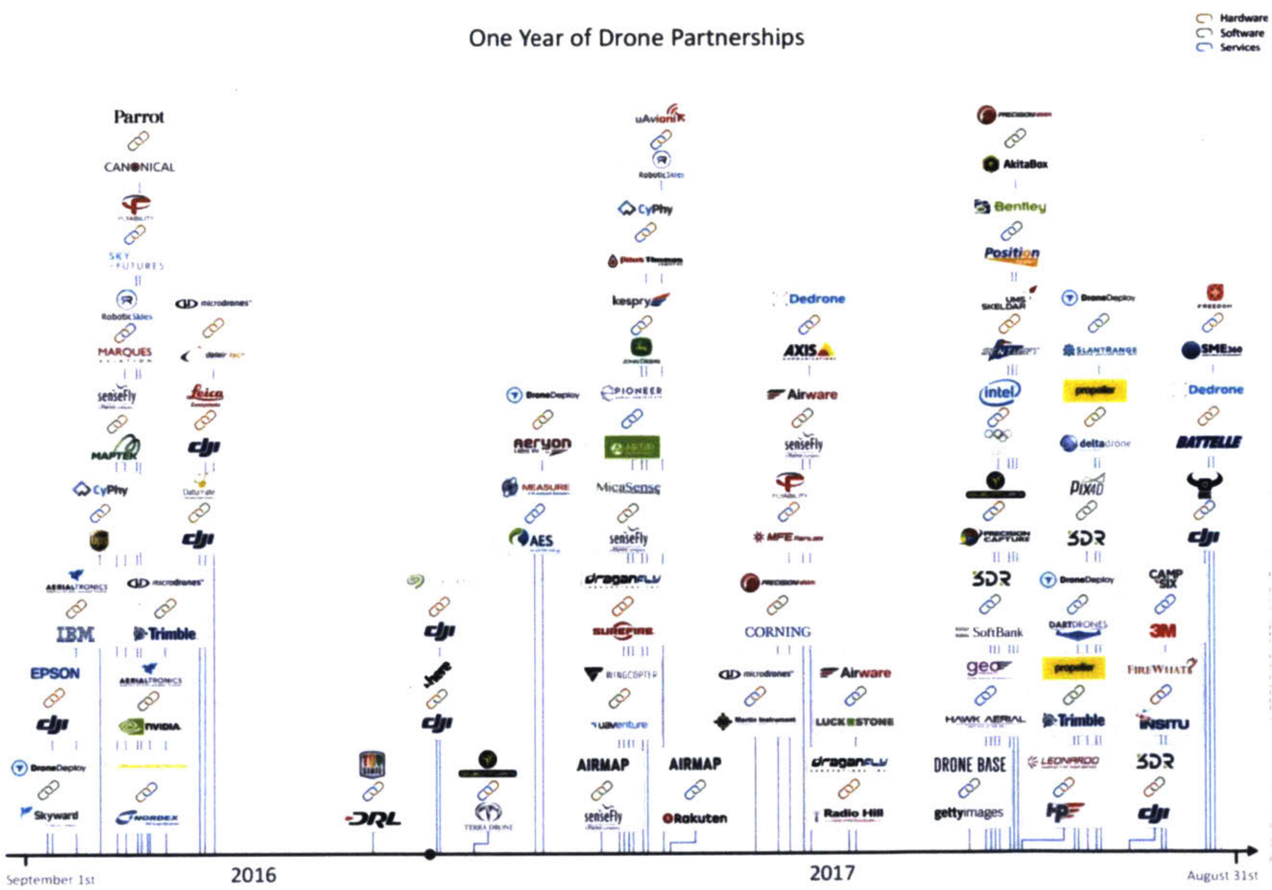

Figure 12: Drone Partnerships [26]

2.1.2. Environment

Organizations are finding various uses for UAS. Figure 13 provides 135 potential applications and the UTM TCL requirements [27].

Communications
- Airborne WIFI Antenna
- Airborne Internet Provider
- Airborne Cell Phone Repeater
- Artificial Satellite

Transportation, Delivery & Interaction
- Emergency Medial Response
- Consumer Package Delivery
- Newspaper and Mail Delivery
- Aerial Application
- Harvesting
- Fireworks Display
- Forest Fire Fighting
- Urban Firefighting
- Construction
- Snow Pack Measurement
- UAS Sports
- UAS Art
- Window Cleaning
- SWOT Operations
- Explosive Disposal

Atmospheric & Earth Science
- Cloud Seeding
- Meteorology
- Atmospheric Profiling
- Hurricane Monitoring
- Pollution Monitoring
- Hydrometric Modeling
- Water Quality Inspection
- Aeromagnetic Survey
- Surface Radiation Profiling

Audiovisual Presence
- Tour Guiding
- Aerial Advertising
- Aerial Lighting
- Aerial Speaker
- Traffic Management
- Crime Deterrent

Aerial Photography, Sensing & Surveillance

- Precision Agriculture
- Livestock Monitoring
- Animal Spotting for Hunting

- Invasive Plant Monitoring
- Ocean Research
- Forest Management
- Animal Tracking and Monitoring
- Mosquito Monitoring
- Wildlife Conservation
- Anti-Poaching
- Anti-Whaling
- Archaeology
- Anthropology

- EM Tower Inspection
- EM Signal Coverage Mapping
- Wind Turbine Inspection
- Bridge Inspection
- Power Line Inspection
- Roadway Inspection
- Airport Inspection
- Solar Panel Inspection
- Rail Inspection
- Landmark Inspection
- Landfill Inspection
- Pipeline Inspection
- Power Plant Inspection
- Industrial Complex Inspection
- Oil Rig Inspection
- Dam Inspection
- Canal Inspection
- Waterway Inspection
- Water Tower Inspection

- Construction Documentation
- Construction Inspection
- Construction Surveying
- Equipment Inventory

- Journalism
- Electronic News Gathering
- Disaster Management
- Flood Warning and Monitoring
- Forest Fire Surveillance
- Urban Fire Search and Rescue
- Search and rescue
- Volcano Monitoring
- Petroleum Spill Monitoring
- HAZMAT and Radiation Inspection
- Damage Assessment
- Real Estate and Property Appraisal
- Insurance Claim Appraisal
- Insurance & Building Code Compliance
- Roof and Home Inspection
- Parking Utilization
- Urban Planning
- Thermal Isolation Analysis

- Event Security & Crowd Control
- Corporate Security
- Home Security
- Personal Security
- Port Security
- Border Security
- Graffiti Prevention
- Child Surveillance and Security
- Explosives Detection

- Crime Scene Photos
- Criminal Pursuit
- Gunshot Triangulation
- Surveillance
- Crowd Monitoring
- Suspect and Vehicle Tracking
- VIP Security

- High Altitude Imagery
- Property Surveying
- Mine & Quarry Volumetric Mapping
- Prospecting
- Geomorphic Modeling
- Cryosphere Mapping
- Terrain Mapping
- Avalanche Monitoring
- Flood Plane Mapping
- Tidal Zone Mapping
- Saltwater Intrusion Mapping
- River Discharge Monitoring
- Coastline and Waterway Erosion Infrastructure Inspection
- Sand Dune and Sand Bar Monitoring

- Maritime Surveillance
- Maritime Scouting
- Anti-Piracy
- Fish Spotting
- Ship Inspection
- Illegal Dumping Detection
- Shark Detection and Alert
- Lifeguarding
- Tsunami Detection and Alert
- Fishery Management
- Whale Watching

- Real Estate Photography
- Nature Photography
- Adventure Sports Photography
- Outdoor Sports Photography
- Professional Sporting Photography
- Filmmaking

TCL-1 Feasible Application
TCL-2 Feasible Application
TCL-3 Feasible Application
TCL-4 Feasible Application
Application not yet supported...

Figure 13: 135 Potential UAS Applications [27]

These applications are also color coded based on where they stand on the UTM technology capability levels (TCL) [27]:

UTM TCL 1: Concluded field testing in August 2015/ongoing testing at FAA site. Addressed rural UAS operations for agriculture, firefighting and infrastructure monitoring. In this TCL, the UAS ground pilot reserved the airspace and adjusted the flight plan if notified of a conflict.

UTM TCL 2: Tests in October 2016 to address beyond-visual line-of-sight operations in sparsely populated areas and provide flight procedures and traffic rules for longer-range applications.

UTM TCL 3: Tests in January 2018 to include cooperative and uncooperative UAS tracking capabilities to ensure collective safety of manned and unmanned operations over moderately populated areas.

UTM TCL 4: Test dates to be determined. Would involve UAS operations in higher-density urban areas for tasks such as news gathering and package delivery, and large-scale contingency mitigation.

One of the main drivers for the use of UAS in commercial industry is to offload tasks that were once considered dull, dirty, dangerous, and difficult [28]. Dull tasks are those that have low interactions, are highly repetitive and need to be conducted continuously with a streamlined process. An example of this is in warehouse management where drones are used to manage inventory and locate boxes [29]. The dirty tasks are tasks that are unsanitary or hazardous but need to be done. An example of this is using UAS in the places like the Fukushima nuclear power plant to monitor the containment area where humans would not be able to enter or survive [30]. Dangerous tasks are those that place humans in harmful environments. UAS could help prevent injuries to humans or loss of human life. An example for this application would be wind turbine inspection where drones are used to inspect the wind turbine blades or to inspect telecommunication towers without the need for a human to climb the tower [31], [32]. Difficult tasks are a new area where drones are expected to tackle tasks that require low error margins and high level of detail.

Drones also are being used extensively due to their ability to reduce time per task and for their high precision. An example of this from the mining industry shows the UAS able to cover 150 acres in 30 minutes, reducing labor costs by 84% and increasing data accuracy by 80% [33]. Using

UAS in the construction industry was found to take just 30 minutes to generate survey grade data of an entire construction site and generated a 30 times reduction in field survey hours [34]. Applying drones to inspections was found to increase inspections by 3 times with over 99% accuracy with millimeter resolution [35].

The current market trend also points to a strong customization towards specific industries. This is being augmented by specialized configurations and analytics tools that suit specific applications [36].

Meanwhile, looking through interviews of cofounders and CEOs of various industry leaders conducted by DroneII gave another view of the direction being taken by the industry and interests customers have. These interviewees come from various organizations such as Aker, Kittyhawk, Measure, Delair-tech, 3DR, Terra Drone and Pix4D. Various interviewees state BVLOS were capabilities highly requested by their customers and expect more systems with these capabilities, the limiting factors being technology and regulations [13], [14], [31], [36], [37]. Another feature in great demand was fully autonomous capabilities with regulations that will allow for this [13], [14], [31], [37]–[39]. UAS being safe to operate in the operational environment and over people was a big concern that was brought up in various discussions [38], [40]–[43]. Data security and ease of use was also a concern they had seen from their customers [13]–[15], [44]. Various interviewees stated that at the current rate the industry is growing, pilot shortages will become a concern in the future [37], [39]. This would mean that, as the industry grows, individual UAS operators would need to manage multiple UAS and systems would need to have greater autonomy. Companies in some applications such as inspections are also coming to realize that they need a drone strategy or be out of business in five to ten years [44]. The commercial UAS industry being a business-to-business (B2B) industry is driven by customers interest in return on investment (ROI) [41], [45]–[47]. This enables customers to purchase and use UAS systems that carry specialized equipment, whose cost would otherwise become a concern. Companies are also looking at ways to integrate UAS into their workflows to be used as a tool by a professional just as a screwdriver or hammer [38], [44], [48].

2.1.3. Technology

Commercial UAS are a product of various technologies which make them possible. Many new technologies being developed are expected to improve the capabilities of UAS and make them more autonomous needing minimal human interaction. Figure 14 gives a high-level breakdown of a UAV and the various sensors involved in its operations.

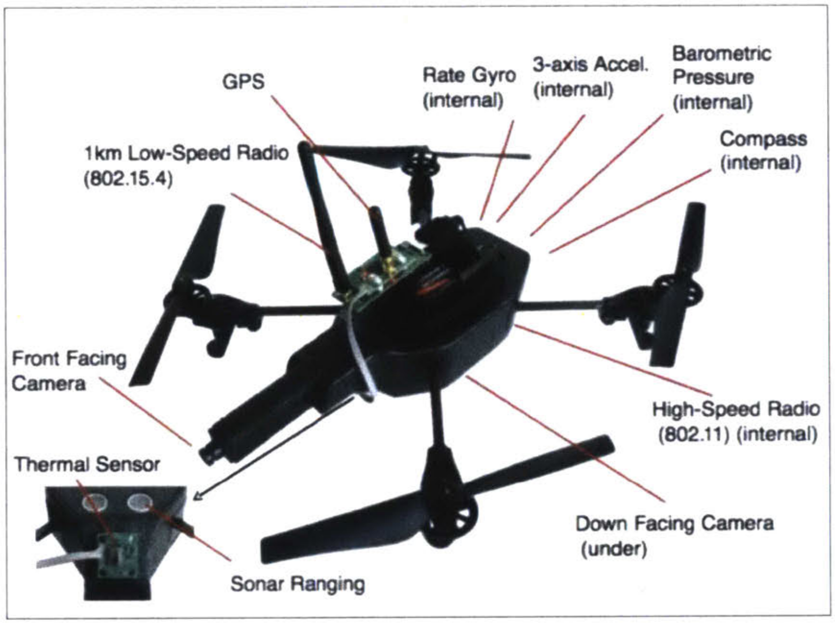

Figure 14: Breakdown of a UAV [49]

2.1.3.1. Autopilot and Sensors

The first technology needs to be considered is the autopilot system. The autopilot system consists of computers and various sensors on the UAV that stabilize the vehicle, control the propulsion system, fly the UAV along a flight path and follow user inputs. But as more powerful autopilots are expected to be integrated into UAS, their ability to automate more user-based tasks will increase. As the weight and power requirements of sensors such as IMUs, barometers, ADS-B receivers, cameras and lidars drop and their performance improves, more of them will be integrated into UAVs giving them more capabilities to complete their tasks and collect data [50]. Some of the newer UAS are already capable of autonomously creating a flight path even from a user inputting the operations area and have collision avoidance capabilities. These systems are also capable of operating by themselves from launch to landing without user interaction and able to avoid obstacles using powerful image recognition and AI capabilities.

