UNIVERSITY OF CALIFORNIA, MERCED

OPTIMAL REMOTE SENSING WITH SMALL UNMANNED AIRCRAFT SYSTEMS AND RISK MANAGEMENT

by

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to my wife, parents, and kittens.

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Portions of this dissertation contains content of material as it appears in [1–10]. The senior co-author listed in these publications directed and supervised the research that forms the basis for this dissertation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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2012 - 2017	**Doctor of Philosophy in Electrical Engineering & Computer Science** *University of California, Merced* Advisor: Dr. YangQuan Chen Dissertation Title: "Optimal Remote Sensing with Small Unmanned Aircraft Systems and Risk Management"
2010 - 2012	**Doctor of Philosophy in Electrical Engineering** (not completed) *Utah State University* Advisor: Dr. YangQuan Chen
2007 - 2010	**Master of Science in Electrical Engineering** *University of Bridgeport*
2007 - 2010	**Master of Science in Computer Engineering** *University of Bridgeport*
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Employment History

2016 - Current	**Director, UC Center of Excellence on Unmanned Aircraft System Safety** *University of California, Office of the President*

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2016 **Graduate Student Teaching Fellow (TF)**
School of Engineering, University of California, Merced
Served as primary lecture instructor (1.5 hours a session, 2 sessions per week) for ME142 - Mechatronics.

2013 - 2015 **Graduate Student Teaching Assistant (TA)**
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Developed a project based lab curriculum designed around student learning outcomes developed for the redesigned course - ME142 Mechatronics (4 Units). Designed and developed lab equipment, integrated new technology each year, evaluated Student Learning Objectives each offering. Served as primary lab instructor (3 hours a session, 3 sessions per week) for 2013-2015.

2012 - 2016 **Lab Manager (GSR)**
MESA Lab, School of Engineering, University of California, Merced
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2010 - 2012 **Graduate Student Researcher (GSR)**
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2007 - 2010 **Graduate Student Teaching Assistant (TA)**
School of Engineering, University of Bridgeport
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Scientific and Professional Membership

- Member, IEEE (Aerospace and Electronics Systems Society, Circuits and Systems Society, Computer Society, Control Systems Society, Systems, Man and Cybernetics Society, Robotics and Automation Society)
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- Member, AUVSI (The Association for Unmanned Vehicle Systems International)
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Teaching

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Independent Study Directed (over 22 student projects)

Senior Capstone Project Advising (4 student projects)

Honors and Awards

- 2016 - Best Paper - International Conference on Unmanned Aerial Systems (ICUAS 2016)
- 2015 - UC Merced Leadership Award - Outstanding Graduate Student
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- 2013 - UC Merced Leadership Award Finalist - Outstanding Graduate Student
- 2011 - Graduate Advisor for AUVSI SUAS Rotary Competition Team (9th Place, 1st team in competition history to do waypoints with rotary-wing vehicle)
- 2010 - Graduate Student Teaching Award, School of Engineering, UB

Institutional Service

- UC ANR IGIS Program Review Committee (2017-)

- Graduate Student Association: President (2014-2015)
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2. B. Stark, Unmanned Aircraft System Risk Management for Higher Education, Workshop in: Drone Educator's Conference, San Bruno, California, USA, October 22 2016.

3. B. Stark, B. Smith, Y. Chen, Emerging sUAS Technology for Precision Agriculture Applications (AgDroneTech15), Workshop in International Conference on Unmanned Aircraft Systems 2015, Denver, Colorado, USA, June 9 2015.

4. B. Stark, Y. Chen, Personalizing Mechatronics Education, Half Day Tutorial in 19th IFAC World Congress, Cape Town, South Africa, August 27 2014.

5. B. Stark, B. Smith, Y. Chen, Emerging sUAS Technology for Precision Agriculture Applications (AgDroneTech14), Workshop in International Conference on Unmanned Aircraft Systems 2014, Orlando, Florida, USA, May 27 2014.

