Safe Autonomy Flexible Innovation Testbed (SAFIT™)

Final Presentation

September 6, 2017

Sally C. Johnson

Jesse C. Couch

Adaptive Aerospace Group, Inc.

Hampton, VA

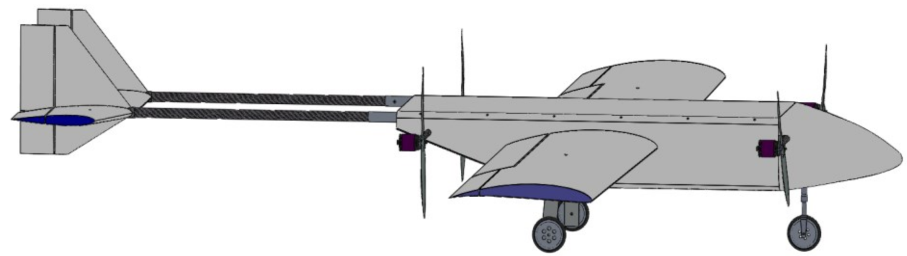
sjohnson@adaptiveaero.com

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

Goals and Objectives

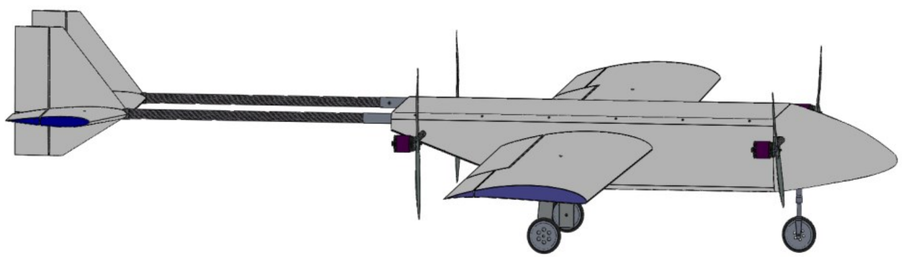
- Goals:
  - Design UAS testbed platform tailored to support NASA's autonomy research
  - Demonstrate feasibility of key innovative features
- Objectives:
  - ✓ Detailed design of SAFIT™ UAS testbed
    - Vehicle design; hardware and software functionality
  - ✓ SAFIT-Wrap™ prototype development and 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

Focused on improving software rather than building vehicle

SAFIT™ Innovative Features

Reconfigurable Vehicle Design

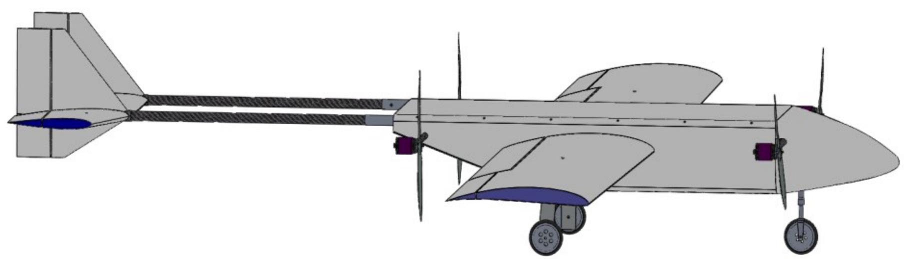
- Vertical Take-Off and Landing
  - 10 minute hover with 3-lb payload
- Conventional Take-Off and Landing
  - 30 minute cruise at 40 mph with 6-lb payload
- Wingspan: 9 feet



