http://c-uas.org

C-UAS

CENTER FOR UNMANNED AIRCRAFT SYSTEMS

The Center for Unmanned Aircraft Systems

National Science Foundation
Industry/University Cooperative Research Program

Highlights

- Significant growth over past year
- New University Research Site
  - Michigan
- Industry Members
  - 30+ total memberships

C-UAS

The National Science Foundation

Center for Unmanned Aircraft Systems

NSF

C-UAS

BYU

CU

VIRGINIA TECH

UNIVERSITY OF MICHIGAN

Industry Members

facebook

bp

BOEING

GE Aviation

NASA

NORTHROP GRUMMAN

NOAA

United Technologies Research Center

L3

TEXTRON Systems CIVIL & COMMERCIAL

NAWC

Aurora FLIGHT SCIENCES

ARL

U.S. DEPARTMENT OF ENERGY

ARDEC ARMAMENTS

UTOPIACOMPRESSION

U.S. DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION

National UAS Training and Certification Center

ALTADEVICES

AV aerovironment

Raytheon

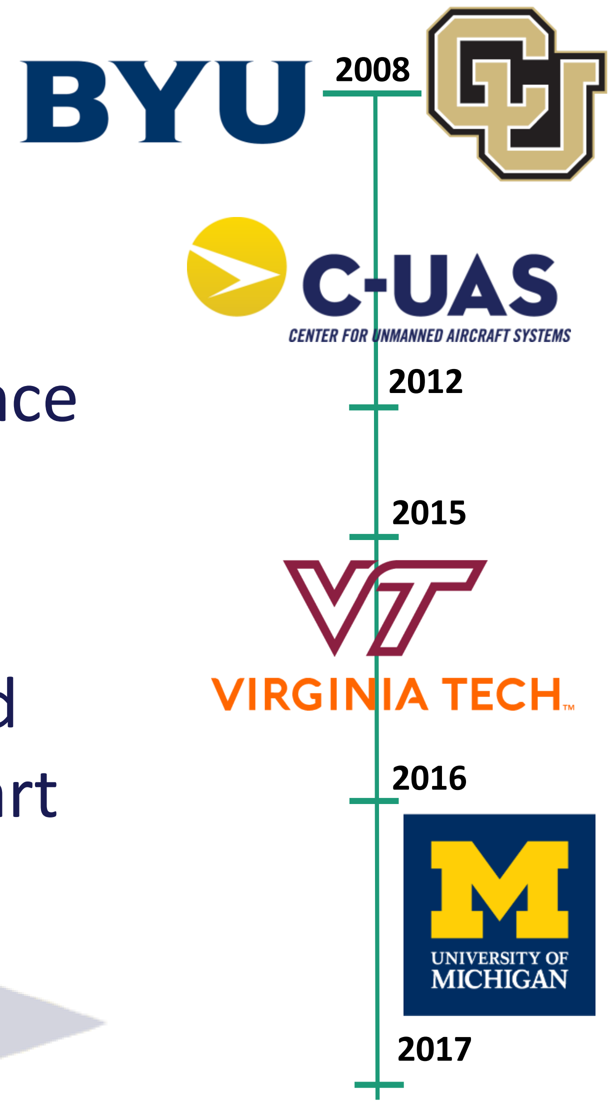
Honeywell Aerospace

INSITU

AFRL THE AIR FORCE RESEARCH LABORATORY

Background

- BYU/CU started discussions about forming UAS center in 2008
- C-UAS established in Mar 2012
- IAB meetings held semi-annually since Jun 2012
- VaTech joined as site in Sep 2015
- Michigan site planning meeting held Oct 2016 – Sep 2017 anticipated start
- Michigan Site Addition approved by NSF July 2017



What is C-UAS?

- C-UAS: Center for Unmanned Aircraft Systems
- *Only* National Science Foundation sponsored unmanned aircraft research center
- I/UCRC: Industry/University Cooperative Research Center
- Objective: Bring together university and industry researchers to collaborate on research
- Mission: Innovation beyond integration
- Who can join? Industry, Government, Academia

Leveraging Membership

Research Funding:

- NSF Funding = $80K + $55K + $65K + $200K + $54K+ $200K = $654K
- Membership funds = $290K + $200K + $200K= $690K
- University waived overhead = $145K + $120K + $100K = $365K
  - Value of space, software tools, hardware tools, facilities, etc.
- $44K membership provides access to $2.2M of research/resources
  - *More if administrative resources considered

Leverage Factor: 50

This will increase proportionally with additional universities

NSF I/UCRC Program Highlights

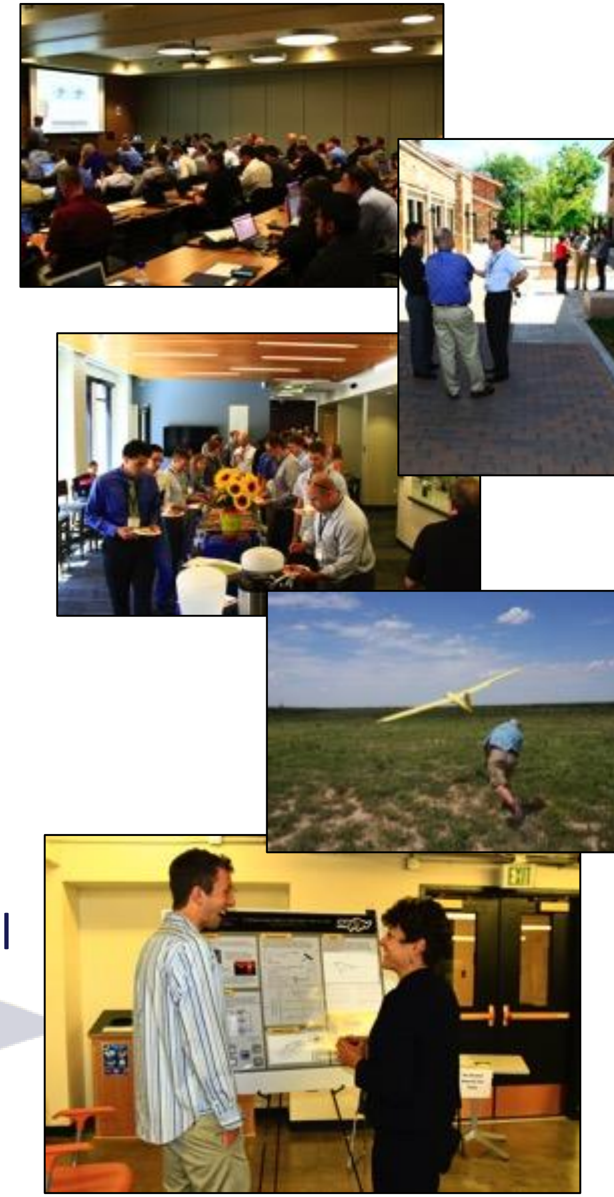
- Established in 1980
- 77 centers, 214 sites currently
- 1166 industry memberships
- Average of 18 industry members per center
- Largest - $14M, Mean - $2.1M, Smallest - $150K

Well established, proven, highly successful program

C-UAS

I/UCRC Model

- Center is consortium of organizations with common research interest
- Funding from members is highly leveraged
- **Shared research portfolio** of pre-competitive technologies
- Collective ownership**, collective decision making**
- Research driven by ideas of industry advisory board (IAB)
- Focus shift
  - Problems facing company to problems facing UAS industry
  - Short-term narrow IP to long-term fundamental research
  - Single organization to multiple organization



C-UAS

C-UAS Vision Statement

Core Purpose

To provide innovative solutions to key technical challenges and superb training for future leaders in the unmanned aircraft systems industry.

Core Values

- Commitment to provide value to our industry members.
- Dedication to the mentoring of students within the center, providing them with outstanding opportunities for research and scholarly development.
- Commitment to collegiality and cooperation among faculty, students, and industry members.
- Alignment with NSF I/UCRC program objectives.

C-UAS Vision Statement

Envisioned Future

- Our students will receive world-class training that is relevant to the UAS industry. Many of them will become recognized leaders in the UAS industry.
- Our scholarship will be recognized as excellent and will set trends within the UAS industry.
- Our industry members will be delighted to be a part of our center and will readily share their enthusiasm for the center with their peers in industry. They will be actively engaged in the work of the center.
- Research outcomes that are of value to our members will be created within the center and our members will regularly utilize the work of the center.
- C-UAS will be a model center within the NSF I/UCRC program.
- The center will be a catalyst for other funding and research opportunities, both within and outside NSF.
- The top university researchers in the UAS field will seek to be a part of our center.
- The top companies and research organizations in the UAS field will be members of our center.
- Our university and industry members will come from a broad range of disciplines and domains involved in UAS.

University Sites

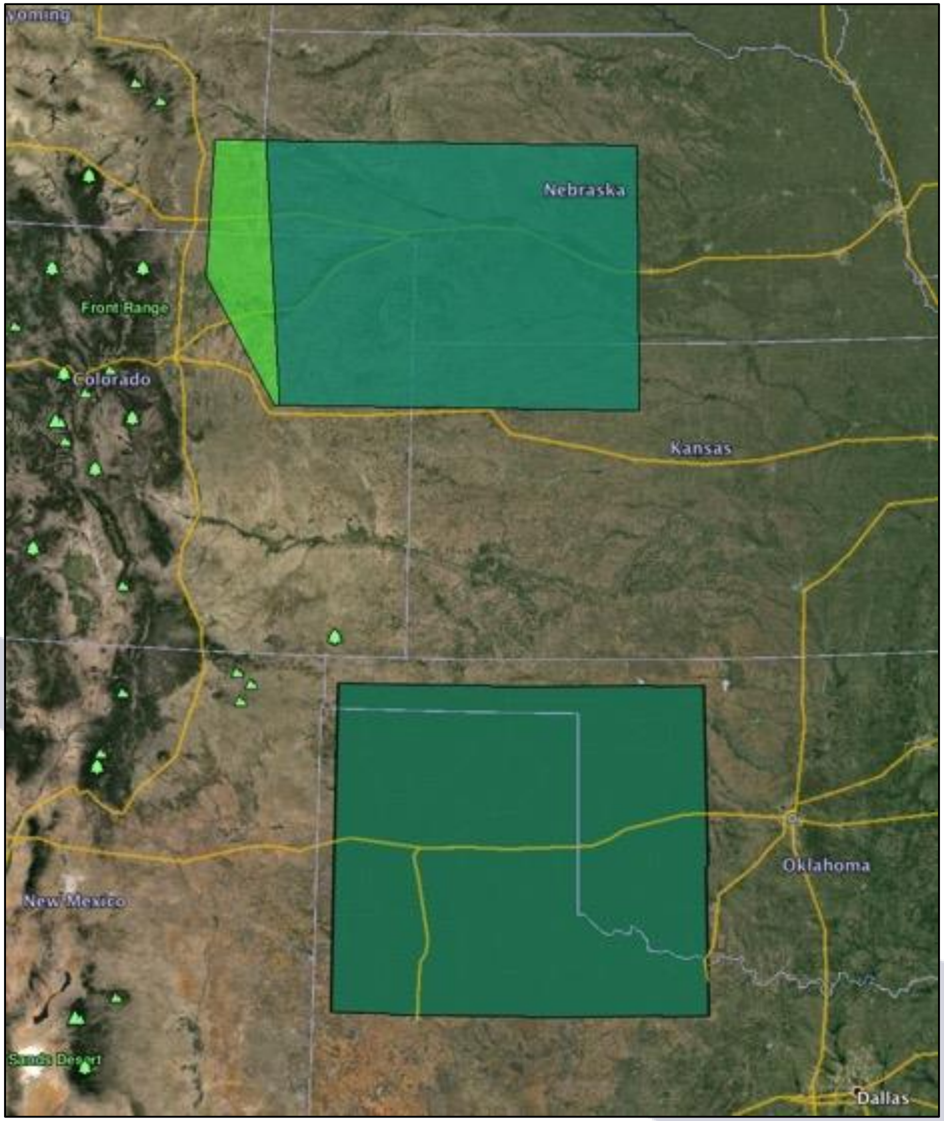
BYU

UNIVERSITY OF MICHIGAN

C-UAS

VIRGINIA TECH

Access to Airspace



Certificates of Authorization (COAs) for over 100,000 sq-mi of airspace

Virginia Tech is directly affiliated with the MAAP FAA test site.

What is the Research?

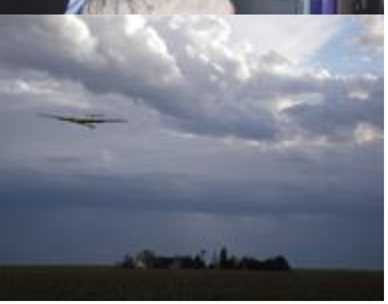
- Fundamental, pre-competitive investigations that complement internal R&D activities of participants
- Determined by industry members
  - Combination of researcher expertise and industry member needs
  - Yearly Industry Advisory Board (IAB) meeting used to allocate research funds to projects based on center member votes

What We Are Not

- We are not like an FAA Center of Excellence
  - Research is determined directly by center membership, not the funding agency
  - Focused on more than integration into the NAS
- We are not like an FAA Test Site
  - No need to commercialize our activity
  - We have access to the MAAP test site and other facilities, with full FAA approval for stationary and nomadic concepts of operation







Current Research

CU17-01: Robust Communication Services in Complex Environments
CU17-02: sUAS Communications and Navigation in the NASA UTM
CU17-03: Active Collaborative Sensing, Learning and Planning with Humans in UAS
CU17-04: CUAS Distributed Sensing for Small UAS Turbulence and Gust Measurements
CU17-05: User-Adaptive Assurances for Enhancing Trust
CU17-06: Verification & Validation of Autonomous Systems: Systematic Quantification of Failure Risks
CU17-07: Robust Fault Detection and Mitigation for Small UAS
CU17-08: Path Following and Advanced Maneuvers for Small Fixed-wing UAS in Wind
CU17-09 CUAS Small UAS Turbulence and Gust Modeling in a Wind Tunnel

BYU17-01: Robust Target Tracking using Teams of Small UAS with Human in the Loop
BYU17-02: Navigation in Cluttered Terrain with Intermittent/Degraded GPS
BYU17-04: s-UAV-based Infrastructure Monitoring: Multi-Scale Flight Optimization
BYU17-05: Robust Moving Target Handoff in GPS Denied Environments
BYU17-06: Optimization of Heterogeneous Group of Vehicles for Achieving Multiple Mission Level Objectives
BYU17-07: Electronically-Steered Arrays (ESAs) for Onboard UAS Satellite Communications
BYU17-08: Probabilistic Programming for Perceptually Driven Autonomous Agents