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9. B. Stark, Y. Chen, K. Cao, Iterative Design Towards Improved Fault Tolerance: A Framework for Improved SUAS Airworthiness, Workshop in: Health Management, Fault-tolerant Control, and Cooperative Control of Unmanned Aircraft, American Control Conference 2012, Organizers: Youmin Zhang, Camille Alain Rabbath, YangQuan Chen, Christopher Edwards, Cameron Fulford, Hugh H.-T. Liu, Liang Tang, Didier Theilliol, and Antonios Tsourdos, June 26, 2012, Montreal, QC, Canada.

10. B. Stark, Y. Chen, K. Cao, Iterative Design Towards Improved Fault Tolerance: A Framework for Improved SUAS Airworthiness, Workshop in: Health Management, Fault-tolerant Control, and Cooperative Control of Unmanned Aircraft, International Conference on Unmanned Aircraft Systems 2012, Organizers: Youmin Zhang, Camille Alain Rabbath, YangQuan Chen, Christopher Edwards, Cameron Fulford, Hugh H.-T. Liu, Liang Tang, Didier Theilliol, and Antonios Tsourdos, Philadelphia, PA, USA, June 12 2012.

Invited Seminars/Talks

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2. B. Stark, Training Safety and Risk Management for Large Scale UAS Operations, Commercial UAV Expo, Las Vegas, NV. November 2nd, 2016.
3. B. Stark, Unmanned Aircraft Systems in Agriculture, California Agricultural Commissioners and Sealers Association Golden State Computer User's Conference, Stockton, California, October 24, 2016.
4. B. Stark, The Alphabet Soup of Drones, University of California Risk Summit, Los Angeles, California, June 8, 2016.
5. B. Stark, Drone Licenses and Operations, University of California Risk Summit, Los Angeles, California, June 7, 2016.
6. B. Stark, Unmanned Aerial Systems at the Merced Vernal Pool and Grassland Reserve, SpARC Invited Seminar, University of California, Merced, Merced, California. October 9, 2015.
7. B. Stark, The use of Unmanned Aerial Systems in Precision Agriculture, UCANR Precision Agriculture Workshop, University of California Davis, Davis, California. March 17, 2015.
8. B. Stark, Human Factors Issues on UAS Operations, UAS Cybersecurity Conference, Cal Poly Pomona, Pomona, California. Dec 12, 2015.
9. B. Stark, The use of Unmanned Aerial Systems for Pest Management, Continuing Education for Pest Management Professionals, UC Cooperative Extension, UCANR. Merced, California, October 7, 2014.
10. B. Stark, UAS Summit on Challenges and Opportunities on the Road to Integration, San Diego, California, June 11 2014.
11. B. Stark, The Federal Aviation Administration Certificate of Airworthiness Process, Earth Sciences Division, Lawrence Berkeley National Lab, Berkeley, California, March 14, 2014.
12. B. Stark, Agriculture and UASs, A Conversation on Precision Agriculture: The future of unmanned systems in Agriculture, VCEDA, Ventura County Office of Education, Camarillo, California, October 17, 2013.
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14. B. Stark, The Trials and Tribulations of Utilizing Unmanned Aerial Systems for Remote Sensing Applications, University of Hawaii-Manoa, Honolulu, HI, USA, December 17 2012.

15. C. Coopmans, B. Stark, A. Quitberg, C. Coffin, Unmanned Aerial Systems, University of Canterbury, Christchurch, New Zealand, July 15 2012

Published Book Chapters

1. B. Stark, Y. Chen, Remote Sensing Methodology for Unmanned Aerial Systems, in: R. Blockley, W. Shyy (Eds.), Encyclopedia of Aerospace Engineering - UAS, John Wiley & Sons, 2016. 17 pages.

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19. C. Yin, B. Stark, S. Zhong, Y. Chen, Global Extremum Seeking Control with Sliding Modes for Output-Feedback Global Tracking of Nonlinear Systems, in: Proc. of 51st IEEE Conference on Decision and Control (CDC 2012), Maui, Hawaii, USA. December 10-13, 2012.

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21. B. Stark, C. Coopmans, Y. Chen, A Framework for Analyzing Human Factors in Unmanned Aerial Systems, in: Proc. of the 2012 Int. Symposium on Resilient Control Systems (ISRCS2012), Salt Lake City, Utah, USA. August 2012.

22. B.Stark, C. Coopmans, Y. Chen, Concept of Operations for Personal Remote Sensing Unmanned Aerial Systems, in: Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2012), Philadelphia, PA, USA. June 12-15, 2012.

