

UNIVERSITY OF CALIFORNIA, MERCED

**OPTIMAL REMOTE SENSING WITH SMALL
UNMANNED AIRCRAFT SYSTEMS AND RISK
MANAGEMENT**

by

Brandon Stark

B.S. Computer Engineering (University of California, Irvine, CA) 2007
M.S. Computer Engineering (University of Bridgeport, CT) 2010
M.S. Electrical Engineering (University of Bridgeport, CT) 2010

A thesis submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy

in

Individual Graduate Program with emphasis in: Electrical Engineering and
Computer Science

Committee in charge:
Professor YangQuan Chen, Chair
Professor Shawn Newsam
Professor Joshua Viers

©Spring 2017

Portions of Chapter 2 ©2014 IEEE, ©2015 IEEE, ©2016 John Wiley & Sons, Inc

Portions of Chapter 3 ©2016 IEEE

Portions of Chapter 4 ©2014 IEEE, ©2015 IEEE, ©2016 IEEE

Portions of Chapter 5 ©2012 IEEE, ©2013 IEEE, ©2014 IFAC, ©2015 IEEE

All other portions and chapters ©Spring 2017 Brandon Stark

All rights are reserved.

The thesis of Brandon Stark is approved:

Professor YangQuan Chen, Chair

Date

Professor Shawn Newsam

Date

Professor Joshua Viers

Date

University of California, Merced

©Spring 2017

to my wife, parents, and kittens.

ACKNOWLEDGEMENTS

The author would like to thank the multitude of contributors of the many components found within this work:

The great group at the Center for Self-Organizing and Intelligent Systems (CSOIS) at Utah State University for developing the AggieAir Minion, including Calvin Coopmans, Austin Jensen, Nathan Hoffer, Aaron Quitberg, and Tobias Fromm.

The ever rotating cast of graduate and undergraduate researchers at the Mechatronics Embedded Systems and Automation Lab contributed at every step, both big and small: Visiting scholars Zhou Li and Chun Yin; co-authors Brendan Smith, Sean Rider and Marwin Ko; undergraduate students who got stuck managing the lab, Brennan Stevenson, Nathaly Navarette, Huong Phan; undergraduate students who contributed data (both successful and less-successful): Andreas Anderson, Yoni Shchemelinin, Matt McGee, Forrest Yeh, and many many more

The overworked cast of employees at the UC Center of Excellence on Unmanned Aircraft System Safety: Alexis Garcia, John-Ronald Abad, Chris Reps and Jessica Palmer.

None of this would be possible without the guidance of the author's ever patient advisor, Dr. YangQuan Chen and the outstanding faculty at UC Merced who have been instrumental in these works: Dr. Joshua Viers, Dr. Shawn Newsam, and Dr. Nicola Lercari. The list would be incomplete without thanking the valuable support from Chris Swarth, Mo Kolster, and Erin Mutch who ensured access, support and training for flight operations in the Merced Vernal Pool and Grassland Reserve. The UC Center of Excellence on UAS Safety would not exist if it was not for the tireless efforts of Ken Smith, Brent Cooley, Al Vasquez and Cheryl Lloyd.

The work presented in this dissertation were supported by the Utah State University Water Research Lab, NSF Rapid (2011-2012) Award # NSF-IIS 1138632, NASA UAS2NAS (2011-2014) Grant # NNXAO77A, UC Merced School of Engineering, Center for Information Technology Research in the Interest of Society (CITRIS), The Nature Conservancy, Southern California Edison Fellowship, and the UC Center of Excellence on UAS Safety.

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

ACKNOWLEDGEMENTS	v
LIST OF FIGURES	xiv
LIST OF TABLES	xx
CURRICULUM VITAE	xxii
ABSTRACT	xxxii

Chapter

1 INTRODUCTION	1
1.1 Dissertation Roadmap	1
1.1.1 Unmanned Aircraft Systems	1
1.1.2 SUAS-Based Remote Sensing Applications	2
1.1.3 UAS Regulation History	4
1.1.4 UAS Safety and Management	6
1.2 Research Motivations and Approach	6
1.2.1 Lack of a General SUAS Remote Sensing Methodology	7
1.2.2 Sources of Error	7
1.2.3 Lack of Optimized Data Collection	7
1.2.4 Changes in UAS Safety and Risk Management	8
1.3 Dissertation Contributions	8
1.4 Dissertation Organization	8
2 SUAS-BASED MULTISPECTRAL REMOTE SENSING	