Joint BYU-VT 17-01: Small Aircraft Flight Encounters (SAFE) Data Repository
Joint BYU-CU 17-02: Multiple Aircraft Sensing System (MASS)





Current Research

VT17-01: UAV/UGV Cooperative Classification for Online UGV Route Planning and Localization

VT17-02: Agile Autopilot Control for Infrastructure Inspection

VT17-03: Security Aware Control Algorithms for Unmanned Aircraft Systems

VT17-04: Autonomy Test & Evaluation, Verification & Validation (ATEVV): An Exploratory Case Study of Motion Planning and Control

VT17-05: Synthesis of Formally Specified, Configurable Hardware Monitors for Flight Control Software

VT17-06: Intelligent Visual Tracking System for Small UAS

VT17-07: UAV/UGV Radiological Search, Classification and Localization

UM17-01: Very Flexible UAS for Aeroelastic Data Collection and Control Development

UM17-02: Emergency Flight Planning with IoT and Onboard Sensor Data used in Decision Making

UM17-03: Exploring Vulnerabilities in Multi-UAV Systems for Swarm Defense: A Control-Theoretic Approach

UM17-04: Simulation of Individual and Swarms of UAS through Realistic Atmospheric Conditions

UM17-05: Electronic Geofencing Guidance and Control with UAS Traffic Management (UTM)

Past Research

Finished Projects

CU1203: Emerging sUAS In-situ Sensing Technology
CU1401: Information and Distributed Optimization
CU1406: Guidance and Control of a Communication Relay
CU1503: Proximity Sensing for sUAS Applications
CU1515: Path Following and Advanced Maneuvers for Small Fixed-Wing UAS in Wind

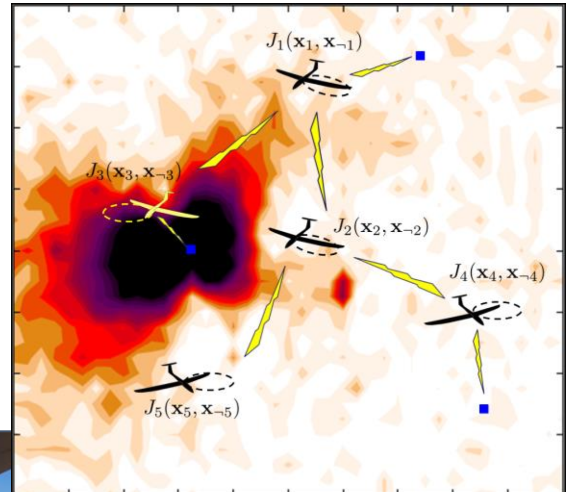
BYU1202: Compact, Efficient Antennas for UAS Applications
BYU1203: Minimizing Operator Workload and Maximizing Operator Usefulness
BYU1205: Reactive Path Planning with Applications to Sense and Avoid
BYU1301: SAA for Small UAS-Avoidance Planning
BYU1302: SAA for Small UAS-Radar Sensing

Current Projects

Robust Communication Services in Complex Environments

(CU 17-01) Eric Frew

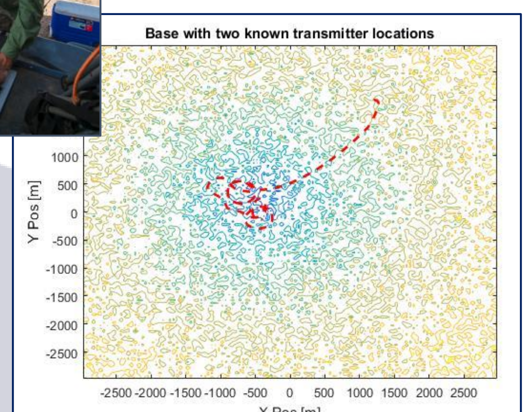
- **Project Goal**: <u>assess</u> the stochastic optimal control and machine learning applied to the <u>coordinated control</u> of unmanned aircraft <u>providing communication services.</u>



- **Technical Approach**
  - Develop RF communication simulation capability
  - Integrate low-cost software defined radio
  - Implement FAT-GP transfer learning
  - Design distributed waypoint placement algorithms
  - Flight test assessment

- **Current Results**
  - Hybrid RF model created based on irregular terrain model (ITM) and Gaussian processes (GP)
  - Waypoint placement and local guidance laws designed

- **Next Steps**
  - Implement spectrum characterization hardware on UAS
  - Implement hybrid model onboard aircraft
  - Field experiments in July/August 2017

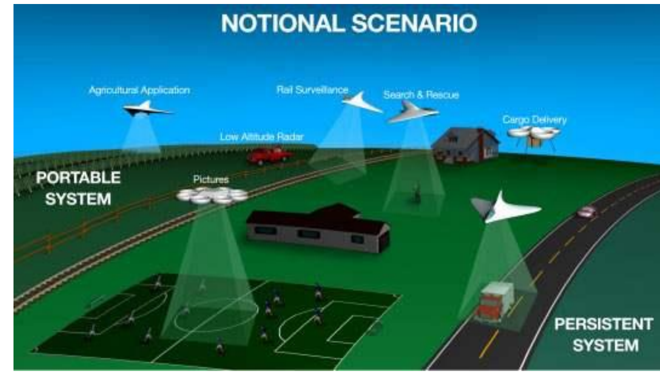


Trajectory of UAS moving to optimal relaying location.

sUAS Communications and Navigation in the NASA UTM

(CU 17-02) Brian Argrow, Dale Lawrence, Eric Frew

Project Goal: Formalize, demonstrate **Safety Risk Management (SRM)**, **Safety Assurance (SA)** processes for sUAS design, concepts of operations, actual flight operations for emerging airspace structure and rules



NASA UTM Concept

Technical Approach

- Develop spreadsheet tool to classify sUAS based on performance prior to SRM analysis
- Implement UTM client for agency-led technology developments/procedures
- Prototype concept-to-flight experiments to implement latest sUAS technologies (e.g., ADS-B)
- Close loop with SA to modify SRM processes based on flight-operations data, UTM, FAA rules

Main Result

- Collaboration opportunity with National Center for Atmospheric Research (NCAR) to investigate requirements for advisories for sUAS operations in weather

Active Collaborative Sensing, Learning, and Planning with Humans in UAS

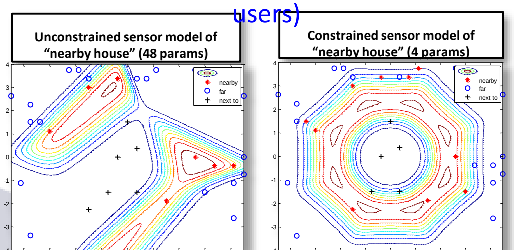
(CU 17-03) Nisar Ahmed

- Humans = *taskable* info providers for UAS (not just info consumers)
  - neither oracles nor disturbances
  - valuable but constrained resources

How to model "soft sensors"?
How/when to task?

Goal: *Proactive cooperative sensing* for enhanced human+ UAS information gathering (search and rescue, ISR, monitoring…)

Structured probabilistic modeling of semantic human sensor data (adapt to multiple scales, contexts, users)



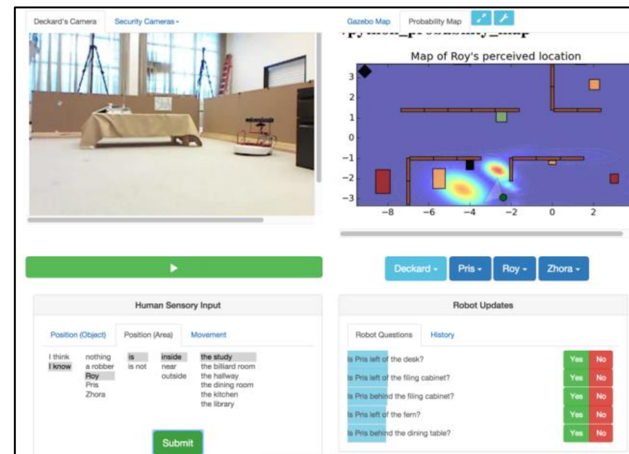
Robotic Search Planner: Robot sensor and dynamics models

Querying AI: Human sensor and task engagement models

Do you see anything?

Information Fusion

Yes, something moving nearby that house



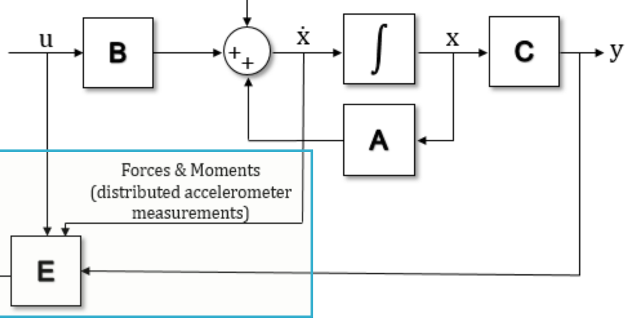
"Cops and Robots" experimental testbed for dynamic indoor target search (ROS/Gazebo + custom Python libraries, iRobot Create ground robots + networked cameras +MoCap hardware)

Value of Information (VOI)- based querying of semantic human sensors ("20 questions"-style semantic human-autonomy dialogue interface for human operator to aid autonomous robot during target search mission)

Small UAS Turbulence Measurement, Modeling, and Mitigation *(CU17-04) Sean Humbert, Brian Argrow, Emily Ranquist*

Objectives

- Use distributed accelerometers to estimate the translational and rotational forces and moments on a Mini Talon UAS
- Develop a gust velocity estimator using the instantaneous forces and moments, inputs, and outputs of the aircraft dynamic model
- Use gust estimator to generate the power spectra for low altitude (<400 feet) sUAS flights



Approach

- Distribute accelerometers along rigid body frame attached to aircraft
- Produce dynamic model for aircraft using System Identification
- Use model to simulate aircraft in presence of known gusts
- Develop gust velocity estimator and compare to known gusts from simulation
- Use gust estimator in low-altitude sUAS flights
- Develop power spectra using gust velocity data

Milestones

- Development of dynamic model for Mini Talon
- Integrate distributed acceleration sensors with Mini Talon airframe
- Design of dynamic gust velocity estimator using forces and moments
- Experimental flight testing
- Power spectrum development using flight data

User–Adaptive Assurances for Enhancing Trust

(CU 17-05) Eric Frew, Brian Argrow, Dale Lawrence, and Nisar Ahmed

This project will assess concepts of assured autonomy from the perspective of the new certification standards for UAS integration that will need to be developed in order to be consistent with the behavior characteristics (non-determinism, complexity, adaptability, etc.) of these emerging frameworks.

Goals:

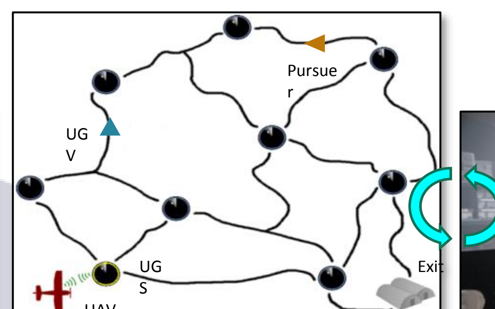
- better understanding of role autonomy can play in key UAS applications, with emphasis on **safety, certification, and trust**
- Identify promising autonomy technologies and map to associated application opportunities
- Develop platform and strategy for experimental assessment of autonomy technologies

Approach:

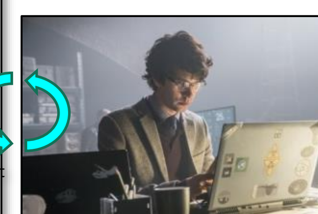
- machine's **"self-confidence"** as possible assurance
- *perceived* ability to execute assigned tasks autonomously *despite uncertainties in: knowledge of world, own state, and own reasoning process and execution abilities*
- seek practical ways to self-assess/-report based on probabilistic reasoning for planning/perception
- Application: autonomous pursuit-evasion escort problem

Hypothesis:

Trust can be enhanced by richer, more **insightful assurances from autonomy about internal processes**



Remote Analyst

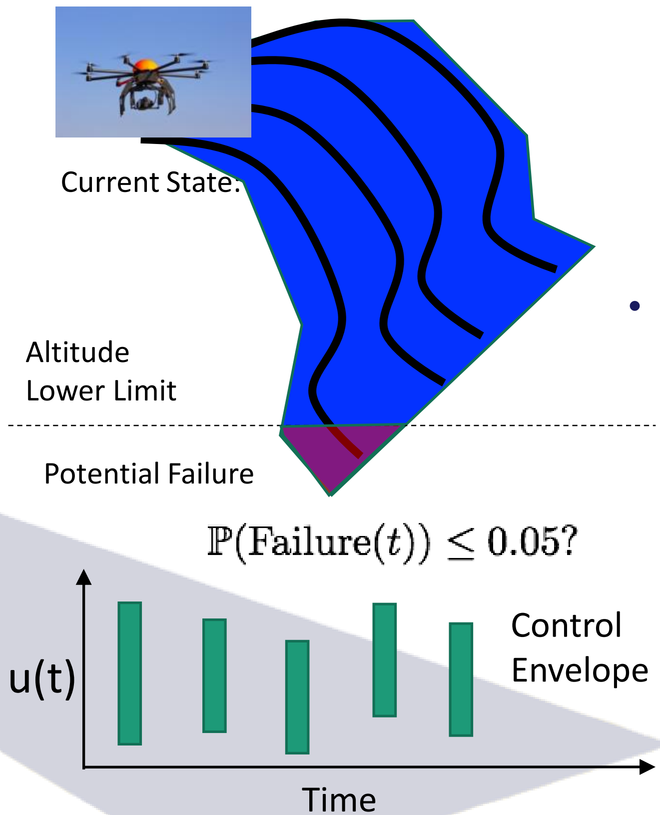


Verification and Validation of Autonomous Systems: Systematic Quantification of Failure Risks

(CU17-06) Sankaranarayanan and Frew

- Formal approach to predictive quantification of failure risks.
  - Describe failures as temporal properties in rich logical specification formalisms.
  - Combine ideas from MPC and runtime monitoring to efficiently monitor failures in real-time.
  - Calculate “control-envelopes” to limit control inputs for guaranteed operation in real-time.
  - Use data-driven models to quantify uncertainty on the fly.

- **Technical Approach**
  - Develop model-predictive monitors for linear models: focus on achieving algorithmic efficiency to allow for fast predictions of impending failure risks.
  - Explore data-driven modeling to capture disturbances and uncertainties on the fly
  - Evaluation through UAV test flights under heavy wind and GPS uncertainties.



