Research Timeline

1980
Automated Maneuvering Attack System (AMAS)

2000
Automation Research

2010
Automated Collision Avoidance

2016
Integrated Safety Work

AFTI/F-16
Advanced Fighter Technology Integration

AFTI & ACAT/F-16
Automated Collision Avoidance Technology

SUAV/iGCAS/SR22
Improved Collision Avoidance System

Dedicated Safety Work

Platform Diversity

Ground Collision Avoidance

Air

Ground

Small UAS

Quad-Rotor

Integrated
Avoid Collisions
Do Not Impede the Pilot
Flight 18 event 6, 45 kts, 100' buffer
SR22 Hardware in the Loop Sim
The Challenge of Autonomy

- Verification & Certification of a Complex System
- A Possible Solution – Run-Time Assurance (RTA)
Safety Systems

- Predict Escape Trajectories
- Predict Future Threat State
- Determine Need to Evade & Threat Lethality
- Evade
- Notify

- Evasion Types
- Maneuvering Capability
- Evasion Trajectory Estimations
- Associated Uncertainties

- Minimum Approach
- Integrity Check
- Time to Evade
- Command Evasion

- Scan/Track Pertinent Threat
- Simplify Threat Profile
- Associated Uncertainties

- Sense Own-State & Atmospherics
  - Sufficient to support trajectory estimation

- Sense Collision Threat
  - Terrain
  - Aircraft
  - Weather
  - Missiles

- Common Interface

- Autopilot Coupler

- Pilot Controls
  - Mode Selection
  - Interface

- Notify
  - Alert
  - Record
  - Recall

- Common Interface

- Trajectory Predictions

- Sense Collision Threat
  - Terrain
  - Aircraft
  - Weather
  - Missiles

- Common Interface

- Autopilot Coupler

- Pilot Controls
  - Mode Selection
  - Interface

- Notify
  - Alert
  - Record
  - Recall
Multi-Monitor RTA
FAA/ASTM Collaboration

• ASTM Committee WK53403
  • Develop a standard practice that safely bounds the flight behavior of autonomous UAS.
  • Originated from our collaboration with them regarding Auto GCAS and integrity management work on early autonomy concepts
  • FAA has asked up to support the ASTM by sharing our techniques, practices and lessons learned as we develop EVAA

• Dec 16 Draft for Public Review
• Feb 17 Published
RTA Framework

ASTM WK53403
Multi-Monitor RTA Framework

Flight Executive components

UNTRUSTED

Flight Control System

Sensors

Integrity Monitor

Recovery Control

Decider

Switch

Safety/Behavioral Monitor

Flight Control System

Mission Systems

Flight Control System
Multi-Monitor RTA Framework

SP Eyes

SP Controller

Flight Control System

UNTRUSTED Systems

Sensors

Integrity Monitor

Recovery Control

Decider

Switch

SP Monitor
~Controllers
• Avoidance Maneuvers
  • Rate/Att. Capture
  • Waypoint Following
  • Altitude Capture
• Aircraft Lighting

Controllers
• ATC
• UTM

Monitors
• Well Clear
  • Well Clear/Sep. Assur.
  • Rules of flight
• Airspace Boundaries
• Personal Space
• Privacy Rights
• Property
  • Property Rights

Controllers
• Avoidance Maneuvers
  • Rate/Att. Capture
  • Waypoint Following
  • Altitude Capture

Monitors
• Communications

Controllers
• Forced Landing
  • Where to Land
• LoC Prevention
• LoC Recovery

Monitors
• LOC
• Power Plant

Controllers
• Pitch Autopilot
• Roll Autopilot
• Speed Autopilot

Monitors
• OLIV
  • A/C State
• Dynamic Consistency
  • Is this OLIV?