2.1.3.2. Batteries

Another technology that affects UAVs are batteries as they make up a significant percentage of the drone weight. Currently, batteries provide most commercial UAV with flight times between

20 minutes to 50 minutes. As battery technology evolves at 5 to 8 percent every year, life spans are expected to double every 8 years allowing UAV to fly longer and farther [18]. This would enable UAVs to operate for longer durations in the air and fly farther. This would allow more UAS to operate in BVLOS conditions.

2.1.3.3. Hybrid VTOL UAVs

A new UAV platform that some UAS manufacturers are turning to is the Hybrid VTOL UAV shown in Figure 15. Hybrid VTOL UAVs are a cross between fixed wing and multicopter UAVs [51], [52]. These systems can takeoff vertically, transition into fixed wing flight for long distance flight and hover midair as required by the mission. These UAVs can fly faster than multicopter style UAVs covering the same area 10 times faster. They can also fly at a higher altitude with a heavier payload capacity than multicopter UAVs and land and takeoff without the need for a runway or a launch and recovery system.

Figure 15: ALTI Transition Fixed-wing VTOL UAV [52]

2.1.3.4. Software Analysis Packages

Software analysis of data generated by UAS is the new direction the Commercial UAS industry is taking. Early commercial UAS would mostly record videos and take pictures in flight with the user reviewing the media generated. New software packages available can analyze pictures, video and data generated to provide results directly to the user. Pix4D is a photogrammetry software package that analyzes images taken by a UAV to create a 3-dimensional model of the terrain for the user review and further analyze [53]. FieldAgent is a data analytics software package by Sentera that analyzes normal or multispectral images of farmlands to identify areas that need additional attention [54]. DroneDeploy has a software packages that allow the user to analyze construction or survey sites and monitor the construction progress [55].

2.1.3.5. 5G Cellular Communication

5G network is the next generation of cellular communication being setup in the US. 5G is expected to bring seamless secure coverage which is important as the number of UAS in the air increase and flying higher and farther. UAS have two types of data being transmitted [56]:

1 Control and non-payload communications (CNPC)
2 Payload communication

CNPC data consists of low bandwidth data that need high reliability, high security and low latency consisting of UAV telemetry, command and control and other information critical to the operation of the UAV. Payload communication is application specific and consists of higher bandwidth data that are mission critical but not critical to UAV operations.

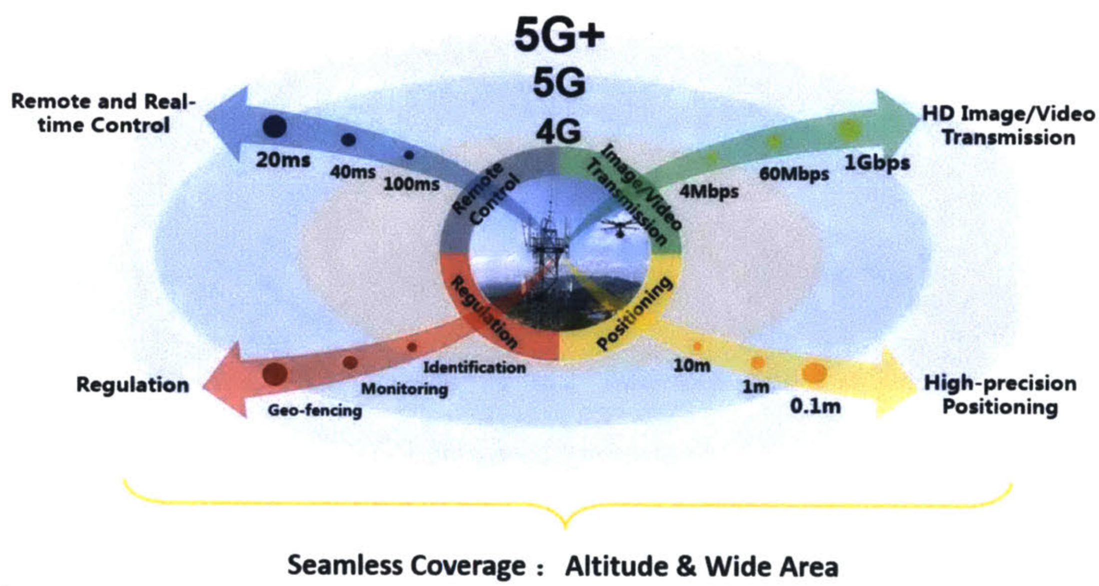

Figure 16: Mobile Networks Benefits to UAS [47]

5G is expected to provide remote and real-time low latency communication capabilities allowing users to monitor and control the UAS. With increasing bandwidth capabilities, higher bandwidth video and data can be streamed back enabling more precise control and analysis. Finally, it is also expected to help setup future UAS regulations and UTM by providing a means for the UAVs to communicate their position to the UTM which can monitor and identify UAVs in the air and communicate back with traffic information and flight corridors [57].

A presentation by Ericsson at an IEEE 5G-IOT Summit in 2017 outlines some of the critical requirements they are aiming for to operate UAS on 5G networks (Figure 17) [58].

Requirement	Agreed value
Data Type	1. Command and Control (C&C) 2. Application Data: includes video (streaming), images, other sensor data, etc.
Heights	Target up to 300m above ground level
Speeds	Target horizontal speeds up to 160 km/h (~100 mph) for all scenarios
Latency	1. C&C: RAN2 understanding is 50ms (one way from eNB to UAV). (update) 2. Application Data: latency value similar to LTE ground based users
Data Rates	1. C&C: [60-100] kbps for uplink and downlink 2. Application Data: up to 50 Mbps for UL
C&C Reliability	As low as 10^{-3} Packet Error Rate

Figure 17: Ericsson 5G requirements for UAS [58]

2.1.4. Regulations

Commercial UAS is a new industry that is constantly evolving, and industry are evolving in parallel. While some regulations have already been established on UAS operations, these severely limit their use and flight envelop. Current commercial aviation rules are shown in Table 3 in the Appendix. These rules currently limit UAVs to under 55 lbs., top speeds capped at 100 miles per hour, cannot carry hazardous materials and require mandatory UAV registration with the FAA. These rules also limit UAV operations to VLOS, under 400 ft altitude from ground and during daylight in clear skies with visibility of 3 miles from the control station. Flights over people and from moving vehicles are not allowed. Right of way needs to be given to manned aircrafts and ATC permission is required when operating in Class B, C, D and E airspace. The operator or optional observer should have sight of the UAV unaided, be a FAA-certified UAV pilot and only be the pilot in command of one UAV operation at any specific instance [59]. Waivers can be obtained for some operations not covered by the Part 107 rules shown in Table 3 in the Appendix.

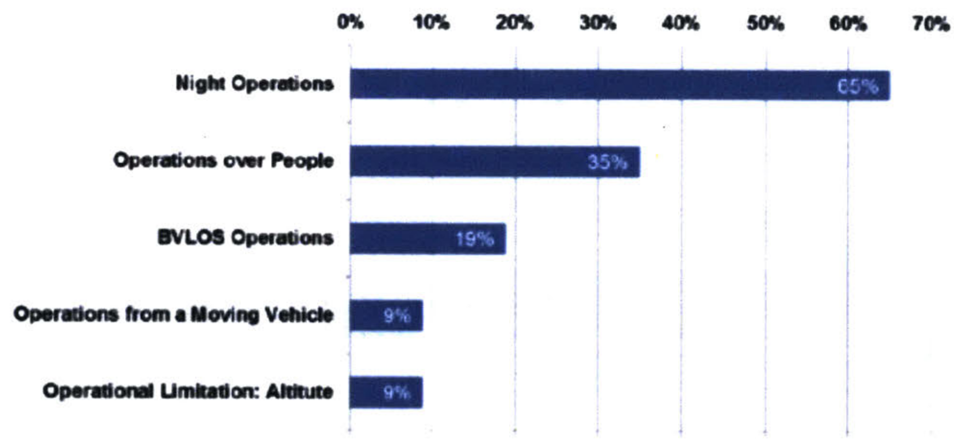

Figure 18: Top 5 FAA UAS Operation Waiver Requests 2016 [23]

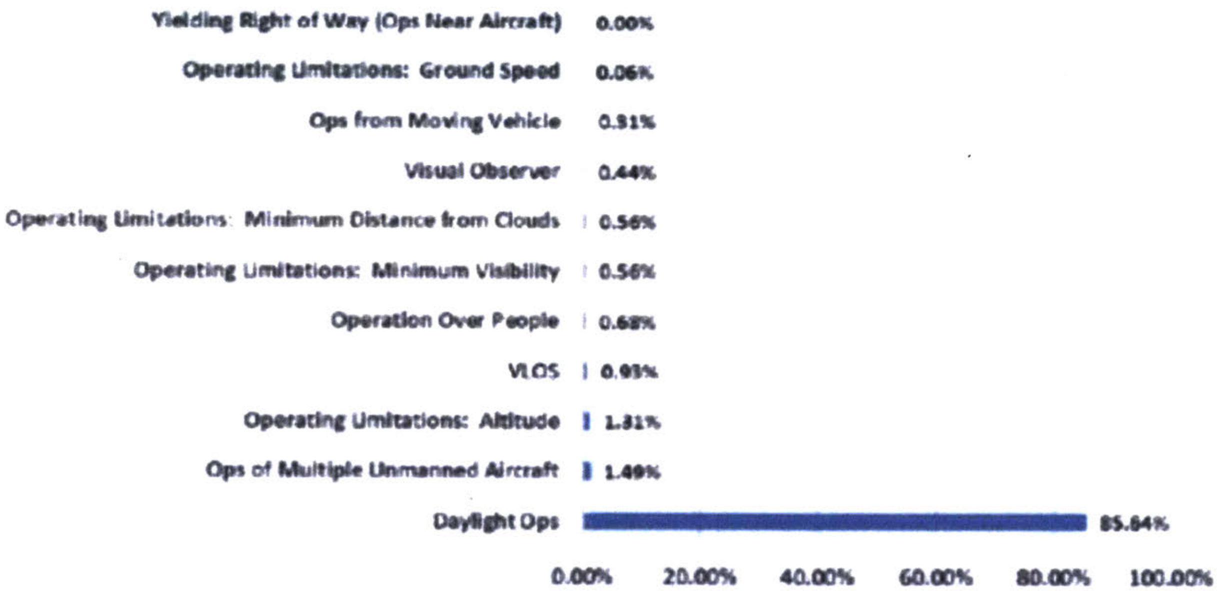

Figure 19: Top FAA UAS Operation Waiver Requests 2017 [21]

The topmost requested waivers for 2016 and 2017 are shown in Figure 18 and Figure 19 respectively. Both figures show that night operations are the most requested waivers. For 2016, operations over people and BVLOS operations were the next highest followed by operations from a moving vehicle and exceeding altitude limits. For 2017, operation of multiple UAVs, exceeding altitude limits, were the next highest followed by BVLOS operations and operation over people. The McKinsey report from 2017 shown in Figure 20 shows the various UAS regulations, their importance, their current state and when they are expected to be updated.

■ <2 years ■ 2–5 years □ >5 years

	Regulation	Importance to growth	Current state	Time to guideline release
Operations	BVLOS[1] operation	Enables long-range applications and operations in urban areas	BVLOS operations prohibited without a waiver	>5 years
Operations	Autonomous flight	Allows for repetitive surveying missions without a pilot	Pilot must retain ability to direct UAS during flight	2–5 years
Operations	Altitude restriction	Allows long transit applications and operations in uncontrolled airspace	Commercial UAS must remain below 400 feet above ground level without waiver	<2 years
Operations	Flight above people	Enables all urban and public safety uses, as well as some surveillance applications	UAS operation over people is prohibited without a waiver	<2 years
Operations	Airspace integration	Enables UAS[2] usage in national airspace and interactions with controllers and manned aircraft	No guidelines govern the integration of UAS into national airspace	2–5 years
Operator	Operator certification	Creates operator certification for airspace system and operator ratings for the vehicle in use	Pilot must have a remote-pilot airman certificate for commercial use; certification is a written test only	2–5 years
Vehicle	Identification	Allows law enforcement and air-traffic control to track flights and identify UAS	No rules for identifying operator of a UAS; rule-making committee is currently addressing this issue	<2 years
Vehicle	Electric propulsion	Creates certification for electric engines for urban operations, since combustion engines will likely be limited in these environments	No way to certify electric engines	2–5 years
Vehicle	Airworthiness	Establishes airworthiness standards so drone will operate in accordance with Federal Aviation Administration rules	No way to determine airworthiness, so drones must conform to ultra-light guidelines	2–5 years
Vehicle	Weight restriction	Enables applications requiring long flights or heavy payloads (such as agricultural spraying)	UAS must be under 55 pounds to operate unless a waiver is approved	2–5 years

[1]Beyond visual line of sight.
[2]Unmanned aerial systems.
Source: Expert interviews; Federal Aviation Administration; McKinsey analysis

Figure 20: USA UAS Regulations and Future [18]

Along with regulations, the future of UAS would also include the UTM being developed to manage UAS traffic. FAA and NASA are collaborating with various federal partner agencies and the industry to explore the architecture of UTM. The UTM vision to manage the airspace to enable multiple UAS operations including BVLOS flights for uncontrolled operations separate from the ATM system [60].