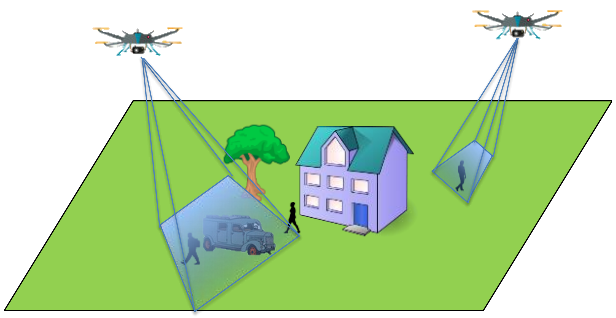
- **Current Results**
  - Model predictive monitor implementation for linear systems [proof of concept completed]
  - Control envelope calculation in real-time.

- **Next Steps**
  - UAV flight test data acquisition [in progress].
  - Linear data-driven models from flight test data.
  - Using the predictive monitoring framework over data-driven models to quantify failure probabilities in real-time

Robust Target Tracking using Teams of Small UAS with Human in the Loop

(BYU 17-01) Randy Beard and Michael Goodrich

- **Project Goals**
  - Develop robust target tracking technologies for cameras on-board small UAS.
  - Track cars/people over long periods of time with minimal human interaction.
  - Track multiple targets using multiple UAS.



- **Technical Approach**
  - Recursive RANSAC
  - New algorithm – developed at BYU
  - Uses fast random search to find potential tracks
  - Robust performance in cluttered data

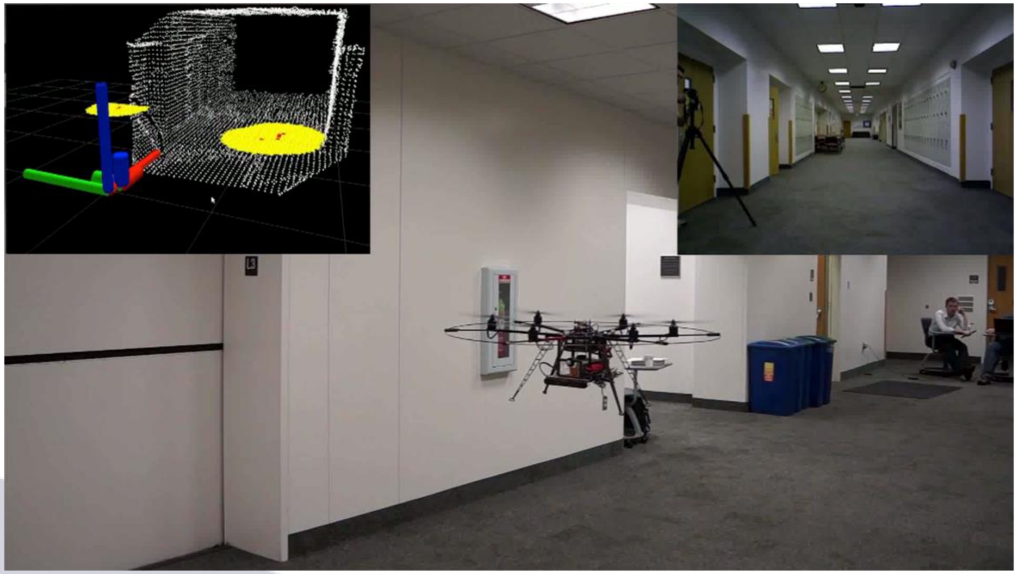
- **Current Results**
  - Track multiple targets from stationary camera
  - Track multiple target from slowly moving camera
  - Application to EO camera, Radar

- **Next Steps**
  - User interface
  - Mast moving platform
  - Multiple vehicle coordination

Navigation in Cluttered Terrain with Intermittent/Degraded GPS

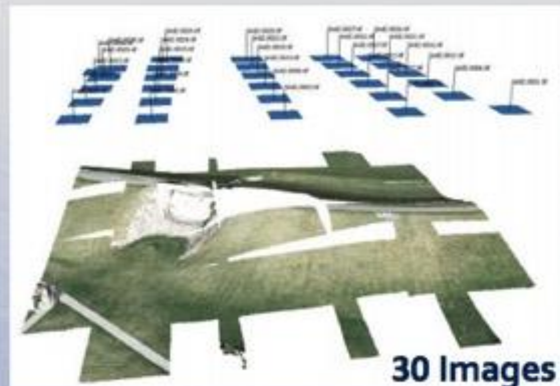
(BYU 17-02) Tim McLain and Randy Beard

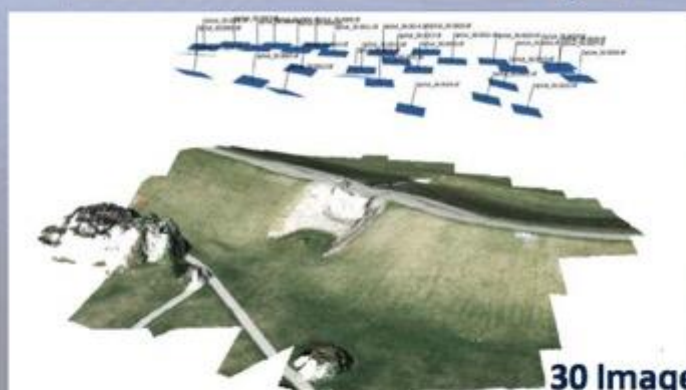
- Utilize SLAM-based relative navigation algorithms to map/navigate
- Focus on increasing robustness to varied environments: day/night, indoor/outdoor, cluttered/sparse
- Relative Nav advantages:
  - Pose estimates fully observable from relative position measurements from lidar, camera → globally consistent map
  - Relative state estimates unaffected by back-end map optimization updates



s-UAS-based Infrastructure Monitoring: Multi-scale Flight Optimization

(BYU 17-04) John Hedengren and Kevin Franke





Constant Number of Images – Compare Accuracy

Grid Survey Model*
Accuracy: **10.0 cm**
(Mean Gaussian Error)

Coverage: **71.4%**

Optimized Survey Model
Accuracy: **3.8 cm** +62%
(Mean Gaussian Error)

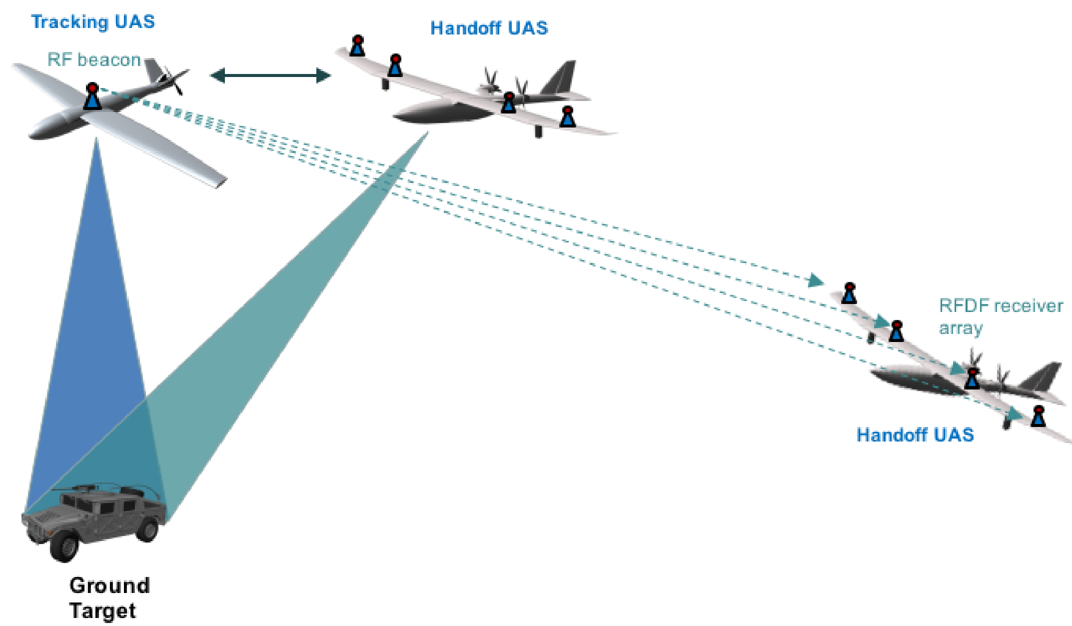
Coverage: **97.1%** +26%

*Grid Survey Plan produced using 70% vertical overlap, 50% horizontal overlap

Robust Moving Target Handoff in GPS Denied Environments

(BYU 17-05) Randy Beard

- **Project Goals**
  - Visually handoff a ground target in GPS denied environment.
  - The tracking of UAS has an RF beacon.
  - The Handoff UAS has a receive array for RF direction finding.



- **Technical Approach**
  - Design and build RF array.
  - Dynamic observer theory to estimate relative geometry.
  - R-RANSAC to detect potential ground targets.
  - Statistical and computer vision methods to ID target.

Current Results

- System working in ROS/Gazebo simulation.
- RFDF system working in bench tests.
- Payload integration in progress.
- Preliminary flight tests are in progress.

Optimization of Heterogeneous Group of Vehicles for Achieving Multiple Mission Level Objectives

(BYU 17-06) Cammy Peterson and Andrew Ning

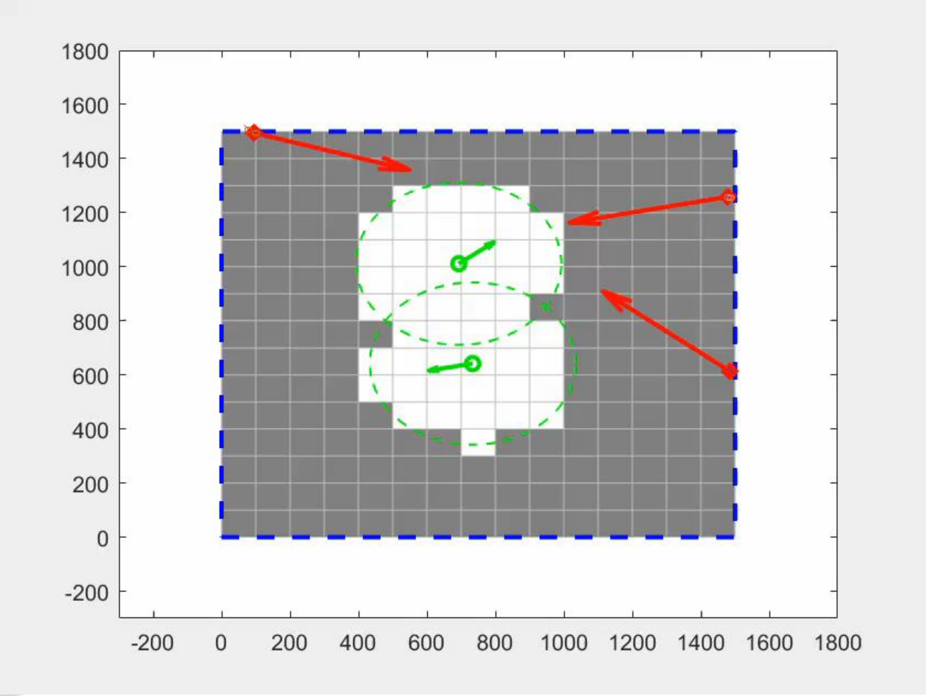
Project Goal: Enable a *heterogeneous* group of autonomous vehicles to *optimally* complete *multiple* mission level objectives.

Technical Approach:

- Information-based metrics for reward functions
- Receding horizon control
- Assume heterogeneous mix of vehicles
- Prioritize mission objectives
- Decentralized decision process

Current Progress:

- Simulation framework for search, track, and classification of targets
- Joint vehicle optimization for collaborative path planning
- Global optimization framework



Electronically Steered Arrays (ESAs) for Onboard UAS Satellite Communications

(BYU 17-07) Karl Warnick

- Goal: Create a mentored research environment with a team of students working on improving phased array antenna systems for UAS satellite and air to ground communications.
- Objectives:
  - Work with L-3 Communications to determine performance requirements
  - Develop a systems engineering model for a UAS-borne transmit/receive ESA system including cross coupling between transmit and receive apertures
  - Use software tools to design a transmit/receive antenna system that achieves low cross coupling sufficient to meet receive link budget and quality of service requirements.
- Outcomes:
  - Enable UAV comms to transition from dish antennas to phased array antennas
  - Spin off technologies for UAV comms applications

Probabilistic Programming for Perceptually Driven Autonomous Agents

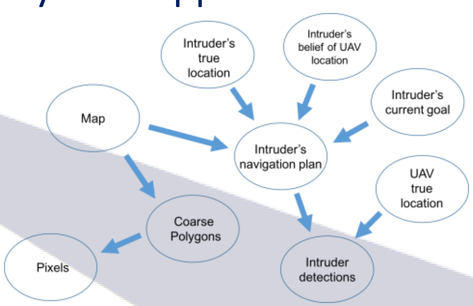
(BYU 17-08) David Wingate

Project Goals

- To explore the use of probabilistic programming in the context of UAVs
- Applied to perception, planning, and high-level reasoning such as theory-of-mind
- Focus area: one agent reasoning about another agent – beliefs, desires, goals, plans, strategies
- Application area: smart intruder detection

Technical approach

- Inherent uncertainty in other agents' mental states motivates a Bayesian approach



- Inference is difficult because of complex models that involve isovists and RRTs

Current results

- Proof-of-concept models and inference algorithms

$$\nabla_\theta\, KL(\,q_\theta(x)\,\|\,p(x|y)) = \nabla_\theta \int_x q_\theta(x) \log\left(\frac{q_\theta(x)}{p(x|y)}\right) \approx \frac{1}{N}\sum_{x_j} \nabla_\theta \log q_\theta(x_j)\left(\log\left(\frac{q_\theta(x_j)}{p(x_j|y)}\right)+1\right), x_j \sim q_\theta(x)$$

- Principled probabilistic models show some improvement in intruder detection rates.
- Computational overhead is high.

