Safe Autonomy
Flexible Innovation Testbed (SAFIT™)

Final Presentation

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Outline

• Requirements Capture
• SAFIT™’s Key Innovative Features
• SAFIT-Wrap™ Integrated Flight Protection
• Simulation Experiment
• Status and Future Plans
SAFIT™ Requirements Capture

An Unmanned Aircraft System (UAS) platform for safely testing NASA’s unproven autonomy applications

- Autonomous systems have characteristics that make them difficult to V&V
  - Learning, adaptation, non-deterministic algorithms
  - Operation in complex environments
  - Multi-vehicle cooperation
- Unique system requirements defined from wide range of NASA research projects
  - Autonomy Incubator
  - UAS Integration in the NAS
  - Adaptive Controls and Controls Upset Research
  - Safety Critical Avionics Systems Research
Goals and Objectives

• Goals:
  – Design UAS testbed platform tailored to support NASA’s autonomy research
  – Demonstrate feasibility of key innovative features

• Objectives:
  – Detailed design of SAFIT™ UAS testbed
    • Vehicle design; hardware and software functionality
  – SAFIT-Wrap™ prototype development and simulation demonstration of
    • Maintaining geofencing within a predefined regular geometric area
    • While providing Detect and Avoid from one or more simulated traffic aircraft
    • While ensuring flight envelope protection
  – Procure/integrate key hardware components and demonstrate flow of data
  – Build prototype of vehicle (under cost sharing)
    • Conduct preliminary vehicle flight performance assessment
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    • While providing Detect and Avoid from one or more simulated traffic aircraft
    • While ensuring flight envelope protection
  ✓ Procure/integrate key hardware components and demonstrate flow of data
  Focused on improving software rather than building vehicle
  Build prototype of vehicle (under cost sharing)
  • Conduct preliminary vehicle flight performance assessment
SAFIT™ Innovative Features

Reconfigurable Vehicle Design

• Vertical Take-Off and Landing
  – 10 minute hover with 3-lb payload
• Conventional Take-Off and Landing
  – 30 minute cruise at 40 mph with 6-lb payload
• Wingspan: 9 feet
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Aero-Propulsive Control System
• Stability and control
• Mimics range of test vehicle performance
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Variable Levels of Autonomy

• Waypoint-based routes
  – Pre-planned
  – Real-time
• Direct control inputs

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Reconfigurable Vehicle Design

- Reconfigurable design enables wide range of mission scenarios
  - Vertical Takeoff and Landing (VTOL)
    - Quad tiltrotor
  - Conventional Takeoff and Landing (CTOL) configuration
    - 40 mph cruise
    - Redundant control surfaces

- Trade study of alternative aero-propulsive power options
  - Internal combustion generator vs all electric

- Modular design
  - 2 wing panels, tail booms, separable empennage, 4 rotor trunnions
  - Access panels for payload modules
Structure & Materials

- Thin-wall Aluminum Fuselage Tubes
- Carbon Fiber Joiner & Trunnion Tubes
- High Density Foam & Fiberglass Surfaces
- Aeromat & Fiberglass Panels
- Fiberglass Nose
- Poplar, Birch Ply Bulkheads
- Aluminum Landing Gear
- Aluminum Motor Mounts
Propulsion

- Using **eCalc**, iterated on propulsion setups assuming a 27lb max weight. Hover: ~15min, Cruise: ~40min-1hr
  - Good past experiences with Hacker Motors, Castle ESCs, and APC propellers

- 4x Hacker A40-10L-14p
  - 2” L
  - 1.6” OD
  - 0.6lb

- 2x 16000mah 6s2p Lipo (22.2V nom)
  - 6.8” x
  - 2.9” x 2.7”
  - 4.2lb

- 4x Castle Phoenix Edge 75A
- 2x 15x10E, 2x 15x10EP
Range of Performance

- Mimics range of vehicle performance by setting limiting parameters:
  - turn rate
  - climb rate
  - power
- Can be changed in-flight
- Features redundant control surfaces to support testing of control upset research systems; resilient control
Variable Autonomy

– Fully autonomous path planning
  • Following route produced in real-time by autonomous path-planning system
  • *Future Autoland/Takeoff Capability*

– Following path preloaded or provided in real-time from Ground Control Station

– Manual control
  • From Ground Control Station
  • Or direct control inputs from test system