Controllers
• Stability & Control
• Structural Limiting
• Envelope Protection

Monitors
• Sensors
  • Air Data
  • Accelerometers
  • Gyros
  • Angle of Attack
  • Sideslip
• FCS
  • Watchdog Timer
  • Output Crosscheck
  • Control Surfaces

Controllers
• Avoidance Maneuvers
  • Rate/Att. Capture
  • Waypoint Following
  • Altitude Capture

Monitors
• Collision Avoidance
  • Ground
  • Obstacle
  • Air Traffic
  • People & Property
• Weather Avoidance
• Person Avoidance
• Population Avoidance
Interlinked RTA Control Framework
Multi-Monitor/Multi-Layered RTA

Communicate

Mission Interoperability Control Level
- Emergency Procedures
- ATC
- UTM
- Squad/Flight

Aviate & Navigate

Aviate Control Level
- Avoidance Maneuvers
- Terrain Capture
- Terrain Caution
- Waypoint Following

Outer-Loop Control Level
- Pitch Autopilot
- Roll Autopilot
- Speed Autopilot
- Autopilot

Inner-Loop Control Level
- Structural Limit
- Regression Modes
- Stability & Control

Controllers – Surfaces, Power-Plant & Thrust Vectoring

Behavioral Control Level
- Avoidance Maneuvers
- Lighting

Well Clear
- Well CtrlSep, Asmc.
- Rules of Flight

Airspace Boundaries

Personal Space

Privacy Rights

Property Rights

I'm thinking the behavioral level is a lesser set of the aviate.
Multi-Monitor/Multi-Layered Comprehensive RTA
Phase 1 – All data base driven

Communicate
Mission Interoperability Control Level
- Emergency Procedures
- ATC
- UTM
- Squad/Flight

Aviate & Navigate
Aviate Control Level
- Avoidance Maneuvers
  - Intruder Capture
  - Attack
  - Support

Higher-Order Mission Guidance
- Collision Avoidance
  - Ground
  - Obstacle
  - Aircraft
  - People
  - Property
- Weather Avoidance
- Weather Avoidance
- Population Avoidance

Emergency / Degraded Control Level
- Forced Landing
- Where to Land
- LoC Prevention
- LoC Recovery

Contingency Monitor
- Loss of Control

Link
Communications

Behavioral Control Level
- Avoidance Maneuvers
- Lighting
- Well Clear
  - Well Ctrl-Sep, Asmc.
  - Rules of Flight
- Airspace Boundaries
- Personal Space
- Privacy Rights
- Property Rights

I’m thinking the behavioral level is a lesser set of the aviate
The Big Picture - Traveler

Trustworthy Autonomy

Certification
- Developing research findings to inform standards development for certifiable autonomy
- Collaborating with ASTM Working Group on autonomy certification guidelines
- FAA Collaboration and Interest

Expandable Variable-Autonomy Architecture (EVAA)
- Stretching the paradigm of autonomy
  - Determinist Rulesets Bounding Autonomous Behavior
  - Risk-Based Decision Making
- A process enabling certification
  - Software Architecture/Framework
  - Test Approach
- Scalable autonomy
  - Pilot-in-the-Loop to “Fully Autonomous”

Low Altitude Small UAS Test Ranges (LASUTR)
- A tool for certification
- High-risk integrated research
Expandable Variable Autonomy Architecture (EVAA)

• A Software Framework
  • A Federated Architecture
    • Safety Systems
    • 1
    • 2
    • 3...
    • Flight Executive
  • Software Structure & Techniques

• Classical & Non-Classical Verification Methods

• Safety Evaluation of the Technology
  • Targeted at Flight Demonstrations
  • Social Interaction
Armstrong’s Traveler Effort

• **Goal: Trustworthy Autonomy**
  - BVLOS to and from uncontrolled areas
  - 400 feet to Surface
  - Any Number of Aircraft per Operator

• **NASA Funded Effort**
  - Leverages a 30 year development of autonomy from DoD & NASA
  - TRL 3 to 5
  - Local Armstrong Directed Objectives
  - Supporting formulation of TACP Autonomous Systems start in 2018

• **Primarily Software Approach and Process Development**
  - Platform ~Agnostic
  - Mission ~Agnostic
  - Sensor ~Agnostic

• **Flight Development and Evaluation in Support of ASTM Regulatory Development**
  - Target Demos to Make an Airworthiness Case to
  - Possible High-Visibility Demo in Spring of 2017
  - Second Demo possible in 2018
LASUTR

How is LASUTR different from FAA Test Sites?