"With UTM, there will be a cooperative interaction between drone operators and the FAA to determine and communicate real-time airspace status. The FAA will provide real-time constraints to the UAS operators, who are responsible for managing their operations safely within these constraints without receiving positive air traffic control services from the FAA. The primary means of communication and coordination between the FAA, drone operators, and other stakeholders is through a distributed network of highly automated systems via application programming interfaces (API), and not between pilots and air traffic controllers via voice."[60]

2.2. Digital Framework

Digital framework, a term defined in the paper by Reid and Rhodes: "Digital system models: an investigation of the non-technical challenges and research needs" collectively includes a digital thread, a digital twin, and a DSM [61]. This concept involves using a model-centric environment designed holistically that allows rapid and effective information sharing and analysis. The Digital Twins concept has become so important that Gartner declared it as one of the 10 strategic trends for 2017 [62].

2.2.1. Digital System Model (DSM)

There are various definitions for a DSM in the industry. DoD defines a DSM as: "A digital representation of a defense system, generated by all stakeholders that integrates the authoritative technical data and associated artifacts which define all aspects of the system for the specific activities throughout the system lifecycle."[63]. Reid and Rhodes refer to DSM as: "The DSM is essentially the proposed product of MBE. It is the integrated model of all technical data out of which individual Digital Twins will be constructed and is the technical grounding that the decision-making analytics of the Digital Thread refers to."[61]. Kraft defines DSM as: "A digital representation of a weapon system, generated by all stakeholders, that integrates the authoritative data, information, algorithms, and systems engineering processes which define all aspects of the system for the specific activities throughout the system lifecycle."[64].

For this thesis, a DSM is defined as a digital model of the UAV that includes the various technical components of the UAV that generate data and would be needed to analyze the performance of the UAV. The model will be updatable to include new technical hardware added to the system. The

DSM can be generic to all the UAVs of the same type if the technical components involved are identical.

2.2.2. Digital Twin

There are various definitions for a Digital Twin in the industry. DoD defines Digital Twin as: "An integrated multiphysics, multiscale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin."[63]. Reid and Rhodes refer to Digital Twin as: "A Digital Twin is an integrated model of an integrated model of an as-built system including, physics, fatigue, lifecycle, sensor information, performance simulations, etc. It is intended to reflect all manufacturing defects and be continually updated to include wear-and-tear sustained while in use. The goal is to more effectively and safely manage the individual product as well as to facilitate investigation of potential design or operational changes on the health of the system."[61]. Kraft further defines Digital Twin as: "An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin."[64].

For this thesis, a Digital Twin is defined as an integrated model that includes a model of the structural elements of the UAV with factory defects and damage during operation, monitors the health and maintenance of the UAV including parts changed, and uses the DSM to analyze the behavior of the UAV. As a perfect digital representation of any physical system is impossible, the Digital Twin will incorporate high-fidelity and low-fidelity models as needed to analyze and generate the UAVs operational factors that are of interest. The model will be updatable as more possible applications for UAVs are found. Each Digital Twin is specific to the UAV it is programmed for and adapts to better model the UAVs behavior as it changes through its lifetime.

2.2.3. Digital Thread

There are various definitions for a Digital Thread in the industry. DoD defines Digital Thread as: "An extensible, configurable and component enterprise-level analytical framework that seamlessly expedites the controlled interplay of authoritative technical data, software, information, and knowledge in the enterprise data-information-knowledge systems, based on the Digital System Model template, to inform decision makers throughout a system's life cycle by providing the capability to access, integrate and transform disparate data into actionable information."[63]. Reid and Rhodes refer to the Digital Thread as: "The Digital Thread is analytic framework for integrating technical data, costs, predictions and other accumulated knowledge over the course of design, development and operation of a system. It is intended to provide ready access to usable information for decision makers during the design process. It includes tools such as tradespace analysis and visualization tools."[61]. Kraft defines Digital Thread as: "An extensible, configurable and Agency enterprise-level analytical framework that seamlessly expedites the controlled interplay of authoritative data, information, and knowledge in the enterprise data-information-knowledge systems, based on the Digital System Model template, to inform decision makers throughout a system's life cycle by providing the capability to access, integrate and transform disparate data into actionable information."[64].

For this thesis, a Digital Thread is defined as a high-level software package that interacts with all the digital twins in the UAS, manages the data generated, and manages the various software packages available for analysis. These analysis packages would be designed to provide the users with information on the operational health of the UAS, which systems need maintenance, generate reports, and other such tasks that help the user make decisions.

2.2.4. Digital Framework in the Industry

The concept of Digital Twin dates to 2002 when it was first introduced by Dr. Grieves as "Conceptual Ideal for PLM". However, it did have all the elements of the Digital Twin: real space, virtual space, the link for data flow from real space to virtual space, the link for information flow from virtual space to real space, and virtual sub-spaces [65].

2.2.4.1. NASA and the US Air Force

NASA and the US Air Force have been looking at applying the digital framework concept to the design of future air and space vehicles. Their goal is to address the shortcomings of conventional approaches for certification, fleet management and sustainment. One approach being considered is integrating a digital twin consisting an ultra-high-fidelity simulation with vehicle on-board health management system, maintenance history and all available history and fleet data to mirror the life of its flying twin and enable unprecedented levels of safety and reliability. The use of a Digital Framework is expected to "decrease system weight by reducing reliance on statistical distributions of material properties, heuristic design philosophies, physical testing and assumed similitude between testing and operational conditions. Once the vehicle is launched, the Digital Twin will increase the reliability of the flying vehicle because of its ability to continuously monitor and mitigate degradation and anomalous events. Additionally, it will enable mission managers to make knowledgeable decisions regarding the consequences of possible in-flight changes to a vehicle's mission."[66]

2.2.4.2. GE Wind Farms and Jet Engines

General Electric (GE) has developed a Digital Twin to be used in wind farms and calls the concept digital wind farm. They built a digital twin of a wind farm and used it to design the most efficient turbine for each pad on the farm. Using a digital twin, they expect to increase electricity production by as much as 20%. To start, GE plans to create a computer model of the wind farm at the planned location. They then pick from various turbine configurations for each pad at the wind farm to design its most efficient real-world mirror. Once the farm has been setup, using the Digital Twin and other machine learning technologies, GE plans to analyze the real-world data and provide suggestions to make the wind farm more efficient.[67], [68]

GE also applied the same technology to jet engines to analyze the data collected from the sensors in the engines and flight recorders. Analyzing this data, they expect to optimize maintenance schedules to prolong the engine lifespans. The technology is even capable of considering the climate the aircraft engine is operating in and request the aircraft be cycled to a different climate location to reduce engine wear.[69]

2.2.4.3. Mitek Analytics

Mitek Analytics has a performance digital twin software that analyzes aircraft engine sensor data collected during normal operation of the aircraft. Their software package is able to identify underperforming jet engines and optimize maintenance schedules. When scaled fleet wide, the digital twin software was found to bring cost savings of 2% or more.[69], [70]

2.2.4.4. Lockheed Martin's Digital Tapestry

Lockheed Martin developed its version of Digital Thread under the name "Digital Tapestry". Digital Tapestry is a fully integrated end-to-end digital environment that weaves together three key digital domains, virtual reality, 3D printing and digital product support processes. Rick Ambrose, executive vice president of Lockheed Martin Space Systems describes the Digital Tapestry as "a seamless digital environment driven by an integrated model-based engineering

(MBE) tool set that keeps the digital data intact from product conceptualization to realization". When the Orion spacecraft was being developed, a Digital Tapestry of the spacecraft was built down to the bolts and telemetry data was feed to it from the vehicle in space to monitor the spacecraft's behavior.[71]–[73]

2.2.4.5. Boeing Digital Twin Replication

Boeing has created a Digital Twin replication software capable of creating a Digital Twin of an aircraft. Using this technology, Boeing has been able to achieve up to a 40% improvement in first-time quality of parts and systems used in aircrafts.[74]

2.2.4.6. Airport Management

An idea being explored is applying Digital Twins to Airport infrastructure. Information about events at an airport is available in advanced control centers. However, the information is being collected and presented independently making it difficult to see the big picture and how the elements interact. This creates difficulty in reviewing airport history due to disruptions. Using Digital Twins would break these silos by creating a 3D model of the airport and organizing all the data in one location. This is expected to improve control and increase predictability.[75]

2.2.4.7. Formula 1

In a sport where every millisecond count, Digital Twins is becoming an important technology. Since 2014, F1 teams have been using it to the benefit of the car, driver and the team. F1 cars generate large amounts of telemetry data during a race such as engine and drivetrain performance, aerodynamics performance, and tire wear which is analyzed live or post-race. This data is used to understand the how the car is performing, when a pit stop is needed and if a breakdown could occur. Using this, the team can custom calibrate each car to the racetrack and the driver.[76]

2.2.4.8. Drones

Digital Twins is already expected to be used in drones and UAS. A Digital twin is expected to help drones improve their abysmal lifespan by using the digital twin to track the drone's maintenance cycles while feeding it drone flight and performance data. Another application is to use UAS video and photography capability to create a real-time digital twin of a terrain, building, or other objects. Finally, a Digital Twin is also expected to be used in creating improvements to an existing drone by using the operational data and the Digital Twin to predict how the improvements or upgrades would affect the drone.[77]

3. Stakeholder Analysis

The next step in this analysis involves exploring the stakeholders, who are an important part of the of the enterprise landscape. "Stakeholders are the people within the ecosystem and within the walls of our enterprise. Enterprise stakeholders are individuals and groups who contribute to, benefit from, and/or are affected by the enterprise. Stakeholders may be either exogenous or endogenous to the enterprise." [17].

3.1. Commercial UAS Stakeholders

Commercial UAS have various stakeholders that contribute to the system directly or indirectly. These stakeholders were identified through literature review and knowledge gathering and are presented below [18], [78]. Figure 21 provides the interactions between the current stakeholders when the UAS Corporate Adopter (Customer) owns and operates the UAS.

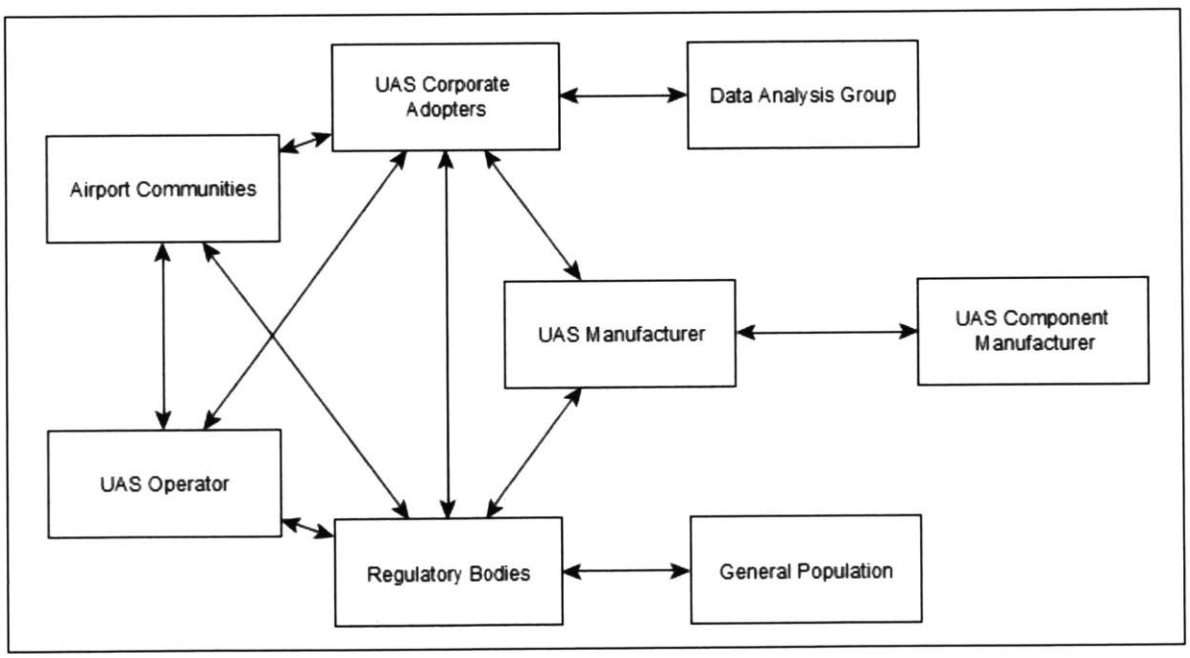

Figure 21: UAS Stakeholders Interactions (UAS Corporate Adopters Owns the UAS)

Figure 22 provides the interactions between the current stakeholders when the UAS Service Provider owns and operates the UAS.