Algorithm 4 *PlanAgent* algorithm for the smart UAV

Given: UAV_location and the following intruder model:
$S_I \sim$ multinomial(possible start locations)
$G_I \sim$ multinomial(possible goal locations)
rrt = PlanIntruder(S_I, G_I)
if *isovist_detect*(UAV_location, rrt) **then**
  p = 0.99
else
  p = 0.01
end if
$detect \sim$ Bernoulli(p)
Use BBVI to condition the model on observations so far, resulting in q_θ
Plan to intercept the intruder at the highest likelihood location:
for $i = 0$ **to** N **do**
  $rrts_i \sim q_\theta$
end for
Calculate expected position of intruder using $rrts$
Return RRT that intercepts intruder

Same as Simple Model

Algorithm 1 Simple inverse planning model

Given: UAV_location
$S_I \sim$ multinomial(possible start locations)
$G_I \sim$ multinomial(possible goal locations)
rrt = PlanIntruder(S_I, G_I)
if *isovist_detect*(UAV_location, rrt) **then**
  p = 0.99
else
  p = 0.01
end if
$detect \sim$ Bernoulli(p)

	Naive Intruder	Smart Intruder
Naive Agent	63%	52%
Smart Agent	74.4%	-

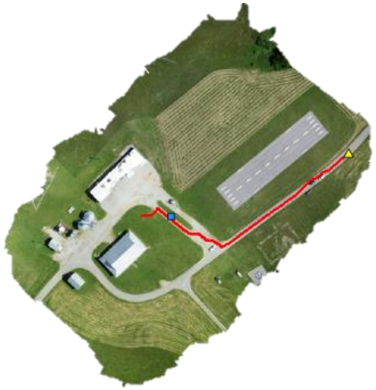
Next steps

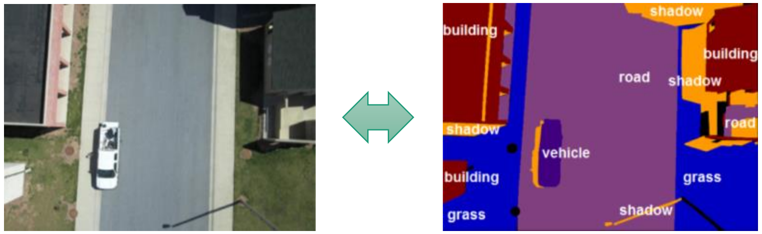
- Improve computational efficiency
- Make models more realistic

UAV/UGV Cooperative Classification for Online UGV Route Planning and Localization

(VT 17-01) Kevin Kochersberger, Dhruv Batra

- **Project Goals**
  - Ground robotic path planning via online learning
  - Aerial and ground-based semantic segmentation for traversable path generation
  - Rapid robotic response





- **Technical Approach**
  - Probabilistic graphical models
  - Vision-derived 2D and 3D datasets improve segmentation precision and recall
  - Higher resolution aerial imagery + UGV multi-modal sensing = improved scene understanding

- **Current Results**
  - Semantic segmentation results for 6 different categories
  - Obstacle avoidance using local and global information

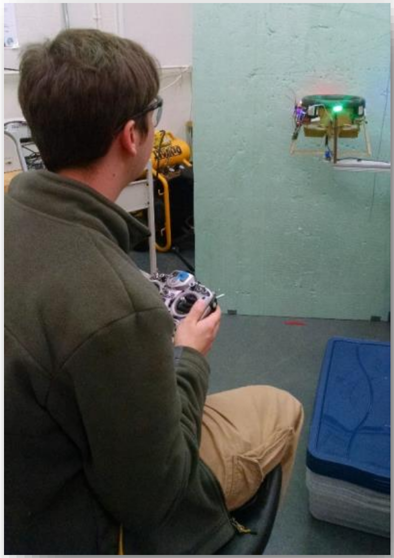
- **Next Steps**
  - More training data with additional categories
  - Multi-UAV/UGV algorithm development and test

Autonomous Navigation and Photogrammetry of Bridges for Inspection

(VT 17-02) Matt Hebdon, Pratap Tokekar

- **Project Goals**
  - Develop tools that enable reliable flight in locations that are not now accessible due to disturbances
  - Quantify the practical limits of performance
  - Experimentally evaluate (e.g. VTTI Smart Road Bridge)

- **Technical Approach**
  - Mature a stochastic autopilot architecture
  - Develop non-stationary stochastic models of disturbances for indoor and outdoor settings
  - Perform extensive experimentation both indoors and outdoors



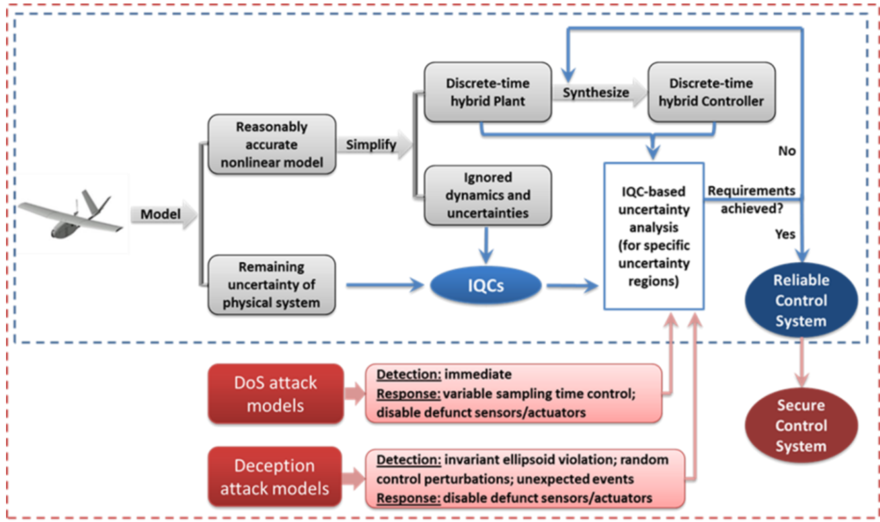
- **Current Results**
  - Kick-off (January 2016)
  - Initial indoor disturbance measurements
  - Initial UAV system identification

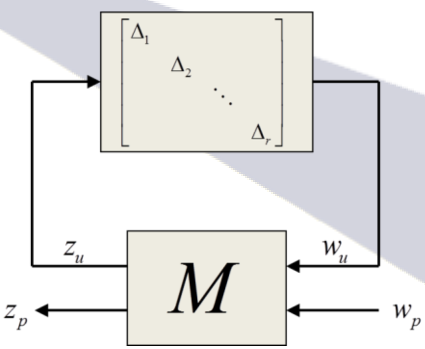
- **On-Going and Next Steps**
  - Disturbance measurements
  - Naive autopilot development
  - Outdoor disturbance measurements
  - Sensor selection

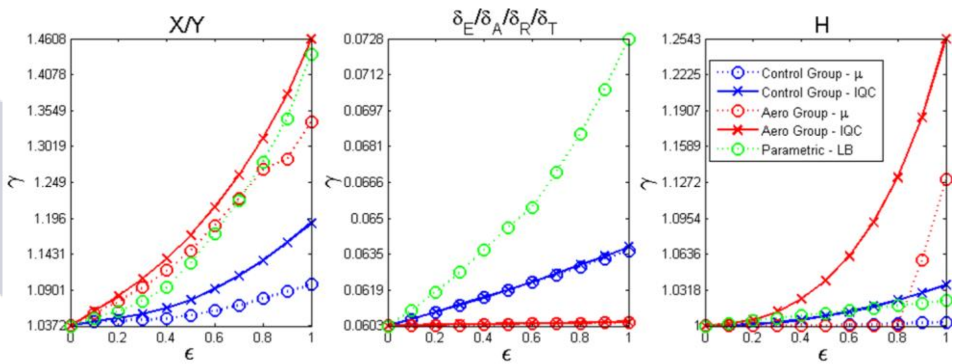
Security Aware Control Algorithms for Unmanned Aircraft Systems

(VT 17-03) Mazen Farhood

- **Project Goals**
  - Robust analysis framework
  - Mathematical certificates for robust stability and performance against random uncertainties and malicious attacks
- **Technical Approach**
  - IQC-based analysis tools
  - Formal, rigorous validation
  - Detection methods based on physical system and analysis tools, along with response strategies







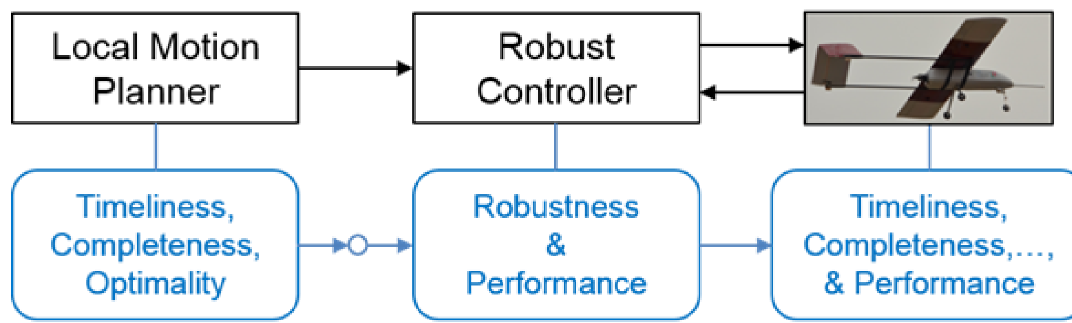
- **Current Results**
  - Robustness analysis of UAS flight control system
  - Uncertainty characterization and quantification
  - Analysis performed on control, aerodynamic, and parametric uncertainties
- **Next Steps**
  - Pinpoint most detrimental uncertainties
  - Determine effective malicious attacks
  - Study and analyze these attacks
  - Develop detection and response strategies

Autonomy Test & Evaluation, Verification & Validation (ATEVV): An Exploratory Case Study of Motion Planning and Control

(VT17-04) Mazen Farhood and Craig Woolsey

- **Project Goals**
  - Develop motion planner with composable guarantees of timeliness, completeness, & optimality
  - Develop a hybrid control system with composable guarantees of performance & robustness
  - Develop a computational & experimental flight test program to verify claims
- **Technical Approach**
  - Controller: Integral quadratic constraint based analysis for determining interfaces
  - Planner: Admissibility conditions for determining verifiable properties
  - Software: Analysis-based code annotation

- **Current Results**
  - Developed a UAS uncertainty framework for analysis of UAS controllers WRT several uncertainty groups and design of controllers with improved robust performance
  - Developed a hierarchical approach for motion planning and hybrid control of vehicles operating in obstacle environments
  - Carried out extensive flight tests for robust control validation



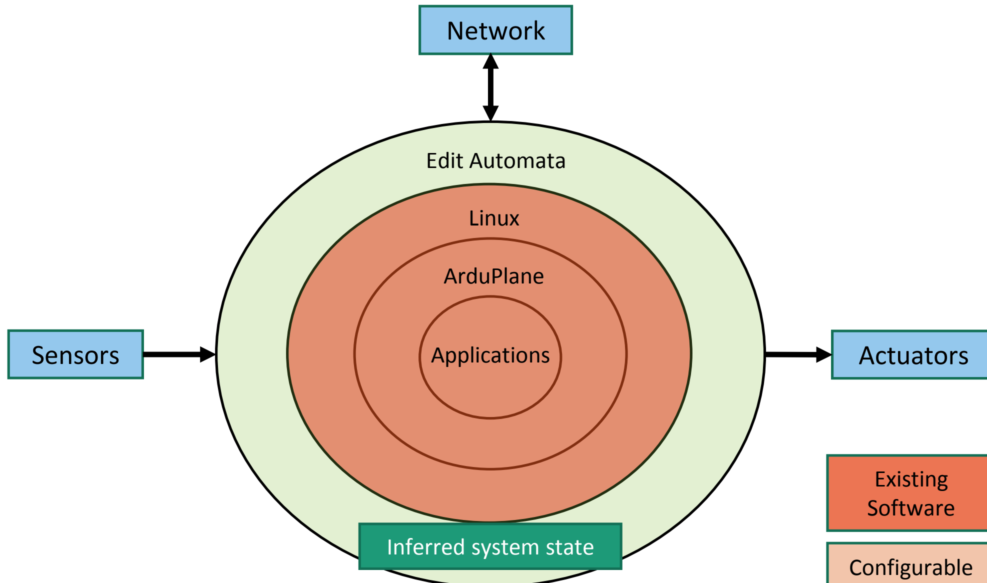
- **Next Steps**
  - Articulate composability for motion planning & control
  - Establish planner/controller composability properties
  - Implement & assess planner/controller in simulation
  - Implement & assess planner/controller in flight tests

Synthesis of Formally Specified, Configurable Hardware Monitors for Flight Control Software

(VT17-05) Cameron Patterson and Mazen Farhood

Objective:

- Ensure that UAS physical behavior is consistent with formal specifications despite external (sensor data and network) attacks and/or internal (malware) attacks
    - Independent of and complementary to conventional protection schemes
    - Last line of defense
    - Unified countermeasure for external and internal threats



Advantages:

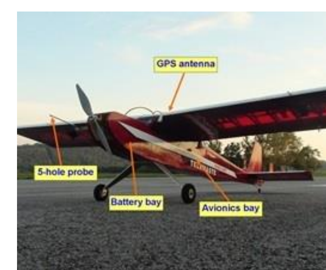
- No need to trust any software including the OS
- Software is unconstrained:
    - Arbitrarily complex
    - No modifications or analysis
    - From untrusted sources
    - Frequently updated

Demonstration with:

- Fixed-wing UAS platform
- Aerotenna flight controller board containing the Xilinx Zynq-7000 SoC
- Linux + ArduPilot middleware

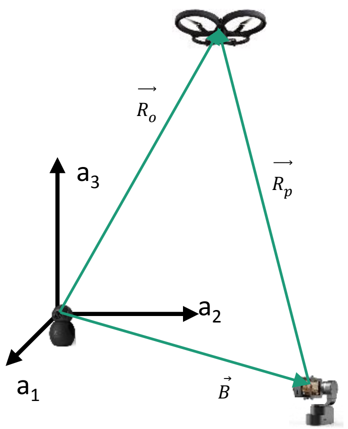
Edit Automata:

- A set of parallel finite state machines that examine application program input and action sequences
    - Implemented in configurable hardware for isolation from software and to maintain real-time performance
- Sequences are transformed when they deviate from specified policies captured in a propositional temporal logic
    - May suppress undesired or dangerous actions, or may insert additional actions into the event stream



Intelligent Visual Tracking System for Small UAS

(VT17-06) Kevin Kochersberger and Craig Woolsey



- **Goal:** Advance the state of the art for vision-based small UAS tracking.
  - **Objective 1:** Develop and assess learning-based algorithms for *detection/classification* using a peripheral + central vision system.
  - **Objective 2:** Incorporate model-based threat trajectory *prediction*.
- **Applications:** Detect-and-avoid; counter-UAS; small UAS traffic surveys

- **Technical Approach**
  - Train a convolutional neural network (CNN) for real-time threat *detection* using real and simulated wide field-of-view imagery.
  - Train another CNN for threat *classification* using a visual-servo'd pan-tilt-zoom (PTZ) camera.
  - *Predict* multiple threat trajectories using state estimate uncertainty to schedule the PTZ system.