23. Z. Li, N. Hoffer, B. Stark, Y. Chen, Design, Modeling and Validation of a T-tail Unmanned Aerial Vehicle, in: Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2012), Philadelphia, PA, USA. June 12-15, 2012.

ABSTRACT

Over the past decade, the rapid rise of Unmanned Aircraft Systems (UASs) has blossomed into a new component of the aviation industry. Though regulations within the United States lagged, the promise of the ability of Small Unmanned Aircraft System (SUAS), or those UAS that weigh less than 55 lbs, has driven significant advances in small scale aviation technology. The dream of a small, low-cost aerial platform that can fly anywhere and keep humans safely away from the 'dull, dangerous and dirty' jobs, has encouraged many to examine the possibilities of utilizing SUAS in new and transformative ways, especially as a new tool in remote sensing. However, as with any new tool, there remains significant challenges in realizing the full potential of SUAS-based remote sensing. Within this dissertation, two specific challenges are addressed: validating the use of SUAS as a remote sensing platform and improving the safety and management of SUAS.

The use of SUAS in remote sensing is a relatively new challenge and while it has many similarities to other remote sensing platforms, the dynamic nature of its operation makes it unique. In this dissertation, a closer look at the methodology of using SUAS reveals that while many view SUAS as an alternative to satellite imagery, this is an incomplete view and that the current common implementation introduces a new source of error that has significant implications on the reliability of the data collected. It can also be seen that a new approach to remote sensing with an SUAS can be developed by addressing the spatial, spectral and temporal factors that can now be more finely adjusted with the use of SUAS.

However, to take the full advantage of the potential of SUASs, they must uphold the promise of improved safety. This is not a trivial challenge, especially for the integration into the National Airspace System (NAS) and for the safety management and oversight of diverse UAS operations. In this dissertation, the challenge of integrating SUAS in the NAS is addressed by presenting an analysis of enabling flight operations at night, developing a swarm safety management system for improving SUAS robustness, investigating the use of new technology on SUAS to improve air safety, and developing a novel framework to better understand human-SUAS interaction. Addressing the other side of safety, this dissertation discuses the struggle of large diverse organizations to balance acceptance, safety and oversight for UAS operations and the development of a novel implementation of a UAS Safety Management System.

Chapter 1

INTRODUCTION

1.1 Dissertation Roadmap

The development of Unmanned Aircraft System (UAS) has grown dramatically over the past several years, with significant advances in technology and regulations. However, there still remains significant challenges to overcome before the full potential of UASs are realized. Of the many challenges, two in particular are of significant interest within this dissertation: validating the use of Small Unmanned Aircraft System (SUAS) for remote sensing applications and improving safety and management of UAS operations. Deploying an SUAS for a remote sensing application is a relatively new challenge and while it has similarities with other remote sensing platforms, the dynamic nature of an SUAS introduces new advantages and challenges, but their effectiveness still requires validation. Moving to take advantage of some of the new advantages of SUAS such as operations at night or multi-vehicle operations, however introduces new challenges on safety and management that must be addressed before new regulations can be implemented. This dissertation presents a collection of advances to solve the challenge of optimal remote sensing with SUASs and risk management.

1.1.1 Unmanned Aircraft Systems

The integration of UAS into the National Airspace System (NAS) is slowly, but surely progressing with the enactment of regulations to enable small UAS, defined as weighing less than 55 lbs. This first step has been a highly anticipated advancement within the UAS industry. For many research applications, both UASs and SUASs have been proposed and encouraged, but the challenges associated with their use and regulations has slowed their adoption. Though UASs in general were declared as the next big thing in 2012, many of the proposed 'big' successes, such as delivery services have failed to materialize before the regulations were enacted in 2016. Though SUAS are only a subset of the UAS industry, it is seen as the most immediate need and potentially largest component.

In 2013, the Association of Unmanned Vehicle Systems International (AUVSI), estimated that up to 80% of UASs operating in the US will be purchased for agricultural applications [11]. Many of these applications were obvious: crop dusting and land surveillance were two of the most commonly cited examples. The technology for these two applications had already been well developed and their adoption was suspected to be eminent. However, the more advantageous agricultural applications, while they had been demonstrated, were considered to be several years away from deployment.