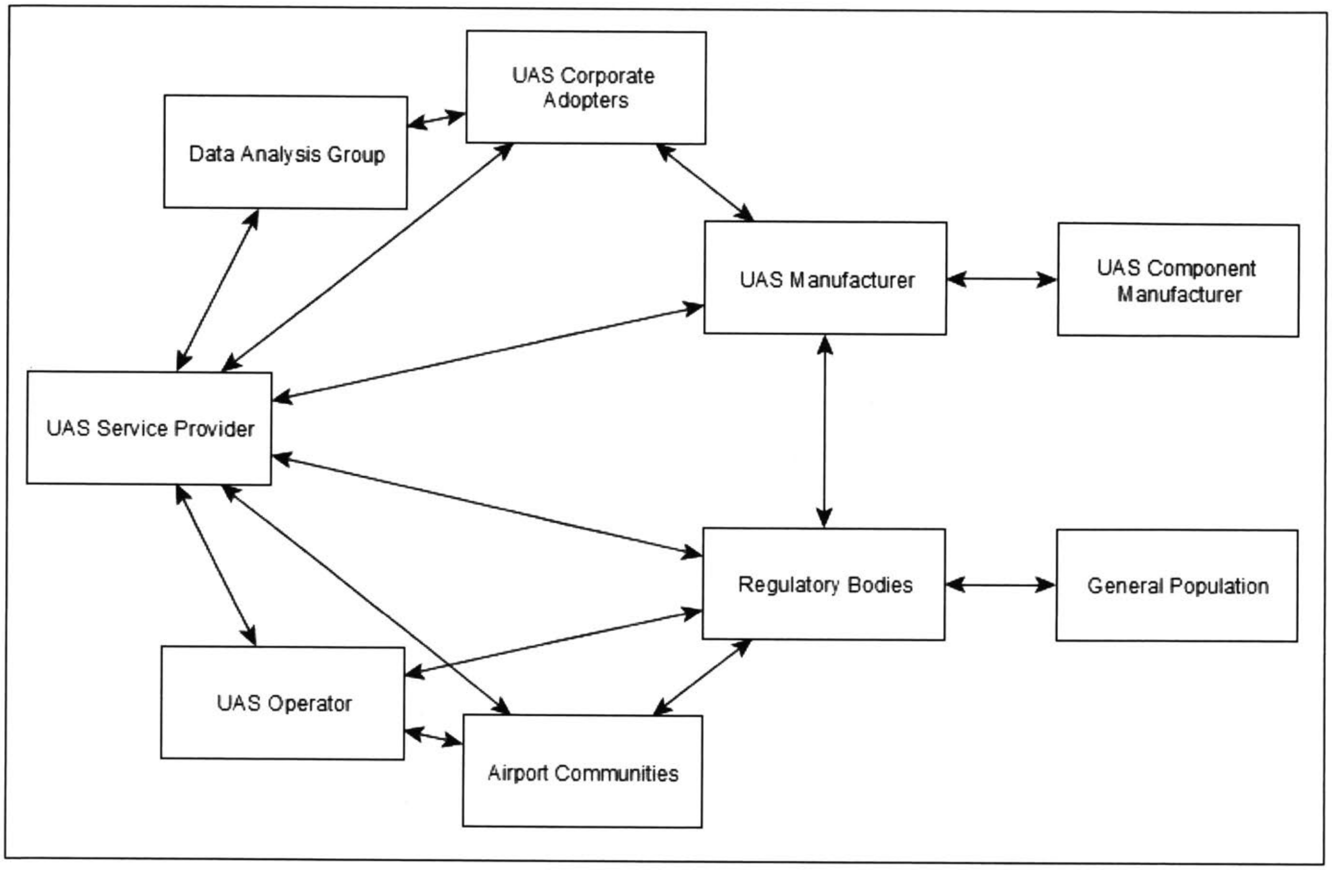

Figure 22: UAS Stakeholders Interactions (UAS Service Provider Owns the UAS)

3.1.1. UAS Manufacturer

UAS Manufacturer are the companies that produce the full UAS. These companies design the UAS, purchase various complex subsystems such as cameras, batteries, communication radios, propulsion systems, software packages, and integrate these subsystems in to a UAS. These systems and their payload are customized to the application they are being designed for.

These companies interact with UAS Corporate Adopters and UAS Service Providers for their feedback on the performance of the system and to identify various avenues of future development. They interact with various Regulatory Bodies to identify regulations that apply to them when designing their UAS, provide suggestions and guidelines for future regulations to the regulatory bodies and to ensure that the systems developed are certified.

3.1.2. UAS component Manufacturer

UAS Component Manufacturer are the companies that design, develop, and produce the various subsystems used in UAS. Examples of these subsystems include the cameras, radios, propulsion systems, and software packages.

These companies mostly interact with various UAS Manufacturers to whom they sell their products. In some cases, component manufacturers develop and supply subsystems that are custom designed to a specific UAS Manufacturer's requirements.

3.1.3. UAS Service Provider

UAS Service Providers are the companies that offer UAS services to potential customers. These companies purchase multiple UAS and operate the UAS at the customer's request, supply the data generated, or analyze the data and present the analysis results. Some of these service providers are organizations that are already established in specific industries and provide UAS services as an additional tool.

UAS Service Providers interact with UAS Manufacturers to procure the systems, UAS Corporate Adopters to provide their services, and UAS Operators who operate the systems. They also interact with the Regulatory Bodies and Airport Communities to get a flight clearance in specific locations.

3.1.4. UAS Corporate Adopters (Customer)

UAS Corporate Adopters are the customers. UAS are operated over or in their operational areas to generate data. The data generated is analyzed at the data analysis group and the results are used in the customers operations.

UAS Corporate Adopter's interactions depend on whether they own and operate the UAS or are dependent on a UAS Service Provider. If they are dependent on a UAS Service Provider, they would only interact with the UAS Service Provider, Data Analysis Group and possibly UAS Manufacturer for feedback. If they operate their own UAS, these stakeholders will interact with UAS Manufacturers to purchase the systems and feedback, UAS Operators to operate the system, Data Analysis Groups to analyze the data generated, and the Regulatory Bodies and Airport Communities to obtain flight clearances at their operational location.

3.1.5. UAS Operators (Pilots)

UAS Operators are the pilots. They operate the UAS at the required location and generate data later sent to the analysis group for them to analyze the data and generate results.

UAS Operators would interact with either the UAS Service Provider or the UAS Corporate Adopter, depending on who owns the UAS. They would also interact with the Regulatory Bodies and the Airport Community to ensure they have proper flight clearance.

3.1.6. Data Analysis Group

The Data Analysis Group develop and operate the software tools needed to analyze the data generated by the UAS and provide results and recommendations. These software tools are designed with specific applications in mind.

The Data Analysis Group would only interact with the UAS Service Provider or the UAS Corporate Adopter to receive the data and provide the analysis results.

3.1.7. Regulatory Bodies

Regulatory Bodies are the government organizations that set the regulations on the UAS certification requirements and operational requirements. They interact with the UAS Manufacturers, UAS Operators, UAS Corporate Adopters, UAS Service Providers, and Airport Communities to develop new regulations, ensure the UAS meets the current regulations and for flight clearances.

3.1.8. Airport Communities

Airport communities consist of the airports, general aviation industry and commercial aviation industry. These stakeholders interact with the UAS Operators, UAS Corporate Adopters, UAS Service Providers, and Regulatory Bodies to ensure the safety of the general aviation and commercial aviation fleet.

3.1.9. General Population

The General Population are people who live in the locations around the UAS. This stakeholder interacts with the Regulatory Bodies request or demand regulations that would keep them safe and ensure their concerns are met.

3.1.10. Unmanned Aircraft System Traffic Management (UTM)

UTM is an infrastructure being designed to track and manage UAS traffic. The structure and operation of UTM is still being researched by NASA, the FAA, and various UAS companies exploring various architectures. This stakeholder is expected to replace operational interactions of the airport communities and regulatory bodies with the UAS operators, UAS corporate adopters and UAS service providers.[60], [79]

3.1.11. Communications Providers

Communications Providers are currently not a stakeholder but are expected to be in the future as UTM becomes more prevalent and especially in the proposed architectures in later sections. They represent the communications infrastructure such as cellular networks, WAN, satellite internet especially as UAS start communicating over these networks rather than using dedicated communications infrastructure used currently. This stakeholder is expected to interact with Regulatory Bodies and UTM to help create the regulations and infrastructure. UAS Manufacturers and UAS Component Manufacturers would have to interact with this stakeholder to ensure their subsystems operate on this network. Other stakeholders such as UAS Service Provides, UAS Corporate Adopters, and UAS Operators are expected to operate on these communication infrastructures.[10]

3.2. Stakeholders Salience

The next part of the stakeholder analysis is the stakeholder salience. Stakeholder Salience can be decided based on three attributes [80]:

- Power: Powerful stakeholders possess power in their relationship to the enterprise and may be capable of imposing their will on the enterprise.
- Legitimacy: Perception that the actions of a stakeholder are desirable, proper, or appropriate within norms, values, and beliefs of the enterprise.
- Urgency: Urgency that exists when the stakeholder's relationship with the enterprise is time-sensitive in nature, and/or is of importance to strategy and operations.

From this, you can categorize stakeholders into 9 types also shown in Figure 23 [80]:

- Dormant Stakeholder: Possess power to impose will, but no legitimate relationship or urgent claim.

- Discretionary Stakeholder: Possess the attribute of legitimacy, but they have no power to influence the firm and no urgent claims.
- Demanding Stakeholder: Have urgent claim but neither power nor legitimacy
- Dominant Stakeholder: Possess power, legitimacy but not urgency
- Dangerous Stakeholder: Possess urgency and power, but lack legitimacy
- Dependent Stakeholder: Lack power, but have urgent and legitimate claim
- Definitive Stakeholder: Possess power, urgency and legitimacy

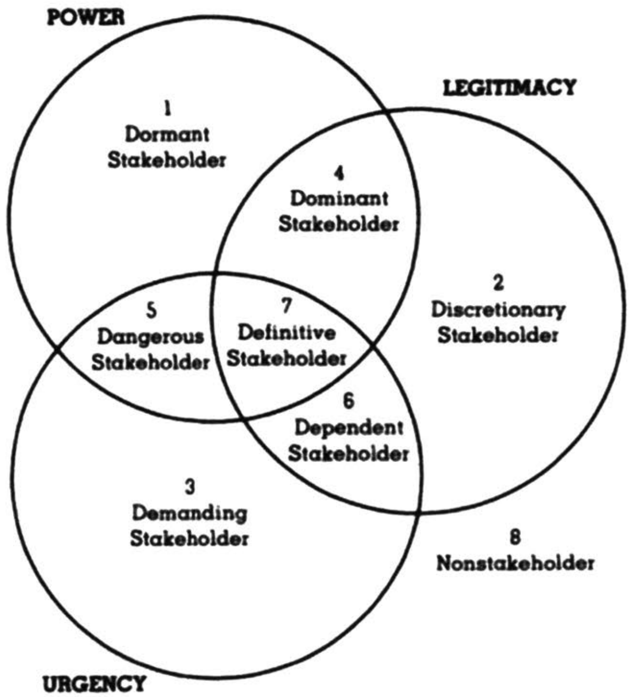

Figure 23: Stakeholder Typology [80]

Looking at the eleven stakeholders identified, we can identify the type of stakeholder by checking whether they have power, legitimacy or urgency as shown in Table 2 and Figure 24. The UAS Service Provider, UAS Corporate Adopters, UAS Airport Communities, and UTM are all Definitive Stakeholders. This is because all these stakeholders have the power to impose their will on the UAS operation, have legitimacy and have urgency due to the time-sensitive nature of the UAS operation. The UAS Manufacturers, UAS Analysis Group, and Regulatory Bodies are Dominant Stakeholders. This is because these stakeholders have the power to decide on the UAS design and regulation and have legitimacy but are not time sensitive. General Population are expected to be a Dangerous Stakeholder as they have the power to demand regulations and the expect urgent actions but don't have a legitimacy in the UAS. Communications Providers are expected to be expected to be a Dependent Stakeholder since they have no power to decide on the operations and regulations of the UAS but would have legitimacy and urgency due to the need for reliable communications infrastructure. Finally, UAS Component Manufacturers and UAS Operators are expected to have legitimacy but no power or urgency.