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



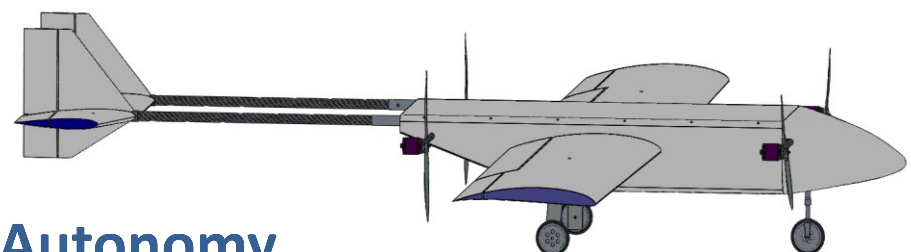
Aero-Propulsive Control System

- Stability and control
- Mimics range of test vehicle performance

SAFIT^{TM} 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



Variable Levels of Autonomy

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

Aero-Propulsive Control System

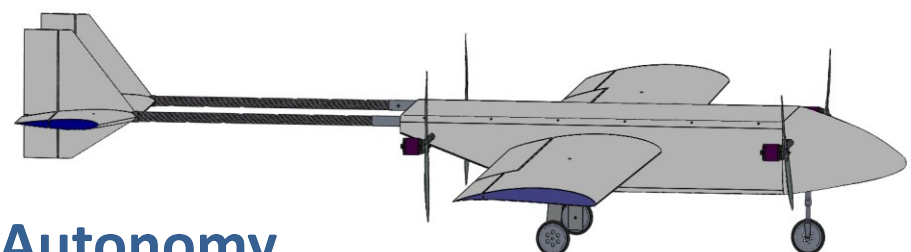
- Stability and control
- Mimics range of test vehicle performance

SAFIT™ Innovative Features

SAFIT-Wrap™ Integrated Flight Protection

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



Variable Levels of Autonomy

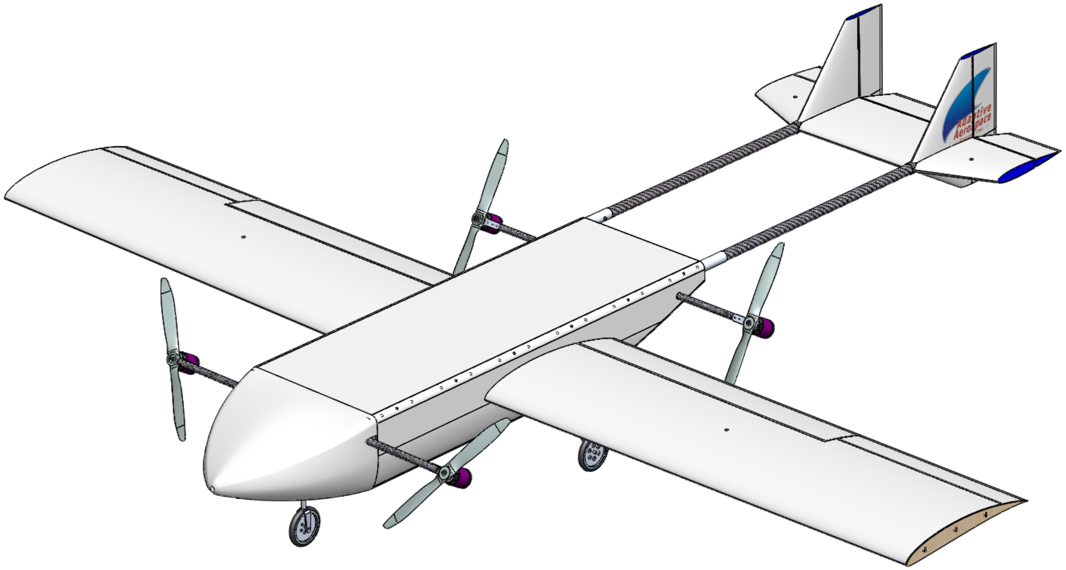
- Waypoint-based routes
  - Pre-planned
  - Real-time
- Direct control inputs