METHODOLOGY	10
2.1 Introduction	10
2.1.1 Methodology and Project Management	11
2.1.2 Formulaic Development	11
2.2 Small Unmanned Aircraft Systems and their Remote Sensing Applications	14
2.2.1 Small Unmanned Aircraft Systems	14
2.2.1.1 Fixed-wing SUAS	15
2.2.1.2 Rotary-wing SUAS	15
2.2.2 Core Concepts in SUAS Remote Sensing Applications	16
2.2.2.1 Detection/Counting Applications	16
2.2.2.2 Identification/Localization	18
2.2.2.3 Analysis	18
2.3 SUAS Imaging Equipment for Remote Sensing	20
2.3.1 Video Systems	20
2.3.2 Digital Cameras	22
2.3.3 Digital Cameras as Calibrated Imagers	24
2.3.4 Multispectral and Hyperspectral Imagers	26
2.4 Thermal Imagers for SUAS	27
2.4.1 Current TIR Applications	28
2.4.1.1 Detection	29
2.4.1.2 Identification	29

2.4.1.3	Analysis	30
2.4.2	TIR Imaging Equipment	31
2.5	Shortwave Infrared Imagers for SUAS	32
2.5.1	Current SWIR Applications	34
2.5.1.1	Detection	34
2.5.1.2	Identification and Analysis	34
2.5.2	SWIR Imaging Equipment	36
2.6	Common Advantages and Disadvantages of SUAS	37
2.6.1	Key Advantages	37
2.6.2	Challenges	38
2.6.3	Identifying the niche of SUAS	38
2.7	Chapter Summary	39
3	ANALYSIS OF DATA ACCURACY SUBJECT TO CAMERA FIELD OF VIEW AND SOLAR MOTION	40
3.1	Introduction	40
3.2	Angular Variation in Reflectance and the Bidirectional Reflectance Distribution Function	41
3.3	SUAS Remote Sensing Model	44
3.3.1	Selection of Subcomponent Reflectance Models	46
3.3.2	Validation of SUAS Remote Sensing Model	47
3.4	Methodology	48
3.5	Results	49
3.5.1	Analysis of Wide FOV	52
3.5.2	Analysis of Solar Motion	64
3.6	Chapter Summary and Implications to SUAS Remote Sensing	73
4	OPTIMAL MULTISPECTRAL REMOTE SENSING	

FRAMEWORK FOR SMALL UAS	75
4.1 Introduction	75
4.1.1 Optimality in Remote Sensing	75
4.1.2 Development of Optimization Criteria	76
4.2 Spatial Optimization	77
4.2.1 Image Resolution	78
4.2.2 Identification of the Object of Interest	79
4.3 Spectral Optimization	79
4.3.1 Spectral Sensitivity	79
4.3.2 Measurements of Spectral Response	82
4.3.3 Use of Shortwave Infrared as an optimal spectral solution . . .	83
4.3.3.1 Soil Moisture Measurements	83
4.3.3.2 Vernal Pool Identification and Analysis	85
4.4 Temporal Optimization	88
4.4.1 Optimal Image Collection to Minimize Shadowing	88
4.5 Optimizing Bird Counts using a TIR Camera at Night	91
4.5.1 Flight Coverage Optimization	92
4.5.2 Optimization of Time of Imagery Collection	97
4.6 Extending the Framework	101
4.7 Chapter Summary	102
5 CHALLENGES FOR THE INTEGRATION OF SMALL UNMANNED AIRCRAFT SYSTEMS INTO THE NATIONAL AIRSPACE SYSTEM	103
5.1 Introduction	103

5.2	Flight Operations at Night	106
5.2.1	Existing Regulations for Flight Operations at Night	107
5.2.1.1	Aircraft Lighting	107
5.2.1.2	Protocols and Pilot Requirements	109
5.2.2	SUAS Flight Operations at Night	109
5.2.2.1	Risk Assessment for Flight Operations at Night . . .	109
5.2.2.2	SUAS Lighting System	112
5.2.2.3	Protocols for Flight Operations at Night	116
5.2.3	Implementation and Regulatory Recommendations	118
5.3	Optimal SUAS Swarm Safety Management	121
5.3.1	Optimal Coverage	122
5.3.2	Distributed Coverage Control with Smart Health Balancing .	124
5.3.2.1	SUAS Vehicle Dynamics and Control	124
5.3.2.2	SUAS Health Management	124
5.3.3	Simulation Results	125
5.3.3.1	Scenario 1	126
5.3.3.2	Scenario 2	129
5.3.3.3	Scenario 3	130
5.3.3.4	Scenario 4	132
5.3.4	Analysis	133
5.4	The Implementation of ADS-B for SUAS	134
5.4.1	Conflict Detection and Resolution Principles	135
5.4.1.1	Air Safety Strategies	135
5.4.1.2	Sensing and Awareness Strategies for Manned Aircraft	136