Table 2: Stakeholder Type

Serial No	Stakeholder	Power	Legitimacy	Urgency	Stakeholder Type
1	UAS Manufacturers	Y	Y	N	4
2	UAS Component Manufacturers	N	Y	N	2
3	UAS Service Providers	Y	Y	Y	7
4	UAS Corporate Adopters	Y	Y	Y	7
5	UAS Operators	N	Y	N	2
6	UAS Data Analysis Group	Y	Y	N	4
7	Regulatory Bodies	Y	Y	N	4
8	Airport Communities	Y	Y	Y	7
9	General Population	Y	N	Y	5
10	UTM	Y	Y	Y	7
11	Communications Providers	N	Y	Y	6

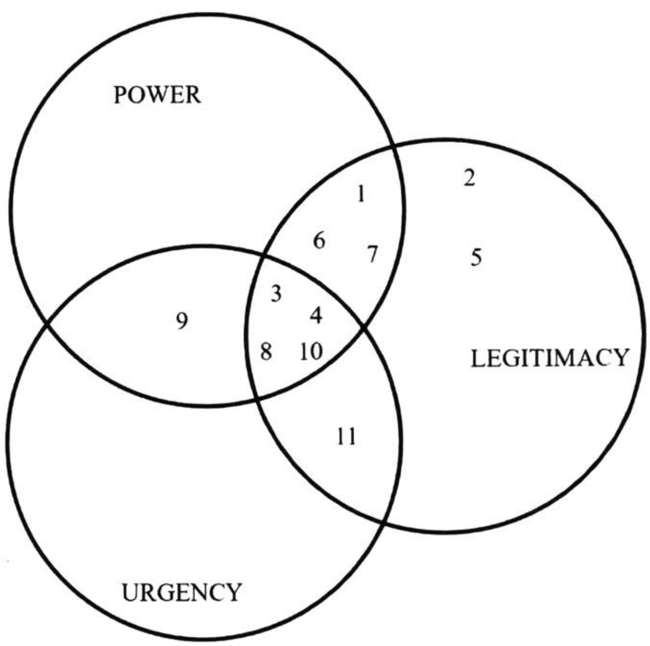

Figure 24: Stakeholder Type

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4. Current Commercial UAS Architecture

This section looks at the current architecture of UAS as well as how it has evolved over time. This change resulted from the integration of various systems that add new capabilities to the UAS. The architecture was generated by studying various UAS systems in the industry and discussing the architecture with industry experts.

4.1. Original Commercial UAS Architecture

Commercial UAS architecture has traditionally been very simple due to its origin from Consumers UAS. The architecture simply consisted of a UAV with a suitable payload and a ground control station (GCS) which included a control interface and a communication radio. Figure 25 below shows the architecture of the UAS and the links between them. The UAS would either be owned by the UAS Corporate Adopters who would operate the UAS by themselves or it would be owned by a UAS Service Provider who would provide UAS services to customers.

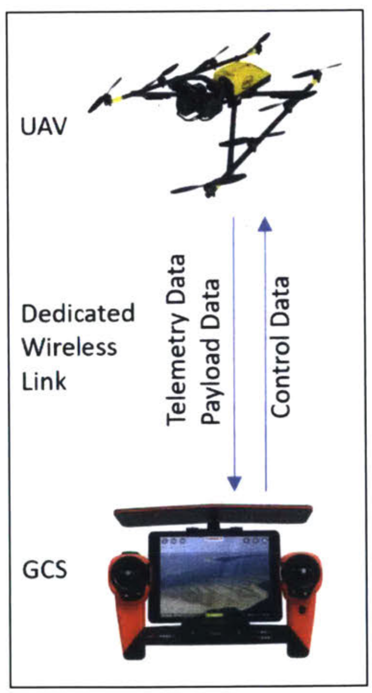

Figure 25: Original Commercial UAS Architecture

The UAV is the actual air vehicle and includes the autopilot, power system, propulsion system, radio, and various other subsystems installed onboard. It also includes a payload that has been selected specifically for the mission or task to be completed.

The GCS consists of the computer, tablet or smartphone with software to operate the UAV and joysticks mounted to also manually control the UAV. The GCS also contains a dedicated radio designed to maintain a link directly to the UAV and receive telemetry and payload data while uploading control data.

4.2. Present Commercial UAS Architecture

The present commercial architecture used in industry is an evolution of the original architecture presented in Section 4.1. As more data is generated using UAS, new analysis tools are being integrated to better analyze the information and provide recommendations. Figure 26 below shows the architecture of the UAS and the links between them.

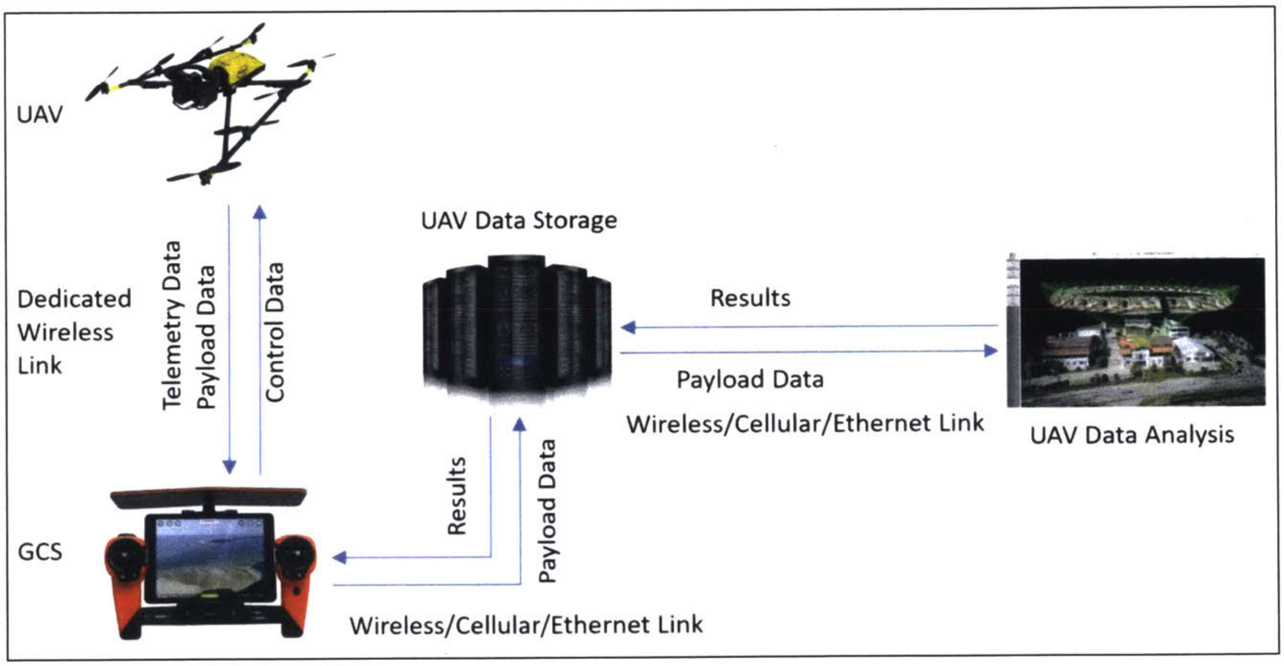

Figure 26: Present Commercial UAS Architecture

Whereas previous imagery, video, and data generated would be stored on the GCS and reviewed manually, the new architecture being used enables the data to be transmitted to a server which stores it. This data is then sent to data analysis software packages which analyze the data and provide results back to the server which is forwarded to the GCS for the operator to review.

The rise of this architecture is due to the need for specialized analysis software tools such as photogrammetry. These software tools also need very powerful processors and graphics cards that necessitate dedicated hardware that can operate them offsite.

As UTM is implemented and UAS are integrated into the infrastructure, UAS are expected to interact with the UTM to be aware of the other UAVs in the airspace. The UAS operator is also expected to interact with UTM for flight permission and to be made aware of the other UAVs in the airspace.

The FAA and NASA defines UTM via the following:

> "While incorporating lessons learned from the today's well-established air traffic management system, which was a response that grew out of a mid-air collision over the Grand Canyon in the early days of commercial aviation, the UTM system would enable safe and efficient low-altitude airspace operations by providing services such as airspace design, corridors, dynamic geofencing, severe weather and wind avoidance, congestion management, terrain avoidance, route planning and re-routing, separation management, sequencing and spacing, and contingency management.
>
> One of the attributes of the UTM system is that it would not require human operators to monitor every vehicle continuously. The system could provide to human managers the data to make strategic decisions related to initiation, continuation, and termination of airspace operations. This approach would ensure that only authenticated UAS could operate in the airspace. In its most mature form, the UTM system could be developed using autonomicity characteristics that include self-configuration, self-optimization and self-protection. The self-configuration aspect could determine whether the operations should continue given the current and/or predicted wind/weather conditions."[79]

4.3. Advantages and Disadvantages of Present Commercial UAS Architecture

The advantage of the present commercial architecture is that it provides a dedicated low latency communication link between the GCS and the UAV designed specifically for this UAS's capabilities. UAS owners (UAS Corporate Adopters or UAS Service Providers) have complete control on how they use the UAS since no external stakeholders directly control this architecture.

The disadvantage of this architecture is the communication link provides a single point failure between the UAV and the GCS. This would also be problem for the UAS when the UAV is sent for BVLOS flights where the communication link might be problematic. The other disadvantage of this architecture is the security of the data generated and who could have access to the data, especially when the UAS is owned by a UAS Service Provider. This architecture is also not designed for the operation of multiple UAVs simultaneously. This architecture also doesn't allow remote operation of the system and needs a human operator present on site. As UAS becomes more autonomous, this architecture is still human centric and needs a human UAS Operator involved. Finally, this architecture is not designed to be scalable with the rapidly expanding communication technology that would simplify operations and could create a shift in the architecture. This would also, create some difficulty in communicating with UTM in the future since it is still dependent on a dedicated communication link.

5. Envisioned Future

The Commercial UAS segment is the fastest growing segment of UAS industry as discussed in Section 2.1.1. As the industry continues to grow, new capabilities for UAS are constantly being requested by customers along with new applications being explored as shown in Section 2.1.2. It was also documented in Section 2.1.4 that while there are existing rules for UAS operations in place, these rules have restrictions that the regulatory bodies are working to expand [18]. Various waivers have also been requested by organizations to operate their UAS beyond the restrictions of the regulations with the top five requested for 2017 starting with the highest are night operations, operations of multiple UAVs, flights exceeding UAV altitude restrictions, BVLOS flights and operations over people in that order respectively [21]. The FAA and NASA are also working on developing a UTM that would automate the UAS fleet management which would enable tracking UAS traffic and making UAS operations safer. Another factor to consider are new technology developments which would give UAS capabilities that were once unimaginable. Finally, with a Digital Framework, UAS will gain more capabilities to monitor themselves and analyze the data. All these lead to the question: What is the future of commercial UAS?

5.1. Future of commercial UAS

From reviewing the industry and literature, a picture of the possible future of the commercial UAS industry starts to emerge.

5.1.1. Full Stack UAS Automation

The first aspect of the future is full stack UAS automation. UAS of the future are expected to be autonomous throughout the operation of the UAV which includes takeoff to landing, UAV storage, changing or charging UAV batteries, path planning, data collection and transfer, along with data analysis. An example of this capability is the UAS manufacturer Airobotics (Figure 27), which already offers a product with self-deployment and landing capabilities that can be scheduled without a pilot, autonomously change payloads, batteries, include various safety features for UAS emergencies, and is industry grade [81]. Other capabilities also expected to be integrated extensively to enable UAS to be more autonomous are obstacles avoidance technology as the technology becomes lighter and less power intensive. This capability would increase flights in proximity to terrain and near people. Finally, Artificial Intelligence (AI) is expected to be used in UAS for flight operations, data analysis, health monitoring, and identification of possible system improvements. Exyn Technologies and Near Earth Autonomy are examples of UAS manufacturers using these technologies in their UAS offering even in GPS denied locations [82], [83].

Figure 27: Airobotics [84]

5.1.2. Integrated Specialized Data Analytics Packages

The second aspect of future UAS is the extensive, onboard or offboard analytics capabilities. UAS are expected to generate large quantities of data which will be very application specific. To solve these problems, analysis packages are expected have better integration into the UAS workflow such that they do not need human intervention. For example, agricultural applications use technology such as multispectral and hyperspectral cameras to analyze the crop health from the air and thermal cameras to analyze standing water in vineyards [85], [86]. In applications such as solar and wind farms, and pipeline monitoring, the images generated would be thermal or normal images to be analyzed for infrastructure damage or other problems. Construction and mining are applications that take normal images or Lidars data and analyze it to generate 3D models of the site.

5.1.3. Operation of Multiple UAS From One GCS

The third aspect of future UAS is going to be operation of multiple UAV by a single UAS Operator or by a single autonomous GCS. There are various applications that would benefit from multiple simultaneous UAS flights such as agriculture, wind and solar farm inspections, pipeline monitoring, and construction due to the large areas they operate over and the time critical nature of some of the flights. Applications such as drone delivery would benefit from multiple UAS being operated by a central GCS that can coordinate the fleet. An example of this capability comes from Intel Corporation operating up to five hundred Shooting Star drones (Figure 28) using a single GCS for light shows [87].