ROS-compatible peripheral/central vision cameras

- **Current Results**
  - Feasibility for 1m threats at 1km.
  - Component selection and initial testing of vision hardware.
  - Algorithm for stereo range using peripheral + central vision.
- **Next Steps**
  - Develop training data sets
  - Train and test CNN-based detect/classify/predict in sim.
  - Train and test CNN-based detect/classify/predict in expt.

Small Aircraft Flight Encounters (SAFE) Data Repository

(Joint BYU-VT17-01) Craig Woolsey, Karl Warnick, & Randy Beard

- **Goal:** Develop a repository of sUAS encounter trajectory data and imagery to support development and evaluation of detect and avoid (DAA) systems by the community.

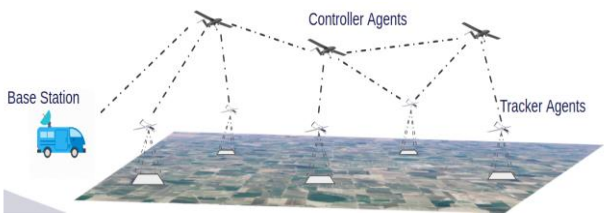
- **Objectives:**
  - Integrate imaging systems into VT eSPAARO sUAS.
  - Develop flight test plans for obtaining imagery:
  - Construct repository and disseminate data
  - Coordinate with other DAA data collection efforts

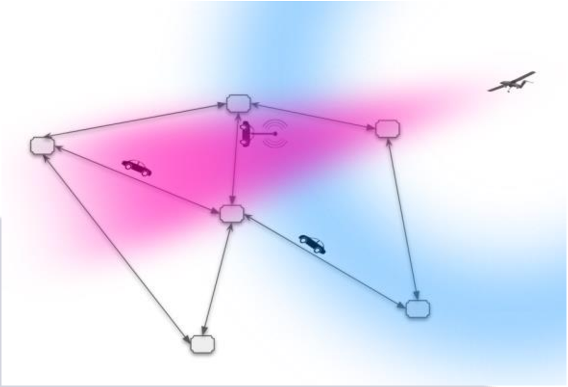
- **Outcomes:**
  - Early access for C-UAS Members to data and preliminary analysis, informing development or acquisition of DAA technology.
  - Demonstrate products of earlier C-UAS research in more realistic scenarios.
  - Raise the C-UAS profile as creator and steward of the SAFE repository.

Multi-agent Sensing System

(Joint BYU-CU17-02) Randy Beard, Cammy Peterson, Eric Frew, Nisar Ahmed

- **Project Goals**
  - Multiple cars, with one carrying an intermittent RF transmitter (e.g. walkie-talkie or cell phone).
  - Cars can rendezvous and pass the transmitter between them.
  - Objective is to identify and track the car with the transmitter.
- **Technical Approach**
  - Robust target tracking and sensor fusion
  - Resource management/cooperative participation
  - Robust communication in a sparse network





- **Current Results**
  - Basic simulation using rosPlane and Gazebo environment
  - Target probability inference using a Bayesian graph
- **Next Steps**
  - Implement particle filter for target
  - Develop path planning to maximize information gain
  - Develop cooperative algorithms for multiple agents

Very Flexible UAS for Aeroelastic Data Collection and Control Development

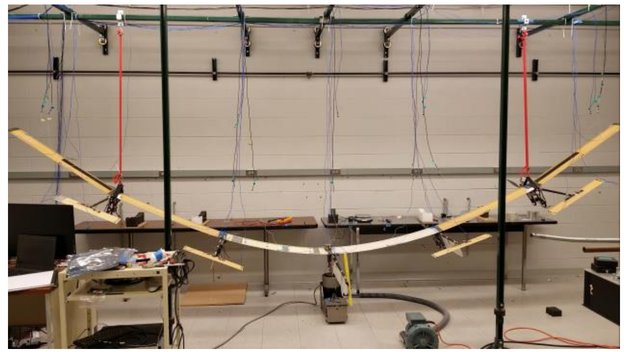
(UM 17-01) Carlos E.S. Cesnik

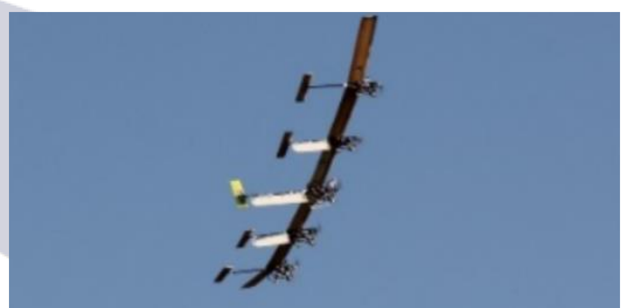
Project Goals

- Establish first-of-kind very flexible aircraft (VFA) reference dataset to be used for coupled nonlinear aeroelasticity-flight dynamics code validation
- Develop enhanced models based on X-HALE experimentally collected data
- Enhance the state-of-the-art Nonlinear Aeroelastic Simulation Toolbox (UM/NAST) with new and improved VFA models

Technical Approach

- Develop very flexible aircraft (VFA) response data in flight and assemble high-quality database to support code validation
- Evaluate UM/NAST's ability to reproduce measured VFA response
- Identify areas of improvement needed on VFA modeling and introduce them into UM/NAST





Current Results

- Acquired preliminary ground vibration (GVT) data
- Successful flight test of new stability augmentation system (SAS) in the risk reduction vehicle (RRV-6) vehicle

Next Steps

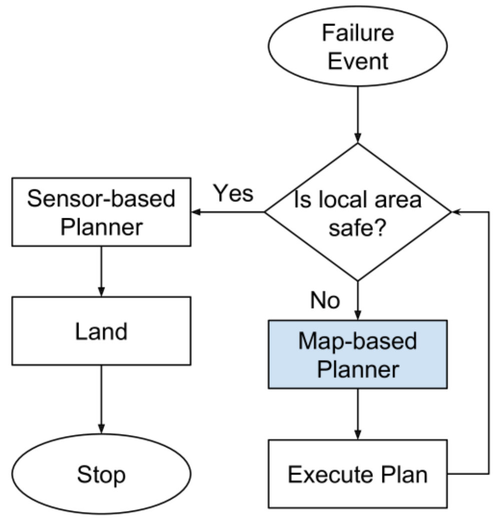
- Continue with the GVT tests:
  - Finalize new support tests on RRV-6
  - Perform GVT of aeroelastic test vehicle (ATV)
- Continue analysis of close-loop flight test results
- Address SAS for better performance during take off and landing
- Transfer software implementation from RRV-6 to ATV

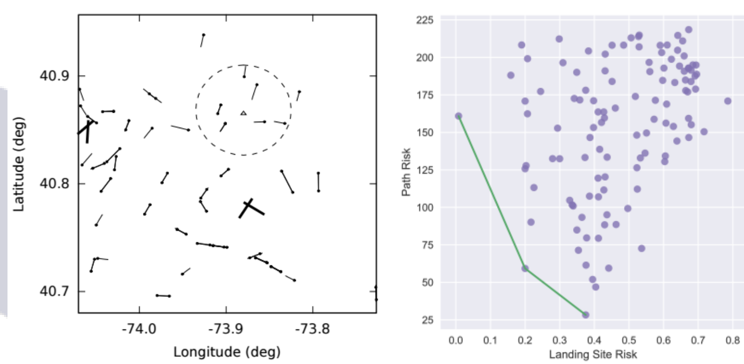
Emergency Flight Planning with Cloud and Sensor Data Fusion

(UM 17-02) Ella M. Atkins

- **Project Goals**
  - Exploit new data (occupancy, traffic) in real-time risk maps
  - Develop metrics over mission goals + risks for urban UAS and UAM (Urban Air Mobility) applications
  - Fuse cloud + sensor data for real-time flight + landing planning

- **Technical Approach**
  - Incorporate open data: Lidar, Image, OSM (OpenStreetMap)
  - Apply ML (machine learning) to classify roof shapes for landing suitability
  - Explore Pareto Fronts to quantify metric tradeoffs
  - Build flight plans for top-N landing sites; select overall risk-minimum plan for emergency landing





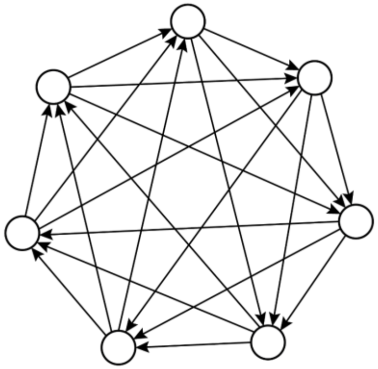
Case study: Road segments as fixed-wing landing sites (left); Pareto Front trading landing site v. flight path risk metrics (right)

- **Current Results**
  - OSM data processed to find low-risk road and open terrain landing sites
  - GIS data processed to find flat and skillion rooftop landing sites
  - Cell call detail report (CDR) data fused with census data to build occupancy maps
  - Case studies completed & published for motor failure, low energy / fuel scenarios
- **Next Steps**
  - Continue to mature data processing and planning capabilities
  - Generalize rooftop ML results to multiple sites/countries
  - Extend results to new failure, environment, platform case studies
  - Apply emergency flight planning to new UAS, UAM platforms

Aerial Swarm Defense: A Control-Theoretic Framework for **Safe and Secure Swarms**

(UM 17-03) Dimitra Panagou

- **Project Goals**
- Derive models for potential aerial swarm attacks
- Establish the notion of **swarm safety and security (resilience)**
- Design **defense mechanisms** against aerial swarms



- **Technical Approach**
- Derive models for collective swarm motion
- Establish (r,s)-robustness for leader-follower communication topologies
- Establish resilient semi-cooperative coordination under leader-follower topologies

- **Current Results**
- Established k-circulant communication topologies for robust consensus under malicious data
- Designed intercept strategies for swarm vs swarm games

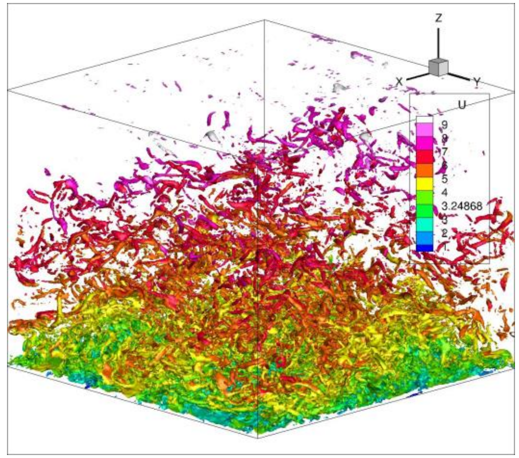
- **Next Steps**
- Establish safety under k-circulant graphs
- Extend filtering of malicious data under semi-cooperative safe control

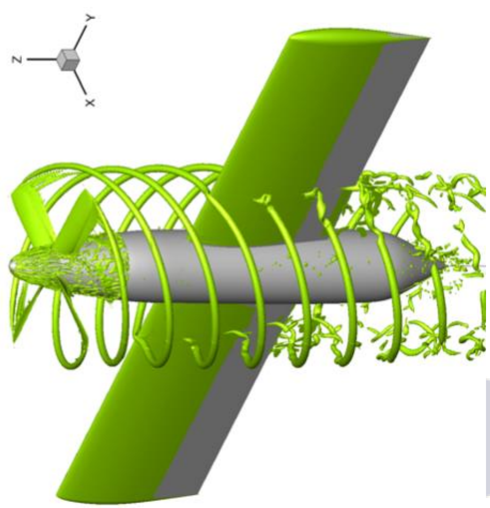
Simulations of UAVs in Realistic Atmospheric Conditions

- **Project Goals**
- Efficient models of atmospheric conditions
- Efficient models of flight aeromechanics
- Analytically expressible library & accessible tools.

- **Technical Approach**
- Large eddy simulations (LES) of atmospheric turbulence – i) low altitude boundary layer (< 1.5 km), ii) Upper troposphere (> 8km)
- Condense LES data into analytically expressible form
- Develop fast , but detailed aeromechanics models of aircraft
- Simulate aircraft performance in atmospheric boundary layer

(UM 17-04) Karthik Duraisamy





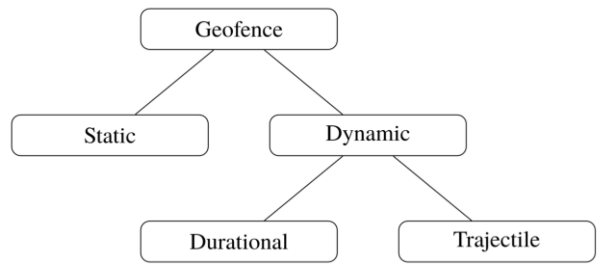
- **Current Results**
- Completed low altitude atmospheric boundary layer simulation
- Verified and validated Aeromechanics model (vortex-panel + wake + propeller model) for fixed wing UAVs

- **Next Steps**
- Formulate high altitude turbulence simulations
- Couple aeromechanics model to high altitude simulations
- Develop technique to condense turbulence simulations in analytically expressible forms

Electronic Geofencing Guidance & Control with UAS Traffic Management (UTM)

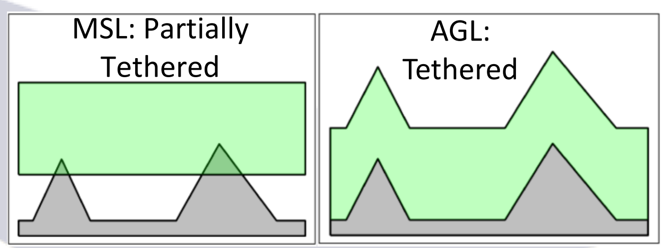
(UM 17-05) Ella M. Atkins

- **Project Goals**
  - Formally specify geofence volumes, trajectories, and permissions
  - Develop efficient algorithms for real-time boundary checking and guidance
  - Assess geofencing metrics for assurance, permissions, and priorities
- **Technical Approach**
  - Define informative geofence data structures with utility across all NAS/UTM stakeholders
  - Investigate altitude references and boundary specifications applicable across terrain, land use, vehicle, airspace classes
  - Develop and validate/verify boundary check algorithms assured to run in real-time
  - Develop and test override logic in M-Air netted flight facility
  - Run simulation case studies across low-altitude rural/urban and transit airspace layers



Geofence Types

Geofencing Case Study: Lower Manhattan
(Red: Keep-out; Blue: Keep-in)



Altitude References to Reconcile for a Shared UTM + Transit Airspace

- **Current Results**
  - Baseline geofence data structures defined
  - Static geofence guidance & override implemented in simulation & a quadrotor
  - Triangle Weight Characterization (TWC) algorithm developed for real-time boundary checking
  - Simulation case studies completed

Next Steps

- Reconcile altitude references in collaboration with C-UAS partners (e.g., NASA)
- Manage adjacent geofence geometries (overlap, gaps)
- Generalize to durational and trajectile geofence types
- Extend simulation case studies to multiple vehicles & dynamic geofence definitions
- Conduct flight tests in M-Air to validate logic, assess impact of nonideal sensor data & winds

Finished Projects

Proximal Sensing for sUAS Applications

(CU 12-03) Dale Lawrence and Brian Argrow

Project Goal: Understand potential new markets and applications for in-situ and proximal sensing systems; identify technologies for investment, development, integrations; prototype, flight-test

Technical Approach

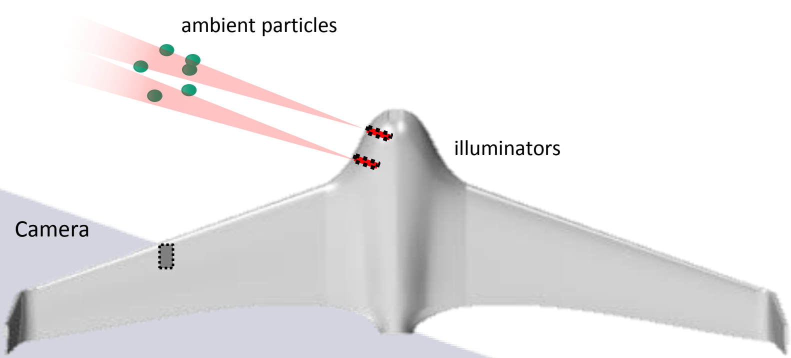
- Clarify sensor requirements based on sUAS capabilities, applications
- Survey commercial systems, components for size/mass/power/cost, development
- Identify promising technologies, application opportunities for further development
- Develop, integrate prototypes into representative vehicles
- Conduct flight testing and validation

Proximity Sensing for sUAS Applications (cont.)