Aero-Propulsive Control System

- Stability and control
- Mimics range of test vehicle performance

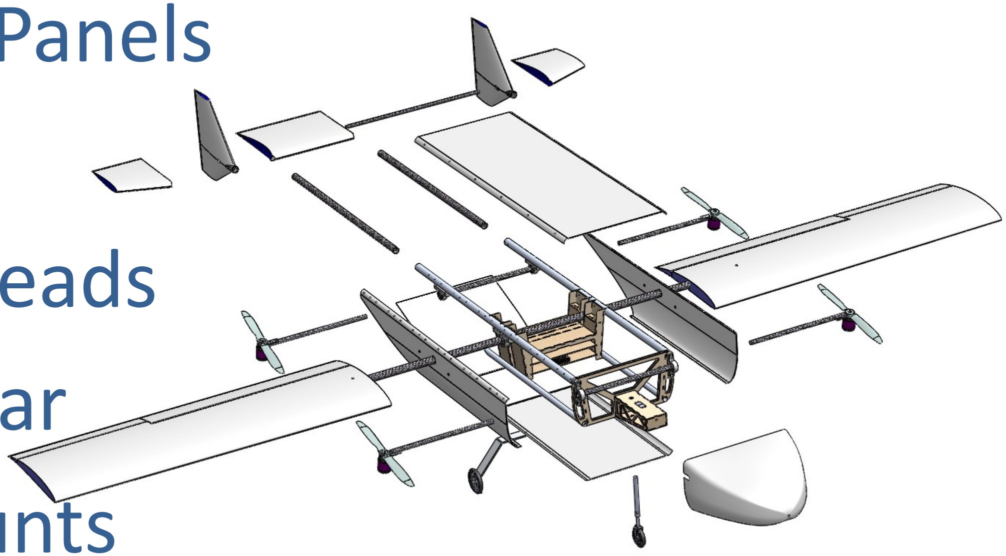
Reconfigurable Vehicle Design

- 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

2” L
1.6” OD
0.6lb

4x Hacker A40-10L-14p

6.8” x
2.9” x 2.7”
4.2lb

2x 16000mah 6s2p Lipo (22.2V nom)

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

Reliable Solution

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

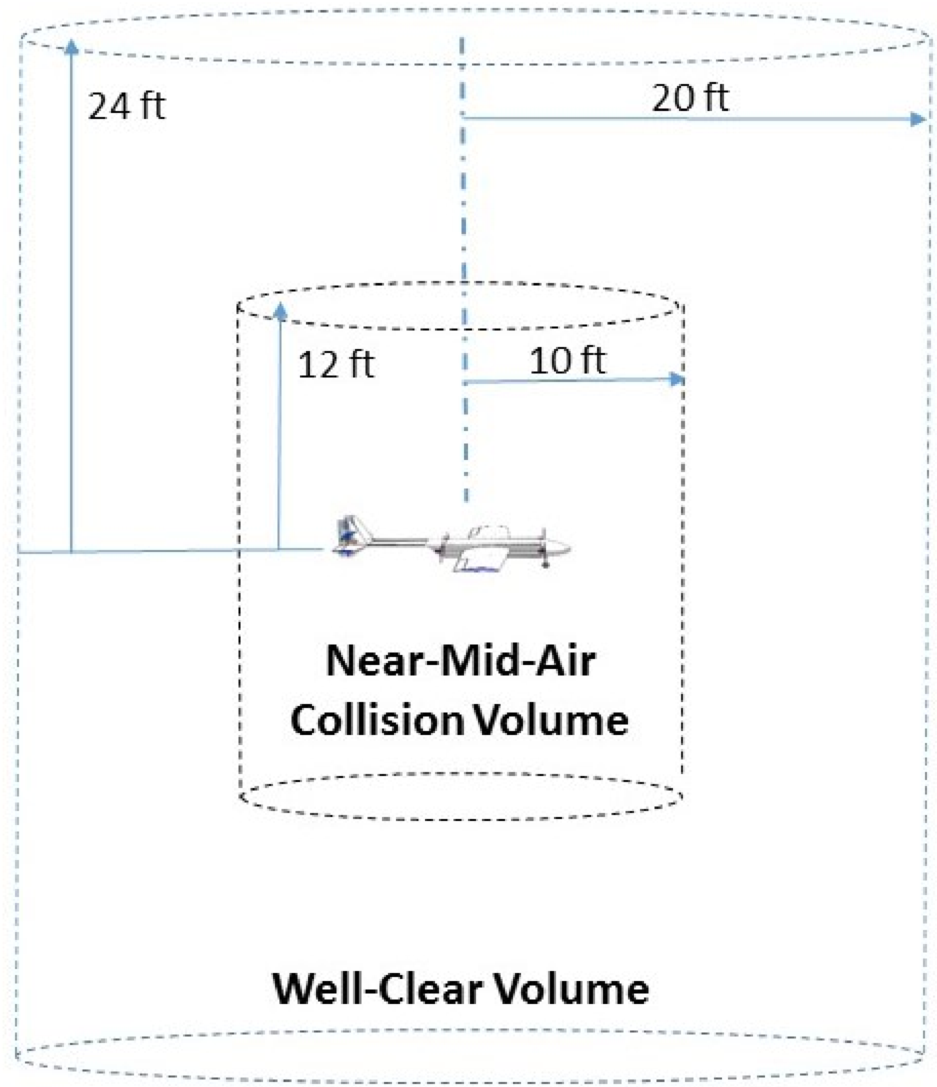
- On-board systems use “Detect And Avoid” algorithms to automatically remain a predefined “Well Clear” distance from traffic
- DAA Well Clear has been defined for large UAS integrated in the NAS
- NMAC and Well Clear have yet to be defined for small urban UAS operations
  - Maneuvering in cluttered environments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