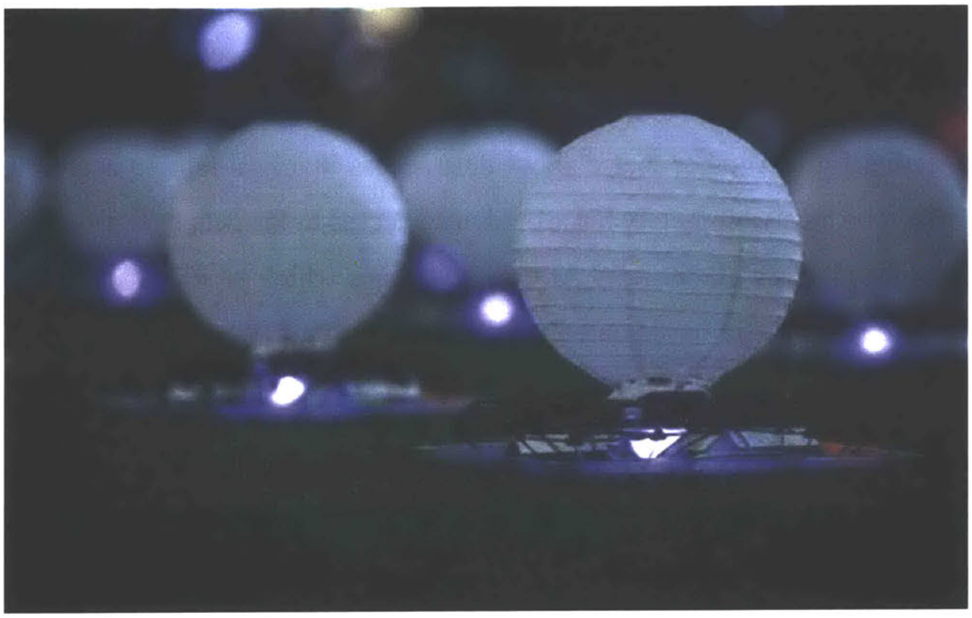

Figure 28: Intel Light Show Drone [88]

5.1.4. Increased BVLOS Operations

The fourth aspect that future UAS will have is BVLOS capabilities [89]. While current regulations allow BVLOS flights with a waiver, future regulations expected to be released for BVLOS flights would not need a waiver. The dedicated communications link used by most UAS have range and bandwidth limitations when operating flights at range due to terrain or obstructions. A dedicated communication link would soon become optional or unnecessary with the future availability of high bandwidth low latency communications from cellular networks. The increasing interest in fixed wing VTOL UAVs will also provide opportunities for longer distance operations. Another factor that expands the number of BVLOS UAS will be increased battery capacity that is expected to double every 8 years allowing for UAS to fly long and farther [18].

5.1.5. Data Security

The fifth aspect of future UAS will be data security and access. As organizations start using UAS over their properties, the security of the proprietary data generated and analyzed, and who has access to the data becomes a matter of concern. Currently, multiple stakeholders in a UAS (UAS

Operator, UAS Service Provider, UAS Corporate Adopters, and the Data Analysis Group) have access to the data generated. Under some cases, UAS Manufacturers could also be part of this data access if allows by the UAS owner. The customer (UAS Corporate Adopters) would want to limit the data access to only the stakeholders they want to provide access to, or the stakeholders that need access to the data. An example of this new importance placed on data security is the partnership between DJI and Microsoft Azure platform for managing and analyzing the drone data in a central location [90]. Another factor about data access involves remote access where UAS stakeholders might be located remotely but would need access to the data or flight. An example of this capability is the Genesis platform by Asteria Aerospace which provides access to flight data live or postflight to remote user based on which data they are authorized to see [91].

5.1.6. Digital Framework Integration

The sixth aspect of future UAS is the integration of part of, or the complete Digital Framework. While reviewing the use of Digital Framework in industry and discussing possible uses in UAS with various subject matter experts, some interesting applications were found which will be covered in this section.

5.1.6.1. Predictive Maintenance and Fleet Management

One application that has been brought up extensively is predictive maintenance and fleet management. Currently, UAS are maintained by recording the number of hours the UAS has flown and the systems are inspected and maintained at preset flight hours. Predictive maintenance involves using a DSM and a Digital Twin to monitor the health, performance, maintenance cycle of the UAS to predict when the next maintenance should be conducted. This would help reduce cost by increasing the flight time between maintenances when the Digital Twin detects that the parts are healthier than expected and reducing the time between maintenances when the Digital Twin detects the part deteriorating quickly, possibly preventing loss of the UAV [66], [77], [92]. To achieve this, various sensors such as accelerometers, gyroscopes, temperature sensors, and stress and strain gauges could be integrated at various key points in the UAS to increase its self-awareness.

The Digital Thread part of the Digital Framework could be used for fleet management. This would interact with the various UAVs in the UAS and track fleet operations and manage maintenance documentation and cycles for the fleet.

5.1.6.2. Data Access Management

As the UAS is operated over multiples flights and possibly, using multiple UAVs, the data generated needs to be managed and stored in a central location. Access to this data and results from the data analytics packages would also need to be controlled. The Digital Thread concept could be used to manage this task.

5.1.6.3. Path Planning

As UAV are manufactured, every UAV will have a slightly performance differences due to minor manufacturing variations between the UAVs. This difference could be a slightly better or worse performing motor, slight structural alignment differences such as wing angles or motor mounting angles, use of different payload or subsystems, differences in center of gravity or something else entirely. These differences give each UAV a performance difference that when considered can be used to create a customized flight plan that could help the UAV performance.

This concept involves each UAV having a DSM and Digital Twin that would be calibrated to the UAV incorporating the UAV performance characteristics. This DSM and Digital Twin could be used by the path planning software to create a flight plan tailored for it [93], [94].

5.1.6.4. UAS Certification

UAS Regulations and UAS certification could benefit significantly from the use of Digital Framework in UAS. The integrations of sensors at various key points on the UAV feeding their information to the DSM and the Digital Twin would provide more accurate ways to monitor the vehicle health [66]. This would make these systems safer to operate that their competitors. Regulations could be created in the future that would consider the advantages this provides requiring new UAVs developed to be certified to these standards. UTM could also interact with the Digital Twin during operations to ensure the UAVs are being operated as per regulations.

5.1.6.5. UAS Manufacturer Analysis Opportunity

Manufacturers would be one the biggest beneficiaries of integrating a DSM and a Digital Twin into their UAS if customers allow them access the telemetry data generated. The first possible use this could provide manufacturers would be the ability to monitor the behavior of thousands of UAS operating in real world conditions and analyze their performance and possible failures. This would provide manufacturers extensive amounts of data on the UAS performance, areas of improvements needed and unanticipated customer use cases of their UAS. The second possible use of this capability by UAS Manufacturers is to test new hardware. Using a DSM and a Digital Twin and the data generated from thousands of UAS, they can simulate digital models of new subsystems that could be integrated into the UAS with better accuracy and confidence.

5.1.6.6. UAS Generated Digital Twin

This is an application that uses UAS to create a Digital Twin of the terrain the UAS is operating on. With the UAS flying over various terrains, the terrain data generated could be used to build a live Digital Twin that would update outdated terrain maps, identify new obstacles and provide the UAS Operators with information on changes. This could also be used to analyze the history of a terrain.

5.2. Factors Needed for Envisioned Future

While the envisioned future presented is possible, various technologies must become viable for use in UAS, and regulations must be ready for these changes.

While the capabilities mentioned are already present in some UAS for simple operations such as user monitored preset flight plans and basic obstacle avoidance, there are various technologies still needed to make this vision viable. The first of these is better sensors that can be mounted on UAS for its flight operations and safety related applications. Most UAS use a combination of computer vision-based sensors, infrared and ultrasonic sensors for obstacle avoidance. While Lidar and Radar are viable, their weight, volume, and power requirements restrict them to limited use cases [95]. The processing power for this capability is also limited, restricting their operations to UAS flying at extremely slow speeds, especially when in an area with high number of obstacles [96]. UAS with these fully autonomous capabilities might not be viable until at least 2025 based on the technology needs.

Another technology needed for this are AI capabilities integrated into UAS operations. While AI is currently being used in limited applications in some UASs, this is mostly for R&D purposes and is still a few years away from being production ready [96], [97].

Communication technology is another factor that must be considered. Implementation of 5G is still being considered for UAS and self-driving cars but this is not expected to be a viable technology until at least 2021 or later [98].

Regulations are another factor to consider for this future. As shown in Figure 20, new regulations are anywhere from less than a year (year 2020) away for some capabilities to over four years (year 2024) away for others. While UTM, expected to manage UAS traffic and operations across the USA is still in development, UTM pilot programs are currently in progress at various UAS test sites [99]. The FAA expects to implement UTM incrementally in the next few years though a timeline hasn't been established yet [60], [79]. Discussion with an expert familiar with UTM estimated its final deployment could extend to beyond 2025.

Finally, the Digital Framework concept is still in its infancy and has never been applied to UAS. While discussing with industry experts on this idea, various hurdles were observed that still need to be overcome. While commercial UAS cost around $25,000, the question of cost to benefit of a Digital Framework for a product in this price range when they could easily be replaced often comes up. An advantage that UAS have is the production scale where the cost of developing the Digital Framework might become viable when spread over hundreds of thousands of units produced.

A Digital Twin will also need various additional sensors integrated into the UAS based on the type of analysis to be conducted. According to an industry expert, new hardware such as motor control units and GPS are starting to integrate various sensors such as accelerometers and gyroscopes because of their low cost and size and new UAS hardware are using new communication protocols that allow them to feedback subsystem health. These factors add additional costs to the UAS which UAS Manufacturers would have to consider. This becomes a question of which came first, the chicken or the egg: Which should come first, the sensor integration or the software to take advantage of them?

Another factor to consider is the security of the DSM and the Digital Twin especially if accessed by a competitor could help them gain a better understanding of the UAS. Also integrating a DSM and Digital Twin into the UAV could affect performance due to the additional power and processing requirements. Finally, UAVs generate large amounts of data for every second of their operation requiring significant bandwidth availability to upload the data through the communications infrastructure to the different parts of the Digital Framework in the UAS.

Looking at all the technologies and regulations that need to be in place, this envisioned future might not happen until at least 2025.

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6. Proposed Architecture

Looking at the envisioned future, various stakeholders involved, technologies in development and regulations coming up, four architectures were identified for UAS integrating a Digital Framework. All these architectures have a common underlying structure (Figure 29) that makes changes to the current architecture presented in Section 4.2. These changes include switching the link between the UAV and the GCS to one managed by a central flight management and data management server (FMDMS). This would allow a central server to manage all flights allowing more autonomy and control of multiple UAVs. This would change the role of the GCS user (UAS Operator) from an individual UAS Operator to one that interacts with the UAS only when the need arises allowing the server to manage the UAS fleet and flight operations automatically. This would also allow the UAS to be operated remotely by the UAS Operator. This structure would enable a secure link for data transfer between the various stakeholders who would need to interact with the UAS and limit access to data as needed by them. The UAS Operator would only be given access to data that would be critical to the flight, while the UAS Data Analysis group would only be given access to the data they would need for analysis. This architecture's use of cellular networks would be a boon due to their presence and cell tower redundancy and communication link with UTM.

The blue stakeholders (UTM, UAS Manufacturer) in Figure 29 are not inside the UAS but communicate with it. The structure could also incorporate the future UTM being developed and would enable autonomous interactions between the UAS and UTM. The FMDMS would interact with the UTM to provide flight plans and receive flight approvals and traffic data. The UAV would transmit its location directly to the UTM to keep it aware of its location and be sent information on traffic.

Finally, a communication link between the FMDMS and the UAS Manufacturer would enable the UAS Manufacturers to receive customer authorized flight data for them to improve their product and release software updates to the UAS.

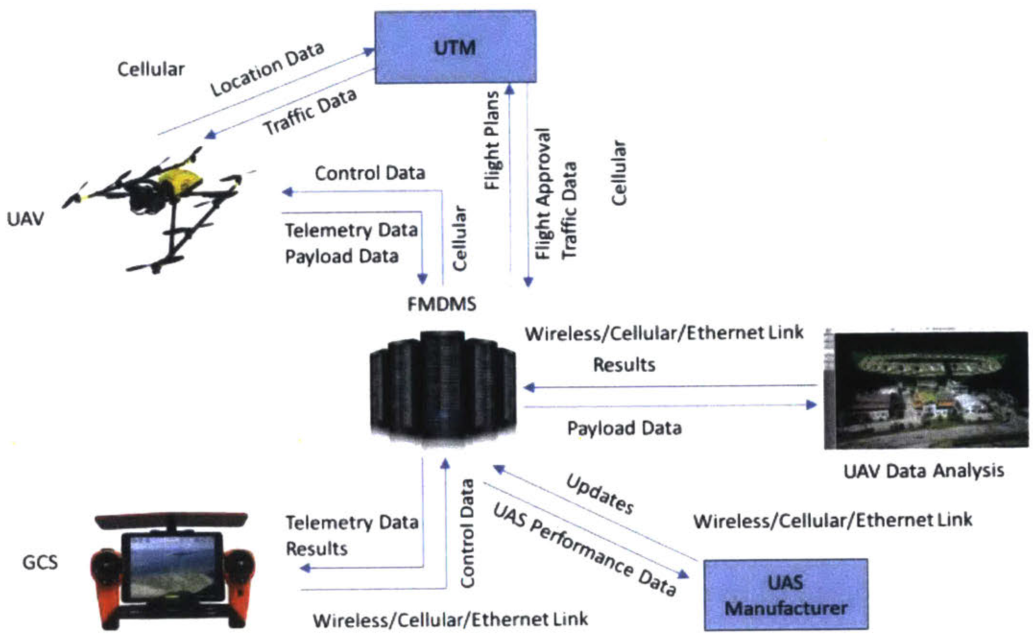

Figure 29: UAS Base Envisioned Structure

6.1. Architecture 1

The first architecture identified has the DSM and the Digital Twin installed in the UAV with the Digital Thread installed at the FMDSM, as shown in Figure 30.