5.4.1.3	Conflict Detection and Resolution Strategies	137
5.4.2	Sense and Avoid Systems	139
5.4.2.1	Sense and Avoid System Classifications and Metrics .	140
5.4.2.2	Automatic Dependent Surveillance - Broadcast . . .	140
5.4.3	Relevant ADS-B Regulations	141
5.4.3.1	Summary of SUAS Regulations	141
5.4.3.2	Regulations on ADS-B	142
5.4.4	Integration of ADS-B into SUASs	142
5.4.4.1	SUAS Specific Remarks and Observations	143
5.4.4.2	ADS-B Implementation Capabilities for SUAS . . .	144
5.4.4.3	Potential Implementations	145
5.4.5	Analysis	148
5.5	Human-SUAS Interaction Model	149
5.5.1	Human Factor Models	150
5.5.1.1	Human Factor Analysis and Classification System .	150
5.5.1.2	Four Stage Model of Human Information Processing	152
5.5.1.3	Automation Model	153
5.5.2	Human Performance Metrics	154
5.5.2.1	Cognitive Workload Factors	154
5.5.2.2	Cognitive Workload	155
5.5.2.3	Situational Awareness	156
5.5.2.4	Complacency	157
5.5.3	Human-SUAS Interaction Framework	158
5.5.4	Application of the Framework	159
5.6	Chapter Summary	159

6 SAFETY MANAGEMENT SYSTEMS IN UNMANNED

AIRCRAFT SYSTEMS	161
6.1 Introduction	161
6.2 Safety Management Systems	162
6.3 Safety Risk Management	164
6.3.1 Identifying Hazards	165
6.3.2 Analyzing and Controlling Risks	167
6.4 Safety Assurance	170
6.4.1 Performance Monitoring	171
6.4.2 UAS Management Process	171
6.5 Safety Policies and Privacy Considerations	175
6.6 Safety Promotion	175
6.6.1 Safety Culture	175
6.6.2 Training and Workshops	176
6.7 Chapter Summary	177
7 SUMMARY AND FUTURE WORK	179
7.1 Concluding Remarks	179
7.2 Future Challenges	180
7.2.1 The Sources of Error and the Challenges of Cross-Sensor Comparability	180
7.2.2 Multi-Aircraft Solutions for Optimal Multispectral Remote Sensing	180
7.2.3 Unmanned Traffic Management	181
BIBLIOGRAPHY	182
Appendix	
A LIST OF ABBREVIATIONS	200

B	FLIGHT OPERATIONS AT NIGHT	204
B.1	Safety Case for UAS Night Operations	205
B.2	COA 2014-WSA-193	217
C	UAS SAFETY MANAGEMENT SYSTEM DOCUMENTS	236
C.1	Hazard Identification Questionnaire	237
C.2	Risk Survey	251
C.3	Excerpt from UC Drones Web App	253
C.4	Best Practices for Privacy	267
C.5	Top 10 Hazards	268
C.6	Top 10 Safety Tips	269
C.7	Myths About Drones	270

LIST OF FIGURES

1.1	Aerial Imagery collected by SUAS.	3
2.1	AggieAir on runway.	15
2.2	Spectral Reflectance in the Visible and Near-Infrared Region. . . .	19
2.3	Frame of real-time video footage, Merced 2013.	21
2.4	Example Orthophoto from SUAS.	23
2.5	Example digital surface model with Hillshade added for clarity. . .	24
2.6	SUAS analysis workflow for converted digital cameras.	26
2.7	Short Wave Infrared (SWIR) Examples.	33
2.8	Comparison of electroluminescence (EL) of Solar Cells.	33
2.9	SWIR Quantum Efficiency.	37
2.10	Illustration of different spatial and temporal scales.	39
3.1	Viewing angle variation within an image.	42
3.2	Observer zenith angle variation.	43
3.3	Visualization of wavelength dependence.	44
3.4	SUAS Simulation Model.	45
3.5	Visual representation of BRDF in a polar plot.	47
3.6	Normalized Nadir Anistropy Factor.	48