– All subject to the protections of SAFIT-Wrap™
SAFIT-Wrap™
Integrated Flight Protection

- Ensures safe flight testing of unproven software
- Integrated flight protection
  - Traffic avoidance
  - Obstacle avoidance
  - Geospatial containment
  - Flight envelope protection
- Limited-capability prototype completed
- Ground Control Station
  - Situation Awareness
  - Alerting status
Wrapper Paradigm

External Environment

WRAPPER
Checks outputs for
- **Correctness**: Solution meets full correctness criteria
- **Reasonableness**: Solution meets reasonableness criteria
- **Safety**: Solution is consistent with safety criteria

Potential Solution

AUTONOMOUS APPLICATION
Plans optimal solution using
- Adaptation to changing environment and mission
- Learning from past successes and mistakes
- Complex, nondeterministic logic

Partitioning
- Certificatable wrapper
- Unproven application
- Timing issues

Wrapper provides
- Monitoring
- Fail-safe solution if needed
Small UAS Traffic Avoidance in an Urban Environment

Manned aircraft under Visual Flight Rules

- Human judgement used to “See And Avoid” and remain “Well Clear” of traffic
- Traffic alert and Collision Avoidance System (TCAS) Near-Mid-Air Collision (NMAC) cylinder
  - Radius: 500 ft
  - Half-height: 100 ft

Traffic avoidance between UAS

- On-board systems use “Detect And Avoid” algorithms to automatically remain a predefined “Well Clear” distance from traffic
- DAA Well Clear has been defined for large UAS integrated in the NAS
- NMAC and Well Clear have yet to be defined for small urban UAS operations
  - Maneuvering in cluttered environments
  - Slower speeds than civil transports
  - Nimble maneuvering
Urban Maneuvering

- **Traffic and Obstacle Avoidance designed for urban maneuvering**
  - NASA’s UAS Traffic Management (UTM)
    - “Flexibility where possible and structure where necessary”
  - Where multiple UAS are operating
    - Vehicles in pre-defined lanes
    - Centralized UTM deconfliction
  - Onboard separation assurance may be needed for non-normal and off-nominal events
    - Vehicles straying out of lanes
    - Timing constraints missed
  - Suburban and rural UAS traffic
    - Unlikely to have UTM centralized deconfliction
    - Onboard separation assurance may be needed
Traffic Avoidance

- Candidate NMAC and Well Clear Volumes developed
- Radius based on 10 ft wingspan
- Height based on altitude sensing accuracy at low altitudes
- Look-ahead time $\tau = 4 - 8$ s for detecting conflicts based on ability to turn at $30^\circ$ per second
- SAFIT™ prototype uses a NASA traffic avoidance algorithm
Obstacle Avoidance

- Building buffer $B_B$ of 10, 15, and 20 ft
- Building look-ahead time $B_L$ of 2, 5, and 8 s
- Unique SAFIT™ obstacle avoidance algorithm paths tangentially to obstacles
Geospatial Containment

- Vertical buffer prevents ground collision as well as ceiling violation
- Large horizontal buffer due to NASA’s flight safety concerns
- Unique SAFIT™ geospatial containment algorithm
Simulation Experiment

Batch simulation of small UAS maneuvering in an urban environment

- Conventional flight (no hovering) at 25-50 mph
- Typical urban streets with sidewalks: 50, 70, and 90 ft width
- Oncoming traffic violating lane rules
- Crossing traffic at intersections
- Flight ceiling of 400 ft AGL
- Ownship position uncertainty (< 5 ft), but no traffic surveillance error
- 7550 total runs

Simple resolution maneuvers were used

- Heading change and climb or descent to immediately resolve conflict
- Purpose: Establish feasibility of simple algorithms
Key Experiment Results (1 of 2)

- A small UAS was shown to successfully avoid traffic between buildings 70 ft apart, including multi-vehicle conflicts
- A buffer of 10 ft appears to be adequate to protect against building collisions
  - Tuning of building look-ahead time vs. buffer size
  - Increased look-ahead time may preclude entering curved streets or approaching T intersections
- Multi-vehicle conflicts can be handled within 50 ft maneuvering corridor
  - 8 s traffic look-ahead time required
  - 4 s traffic look-ahead time resulted in several NMACs and building collisions
Key Experiment Results (2 of 2)