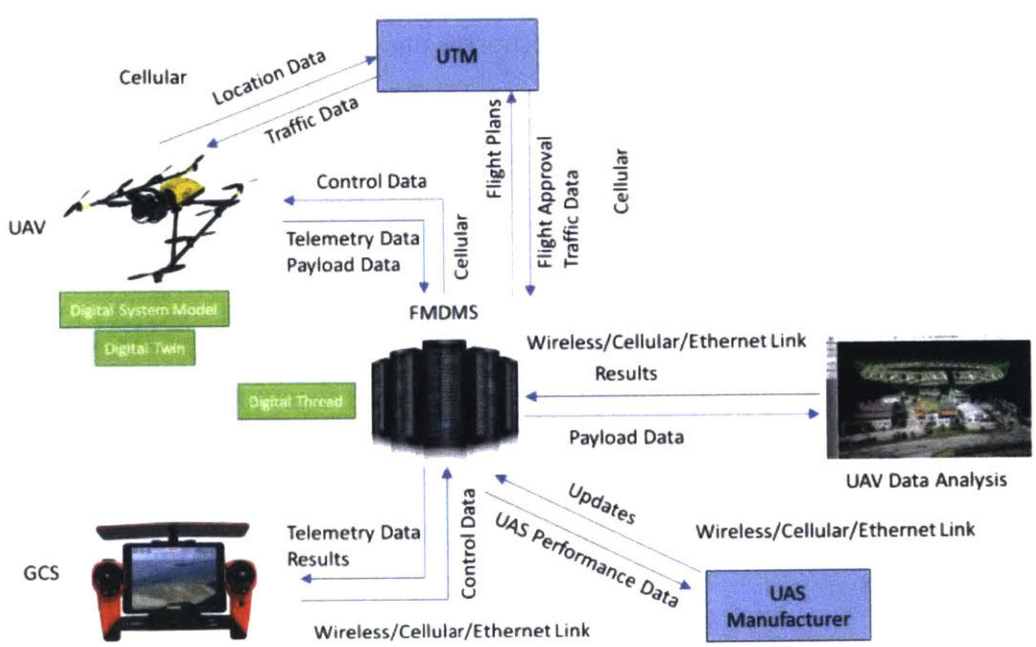

Figure 30: UAS Digital Framework Architecture 1

The advantage of this architecture is having the DSM and Digital Twin in the UAV. This would enable large amount of data onboard to be easily accessed by the Digital Twin. It would only need to send information needed for the operation of the Digital Thread, reducing the bandwidth limitations of the communication network. The Digital Thread would also be installed inside the UAS in the FMDMS providing the UAS with direction access to the information being provided by the Digital Twin. The other advantage this architecture provides is when the UAS operates multiple UAVs under it, specifically each UAV would come with its own integrated DSM and Digital Twin. This architecture would integrate all three aspects of the digital framework into the UAS itself simplifying who has control over it. This architecture would also create the opportunity for the UAS owner to be able to use different sources for the DSM, Digital Twin and the Digital Thread. The DSM and Digital Twin could be used to analyze the data generated live in flight which could lead to new capabilities not yet explored.

The disadvantage of this architecture is that the UAS Manufacturer would have limited access to the operational data of UAS to use for their benefit. Additionally, this architecture would require computational hardware dedicated to the DSM and the Digital Twin, increasing the complexity of the UAV which could affect its overall performance. Maintaining the DSM and the Digital Twin would be more complex for the UAS manufacturer when they do not have access to these systems because of communications constrains. This architecture would have difficulty upgrading the DSM and the Digital Twin when they exceed the computational limitations of the UAV, when hardware upgrades are required that could affect the performance of the systems. The UAS Manufacturer would also fear that the DSM and Digital Twin could be accessed by a competitor gaining a better understanding of the system. The UAS owner would also need to dedicate resources to maintain the UAS himself, making it possibly expensive for small budget customers.

This architecture would significantly benefit the UAS owner who would be the UAS Corporate Adopter or the UAS Service Provider since they would have direct control over who has access to the UAS data. In this case, they will also have to manage and maintain the Digital Framework infrastructure which could add to his operation expense. This architecture would also benefit the UAS Manufacturer since, if allowed by the owner of the UAS, would have access to the limited data uploaded to the FMDMS.

6.2. Architecture 2

The second architecture that was identified has the DSM, the Digital Twin and the Digital Thread installed at the FMDSM as shown in Figure 31.

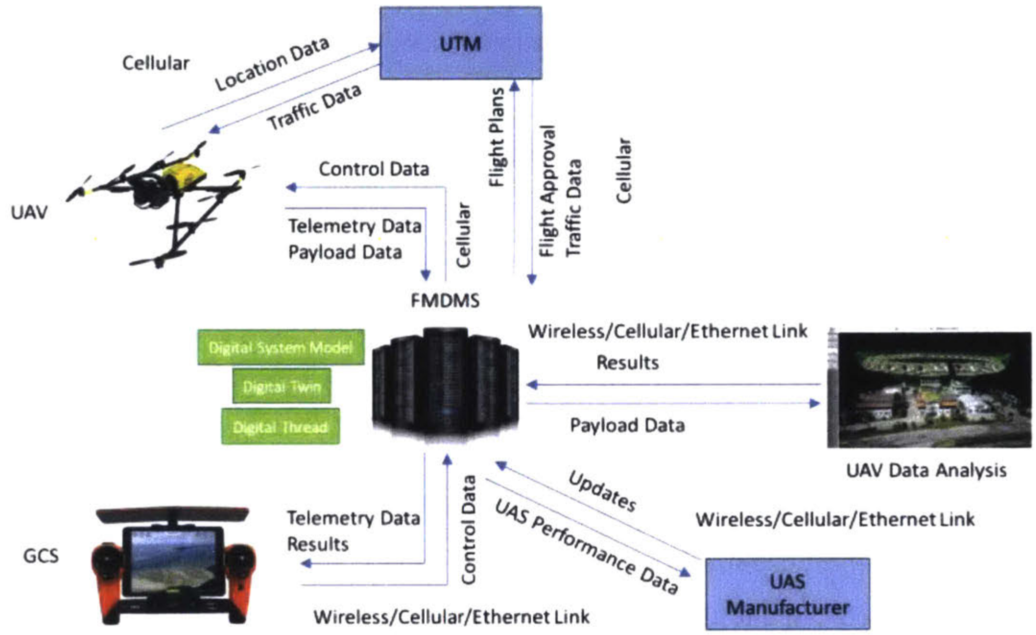

Figure 31: UAS Digital Framework Architecture 2

The advantages of this architecture are the colocation of the DSM, Digital Twin and the Digital Thread in the FMDMS increasing the ease of interactions within the Digital Framework. This would require the UAV to upload all required data for analysis by the Digital Twin to the FMDMS. This will also allow for the Digital Thread to use this information. This architecture would also increase the ease in updating and maintaining the entire Digital Framework since it can be accessed when needed. This architecture would also not have problems upgrading the DSM and the Digital Twin due to computational restriction as the hardware can be easily upgraded as required, not affecting the performance of the UAV. When adding more UAVs to the UAS, a new DSM and Digital Twin would just need to be uploaded into the FMDMS. This architecture would also create opportunities for the UAS owners to use different sources for the DSM, Digital Twin and the Digital Thread. Finally, this architecture provides UAS Manufacturer more data transmitted from the UAV to the FMDMS for the Digital Twin to analyze, provided the UAS owner grants access to this information.

The disadvantage of this architecture is the high bandwidth requirements to transfer all the data required by the Digital Twin to analyze the UAVs performance once the system lands. Another disadvantage of this architecture is that the UAS Manufacturer would have limited access to the operational data of UAS. The UAS Manufacturer would also fear that the DSM and Digital Twin could be accessed by a competitor gaining a better understanding of the system. The Digital Twin would not be able to analyze the UAS performance in real time due to the amount of bandwidth needed for a live analysis. The UAS owner would also need to dedicate resources to maintain the UAS by himself, making it possibly expensive for small budget customers.

This architecture would significantly benefit the UAS owner who would be the UAS Corporate Adopter or the UAS Service Provider since they would have direct control over who has access to the UAS data. But he would also have to manage and maintain the Digital Framework infrastructure which could add to his operation expense. This architecture would also benefit the UAS Manufacturer since, if allowed by the owner of the UAS, would have access to the entire data generated by the UAS for the Digital Twin.

6.3. Architecture 3

The third architecture that was identified has the DSM and the Digital Twin installed at the UAS Manufacturer and the Digital Thread installed at the FMDMS as shown in Figure 32.

The advantage of this architecture is the UAS Manufacturer would have control over the DSM and the Digital Twin and could manage and update the models more easily without accessibility issues. The UAS owner would have control over the Digital Thread, which would also be their primary interest in the Digital Framework and be able to manage their own data. This would also ensure that the DSM and the Digital Twin would not fall in competitor's hands since they would be the only ones with the models. Additionally, since the UAS would to have upload all the data that the Digital Twin would need, the UAS Manufacturer would also be able to access the data and analyze it for each individual system. They will be able to use the data generated for other development projects they have or share it with other organization. The UAS owner would not have to worry about the maintenance of the DSM and the Digital Twin since the UAS Manufacturer, the one who develops them, would also operate them and manage them. This would reduce the difficulty in upgrading the DSM and the Digital Twin due to computational restriction as the hardware can be easily upgraded when needed not affecting the performance of the UAV. When adding more UAVs to the UAS, adding a new DSM and Digital Twin would just involve uploading them to UAS Manufacturer's servers. Finally, the UAS Manufacturer could have extensive amount of data from various customers allowing them greater opportunities to analyze the performance of their product.

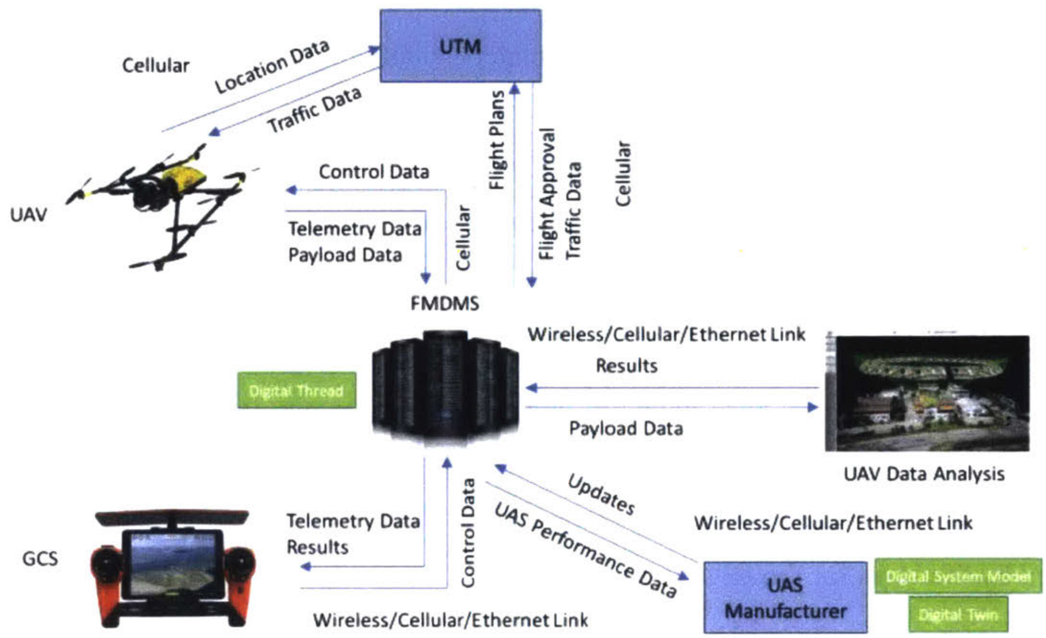

Figure 32: UAS Digital Framework Architecture 3

The disadvantage of this architecture is the high bandwidth requirements to transfer all the data needed by the Digital Twin to analyze the UAVs performance once the system lands. This architecture also suffers from having large amounts of performance data travelling between the UAV, the FMDMS and UAS Manufacturer. Another weakness of this architecture is the split in control and management of the Digital Framework between the UAS owner and the UAS Manufacturer. The Digital Twin would not be able to analyze the UAS performance in real time due to the amount of bandwidth needed for a live analysis.

The split in control of the Digital Framework spread between the UAS owner and the UAS Manufacturer could make their relationship more complex. This architecture could benefit the UAS Manufacturer and the UAS owner (UAS Corporate Adopter or the UAS Service Provider) since both would have access to all the data generated from the UAV. They would also only need to manage the parts of the Digital Framework that would be critical for them.

6.4. Architecture 4

The fourth architecture that was identified has the DSM, the Digital Twin and Digital Thread installed at the UAS Manufacturer as shown in Figure 33.