3.7	Simulated aerial image highlighting the effect of camera FOV on red reflectance.	50
3.8	Simulated aerial image highlighting the effect of camera FOV on NIR reflectance.	51
3.9	Simulated aerial image highlighting the effect of camera FOV on NDVI.	52
3.10	Simulated aerial image highlighting the effect of camera FOV. . . .	53
3.11	Distribution of NDVI from satellite imagery.	54
3.12	Distribution of NDVI from SUAS imagery.	55
3.13	Comparison of Satellite and SUAS calculations of NDVI - C_{ab}	56
3.14	Comparison of Satellite and SUAS calculations of NDVI - LAI. . . .	57
3.15	Comparison of satellite and SUAS calculations of NDVI - C_{ab} + LAI. .	58
3.16	Comparison of satellite and SUAS relationships of C_{ab} and NDVI - C_{ab} variation.	59
3.17	Comparison of satellite and SUAS relationships of LAI and NDVI - LAI variation.	60
3.18	Comparison of satellite and SUAS relationships of LAI and NDVI - C_{ab} + LAI variation.	61
3.19	Mean error between satellite imagery and an increasing camera field of view (FOV).	62
3.20	Correlation fit between satellite imagery and an increasing camera FOV.	63
3.21	Comparison of satellite and SUAS relationships of LAI, NDVI and Image Zenith Angle.	64
3.22	Variation in NDVI from an SUAS - Flat - Full Day.	65

3.23	Variation in NDVI from an SUAS - C_{ab} - Full Day.	66
3.24	Variation in NDVI from an SUAS - LAI - Full Day.	67
3.25	Variation in NDVI from an SUAS - C_{ab} + LAI - Full Day.	68
3.26	Relationship between C_{ab} and NDVI in satellite and SUAS imagery - Full Day.	69
3.27	Relationship between LAI and NDVI in satellite and SUAS imagery - Full Day.	70
3.28	Boxplot of NDVI variance in the afternoon (12:30pm to 1:00pm). . .	71
3.29	Boxplot of NDVI variance in the morning (8:00am to 8:30am). . . .	72
3.30	Variation in NDVI correlation over a 30 minute interval.	73
4.1	Spectral Sensitivity for a Canon 600D Camera.	80
4.2	Spectral Sensitivity of standard filters of a Tetracam MINI-MCA6 Standard System.	81
4.3	Spectral Sensitivity of Landsat 8.	81
4.4	Example image of soil moisture data collection.	84
4.5	Reflectance of soil in SWIR.	85
4.6	Orthomap in Color.	86
4.7	Orthomap in NIR.	87
4.8	Orthomap in SWIR.	87
4.9	Reference NIR Image.	90
4.10	Time at which shadows are minimized for reference NIR image. . .	91
4.11	Flight Altitude and Ground Sampling Distance.	93

4.12	Acreage coverage per flight and image overlap.	94
4.13	Simulated distribution of sleeping bird length.	96
4.14	Simulated Images Set of Crane and Mallard.	97
4.15	Closeup on TIR Image from March 5th, 2015.	98
4.16	Closeup on TIR Image from Nov 13th, 2014.	99
4.17	Correlation between air and measured bird temperatures.	100
4.18	Correlation between water temperature and measured bird temperature.	101
5.1	Diagram of existing Aircraft Light Regulations §23.1383, §23.1385, §23.1387 and §23.1401.	108
5.2	Wingtip Lights, Underwing Lights and Tail Lights for Small Unmanned Aircraft System (SUAS).	112
5.3	Underwing lights parallel with leading edge of wing.	113
5.4	Underwing lights perpendicular with leading edge of wing.	113
5.5	Perspective view of underwing lights parallel with leading edge of wing.	114
5.6	Perspective view of underwing lights perpendicular with leading edge of wing.	114
5.7	Perspective view of underwing lights parallel with leading edge of wing with SUAS at 20° yaw.	114
5.8	Perspective view of underwing lights perpendicular with leading edge of wing with SUAS at 20° yaw.	115
5.9	Diagram of lighting system for a mechanically assisted launch. . . .	116
5.10	Diffusion control using four SUASs in a Centroidal Voronoi Tessellations (CVT) framework.	126