In the following years, these applications became the subject of many research projects. The more rigorous scientific applications of crop yield estimations, soil moisture monitoring, pest management, or soil salinity control require a level of robustness, reliability, and precision that many platforms are unable to satisfy. Current platforms for researching these aspects have typically been developed specifically for these purposes; however, this is not a sustainable effort. If wide-spread adoption is to be achieved, researchers must be able to focus on the research project at hand, and not on the development of the platform. While much research can be accomplished with the large, full-scale sized UASs, the greatest avenue to applications remains in the use of the SUASs as these platforms are currently the most accessible to researchers and for agricultural applications and have the highest variation in quality.

1.1.2 SUAS-Based Remote Sensing Applications

Led by the development of small, high resolution cameras as well as suitable multispectral cameras, SUASs have demonstrated a significant level of capabilities for both agricultural and environmental applications [12]. There are large varieties of applications being investigated that are enabled by the high-resolution imagery provided by SUASs including irrigation timing control [13], canopy coverage and yield estimation [14], and disease and pest management [15]. Highly desirable metrics such as crop water stress estimation have also been investigated using SUASs [16]. Utilizing established remote sensing indices such as Normalized Difference Vegetation Index (NDVI) has also enabled a variety of applications valuable for agricultural such as yield estimation [17], and crop harvest yield attributes [18]. Multispectral indices such as Photochemical Reflectance Index (PRI) [19] as well as more complex analysis utilizing hyperspectral imagery [20] have also been demonstrated to be effective estimators for metrics such as water stress.

Environmental applications, including conservation efforts, are also a prime example of the value of SUASs. They have been utilized frequently for a variety of applications, including wetland mapping [21] and rangeland management. The land classified as rangelands comprises of over half of the usable land in the world and has significant agricultural and economic value. Conservation and management of these lands can be a challenging task due to the wide variety of activity and large areas [22]. Satellite imagery can be used for decision support, but the resolution of the imagery is typically insufficient. Finer details such as individual vegetation and small water features are impossible to see and become difficult for management.

Accurate assessment of small features, such as dead matter or litter have been identified as one of the most important indicators for assessing long-term sustainability of the land [23]. Current methods, using satellites or field-crews, suffer from high costs and limited actionable intelligence due to the sparse nature of the evaluations. SUASs provide a new and cost efficient method for data collection for better rangeland management [23–25]. These autonomous systems have several advantages over satellite imagery or manned aircraft. They can fly at very low altitudes, enabling high resolution imagery, can accomplish a wide variety of mission, can have a higher revisit frequency and can be much safer and cheaper to operate. As a result, remote sensing applications for SUASs have seen significant growth as their utility gains credibility.

In general, the use of SUAS technology for agriculture or environmental monitoring is an extension of existing methodology utilizing aerial or satellite imaging for monitoring crops. Literature is well-established on the effectiveness for such applications as pest, weed or disease monitoring or damage assessment. The advent of SUASs, paired with Global Positioning Systems (GPSs) and high resolution cameras provides the ability to utilize imagery, such as that seen in Figure 1.1, to improve that methodology and enable improved practices.

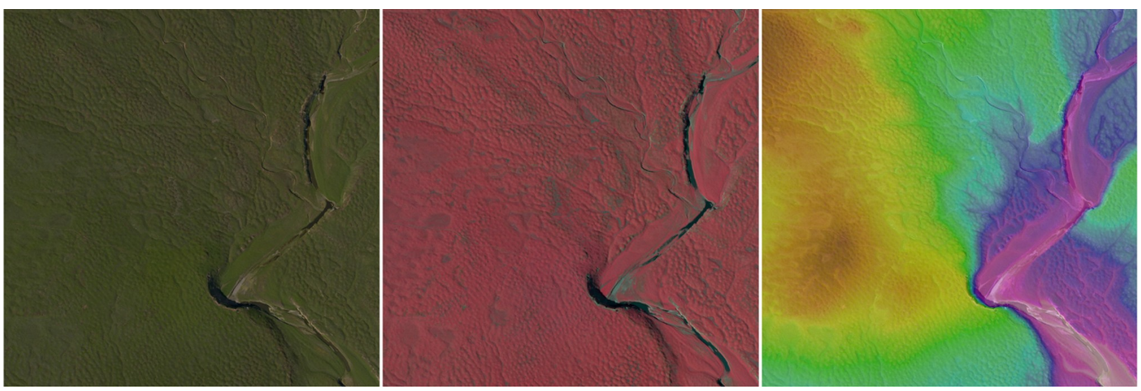

Figure 1.1: Aerial Imagery collected by SUAS over Merced Vernal Pool and Grassland Reserve, March 4th, 2015. (a) Color (b) False Color NIR Composite (c) Elevation Map