(CU 12-03 → CU 15-03) Dale Lawrence and Brian Argrow

Achievements and Current Objectives:

- Identified need for accurate transverse-component wind measurement
- Developed, tested prototype optical measurement system
- Wind-tunnel results show 12 cm/s accuracy
- Understand eye-safety issues
- Developing understanding for requirements for clear-air, 3-component velocity sensor



Information and Distributed Optimization

(CU 14-01) Jason Marden and Eric Frew

Project Goal: Establish a ***fast-converging*** distributed optimization framework in which agents respond to ***locally available information*** and converge to ***near-optimal*** collective behavior

highly heterogeneous system

homogeneous system

slow convergence

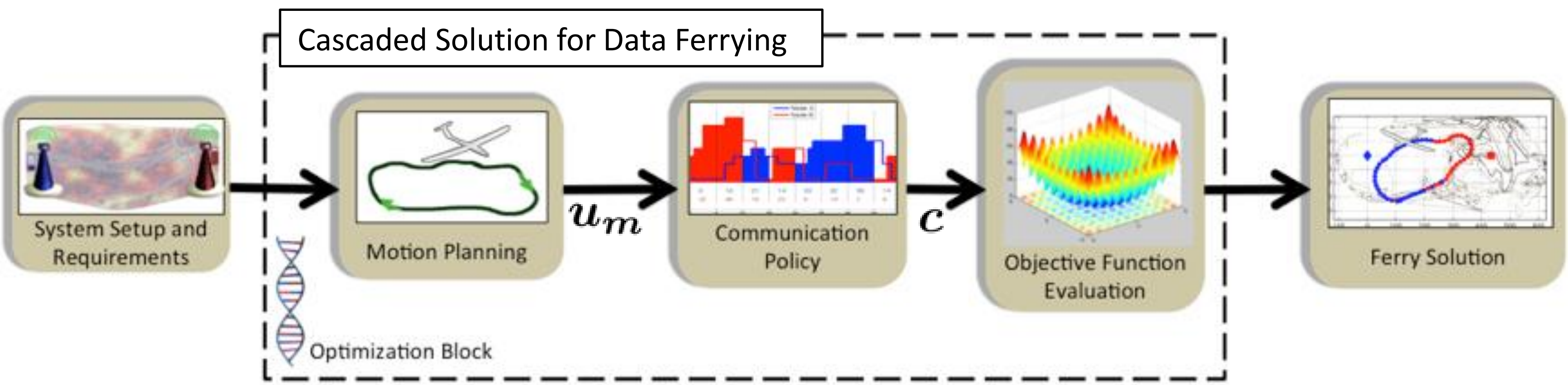
fast convergence

- Technical Approach
  - Game-theoretic control to map locally available information to a local decision
  - Control laws = utility design + learning rules
  - Convergence results through stochastic analysis

- Main Results
  - Characterize tradeoffs in log-linear learning between population homogeneity and convergence rates
  - Convergence to coarse-correlated equilibria

Guidance and Control of a Communication Relay

(CU14-06) Eric Frew

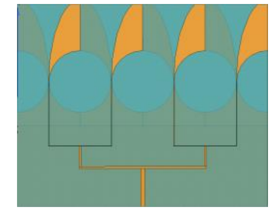


Compact, Efficient Antenna Systems for Broadband and Multiband Applications, Electronically Steered Arrays, and MIMO Communications on UAVs

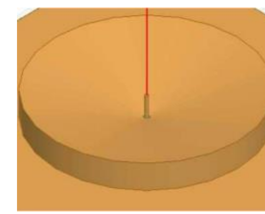
(BYU 1202) Karl F. Warnick

Design methods are needed that push antennas to the physical limits for bandwidth, size, beam pattern, and efficiency. Project developments include:

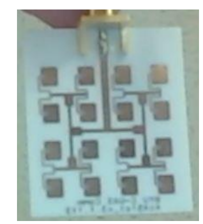
- Fan beam edge-fire Vivaldi array antenna for UAV sense and avoid radar
  Innovation: Horizontal fan beam to reduce ground clutter and slender profile to fit UAV size constraints



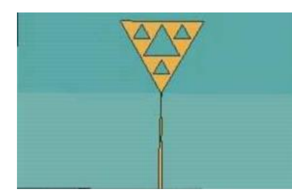
- Annular beam antenna for RF-sensor based GPS denied navigation system
  Innovation: Enable lightweight real time GPS denied navigation radar, antenna has a null in pattern at nadir to reduce bright specular return



- Multifunction planar ultrawideband antenna
  Innovation: Allow multiple radio services with a single PCB integrated antenna
- High gain passive planar phased array for UAV to satellite link
  Innovation: High efficiency planar array antennas with performance similar to dish antennas but with low profile form factor



- Progress towards one of the first-ever high quality planar dual circular polarization antenna designs
  Innovation: Enable high efficiency electronically steered circularly polarized phased array antennas



Maximizing Human Effectiveness
Minimizing Operator Workload

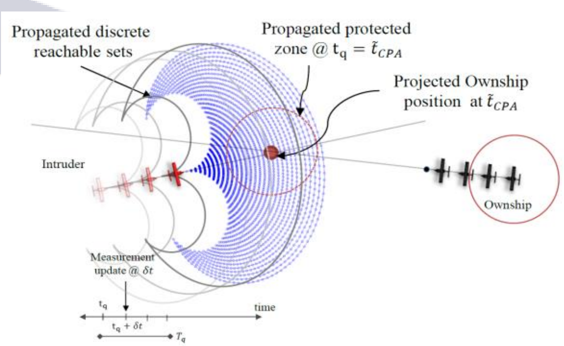
(BYU12-03: Mike Goodrich)

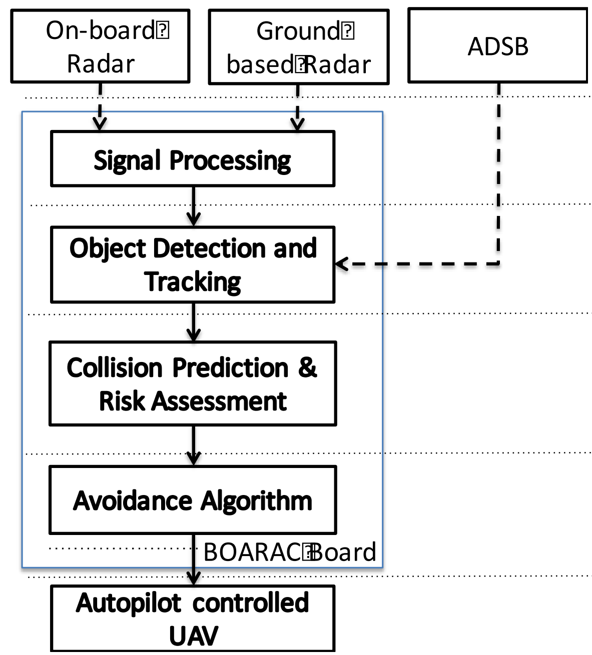
- Key issue: operator overload
  - Design interfaces/autonomy to eliminate bottlenecks in cognition/processing
  - Use formal verification methods to discover/understand bottlenecks

Sense and Avoid for Small UAS

(BYU 13-01) Randy Beard

- Project Goals
  - Develop sense and avoid technologies for small UAS
    - On board radar
    - Ground based radar
    - ADS-B
  - Applicable to both fixed wing and multi-rotors
  - Flight test algorithms using actual radar.





Technical Approach

- Pre-processing
- Range compression

- Recursive RANSAC
- Kalman Filter with PDA and IMM

- Probabilistic prediction model using Lincoln Lab uncorrelated maneuver model.

- Chain-based algorithm
- Local level frame planning (new)

- Pixhawk autopilot

Lightweight Phased Array Radar for UAS Collision Avoidance

(BYU 13-02) Karl Warnick

Faculty directors: Karl F. Warnick, Randal Beard (BYU)

MS students: Jonathan Spencer, Kaleo Roberts, Michael Boren

Radar specifications:

- X-band FMCW 4-channel phased array radar
- FPGA/CPU digital signal processing board
- 15 W power consumption
- 120g weight (without antennas)
- Target detection, tracking algorithms implemented
- Can be used on the ground for micro air traffic control or mounted on UAS

Successful tracking of targets in range and angle demonstrated in the field

Commercialization efforts are underway

CENTER FOR UNMANNED AIRCRAFT SYSTEMS

C-UAS Publications

Dec. 2012-Nov. 2013

- **Articles Published in Refereed Journals: BYU site**

Nichols, J. and McLain, T. A Nonlinear Guidance Law for Visual Pursuit of a Cooperative Aerial Target in Wind, *International Journal of Micro Air Vehicles,* vol. 5, no. 2, pp. 127-144, 2013.

- **Papers Presented at National / International Conferences & Published in Proceedings: BYU site**

T.J. Gledhill, Eric G. Mercer, and Michael, A. Goodrich, Modeling UASs for Role Fusion and Human Machine Interface Optimization, Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics.

Leishman, R., Koch, D., McLain, T., and Beard, R. Robust Motion Estimation with RGB-D Cameras, *Proceedings of the AIAA Guidance, Navigation, and Control Conference,* AIAA 2013-4810, August 2005, Boston, Massachusetts.

Klaus, R. and McLain, T. A Radar-based, Tree-branching Sense and Avoid System for Small Unmanned Aircraft, *Proceedings of the AIAA Guidance, Navigation, and Control Conference,* AIAA 2013-4789, August 2013, Boston, Massachusetts.

Sahawneh, Laith, Beard, Randal W., Avadhanam, Sharath, Bai, He. "Chain-based Collision Avoidance for UAS Sense-and-Avoid Systems", *Proceedings of the AIAA Guidance, Navigation, and Control Conference,* AIAA 2013-4995, August 2013, Boston, Massachusetts.

Robert Leishman, Timothy W. McLain, Randal W. Beard, “Relative Navigation Approach for Vision-Based Aerial GPS-Denied Navigation,” International Conference on Unmanned Aircraft Systems, Atlanta, GA, May, 2013.

Robert Leishman, Daniel Koch, Tim McLain, Randal W. Beard, “Robust Motion Estimation with RGB-D Cameras,” AIAA Infotech@Aerospace, Boston, MA, Paper no. AIAA-2013-4810, August, 2013.

Eric B. Quist, Randal W. Beard, “Radar Odometry on Small Unmanned,” AIAA Guidance, Navigation, and Control Conference, Boston, MA, Paper no. AIAA-2013-4698, August, 2013.

- **Theses/Dissertations: BYU site**

Robert A. Klaus, Development of a Sense and Avoid System for Small Unmanned Aircraft Systems, MS Thesis, Department of Mechanical Engineering, Brigham Young University, August 2013.

Joseph W. Nichols, Vision-based Guidance for Air-to-Air Tracking and Rendezvous of Unmanned Aircraft Systems, PhD Dissertation, Department of Mechanical Engineering, Brigham Young University, August 2013.

Dec. 2013 - Nov. 2014

- **Papers Presented at National / International Conferences & Published in Proceedings:**

Anthony J. Carfang and Eric W. Frew. “Fast Bandwidth Allocation Policies for Persistent Data Ferrying.” 4th International Workshop on Wireless Networking and Control for Unmanned Autonomous Vehicles, Atlanta, GA, Dec. 2013.

Anthony Carfang, Neeti Wagle and Eric W. Frew. “Improving Data Ferrying by Iteratively Learning the Radio Frequency Environment.” 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Chicago, IL, Sept 14-18, 2014.

Eck, J., Morin, M., and Warnick, K. F., "Meta-reflector antenna with annular pattern for electromagnetic orientation in UAS applications," 2014 IEEE International Symposium on Antennas & Propagation & USNC-URSI Meeting, Memphis, TN, July 6-11, 2014.

Sahawneh, L., and Beard, R., "A Probabilistic Framework for Unmanned Aircraft Systems Collision Detection and Risk Estimation," IEEE Conference on Decision and Control, Los Angeles, CA, 2014 (to appear).

Sahawneh, L., and Beard, R., "Chain-based Collision Avoidance for UAS Sense and Avoid Systems," AIAA Guidance, Navigation, and Control Conference, Boston, MA, Paper no. AIAA-2013-4995, August, 2013.

Mackie, J.S.,, and Warnick, K.F., "Compact FMCW radar for a UAS sense and avoid system," 2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI Meeting, Memphis, TN, July 6-11, 2014.

Moore, J.J., Ivie, R., Gledhill, T.J., Mercer, E., and Goodrich, M.A., "Modeling Human Workload in Unmanned Aerial Systems". Proceedings of the AAAI Workshop on Formal Verification in Human Machine Systems. March 2014, Stanford, California.