5.11	Plot of SUAS Health for four SUASs with an initial health of $h_i(0) = 0.80$ and normal degradation rate for Nominal.	127
5.12	Plot of SUAS Health for four SUASs with an initial health of $h_i(0) = 0.80$ and normal degradation rate for Smart Health Balancing (SHB).	128
5.13	Plot of the difference between SUAS health and mean health for Nominal.	128
5.14	Plot of the difference between SUAS health and mean health for SHB.	129
5.15	Plot of SUAS Health for four SUASs with an initial health of $h_i(0) = 0.80$ and double degradation rate for SUAS 4 for Nominal.	130
5.16	Plot of SUAS Health for four SUASs with an initial health of $h_i(0) = 0.80$ and double degradation rate for SUAS 4 for SHB.	130
5.17	Plot of SUAS Health for three SUASs at $h_i(0) = 0.80$ and SUAS 4 at $h_4(0) = 0.60$ for Nominal.	131
5.18	Plot of SUAS Health for three SUASs at $h_i(0) = 0.80$ and SUAS 4 at $h_4(0) = 0.60$ for SHB.	131
5.19	Plot of SUAS Health for four Unmanned Aircraft Systems (UASs) with an initial health of $h_i(0) = 0.8$ and a 0.3 health impact for SUAS 4 for Nominal.	132
5.20	Plot of SUAS Health for four UASs with an initial health of $h_i(0) = 0.8$ and a 0.3 health impact for SUAS 4 for SHB.	133
5.21	Layered approach for collision avoidance.	135
5.22	Recommended minimum see and avoid scanning range for PICs.	136
5.23	Visualization of UAS collision avoidance shells.	139
5.24	Representation of SUAS with ADS-B (In/Out).	146
5.25	Representation of GCS with ADS-B (In/Out).	146

5.26	Representation of SUAS with ADS-B Out, GCS with ADS-B In. . .	146
5.27	Representation of GCS with ADS-B In Only.	147
5.28	Representation of SUAS with ADS-B In Only.	147
5.29	The ‘Swiss Cheese’ model of accident causation.	151
5.30	Block diagram of four stage model of information processing. . . .	152
5.31	Levels of Automation for SUAS CGS Operator.	154
5.32	Cognitive Workload Profile of a UAS Ground Control Operator. . .	156
5.33	Human-SUAS Interaction Framework.	158
6.1	Safety Management System.	162
6.2	Enterprise Risk Management and the Risk Management Process. .	164
6.3	The SHELL hazard model.	166
6.4	Safety risk matrix example.	167
6.5	Example risk analysis from leading indicators.	169
6.6	Safety risk management and safety assurance processes.	170
6.7	UAS flight operations process.	172
6.8	Occurance of UAS risk analysis escalation.	173
6.9	Venn diagram of legal and safety requirements.	174
6.10	UC UAS Usage and common aircraft.	178

LIST OF TABLES

2.1	Sampling of TIR SUAS Application Publications.	28
2.2	Available TIR cameras.	31
2.3	Satellite SWIR Bands between 1.2 - 2.3 μm	35
3.1	Parameters in SUAS Simulation Model	45
3.2	The variation of NDVI in the simulation sets due to wide FOV. . .	54
4.1	Optimality Criterion Arguments.	76
4.2	Common Vegetation Indices.	82
4.3	Estimated Bird Characteristics.	95
4.4	Various average temperatures as measured from TIR imagery. . . .	99
5.1	Compilation of safety issues described in literature.	104
5.2	Pre-Flight Preconditions.	110
5.3	Launch & Recovery Operations.	110
5.4	Standard Mission Operation.	110
5.5	Relevant Federal Aviation Regulations.	120
5.6	Time for first SUAS to reach $h_i(t) = 0.4$	133
5.7	Recognition and reaction times for PICs.	137
5.8	Automation levels.	153

5.9	Summarization of Cognitive Load Theory.	155
6.1	Example key indicators for hazard identification.	168
6.2	Example UAS leading and lagging indicators.	171
6.3	Escalation Definitions.	173

CURRICULUM VITAE

Brandon Stark

(Last Updated: March 12th, 2017)

Contact Information

667 Sonora Ave
Merced, CA 95340
bstark2@ucmerced.edu

Education

- 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
- 2003 - 2007 **Bachelor of Science in Computer Engineering**
Minor: Art History
University of California, Irvine

Employment History

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

Led the creation of a new department within the University of California, Office of the President in the Office of Risk Services dedicated to managing risk and safety for Unmanned Aircraft Systems across the University of California. Developed UC systemwide policies for UAS activity, developed a UC UAS Safety Management System, implemented effective tracking mechanisms for enterprise risk management and safety assessments.