While there has been a recent interest of the agricultural implications of high-resolution or multispectral imagery, there remains a significant amount of work. Many of the solutions found in literature utilize specialized equipment, controlled environments, and rely on analysis expertise. These solutions are currently not implementable at any level of commercial operation and further development is necessary. The majority of existing methodology described in literature for SUASs was developed for low resolution satellite imagery or through the use of handheld hyperspectral sensors with high spectral resolution, meaning that these are not optimized for use by SUASs, which can provide high resolution imagery with limited spectral resolution and potentially with a higher temporal resolution [26]. In some cases, methods developed for satellite-based remote sensing were found inconclusive for SUAS remote sensing [27]. Realizations such as these have led to more detailed investigations into developing SUAS data test sites [28], and further analysis into developing SUAS specific solutions [29].

1.1.3 UAS Regulation History

However, in order to utilize UASs or SUAS for any purpose, there are regulatory and safety hurdles. In the U.S., the FAA is the official agency that governs the use of the NAS. Utilizing federal regulations, standards and policies, the Federal Aviation Administration (FAA) develops and enforces strategies and rules that promotes air safety and an efficient use of the NAS. While UASs have been in existence since the early 1930's, regulations regarding their use have only existed since 2005.

In 2005, the FAA published AFS-400 UAS Policy 05-01. This provisional report established the first official sanctions of UASs allowing UAS operators to apply for a Certificate of Waiver or Authorization (COA) that permits the use of a specific unmanned aircraft or a class of unmanned aircraft to specific operational bounds. These COAs are only offered to military or public agencies and only for U.S. government functions. This definition includes state agencies and research institutes such as public universities. However, this policy excluded the option of sanctioned civil or commercial use [30].

In 2008, the policy was updated with the Interim Operational Approval Guidance 08-01 report. This document continued the offering of COAs to public agencies, but also included a mechanism for civil operators to apply for a Special Airworthiness Certificate in the Experimental Category, subject to strict limitations and to the applicable regulations of 14 Code of Federal Regulations (CFR) parts 61 and 91 [31].

An early attempt to develop regulations for civil use was published in 2009 to address the rules and operations for SUASs. The 'Comprehensive Set of Recommendations for SUAS Regulatory Development,' written by the SUAS aviation rulemaking committee (ARC) proposed similar operations as its predecessors such as IOAG 08-01, but stricter limitations and regulations on use. In this report, SUASs are proposed to strict altitude and lateral distances of 400ft and 1200 ft respectively while utilizing visual line of sight (VLOS) as the primary method of mitigation for mid-air collisions [32]. Limitations on flight altitude and lateral distance, 400 ft and 1200 ft, were recommended due to the limited capability of visual observers for conflict detection and resolution services. The report does not consider Sense and Avoid Systems (SAASs) such as real-time video links or real-time air traffic monitors to aid in situational awareness to allow extended flights in terms of distance, altitude and duration. The recommendations by the SUAS ARC also includes a primary means of collision avoidance by recommending that an SUAS dive to a lower altitude and yield right-of-way, as a pilot would expect a similarly sized bird do as a manned aircraft approaches [32]. Due to the visibility challenges of an SUAS, it was decided that the a vertical evasive maneuver would prove to be the optimal maneuver to avoid the collision volume.

In addition to the operational bounds, the recommendations posed by the SUAS ARC include additional qualifications for operation in each available class of airspace. SUAS operations typically occur in Class E or G airspace, where air traffic is sparse and where visual flight rules (VFR) are allowed during visual meteorological conditions (VMC), a common aviation term that quantifies the safe operational weather and visibility. Other airspace classes may be used, but the altitude limitations keep this usage to a minimum, applicable only when near the Class C and D airspace extends to the surface around airports. Operation near these airports are recommended to be prohibited unless special authorization is given from the local Air Traffic Control (ATC) and ATC contact is maintained [32].