Dec. 2013 - Nov. 2014

- **Articles Published in Refereed Journals**:

Anthony J. Carfang, Eric W. Frew, and Derek Kingston. "Cascaded Optimization of Aircraft Trajectories for Persistent Data Ferrying." AIAA Journal of Aerospace Information Systems. (Accepted 8/26/14).

DeFranco, P., Mackie, J., Morin, M., and Warnick, K.F., "Bio-inspired electromagnetic orientation for UAVs in a GPS-denied environment using MIMO channel sounding," IEEE Transactions on Antennas and Propagation, Vol. 62, No. 10, pp. 5250-5259, 2014.

Hedengren, J. D. and Asgharzadeh Shishavan, R., Powell, K. M., and Edgar, T. F., "Nonlinear Modeling, Estimation and Predictive Control in APMonitor", Computers and Chemical Engineering, Volume 70, pg. 133-148, 2014.

Leishman, R., Macdonald, J., Beard, R., and McLain, T. "Quadrotors and Accelerometers: State Estimation with an Improved Dynamic Model", IEEE Control Systems, vol.34, no.1, pp. 28-41, February 2014.

Leishman, R. and McLain, T. "A Multiplicative Extended Kalman Filter for Relative Rotorcraft Navigation", AIAA Journal of Aerospace Information Systems, 2014. Accepted.

Leishman, R., McLain, T., and Beard, R. "Relative Navigation Approach for Vision-based Aerial GPS-denied Navigation", Journal of Intelligent and Robotic Systems, vol. 74, no. 1-2, pp. 97-111, April 2014.

Nichols, J., Sun, L., Beard, R., and McLain, T. "Aerial Rendezvous of Small Unmanned Aircraft Using a Passive Towed Cable System", AIAA Journal of Guidance, Control, and Dynamics, vol. 37, no. 4, pp. 1131-1142, 2014.

Dec. 2014 - Nov. 2015

- **Papers Presented at National / International Conferences / Published in Proceedings: BYU Site**

R. Stocker, N. Rungta, E. G. Mercer, F. Raimondi, J. Holbrook, C. Cardoza, and M. A. Goodrich, “An Approach to Quantify Workload in a System of Agents.” In *Proceedings of the 14th International Conference on Autonomous Agents and Multiagent Systems,* Istanbul, Turkey, May 2015.

J. Spencer and K. F. Warnick, “A compact X-band collision avoidance phased array radar system for unmanned aerial systems,” 2015 IEEE International Symposium on Antennas and Propagation and CNC/USNC-URSI Meeting, Vancouver, Canada, July 19-25, 2015.

Palmer, L.M., Franke, K.W., Martin, R.A., Sines, B.E., Rollins, K.M., and Hedengren, J.D., The Application and Accuracy of Structure from Motion Computer Vision Models with Full-Scale Geotechnical Field Tests. Proceedings, 2015 International Foundation Congress and Equipment Expo, Paper 301, ASCE, IFCEE 2015, pp. 2432-2441, doi: 10.1061/9780784479087.225, Reston, VA, 2015.

Dec. 2014 - Nov. 2015

- **Papers Presented at National / International Conferences / Published in Proceedings: CU Site**

Eric Frew, Austin Lillard, Brian Argrow, and Dale Lawrence (2015). Assurances for Enhanced Trust in Autonomous Systems. *AAAI Fall Symposium on Self-confidence in Autonomous Systems*, November 12-14, 2015, Washington DC. [not included in last year's report].

Elston, J., Argrow, B., Stachura, M, “Covariance Analysis of Sensors for Wind Field Estimation by Small Unmanned Aircraft,” *AIAA SciTech Conference*, Kissimmee, FL, Jan 2015.

Laurence III, R.J., Elston, J.S., and Argrow, B., “A Low-Cost System for Wind Field Estimation Through Sensor Networks and Aircraft Design,” *AIAA SciTech Conference*, Kissimmee, FL, Jan 2015.

Nichols, T.W., Elston, J.S. and Argrow, B., “Analysis of the Accuracy of MEMS Magnetometers in Small UAS for use in State Estimation,” *AIAA SciTech Conference*, Kissimmee, FL, Jan 2015.

Pope, D., Argrow, B., and Lawrence, D.A., “Optical Flow Techniques for Wind-Velocity Sensing on a Small Unmanned Aircraft System”, *AIAA SciTech Conference*, Kissimmee, FL, Jan 2015.

Laurence III, R.J., Elston, J.S., and Argrow, B.M., “Probeless Wind Sensing with Distributed Pressure Sensors,” *International Society for Atmospheric Research Using Remotely Piloted Aircraft (ISARRA)* 2015 (May 2015).

Laurence III, R.J., Elston, J.S., and Argrow, B.M., “Probeless Wind Sensing with Distributed Pressure Sensors,” *International Society for Atmospheric Research Using Remotely Piloted Aircraft (ISARRA)* 2015 (May 2015).

Nisar Ahmed (2015). “Softmax Modeling of Piecewise Semantics in Arbitrary State Spaces for 'Plug and Play' Human-Robot Sensor Fusion”, *2015 Robotics: Science and Systems Workshop on Model Learning for Human-Robot Communication*, Rome, Italy, July 2015.

Dec. 2014 - Nov. 2015

- **Articles Published (or Accepted) in Refereed Journals & Edited Books: BYU Site**

L. Sahawneh*, J. Mackie*, J. Spencer*, R. W. Beard, and K. F. Warnick, "Airborne radar-based collision detection and risk estimation for small unmanned aircraft systems," *Journal of Aerospace Information Systems*, accepted.

Sahawneh, L., Duffield, M., Beard, R. & McLain, T., (2015). Detect and Avoid for Small Unmanned Aircraft Systems using ADS-B, *Air traffic Control Quarterly: An International Journal of Engineering and Operation,* (accepted for publication).

Wheeler, David O., Nyholm, Paul W., Koch, Daniel P., Ellinson, Gary J, McLain, Timothy W., Beard, Randal W., "Relative Navigation in GPS-Degraded Environments" in *Encyclopedia of Aerospace.* [Accepted for Publication].

- **Articles Published (or Accepted) in Refereed Journals: CU Site**

Anthony J. Carfang, Eric W. Frew, and Derek Kingston. "Cascaded Optimization of Aircraft Trajectories for Persistent Data Ferrying." *AIAA Journal of Aerospace Information Systems*. 11(12): 807-820, 2014.

Elston, J., Argrow, B., Stachura, M., Weibel, D., Lawrence, D., and Pope, D., "Overview of Small Fixed-Wing Unmanned Aircraft for Meteorological Sampling, *Journal of Oceanic and Atmospheric Technology,* Vol. 32, 1, pp. 97-115, doi: 10.1175/JTECH-D-13-00236.1 (2015).

Anthony Carfang, Neeti Wagle, and Eric W. Frew. "Integrating Nonparametric Learning with Path Planning for Data Ferry Communications." *AIAA Journal of Aerospace Information Systems*, Accepted 5/28/15.

Dec. 2016-2017

- **Book Chapters (BYU)**

Wheeler, D. O., Nyholm, P. W., Koch, D. P., Ellingson, G. J., McLain, T. W., Beard, R. W. (2016). Relative Navigation in GPS-Degraded Environments. Encyclopedia of Aerospace Engineering John Wiley & Sons, Ltd..

- **Inventions (BYU)**

Randal Beard. *Vision-Based Automated Multiple Target Detection & Tracking System.*

- **Journals or Juried Conference Papers (BYU)**

Benjamin Lewis, Randal Beard (2016). A Framework for Visual Return-to-Home Capability in GPS-denied Environments. *International Conference on Unmanned Aircraft Systems (ICUAS).*

Duffield, M. O., McLain, T. W. (2017). A Well Clear Recommendation for Small UAS in High-Density, ADS-B-Enabled Airspace. *AIAA Infotech@Aerospace (SciTech Forum).*

Franke, K.W., Rollins, K.M. Ledezma, C., Hedengren, J.D., Wolfe, D. Ruggles, S., Bender, C., Reimschiissel, B. (2016). Reconnaissance of Two Liquefaction Sites using Small Unmanned Aerial Vehicles and Structure from Motion Computer Vision Following the April 1, 2014 Chile Earthquake. *Journal of Geotechnical and Geoenvironmental Engineering.*

Jackson, J., Ellingson, G., McLain, T. W. (2016). ROSflight: a Lightweight, Inexpensive MAV Research and Development Tool*. International Conference on Unmanned Aircraft Systems (ICUAS).*

James Jackson, David Wheeler, and Tim McLain (2016). Cushioned Extended-Periphery Avoidance: a Reactive Obstacle Avoidance Plugin. *International Conference on Unmanned Aircraft Systems (ICUAS).*

Koch, D., McLain, T. W., Brink, K. (2016). Multi-Sensor Robust Relative Estimation Framework for GPS-Denied Multirotor Aircraft. *International Conference on Unmanned Aircraft Systems (ICUAS).*

Martin, R.A., Blackburn, L., Pulsipher, J., Franke, K., Hedengren, J.D. (2016). Quantifying Potential Benefits of Multi-Scale UAV Monitoring of Long Linear Infrastructure*. Journal of Photogrammetry and Remote Sensing.*

McClelland, H. G., C. Kang, C. A. Woolsey, A. K. Roberts, Buck, D., Cheney, Thomas, and K. F. Warnick (2017). Small Aircraft Flight Encounters Database for UAS Sense and Avoid. *AIAA SciTech 2017.*

Dec. 2016-2017

- **Journals or Juried Conference Papers (cont.) (BYU)**

McLain, T. W., Wikle, J. K., Beard, R. W., Sahawneh, L. R. (2016). Minimum Required Detection Range for Detect and Avoid of Unmanned Aircraft Systems. *Journal of Aerospace Information Systems.*

S. Ruggles, J. Clark, K.W. Franke, D. Wolfe, B. Reimschiissel, R.A. Martin, T.J. Okeson, J.D. Hedengren (2016). Comparison of SfM Computer Vision Point Clouds of a Landslide Derived from Multiple Small UAV Platforms and Sensors to a TLS based Model. *Journal of Unmanned Vehicle Systems.* (4), 246.

Wheeler, D. O., Koch, D. P., Jackson, J. S., McLain, T. W., Beard, R. W. (2017). Relative Navigation: An observable approach to GPS-degraded navigation. *Control Systems.*

- **Thesis/Dissertations (BYU)**

Benjamin Paul Lewis. *A Visual Return-to-Home System for GPS-Denied Flight.* (2016). Brigham Young University.

Joshua Y. Sakamaki, Randal W. Beard, Michael D. Rice, Timothy W. McLain. *Cooperative Estimation for a Vision-Based Multiple Target Tracking System.* (2016). Brigham Young University.

Derek Wolfe. *Quantifying Aerial LiDAR Accuracy of LOAM for Civil Engineering Applications*. (2016). Brigham Young University.

Samantha Anna Ruggles. *Quantifying Computer Vision Model Quality Using Various Processing Techniques.* (2016). Brigham Young University.

C-UAS Success Stories

C-UAS Success Stories

August 2017

- VT Aerospace & Ocean Engineering doctoral student Hunter McClelland has been awarded the NASA Earth and Space Science Fellowship
- VT Aerospace & Ocean Engineering Professor Craig Woolsey received the 2017 Dean's Award for Excellence in Research for VT's College of Engineering
- VT Aerospace & Ocean Engineering Professor Craig Woolsey has been nominated to serve on a committee being formed by the National Academies' Aeronautics and Space Engineering Board to investigate Risks of UAS Integration into the National Airspace System
- VT Aerospace & Ocean Engineering Professor Craig Woolsey served as an invited panelist for the 2017 AIAA SciTech "Forum 360" panel titled "Transitioning Your Idea from the Lab to Flight Test"
- BYU Professor John Hedengren was promoted to Associate Professor
- BYU Two students in the PRISM group, Abe Martin and Landen Blackburn, were invited for internships at AFRL. Trent Okeson was selected for an internship at ExxonMobil.
- BYU Dr. Franke and Brian Pulsipher were selected to visit Japan for 3 weeks and perform UAV flights for geotechnical studies related to earthquakes, funded by NSF

C-UAS Success Stories

August 2017 continued…

- CU Boulder PhD student Luke Burks' paper, "Optimal Continuous State POMDP Planning with Semantic Observations" (Luke Burks and Nisar Ahmed) was accepted to the 2017 IEEE CDC. This paper was sponsored by CUAS project CU14-02: "Harnessing Human Perception in UAS via Bayesian Active Sensing".
- CU Boulder and Orbit Logic, Inc. (Greenbelt, MD) recently received a Phase 1 STTR from the Office of Naval Research (ONR) for the project "Data Architecture Enabling Robust Cooperative Autonomy with Minimal Information Exchange" The team leads are Ken Center (Orbit Logic), Profs. Eric Frew and Nisar Ahmed.
- CU Prof. Nisar Ahmed was awarded a $353,936 Remote Sensing BAA contract by the Air Force Space and Missile Systems Command for the project "Collaborative Analyst-Machine Perception for Robust Data Fusion".

C-UAS

C-UAS Success Stories

August 2017 continued…

- The CU Ttwistor UAS was used to deliver the first real-time drone data to the National Weather Service in Norman, OK through a project funded by IAB member NOAA UAS Program Office
- New CU COAs expand Great Plains coverage to 500,000 sq-mi over 11 states
- CU obtains a "Swarming COA" that enables operation of up to 30 aircraft at one time by a single pilot. This COA was obtained in part to support a collaborative project with the Korea Advanced Institute of Science and Technology (KAIST).
- CU obtains FAA permission for night time operations.
- The CU Aerospace Engineering Sciences department receives a $15M endowment to become The Ann and H.J. Smead Aerospace Engineering Sciences Department
- CU Brian Argrow is named chair of the Smead Aerospace Engineering Sciences Department

C-UAS Success Stories

August 2017 continued…

- The University of Michigan will be opening an outdoor drone testing complex known as M-Air in early 2018
  - https://unmanned-aerial.com/m-air-drone-testing-complex-coming-university-michigan
- Carlos Cesnik, University of Michigan C-UAS Co-PI, is director of a new $8.25M Airbus center for high-efficiency aircraft with flexible wings
  - https://news.engin.umich.edu/2017/06/bend-it-like-airbus/

C-UAS

C-UAS Success Stories

August 2017 continued…

- Kevin Franke received the Ira A. Fulton College of Engineering and Technology Excellence in Education Award for 2016. (It is given to one faculty member from the entire college each year.)
- John Hedengren was named the 2016 Outstanding Chemical Engineering Faculty at BYU
- Kevin Franke was invited to Italy (twice!) to map how an earthquake and its aftershocks impacted ancient and modern infrastructure.
- Tim McLain was awarded the State of Utah Governor's Medal for Science and Technology in the category of academic/research.
- C-UAS and CU PhD student Brett Israelsen won the Intelligent Systems Best Student Paper Award at the SciTech 2017 InfoTech@Aerospace Forum, for his paper "Towards Adaptive Training of Agent-Based Sparring Partners for Fighter Pilots" (Brett Israelsen, Nisar Ahmed, Kenneth Center, Roderick Green, Winston Bennett Jr.)