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)

School of Engineering, University of California, Merced

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

Founding manager. Managed all aspects of the Mechatronics, Embedded Systems and Automation Lab including lab safety, lab hiring, project management, research management, purchasing and inventory control. Developed and conducted a wide range of research projects, including those aimed at mentoring undergraduates. Developed outreach activities, and hosted high profile seminars. Grew membership to 80 undergraduate students.

2010 - 2012

Graduate Student Researcher (GSR)

CSOIS, School of Engineering, Utah State University

Developed and implemented Unmanned Aerial Systems, including autopilot development for fixed-wings and rotary wings, human-factors of UASs and safety systems for UASs. Managed inventory control.

2007 - 2010

Graduate Student Teaching Assistant (TA)

School of Engineering, University of Bridgeport

Developed the curriculum and taught for several lab sections, including analog circuits, digital logic II and FPGA design.

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)
- Member, ASME (American Society of Mechanical Engineers)
- Member, AUVSI (The Association for Unmanned Vehicle Systems International)
- Member, URMIA (University Risk Manager and Insurance Association)

Teaching

Teaching Experience abridged to only UC Merced

Instructor of Record, Primary Lecturer

ME142 Mechtronics (4 units) - Junior level technical elective (Spr 2016)

Lab Teaching Assistant Experience

ME142 Mechatronics (4 units) - Junior level technical elective (Spr 2013, Spr 2014, Spr 2015)

Invited Lectures

ENG065 Circuits - Passive Filters (Fall 2012, Spr 2013, Fall 2013, Spr 2014, Fall 2014)

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
- 2014 - UC Merced Leadership Award Finalist - Outstanding Graduate Student
- 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)
- UC Merced Graduate Representative: University of California, Council of Presidents (2014-2015)
- Graduate Student Representative: Academic Senate Committee - Graduate Council (2014-2015)
- Graduate Student Representative: Graduate Student Committee on Research (2014-2015)
- Graduate Student Representative: Graduate Student Social Committee (2014-2015)
- Graduate Student Representative: Graduate Student Professional Advancement Initiative (2014)
- Graduate Student Representative: Vice-Chancellor for Administration Student Advisory Board (2012-2013, 2014-2015)
- Graduate Student Representative: Search Committee for Dean of the School of Engineering (2014-2015)
- Graduate Student Representative: Research Week Advisory Board (2013-2015)
- Graduate Student Representative: Academic Senate Committee CAPRA (2014)
- Graduate Student Representative: Academic Senate Committee Committee on Research (2013)
- Academic Representative: Buhach Colony High Engineering Advisory Board (2013-2014)
- Graduate Student Association: Secretary (2013-2014)
- Graduate Student Representative: Transportation and Parking Services Advisory Board (2013-2014)

Workshops Presented

1. B. Stark, Understanding Risks and Safety for Drones, Workshop in: Bay Area Community College Symposium, Hayward, California, USA, January 9 2017.
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.
6. B. Stark, Z. Li, B. Smith, Y. Chen, Personalizing Mechatronics Education Utilizing an Open-Source Real-Time Control System Rapid Prototyping Platform, Half Day Tutorial in: ASME IDETC MESA2013, Portland OR, USA, August 3 2013.
7. B. Stark, Y. Chen, 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, ECC 2013, Organizers: Youmin Zhang, Camille Alain Rabbath, YangQuan Chen, Christopher Edwards, Cameron Fulford, Hugh H.-T. Liu, Liang Tang, Didier Theilliol, and Antonios Tsourdos, Zurich, Switzerland, July 16, 2013.
8. C. Coopmans, B. Stark, A. Jenson, Y. Chen, SUAS Airworthiness, Architecture and Human Factors, Half Day Tutorial in International Conference on Unmanned Aircraft Systems 2013, Atlanta, GA, USA, May 28 2013.
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

1. B. Stark, N. Niravanh, S. Hendershot, Drones in the University of California: Mitigation of Risks through Collaboration and Shared Resources, Western Regional Conference of University Risk Managers and Insurance Association, Tucson, Arizona, USA, March 22 2017.