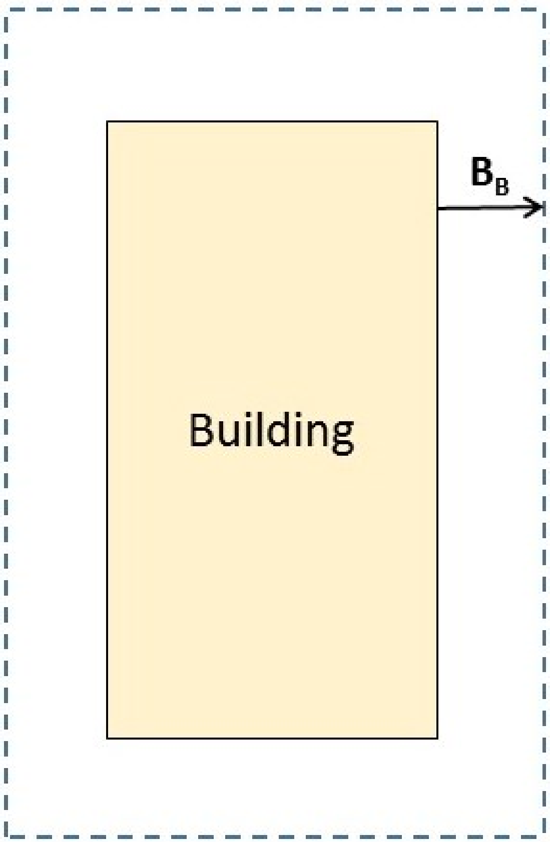
Traffic Avoidance

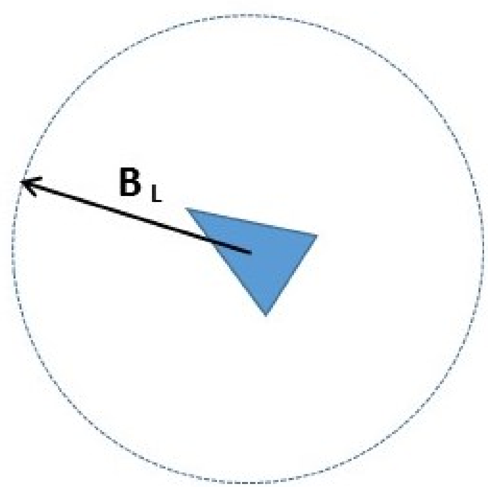
- Candidate NMAC and Well Clear Volumes developed
- Radius based on 10 ft wingspan
- Height based on altitude sensing accuracy at low altitudes
- Look-ahead time τ = 4 - 8 s for detecting conflicts based on ability to turn at 30º per second
- SAFIT™ prototype uses a NASA traffic avoidance algorithm