- An additional buffer of 5 ft outside the Well Clear Volume appears to be adequate to protect against Well Clear violations
  - Necessary due to navigation/position uncertainty
  - Initial maneuvers were sometimes insufficient to avoid Well Clear violation
- Candidate Well Clear and NMAC volumes were developed for small UAS maneuvering in an urban environment
  - The Well Clear Volume was shown to protect against NMACs in challenging scenarios
- Feasibility of simple resolution maneuvers was established
  - Appropriate for simple encounters in low traffic density
  - Shown to be effective in complex multi-vehicle conflicts
  - Suitable as supplement to UTM
Two papers presented at AIAA Aviation Technology, Integration, and Operations Conference, June 2017:

• Johnson, Sally, and Couch, Jesse, “A Wrapper Paradigm for Trusted Implementation of Autonomy Applications”

• Johnson, Sally, Petzen, Alexander, and Tokotch, Dylan, “Exploration of Detect-and-Avoid and Well-Clear Requirements for Small UAS Maneuvering in an Urban Environment”
Current and Future Work (1 of 2)

• AAG plans to build and fly our SAFIT™ vehicle in the future, when we have a customer that needs its unique capabilities

• AAG is in the process of implementation and flight demonstration of prototype SAFIT-Wrap™ on two AAG-owned Mini SkyHunter Aircraft to be completed by November 2017

• AAG is in the process of marketing our SAFIT™ testbed to NASA’s research projects
  – Safe flight evaluation of unproven autonomy applications
  – Full-service support:

  • Experiment Design/Reviews
  • Algorithm Development
  • Software and Hardware Integration
  • IRB and ASRB Approvals

  • Flight Operations
  • Data Collection and Analysis
  • Demos and Technical Presentations
  • Report Writing
Current and Future Work (2 of 2)

AAG was awarded a NASA 2017 Phase I SBIR to generate a strategy for developing, verifying and certifying a high-integrity version of SAFIT™ for UAS

Our Product Vision:

• A high-integrity flight management system and ground control station
  – to support safe operation of multiple UAS
  – across a wide range of commercial and research missions
  – including Beyond Visual Line of Sight operations
  – certified for commercial UAS operations under a future standard

• To be marketed as a commercial product
  – Marketed to commercial UAS manufacturers as an optional flight management system
  – Marketing of high-integrity core functionality for other developers to build upon

• Future spin-off version to support unpiloted passenger aircraft for On Demand Mobility
Is There a Commercial Need for a High-Integrity Version of SAFIT™?

• ArduPilot, hosted on PixHawk hardware, is the most popular flight management system for UAS
  – Open source software is continually updated with new features, such as obstacle avoidance and geospatial containment; unstable and unreliable
  – Hardware and connections are unreliable

• Major ArduPilot/PixHawk Issues AAG Experienced in the Field:
  – Compass “inconsistency” on new hardware
    • Brand new out of the box hardware would have launch denial faults
  – Unstable degraded flight
    • GPS/Compass sensor came off the mast; aircraft was difficult to control and dangerous even manually flying
  – Fly-aways
    • In a couple of instances the UAV would suddenly change flight modes without warning and fly away
V&V Strategy for High-Integrity SAFIT™

Ultra-high-integrity
- Formal specification of algorithms
- Verification that specification satisfies limited safety properties
- Manual analysis and extensive testing for correct implementation

High-integrity
- Manual analysis and extensive testing for correct implementation

Low-pedigree
- Manual analysis and testing

Partitioning
- Simple, ultra-high reliability code must be separated from complex, unproven code

Formal methods
- Applied to specification, not code
- Careful design and analysis of design are key
- Covers all possible combinations of inputs
- Boolean logic: frequently reveals corner cases with unexpected behavior
- Real math: error bounding on approximations
Concluding Remarks

• The LEARN SAFIT™ grant enabled AAG to
  – Develop a UAS testbed capability to support a wide range of NASA’s research projects, including autonomy research
  – Initiate development of a flight management system for safe implementation of autonomous UAS operations in the National Airspace System

• The key barrier to widespread use of autonomy is V&V
  – No easy answers, but we believe a high-integrity version of SAFIT™ can help

• The FAA has not yet adopted a certification standard for UAS in the National Airspace System
  – Maneuvering autonomously
  – Single operator handling multiple UAS
  – Beyond Visual Line of Sight operations

• We plan to work with the FAA to ensure that the V&V strategy for High-Integrity SAFIT™ will be sufficient for the future standard