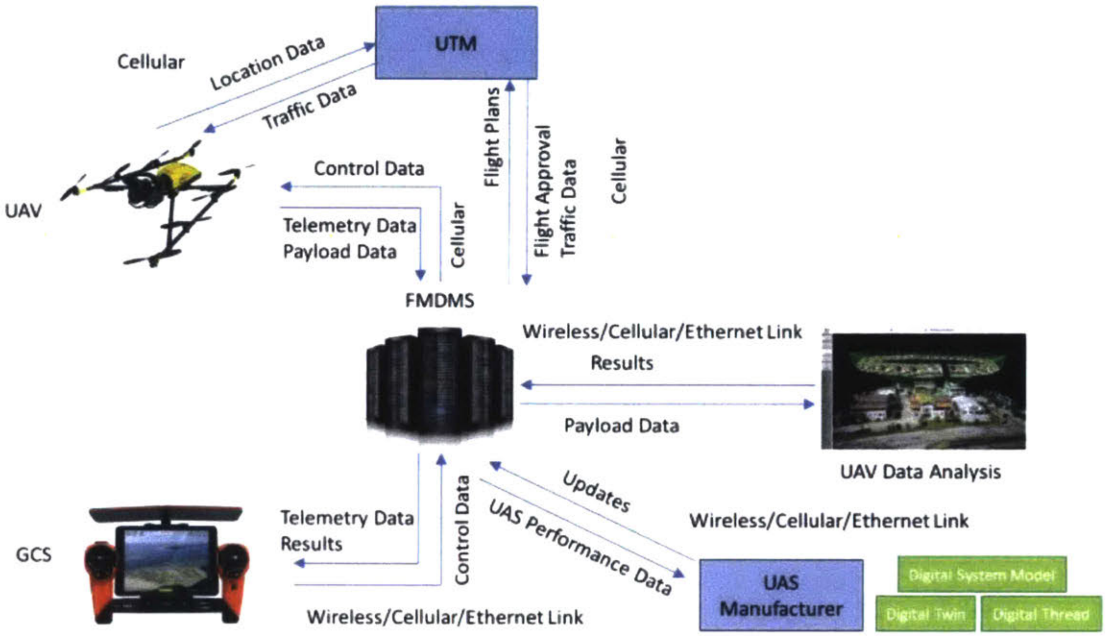

Figure 33: UAS Digital Framework Architecture 4

The advantage of this architecture is the UAS Manufacturer would have control over the entire Digital Framework. This would also ensure that the DSM and the Digital Twin would not fall in competitor's hands since they would be the only ones with access to the models. The UAS would also need to upload all the data that the Digital Twin would need to the UAS Manufacturer who would also be able to access the data and analyze it for each individual system. They could use the data generated for other development projects they have or share it with other organization. The UAS owner would not have to worry about the maintenance of the entire Digital Framework since the UAS Manufacturer, the one who develops them, would also operate them and manage them. This would reduce the difficulty in upgrading the Digital Framework due to computational restriction as the hardware can be easily upgraded when needed not affecting the performance of the UAV. When adding more UAVs to the UAS, adding a new DSM and Digital Twin would just involve uploading the software to the FMDSM. Finally, the UAS Manufacturer could have extensive amount of data from various customers which would give him the opportunity to analyze their performance. The UAS Manufacturer would also be able to leverage this capability to future customers.

The disadvantage of this architecture is the high bandwidth requirements to transfer all the data needed by the Digital Twin to analyze the UAVs performance once the system lands. This architecture also suffers from having large amounts of performance data sent to the UAS Manufacturer which might be cause for concern for some UAS owners. The UAS owner would not have control over the entire Digital Framework and would only be able to request features he needs but not add them himself. The Digital Twin would not be able to analyze the UAS performance live due to the amount of bandwidth needed for a live analysis.

This architecture would benefit the UAS Manufacturer the most because of the vast amount of data they would have access to. While the UAS owner would lose control over the Digital Framework to the UAS Manufacturer, they would benefit by not having to worry about the maintenance and management, simplifying their operations.

7. Conclusion and Future Work

This thesis was written to investigate commercial UAS and answer the three questions that were identified in Section 1.2. Towards this goal, the ARIES framework process was used to create a structured approach to this analysis. The first task involved understanding the enterprise landscape. This was done by reviewing literature on the commercial UAS industry such as the current state of the commercial UAS industry, trends in the industry, reviewing interviews of various industry leaders, identifying the technologies involved, and various regulations. Literature on Digital Framework and how the concept is being used in the industry was reviewed. The next steps in the process was identifying the stakeholders that are involved in or interact with a UAS, identifying the various links between them, and conducting a stakeholder salience. From this understanding of the industry, the current architecture of a UAS was identified and analyzed to understand its advantages and disadvantages.

The next phase of this document was identifying the envisioned future and how the various technologies and regulations will affect it and the possible applications of Digital Framework in UAS were explored. Next, we explored the factors that must be overcome to enable this future the possible timeline of this future. Finally, we identified a possible structure future UAS could use and four architectures of how a Digital Framework could be integrated into a UAS.

7.1. Thesis Summary

Commercial UAS industry was found to be rapidly growing with significant market potential. While their unit numbers make up 6% of Consumer-Commercial UAS, their $ market share is 60% of the Consumer-Commercial UAS market due to their cost per unit (Figure 9). The industry is also going through a consolidation phase where various members are buying out others or partnering with others to offer more complete products designed for specific applications (Figure 11, Figure 12). Commercial UAS have also found use in various applications that are only increasing in numbers as regulations and technology evolves (Figure 13). These applications have found benefits from using UAS to reduce task completion time by up to 30 times and increased task accuracy. Technology is a major contributor to UAS development with more sensors and AI integration driving their future development. New UAV platforms and new data analytics packages are helping these systems solve new problems while 5G communications infrastructures is expected to bring significant benefits to UAS. While regulations are in place that set some restrictions to UAS use, these are expected to evolve as technology and UAS understanding improve and UTM is implemented (Figure 20). Digital Framework was explored and found to be a new concept that is finding significant use in the industry from wind farm operations to aircraft maintenance to manufacturing to car racing.

The stakeholder analysis helped to identify various stakeholders and the interactions between them based on whether a UAS Service Provider or UAS Corporate Adopter owns and operates the UAS (Figure 21, Figure 22). While nine stakeholders were identified that interacted with the Commercial UAS directly or indirectly, two new stakeholders were found that were expected to also interact with Commercial UAS in the future. A stakeholder salience was also conducted that identified the type of stakeholder and the effect they could have on the commercial UAS (Figure 24). Four stakeholders were identified to be definitive stakeholders, three stakeholders were identified to be dominant stakeholders, two to be discretionary stakeholders, one dangerous stakeholder and finally one to be a dependent stakeholder.

The next step was identifying the current UAS architecture and exploring its advantages and disadvantages. While the current architecture was found to suit the current needs of the Commercial UAS industry, it was not found to be scalable, unable to reasonably support BVLOS flight capabilities, or not designed to operate multiple UAVs.

All these analyses led to the envisioned future. This future is expected to have full stack UAS automation with integrated data analysis packages. These UAS are also expected to have multiple UAVs in them with BVLOS capabilities and secure data links and data storage. The integration of a Digital Framework into Commercial UAS is expected to provide UAS with various capabilities such as predictive maintenance and fleet management, data access management, path planning, UAS certification, analysis opportunities to UAS Manufacturers and generation of a digital twin of the operational terrain (Section 5.1.6). While this future is viable, its dependent on various technologies maturing and regulations being place.

Towards this future, an architecture for the future UAS (Figure 29) was proposed and four possible architectures that incorporated a Digital Framework into Commercial UAS were identified (Figure 30, Figure 31, Figure 32, Figure 33). The first and second architectures significantly benefit the UAS Owners and were found to be less beneficial to the UAS Manufacturer. The third was found to be benefit both the UAS Owner and the UAS Manufacturer but was also found to add complications to their relationship due to the distributed ownership of the Digital Framework. The fourth architecture was found to benefit the UAS Manufacturer significantly due to his ownership of the Digital Framework with some benefits to the UAS Owner.

7.2. Limitations and Future Work

While, Digital Framework is still a relatively new concept, organizations in several industries are already finding significant benefits to using this concept. Commercial UAS are also a relatively new concept that are finding more applications and possibilities. As the two concepts evolve, it is expected that Digital Framework would be applied to Commercial UAS. While this thesis explored how this integration could take place, there are significant avenues of research still left unexplored here due to the scope and time available to conduct more research and interview industry experts.

This research could be expanded to identify other possible architectures for commercial UAS. This can be explored by categorizing them together based on commonalities such as similar workflows, same technologies in use, similar regulatory requirements or similar applications. Another aspect of the UAS that could be explored is modeling the various links within a UAS, how various architectures affect them and how this would improve or degrade the performance of the various parts of the UAS and affect the relations between the stakeholders. Finally, this research can be expanded to a global scale by looking at various nations and how Commercial UAS could evolve based on their regulations.

While various architectures were presented for the integration of Digital Framework into Commercial UAS, these could not be validated extensively by various industry experts which could be an avenue of research. Expanding the research to identify how specific UAS industries could benefit from a Digital Framework and conducting case studies would be an interesting problem. The various applications identified for Digital Framework in Commercial UAS could be explored in detail and modelled. This could lead to identifying the various components present in a UAS, or that need to be integrated into a UAS to make these applications viable. As more subsystems become integrated into a UAS, the Digital Twin and DSM component could be modularized to each subsystem, making it simpler when changing payloads or a component on a UAS. This would lead to interesting problems on data transfer, interface requirements between Digital Twins among others.

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Appendix

Table 3: Summary of Small UAV Rule (Part 107) [100]

Operational Limitations	• Unmanned aircraft must weigh less than 55 lbs. (25 kg). • Visual line-of-sight (VLOS) only; the unmanned aircraft must remain within VLOS of the remote pilot in command and the person manipulating the flight controls of the small UAS. Alternatively, the unmanned aircraft must remain within VLOS of the visual observer. • At all times the small unmanned aircraft must remain close enough to the remote pilot in command and the person manipulating the flight controls of the small UAS for those people to be capable of seeing the aircraft with vision unaided by any device other than corrective lenses. • Small unmanned aircraft may not operate over any persons not directly participating in the operation, not under a covered structure, and not inside a covered stationary vehicle. • Daylight-only operations, or civil twilight (30 minutes before official sunrise to 30 minutes after official sunset, local time) with appropriate anti-collision lighting. • Must yield right of way to other aircraft. • May use visual observer (VO) but not required. • First-person view camera cannot satisfy "see-and-avoid" requirement but can be used as long as requirement is satisfied in other ways. • Maximum groundspeed of 100 mph (87 knots). • Maximum altitude of 400 feet above ground level (AGL) or, if higher than 400 feet AGL, remain within 400 feet of a structure. • Minimum weather visibility of 3 miles from control station.

	• Operations in Class B, C, D and E airspace are allowed with the required ATC permission.
	• Operations in Class G airspace are allowed without ATC permission.
	• No person may act as a remote pilot in command or VO for more than one unmanned aircraft operation at one time.
	• No operations from a moving aircraft.
	• No operations from a moving vehicle unless the operation is over a sparsely populated area.
	• No careless or reckless operations.
	• No carriage of hazardous materials.
	• Requires preflight inspection by the remote pilot in command.
	• A person may not operate a small unmanned aircraft if he or she knows or has reason to know of any physical or mental condition that would interfere with the safe operation of a small UAS.
	• Foreign-registered small unmanned aircraft are allowed to operate under part 107 if they satisfy the requirements of part 375.
	• External load operations are allowed if the object being carried by the unmanned aircraft is securely attached and does not adversely affect the flight characteristics or controllability of the aircraft.
	• Transportation of property for compensation or hire allowed provided that:
	    o The aircraft, including its attached systems, payload and cargo weigh less than 55 pounds total
	    o The flight is conducted within visual line of sight and not from a moving vehicle or aircraft; and
	    o The flight occurs wholly within the bounds of a State and does not involve transport between (1) Hawaii and another place in Hawaii through airspace outside Hawaii; (2) the District of Columbia and another place in the District of

	Columbia; or (3) a territory or possession of the United States and another place in the same territory or possession. • Most of the restrictions discussed above are waivable if the applicant demonstrates that his or her operation can safely be conducted under the terms of a certificate of waiver.
Remote Pilot in Command Certification and Responsibilities	• Establishes a remote pilot in command position. • A person operating a small UAS must either hold a remote pilot airman certificate with a small UAS rating or be under the direct supervision of a person who does hold a remote pilot certificate (remote pilot in command). • To qualify for a remote pilot certificate, a person must: o Demonstrate aeronautical knowledge by either: ▪ Passing an initial aeronautical knowledge test at an FAA-approved knowledge testing center; or ▪ Hold a part 61 pilot certificate other than student pilot, complete a flight review within the previous 24 months, and complete a small UAS online training course provided by the FAA. o Be vetted by the Transportation Security Administration. o Be at least 16 years old. • Part 61 pilot certificate holders may obtain a temporary remote pilot certificate immediately upon submission of their application for a permanent certificate. Other applicants will obtain a temporary remote pilot certificate upon successful completion of TSA security vetting. The FAA anticipates that it will be able to issue a temporary remote pilot certificate within 10 business days after receiving a completed remote pilot certificate application. • Until international standards are developed, foreign-certificated UAS pilots will be required to obtain an FAA-issued remote pilot certificate with a small UAS rating.

	A remote pilot in command must: • Make available to the FAA, upon request, the small UAS for inspection or testing, and any associated documents/records required to be kept under the rule. • Report to the FAA within 10 days of any operation that results in at least serious injury, loss of consciousness, or property damage of at least $500. • Conduct a preflight inspection, to include specific aircraft and control station systems checks, to ensure the small UAS is in a condition for safe operation. • Ensure that the small unmanned aircraft complies with the existing registration requirements specified in § 91.203(a)(2). A remote pilot in command may deviate from the requirements of this rule in response to an in-flight emergency.
Aircraft Requirements	• FAA airworthiness certification is not required. However, the remote pilot in command must conduct a preflight check of the small UAS to ensure that it is in a condition for safe operation.
Model Aircraft	• Part 107 does not apply to model aircraft that satisfy all of the criteria specified in section 336 of Public Law 112-95. • The rule codifies the FAA's enforcement authority in part 101 by prohibiting model aircraft operators from endangering the safety of the NAS.