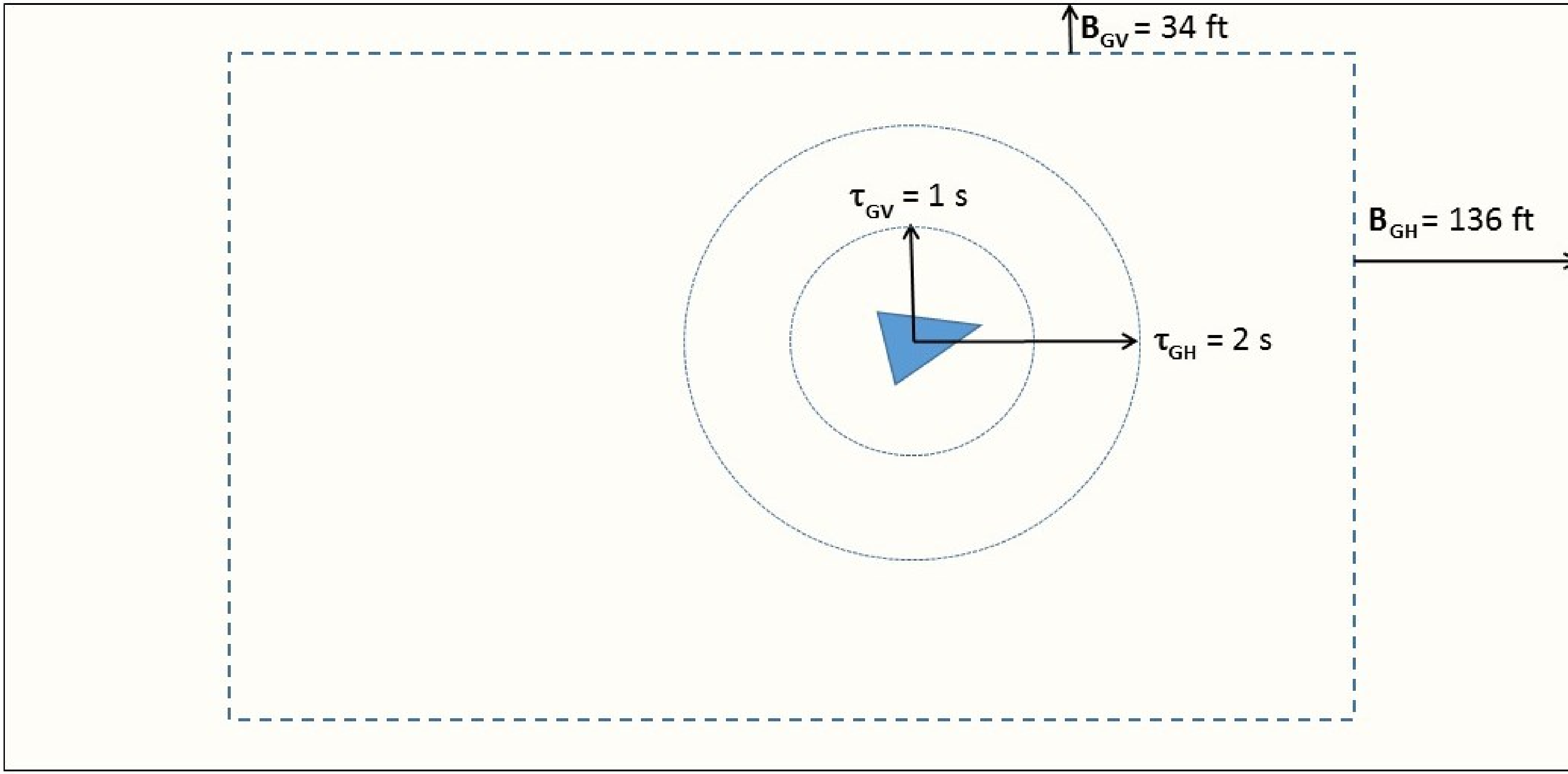
Obstacle Avoidance

- **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

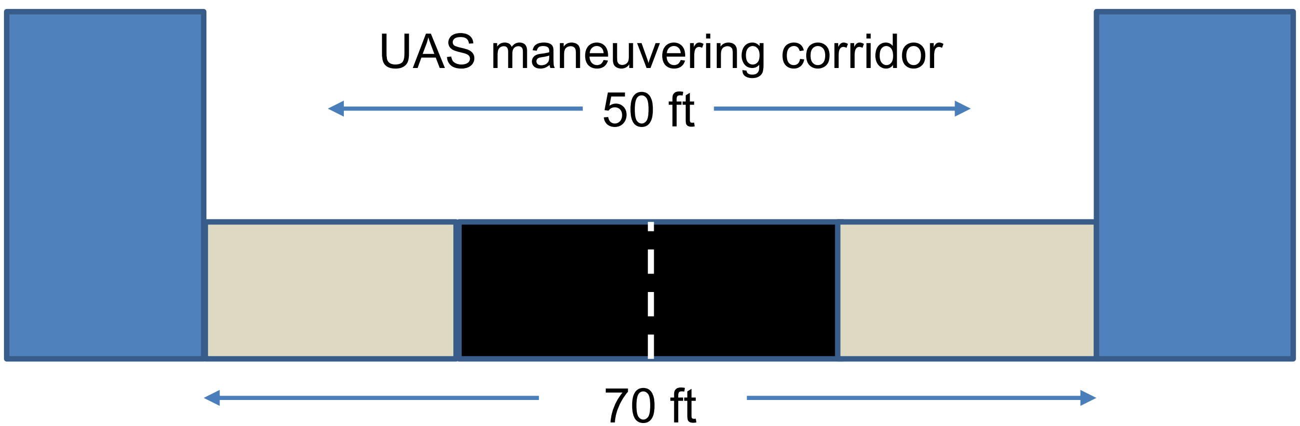
- Conventional flight (no hovering) at 25-50 mph
- Typical urban streets with sidewalks: 50, 70, and 90 ft width
- Oncoming traffic violating lane rules
- Crossing traffic at intersections
- Flight ceiling of 400 ft AGL
- Ownship position uncertainty (< 5 ft), but no traffic surveillance error
- 7550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

Publications