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.
13. B. Stark, UASs in Academia, VCUAS Alliance R&D, California State University, Channel Islands, Camarillo, California, May 13 2013.
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.
2. B. Stark, C. Coopmans, Y. Chen, Concept of Operations of Small Unmanned Aerial Systems: Basis for Airworthiness Towards Personal Remote Sensing, in: K. Valavanis (Ed), Handbook of Unmanned Aerial Vehicles, Springer 2013. 18 pages.
3. C. Coopmans, B. Stark, A. Jenson, Y. Chen, Mac McKee, Cyber-Physical Systems Enabled by Small Unmanned Aerial Vehicles, in: K. Valavanis (Ed), Handbook of Unmanned Aerial Vehicles, Springer 2013. 18 pages.
4. B. Stark, Y. Chen and M. KcKee, AggieVTOL: A Vertical Take Off and Landing Unmanned Aerial Vehicle Platform for Personal Remote Sensing, in: T. Sobh, X. Xiong, Prototyping of Robotic Systems: Applications of Design and Implementation, IGI Global Press 2012, 35 pages.

Journal Papers

1. S. Hogan, M. Kelly, B. Stark, Y. Chen, Unmanned Aerial Systems in Agriculture and Natural Resources, California Agriculture 71 (5) (2017) 5-14.
2. C. Yin, B. Stark, Y. Chen, S. Zhong, E. Lau, Fractional-order Adaptive Minimum Energy Cognitive Lighting Control Strategy for the Hybrid Lighting System, Energy and Buildings 87 (1) (2015) 176-184.
3. C. Yin, B. Stark, Y. Chen, S. Zhong, Adaptive Minimum Energy Cognitive Lighting Control: Integer Order vs Fractional Order Based on Extremum Seeking, Mechatronics 23 (7) (2013) 863-872.
4. B. Stark, C. Coopmans, Y. Chen, Concept of Operations for Personal Remote Sensing Unmanned Aerial Systems, Journal of Intelligent and Robotic Systems, (2012).

5. Z. Li, N. Hoffer, B. Stark, Y. Chen, Design, Modeling and Validation of a T-tail Unmanned Aerial Vehicle, *Journal of Intelligent and Robotic Systems*, (2012).
6. A. Abuzneid, B. Stark, Improving BGP Convergence Time via MRAI Timer, *Novel Algorithms and Techniques in Telecommunications and Networking*, (2010) 105-110.

Conference Papers

1. B. Stark, Y. Chen, A framework of optimal remote sensing using small unmanned aircraft systems' in: *Proc. of the 12th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA)*, Auckland, New Zealand. August 29-31, 2016.
2. T. Zhao, B. Stark, Y. Chen, A. Ray, D. Doll, Challenges in water stress quantification using small unmanned aerial systems (sUAS): Lessons from a growing season of almond, in: *Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2016)*, Arlington, Maryland, USA. June 7-10, 2016.
3. B. Stark, T. Zhao, Y. Chen, An Analysis of the Effect of the Bidirectional Reflectance Distribution Function on remote sensing accuracy from Small Unmanned Aircraft Systems, in: *Proc. of the Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2016)*, Arlington, Maryland, USA. June 7-10, 2016.
4. B. Smith, G. John, B. Stark, L. Christensen, Y. Chen, Applicability of Unmanned Aerial Systems for Leak Detection, in: *Proc. of International Conference on Unmanned Aerial Systems (ICUAS2016)*, Arlington, Maryland, USA. June 7-10, 2016.
5. B. Stark, M. McGee, Y. Chen, Short Wave Infrared (SWIR) Imaging using Small Unmanned Aerial Systems (sUAS), in: *Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2015)*, Denver, Colorado, USA. June 9-12, 2015.
6. B. Stark, B. Smith, N. Navarrete, Y. Chen, Airworthiness and Protocol Development for Safe Night Flying Missions for Small Unmanned Aerial Systems (sUASs), in: *Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2015)*, Denver, Colorado, USA. June 9-12, 2015.
7. B. Smith, B. Stark, T. Zhao, Y. Chen, An Outdoor Scientific Data Drone Ground Truthing Test Site, in: *Proc. of the International Conference on*

Unmanned Aircraft Systems (ICUAS2015), Denver, Colorado, USA. June 9-12, 2015.