Agile/Flexible
• No COA allows for rapid changes based on evolving requirements

Interoperability
• Ability to test multiple aircraft/concept in an integrated manner

High-Risk Testing for New Concepts
• BVLOS
• Autonomy
• Night operations
• Controlled “risk” including controlled “crashes” without FAA accident notification requirements
High-risk research conducted at LASUTR

This generates research findings to help formulate testing requirements

Research findings are shared with community of interest (FAA, Test Sites, industry, academia)

FAA generates testing requirements for Test Sites (and other entities)
NASA South – Range for High-Risk Research

• **Terrain**
  - Flat
  - Virtual Cliff
  - Virtual Hill
  - 4 mile loop
    - Much longer at other LASUTR sites

• **Obstacles**
  - Cell Tower
  - Shuttle Hangar
  - Light Poles
  - Power Lines
  - Virtual High-Tension Power Line
  - Virtual Power Lines
  - Virtual Antenna with Guy Lines
  - Trees
Command, Control & Monitoring Architecture

During Test & Evaluation

Blue text & lines indicate the core autonomous system.
Orange text & lines indicate flight test only components.

- **Traveler System**
  - Infotainment System
  - A/C vector / Map & LRO
  - Monitoring Only

- **Traveler GCS**
  - Test-C2 Test Only
  - System Control

- **Test Director & Safety Officer**
  - Monitoring Only

- **Safety Pilot-C2**
  - Test Safety Only
  - Emergencies Only

- **COTS-C2**
  - COTS GCS
  - COTS-C2 Only

- **Core Flight Control Computer**

- **Traveler System & EVAA**

- **Cellular**
  - LASUTR TSPI
  - POCs

- **Lighting & Sound**

- **UTM**

- **Infotainment System**
  - A/C vector / Map & LRO
  - Monitoring Only

- **System Monitors**
  - RT mon..
Phase 1
Integrated Testing

Traveler System

A/C & Flight Control System
- WP Navigation
- Roll & Vz Capture
- Autopilots
- Core Flight Controls
- GPS/INS

Test Resources
- LASUTR
- Traveler GCS
- COTS GCS
- Chase Vehicle
- COTS GCS
- RC Controller
- RT Monitors
- CIT

Mission System
- Route Follower
- Route Planner
- Terrain Following
- Ops Manager
- Social Interface

EVAA
- Flight Executive
- Mission Manager
- Coupler
- Decider
- Health Monitor

Map Manager
- Terrain Map
- Feature Map
- Risk Map

Trajectory Generator
- AC1
- AC2
- ACn

Population Avoidance
- GCAS
- GeoFence
- FLS
- Flight Test

Legend
- RTA Functions
- Untrusted Controllers
- Baseline Aircraft
- Sensors
EVAA Phase 2 Aircraft

• VTOL & Forward Flight Capable
• Payload Capacity for Sensors & EVAA
  • EVAA Processors, Wiring & Interfaces
    • 1 - oDroid XU4 0.16 lbs.
    • 2 – Ardino Processors
    • Speaker
    • Lights 0.35 lbs.
  • Sensors
    • 4 - Stereo-Vision Camera Pairs and Processors
    • ADS-B 0.07 lbs.
    • UTM Wireless Interface
    • Flight Test TSPI, etc. 0.57 lbs.
• 50 to 75 MPH Flight Speed
• 50 to 75 Mile Range
• Easy Break-Down & Assembly for Transportation to and from Test Sites
EVAA RTA Framework

Phase 1

542 IP

542 Evaluates & Models Sensors

Sensors

Sensors

Sensors

RTA Input Manager

Mission System

OLIV

FLS

GeoFence

GCAS Monitor

542 IP

RTA Switch

542 IP

542 IP

542 Airworthiness Certification

Vehicle Management System

542 Implements, Evaluates & Models Autopilot Recoveries

542 Systems Certification

542 IP
Expandable Variable-Autonomy Architecture (EVAA) Hardware Structure

- **FCS** (PixHawk)
- **Autopilot** (PixHawk)
- **IMU**
- **Safety Pilot**
- **Mission Computer** (`oDroid Xu3/4`)
- **Social Interface Computer** (`Ardrino`)
- **Processed Sensor Data**
- **Raw Sensor Data**
- **Sensor Data**
- **Processed Sensor Data**
- **Ethernet (DDS)?**