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	• Flight Operations
• Algorithm Development	• Data Collection and Analysis
• Software and Hardware Integration	• Demos and Technical Presentations
• IRB and ASRB Approvals	• 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

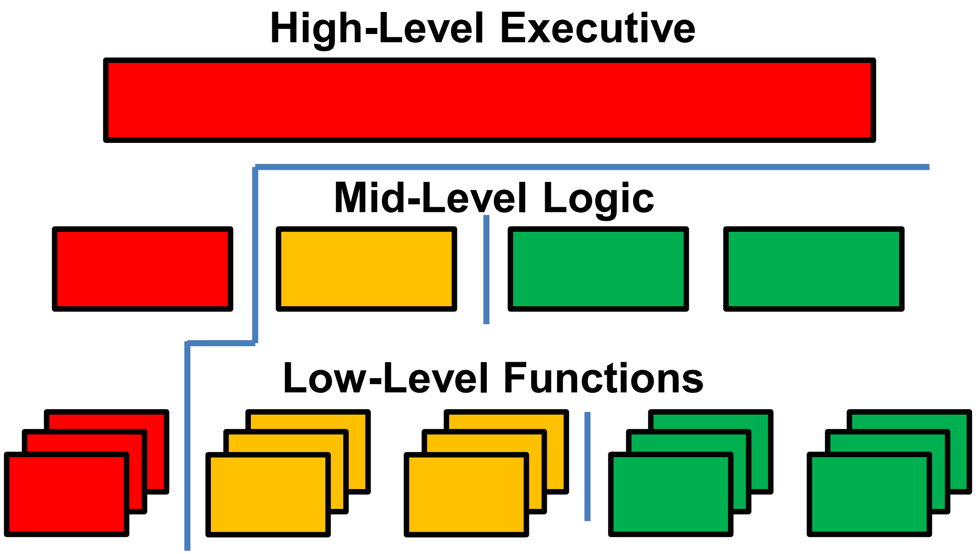
Our Product Vision:

- **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™



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

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

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**