C-UAS Success Stories

February 2017

- Kevin Franke received the Ira A. Fulton College of Engineering and Technology Excellence in Education Award for 2016. (It is given to one faculty member from the entire college each year.)
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- C-UAS and CU PhD student Brett Israelsen won the Intelligent Systems Best Student Paper Award at the SciTech 2017 InfoTech@Aerospace Forum, for his paper “Towards Adaptive Training of Agent-Based Sparring Partners for Fighter Pilots” (Brett Israelsen, Nisar Ahmed, Kenneth Center, Roderick Green, Winston Bennett Jr.)

C-UAS Success Stories

August 2016

- Dan Koch (BYU graduate student) was selected as a recipient of the National Defense Science and Engineering Graduate (NDSEG) Fellowship (approx. $120K award).
- Abe Martin was a 3 Minute Thesis competition finalist at BYU ($5000 award) for his presentation on his UAV research.
- John Hedengren is new web editor for the American Automatic Control Council.
- John Hedengren awarded faculty of the year award for BYU Chemical Engineering Department.
- Kevin Franke received the outstanding instructor award (student's choice) for the civil and environmental engineering department in 2016.
- Kevin Franke invited as one of 52 researchers worldwide to participate in NSF-sponsored workshop to improve the prediction of liquefaction effects.
- Kevin Franke selected to be on 5-person team sponsored by the NSF to perform post-earthquake geotechnical reconnaissance in Kumamoto Japan following M 7.0 earthquake there in April 2016. Dallin Briggs was official UAV pilot for team.
- Craig Woolsey spoke at the Academic Summit

C-UAS Success Stories

August 2016 cont….

- Four faculty participated on the C-UAS panel at the Midwest conference
- BYU C-UAS site hosted Utah's Senator Orrin Hatch
- Randy Beard gave the plenary talk at the Chinese Guidance Navigation and Control Conference (CGNCC2016) in Nanjing, China on August 13
- Craig Woolsey worked with local industry to establish the newly formed Ridge and Valley Chapter of AUVSI
- Craig was also indirectly involved in the completion of the Virginia Governor's work on Unmanned Systems (http://vus.virginia.gov/).
- Virginia Tech's public affairs office will soon send out a press release highlighting Karl Warnick and Craig Woolsey's work on SAFE repository tests
- Brian Argrow led a successful summer campaign flying UAS in and around thunderstorms. The highlight was an 80-mile flight across a moving front associated with convective initiation.

C-UAS Success Stories

August 2016 continued...

- Eric Frew was awarded a grant from the Air Force Office of Scientific Research titled “Coordinated Persistent Airborne Information Gathering: Cloud Robotics in the Clouds.”
- The University of Colorado established the Integrated Remote and In Situ Sensing (IRISS) initiative as part of it Grand Challenge activity. IRISS, led by Brian Argrow, has hired two professional UAS engineers / pilots and a chief technologist to support UAS activity across the University of Colorado.
- The CU Low-Speed Wind Tunnel is officially operational.
- C-UAS students Nick Sweet and Matt Aitken graduated from CU with their MS degrees.
- C-UAS student Laith Sahawneh graduated from BYU with his PhD degree and is now completing a post-doc at AFRL Munitions Directorate.
- White House has announced that $35M in drone research funding will be available through NSF in coming years

C-UAS Success Stories

February 2016

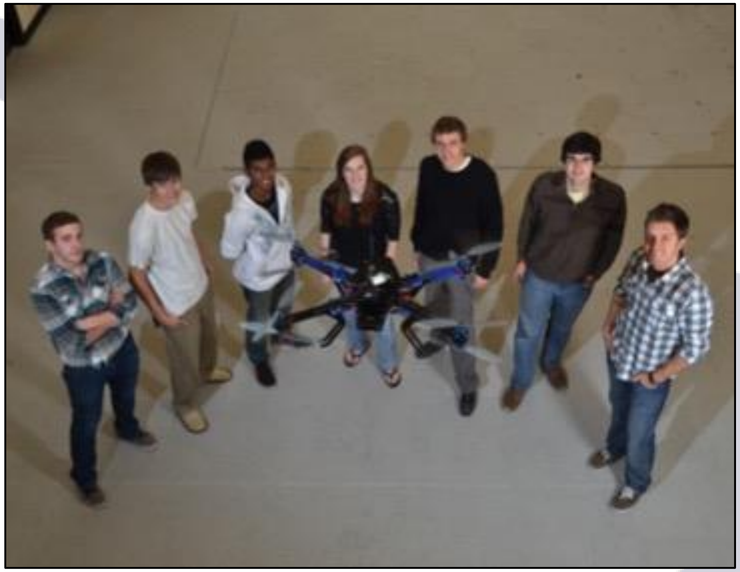
- Laith Sahawneh completed dissertation and has joined Air Force Research Labs, Munitions Directorate as a post doctoral researcher.
- John Hedengren inducted into BYU's Athletic Hall of Fame for his accomplishments as student athlete (MWC cross country champion, All American, member men's national championship team).
- VT Site addition funded by NSF with membership commitments from ARL, Stantec, L-3 Unmanned Systems, NASA Langley, and NAVAIR.
- The Unmanned Systems Lab, directed by Dr. Kevin Kochersberger, flew radiation and imaging flights at Ft. Indiantown Gap, PA with an RMAX helicopter (Apr 28-30).
  Data is used in classification for improved radioactive source localization. Funded by DTRA.
- Craig Woolsey began work with VT faculty colleagues Shane Ross and David Schmale on a multi-university NSF-sponsored project titled "Hazards SEES: Advanced Lagrangian Methods for Hazards Prediction, Mitigation and Response." The project is seeking to develop Lagrangian methods to predict regional flow. A major component is coordinated ocean and atmospheric sampling at the Martha's Vineyard Coastal Observatory in the summers of 2017 and 2018.

C-UAS Success Stories

Feb. 2016 continued…

- A team of undergraduate students led by Craig Woolsey and VT faculty colleague Mike Philen flew a flexible-matrix composite (FMC) flap aboard the eSPAARO UAS in May 2015. The project won first place in the AIAA Region I Student Conference.
- Brian Argrow was named a 2016 AIAA Fellow.
- Brian Argrow was selected to lead the University of Colorado's Integrated Remote and In Situ Sensing (IRISS) Initiative. The initiative includes an internal commitment of over $3M to operationalize CU's unmanned aircraft system expertise for applications such as soil moisture mapping, severe storm sampling, archeological mapping, and studying ecosystem health.
- Eric Frew leads a collaborative team that recently received $1.9 million from the National Robotics Initiative to develop unmanned aircraft systems capable of performing targeted observation in severe storms.
- The Research and Engineering Center for Unmanned Vehicles (RECUV) at CU-Boulder has added three new members: John Farnsworth (AES), experimental aerodynamics and fluid mechanics; Sean Humbert (ME), bio-inspired flight control and sensor fusion; and Dan Szafir (CS); human-robot interaction. John Farnsworth has led the construction of a new low-speed wind tunnel at CU.

Student Success



- A team of BYU student engineers mentored by CUAS researchers Randy Beard and Karl Warnick led the way at Perseus III Tech Demo sponsored by US DoD showcasing counter-UAS capabilities
- Placed student interns with various industry members
- Fellowships awarded to CUAS students: Jared Wikle; Matt Duffield; Ben Lewis; Holly Borowski
- CUAS PhD student Anthony Carfang accepted position with IAB member Boeing

C-UAS Success Stories

August 2015

- Kevin Franke received 2015 Student's Choice Award for Outstanding Faculty in Civil Engineering at BYU
- Kevin Franke named the 2015 Engineering Educator of the Year by the Utah Engineering Council
- A team of BYU student engineers mentored by Randy Beard and Karl Warnick led the way at Perseus III Tech Demo sponsored by US DoD showcasing counter-UAS capabilities
- Tim McLain testified before the Small Business Subcommittee of US House of Representatives on the role of small businesses in the growth of UAS industry in US
- John Hedengren received a NSF EAGER award to investigate the combination of planning/scheduling optimization with control design
- Prof. Jason Marden was named 2015 ONR Young Investigator
- Prof. Brian Argrow organized AIAA-sponsored panel at NASA UAS Traffic Management Convention titled "Small UAS in the Educational Setting"
- Prof. Nisar Ahmed is co-organizer of AAAI 2015 Fall Symposium on "Self-Confidence in Autonomous Systems"

C-UAS Success Stories

August 2015 continued…

- Prof. Eric Frew is Workshop Chair of 2016 American Control Conference.
- CU received COA covering approximately 54,000 sq-mi over portions of Oklahoma and Texas
- Prof. Dale Lawrence had successful deployment at RISH radar observatory in Shigaraki, Japan and is currently flying above Arctic Circle at Oliktok Point, Alaska
- Eric Frew led successful NSF FRP proposal with CU and BYU collaborators
- VaTech student team advised by Craig Woolsey and Michael Philen won 1st place in team paper category at AIAA regional competition with their entry, "Implementation of Flexible Matrix Composite Actuators into the eSPAARO UAV." They will present at SciTech 2016.
- GaTech has submitted letter of intent to join C-UAS
- Recent Graduates
  - Anthony Carfang, CU, PhD AES, accepted a position at Boeing
  - Paul Nyholm, BYU, MS ME, now employed at Lawrence Livermore National Lab

C-UAS Success Stories

February 2015

- Randy Beard named Fellow of IEEE
- Derek Kingston of our IAB received AFRL Early Career Award, recognizing distinguished and exceptional achievements to Air Force R&D community
- Kevin Franke selected as 2014 ASCE Utah Engineering Educator of the Year
- John Hedengren received the AIChE Himmelblau award for contributions to computer-based engineering education. Citation mentioned interdisciplinary work, especially with UAVs
- IAB members BP and AeroVironment receive first FAA commercial use license for UAS operations over land in Alaska – Curt Smith played big role
- VaTech held planning meeting for their proposed C-UAS site
  - Full proposal to NSF to be submitted in March

C-UAS Success Stories

July 2014

- Mike Goodrich, Eric Mercer – Successful AAAI Spring Symposium 2014, Formal Verification and Modeling in Human-Machine Systems
  - Well attended, significant focus on UAS
- Eric Mercer – Guest Editor for special issue of IEEE Transactions on Human-Machine Systems on same topic
- Mike Goodrich, Eric Mercer – Organizing special issue of Journal of Human-Robot Interaction on humans and flying robots
- Mike Goodrich – Named chair of BYU Computer Science Department in June
- Brian Argrow – Organized and Chaired AIAA/AUVSI 2nd Workshop on Civilian Applications of UAS
  - Held at AUVSI Unmanned Systems 2014
  - 4-1/2 hour, standing-room only (400+ attendees)
  - A-list of panelists and moderators

C-UAS Success Stories

July 2014 continued…

- John Hedengren – 2014 CACHE David Himmelblau Award for Innovations in Computer-based Chemical Engineering
- Kevin Franke – Based on work in C-UAS, 1 of 30 selected to participate in Keck Institute of Space Studies workshop at Caltech
- Kevin Franke – First to fly UAVs over liquefaction sites following April 1 earthquake in Chile
- VaTech has submitted letter of intent to join C-UAS
  - Planning grant proposal to be submitted in September
- Recent Graduates
  - James Mackie, MSEE, BYU "Compact FMCW Radar for GPS-denied Navigation and Sense and Avoid"
  - Jose Mojica, MSChE, BYU "A Dynamic Optimization Framework with Model Predictive Control Elements for Planning"

C-UAS Success Stories

January 2014

- Joe Nichols, Technical Advisor for Flight Test and Evaluation, USAF, Edwards AFB
- Innovative Managing Director award received from NSF
  - Brad Whitby hired 1/20/14
- Mike Goodrich, Eric Mercer – AAAI Spring Symposium 2014, Formal Verification and Modeling in Human-Machine Systems
- Randy Beard, Tim McLain – Research featured on cover of *IEEE Control Systems,* Feb 2014
- Karl Warnick – Organizing special session on Antennas and Sensors for UAS at IEEE International Symposium on Antennas and Propagation, July 2014
- Eric Frew - Serving on the National Research Council's Committee on Autonomy Research for Civil Aviation
- Brian Argrow - Organizing the second Symposium for Civilian Applications of Unmanned Aircraft Systems (CAUAS-2) at the AUVSI's Unmanned System 2014 Meeting, May 12, 2014.
- Eric Frew and Randy Beard were named as Associate Fellows of AIAA.

C-UAS Success Stories

August 2013

- Student internships with IAB member organizations
  - Anthony Carfang – AFRL Aerospace Systems (summer 2012)
  - Robert Klaus – Insitu (spring 2013)
  - David Wheeler – AFRL Aerospace Systems, Boeing Defense Systems (summer 2013)
  - Peter Niedfeldt – UTRC (fall 2013)
- Graduate degrees completed
  - Joe Nichols - PhD, considering options
  - Robert Klaus - MS, headed to MIT Lincoln Lab
- Mike Goodrich, Eric Mercer – AAAI Spring Symposium 2014, Formal Verification and Modeling in Human-Machine Systems
- Brian Argrow – Taught course in Spring 2013 on UAS integration in the NAS (available through CU online system)

C-UAS Success Stories

August 2013 continued…

- Eric Frew – Taught course in Spring 2013 on small UAS guidance and control. Used *Small Unmanned Aircraft Theory and Practice* by Beard/McLain (available through CU online system)
- Karl Warnick – Fellow IEEE
- CORBI award between C-UAS and CHREC received from NSF
- CU hired professional system engineer and UAS pilot to support flight operations
- Both BYU and CU were part of teams that submitted proposals for FAA test sites
- CU obtained COAs with permission to fly two unmanned aircraft in same environment
- Brian Argrow – Completed term on UAS Subcommittee of the NASA Advisory Council's Aeronautics Research Committee (Focus: UAS in the NAS)

Thank you!

http://c-uas.org

C-UAS
CENTER FOR UNMANNED AIRCRAFT SYSTEMS