8. T. Zhao, B. Stark, Y. Chen, A Detailed Field Survey of Direct Correlations Between Ground Truth Crop Water Stress and Normalized Difference Vegetation Index (NDVI) from Small Unmanned Aerial System (sUAS), in Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2015), Denver, Colorado, USA. June 9-12, 2015.
9. M. Ko, B. Stark, Y. Chen, An Evaluation of Hurst Parameter Estimation for Differentiating Between Normal and Abnormal Heart Rate Variability, in: Proc of ASME/IEEE Conference on Mechatronics and Embedded Systems and Applications (MESA 2015), Boston, Massachusetts, USA. August 2-5, 2015.
10. B. Stark, B. Smith, Y. Chen, Survey of Thermal Infrared Remote Sensing for Unmanned Aerial Systems, in: Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2014), Orlando, Florida, USA. May 27-30, 2014.
11. B. Stark, Y. Chen, Optimal Collection of High Resolution Aerial Imagery with Unmanned Aerial Systems, in: Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2014), Orlando, Florida, USA. May 27-30, 2014.
12. B. Stark, B. Stevenson, K. Stow-Parker, Y. Chen, Embedded Sensors for the Health Monitoring of 3D Printed Unmanned Aerial Systems, in: Proc. of the International Conference on Unmanned Aircraft Systems (ICUAS2014), Orlando, Florida, USA. May 27-30, 2014.
13. B. Stark, B. Smith, Y. Chen, in: A Guide to Selecting Small Unmanned Aerial Systems for Scientific Research Applications, in: Proc. of Research, Education and Development of Unmanned Aerial Systems (RED-UAS), Compiegne, France. November 20, 2013.
14. B. Stark, S. Rider, Y. Chen, Optimal Pest Management by Networked Unmanned Cropdusters in Precision Agriculture: A Cyber-Physical System Approach, in: Proc. of Research, Education and Development of Unmanned Aerial Systems (RED-UAS), Compiegne, France. November 20, 2013.
15. B. Stark, B. Smith, Z. Li, Y. Chen, Take Home Mechatronics Control Lab: A Low-Cost Personal Solution and Educational Assessment, in: Proc. of ASME/IEEE Conference on Mechatronics and Embedded Systems and Applications (MESA 2013), Portland, Oregon, USA. August 4-7, 2013.

16. B. Stark, T. Patel, Y. Chen, HRV Monitoring for Human Factor Research in UAS, in: Proc. of ASME/IEEE Conference on Mechatronics and Embedded Systems and Applications (MESA 2013), Portland, Oregon, USA. August 4-7, 2013
17. C. Yin, Z. Li, B. Stark, Y. Chen, Minimum Energy Cognitive Lighting Control: Stability Analysis and Experiments, in: Proc. of ASME/IEEE Conference on Mechatronics and Embedded Systems and Applications (MESA 2013), Portland, Oregon, USA. August 4-7, 2013.
18. B. Stark, B. Stevenson, Y. Chen, ADS-B for Small Unmanned Aerial Systems: Case Study and Regulatory Practices, in: Proc. of International Conference on Unmanned Aircraft Systems (ICUAS 2013), Atlanta, Georgia, USA. May 27-30, 2013.
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.
20. C. Coopmans, B. Stark, C. Coffin, A Payload Verification and Management Framework for Small UAV-Based Personal Remote Sensing Systems, in: Proc. of the 2012 Int. Symposium on Resilient Control Systems (ISRCS2012), Salt Lake City, Utah, USA. August 2012.
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 discusses 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 (AU-VSI), 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 range-land 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.

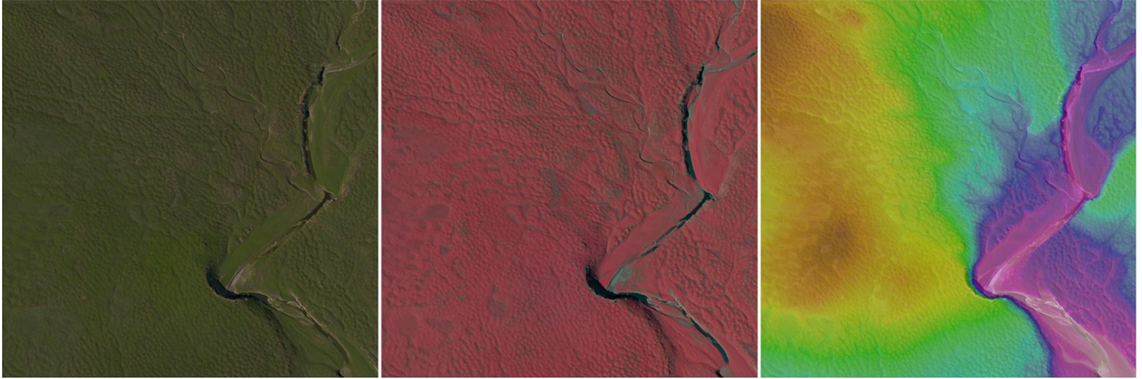


Figure 1.1: Aerial Imagery collected by SUAS over Merced Vernal Pool and Grassland Reserve, March 4th, 2015. (a) Color (b) False Color NIR Composite (c) Elevation Map

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.