The FAA revisited the issue of UAS operations in a Concept of Operations (CONOPS) for Unmanned Aircraft Systems report, first issued in 2011 and updated in 2012, to address the necessary requirements that a UAS must meet to be worthy of integration into the NAS [33]. In this report, the FAA shares their view of a UAS operating safely and efficiently with other air traffic by utilizing a 'file-and-fly' approach; filing a flight plan similar to existing instrument flight rules (IFR) flight plans before receiving flight authorization, without the need for creating a segregated airspace specifically for UASs [33]. However, as with many of the other mentioned reports, the FAA CONOPS for UASs specifically excludes describing operations for SUASs as not fitting within their concept narrative.

One of the major steps towards UAS operations was the FAA Modernization and Reform act of 2012 that introduced several legal definitions for UAS, SUAS, pushed for the integration of civil UAS into the NAS and introduced two significant regulations, commonly known as Section 333 and Section 336 [34]. These two sections introduced a process for the FAA to allow civil UAS flight operations after a safety review (Section 333) and established the regulations for recreational UAS flying, which includes the definition of 'model aircraft.'

It was not until 2015 that progress had been made on civil UAS operations. In February, the FAA released a Notice of Proposed Rule Making (NPRM) for SUAS operations. Building off some of the proposals from the 2009 recommendation report, it promoted a safety-based approach rather than a technical standard based approach. The regulations were finalized in August 2016 in Title 14 of the CFR, Part 107 [35]. This set of regulations primarily enabled the use of SUAS within Class G airspace while introducing a new remote pilot in command (RPIC) certificate and introduced a SUAS rating. In contrast to a Public Agency COA or Section 333 COA, the new regulations did not require an aircraft airworthiness certificate or the use of a Visual Observer (VO). However, the new regulations placed an increased emphasis on risk and safety management, and placed the responsibility of maintaining safety squarely on the RPIC.

Unlike previous proposals for SUAS operations, the FAA introduced an airspace authorization process and a waiver process for flight operations beyond the limitations within 14 CFR 107. The airspace authorization enables SUAS operators to request airspace authorization in Class B, C, D and surface E airspace. The waiver process enables SUAS operators to request waivers to specific regulations in 14 CFR 107, provided the applicant made a sufficient case to ensure an Alternate Means of Compliance (AMOC).

1.1.4 UAS Safety and Management

Throughout the process of developing UAS regulations, the FAA began to shift many safety responsibilities from the aircraft manufacturers and the FAA to the UAS operators. This can be seen in the relaxation of aircraft certification standards (a manufacturer required component in earlier COAs) to no longer being required under 14 CFR 107, though specifically for SUAS. However, this places additional consideration to be thorough with safety on the part of the operator.

As a result, the role of UAS safety management has grown significantly as more UAS enter the NAS. In the simple cases enabled under 14 CFR Part 107, such as Class G airspace, integration into the NAS has been relatively straight forward. However, as more operators propose flight operations under the 14 CFR 107 waiver process, additional safety research is necessary. Areas such as determining safety standards for non-standard flight operations [7], balancing multi-aircraft health and safety [4], improving UAS traffic management [2] and exploring human factors [1] are key components to improving UAS safety [36].

Beyond improving UAS safety as more aircraft enter the NAS, the reliance on operator judgment has changed the way that UAS safety needs to be managed. For large organizations, UAS operations may pose significant risks as a wide range of users and aircraft may be deployed. While the FAA transfers risk to the UAS operators, in practice, all of this risk is transferred to the organization as the operators are acting on behalf of the organization. As a result, UAS risk and safety management are expected to play significant roles in the coming years.

1.2 Research Motivations and Approach

The UAS industry is rapidly growing, however, as presented previously, there are significant gaps that remain to be addressed. In this section, these gaps are identified and their approach to resolution is described.

1.2.1 Lack of a General SUAS Remote Sensing Methodology

The use of SUASs in remote sensing applications is still in need of maturation. As more and more applications are developed and documented, the need for a guide for the development of an SUAS remote sensing methodology has become apparent. A well-developed methodology is critical for project success as it defines with clarity, the end goal, the implementation, the data collection strategy and provides metrics for success and project completion. Failure to accurately develop a methodology can lead to significant development delays, spiraling costs, or complete project failure [8].

Addressing this general challenge requires an investigation of the advantages and disadvantages of SUAS operations and their remote sensing equipment to better inform the reader. While many view SUAS operations as an alternative to satellite based imagery, this is an incomplete view. This is especially true in the use of other remote sensing equipment such as Thermal Infrared (TIR) [5] and Short Wave Infrared (SWIR) imagers [6].

1.2.2 Sources of Error

The data processing workflow for UAS-based Remote Sensing is currently a multi-staged process of data collection and several layers of calibration and corrections. Sensor corrections such as noise cancellation, radiometric calibration and lens corrections as described in [37] have commonly been employed to generate 'accurate' data. Alternatively, *in situ* calibration techniques have been employed [38].

However, this workflow is subject to the introduction of errors at every stage of processing that may inadvertently result in poor quality results. The question is posed, is it even possible to collect perfect results? What are the limiting factors that influence data accuracy and what can be done to mitigate their influence? One such source of error is found in the wide field of view (FOV) cameras commonly deployed on SUAS and is shown to have profound impacts on data accuracy [10].

1.2.3 Lack of Optimized Data Collection

In addition to requiring several layers of corrections to extract calibrated data, the current processes for data collection are still significantly inefficient or possibly insufficient. Even in the best cases, despite all the processing, significant amounts of the collected data may go unused in the final analysis stages or are of minimal value. An example flight output such as in Figure 1.1 is generated from upwards of 30 GB of image data for less than 300 acres of coverage at 8 cm resolution. If the desired data was to determine the spatial pattern of large features, the research question posed is could less data be collected and still provide meaningful results? However, in order to address optimized data collection, defining 'meaningful data' is necessary and is the subject of the next challenge, optimizing the data analysis processes. This can be expanded into a more general question of optimality. How is an optimal SUAS flight defined with regards to data collection? What are the factors that influence data collection from an SUAS and how can it be adjusted? It can be shown that an optimality framework can be developed from spatial, spectral and temporal factors [9].

1.2.4 Changes in UAS Safety and Risk Management

As described previously, the rapid growth of the UAS industry and the changes in the U.S. regulatory environment has shifted SUAS safety responsibilities from the FAA to the SUAS operator. This transfer of responsibility has profound impacts on future expansions of UAS and SUAS operations and on the oversight responsibility for large organizations in particular. In order to realize the full potential of all UAS operations in the NAS further analysis of some of the barriers to more complex cases is required. For the large organizations, a whole new structure of safety management is necessary.

1.3 Dissertation Contributions

The major contributions of this dissertation include, but are not limited to the following:

1. Described and enumerated the unique challenges and requirements in developing a specific SUAS methodologies for multispectral remote sensing applications.
2. Introduced the use of SWIR for SUAS-based remote sensing applications.
3. Analyzed the introduction of error in SUAS based remote sensing platforms from the bidirectional reflectance distribution function (BRDF).
4. Established a framework for optimizing remote sensing data collection with regards to spatial, spectral and temporal factors.
5. Developed the first SUAS safety case for flight operations at night.
6. Investigated the use of Automatic Dependent Surveillance-Broadcast (ADS-B) as a SAAS.
7. Developed and implemented the first UAS Safety Management System (SMS).

1.4 Dissertation Organization

The dissertation is organized as follows. The research motivations and contributions are introduced in Chapter 1. Chapter 2 addresses the challenges of SUAS remote sensing methodology and the use of TIR and SWIR imagers. The effect of the BRDF on the accuracy of data collected by SUAS is analyzed in Chapter 3. The optimality of multispectral remote sensing is investigated in Chapter 4 with the development of a generalized framework with regards to spatial, spectral and temporal factors. Chapter 5 changes direction and discusses the safety challenges of the integration of UAS into the NAS. The development and implementation of a novel SMS specific for UAS operation management is discussed in Chapter 6. Finally, Chapter 7 concludes the dissertation with discussions of future research directions.