Versatile Experimental Autonomy Research Aircraft Technology (VEARAT)

LEARN Seminar

Contract No. NNX15AW45G
15 Oct 2015 to 31 Jan 2017

Dr. Shiv Joshi, PI

06 Sep 2017

Team

- **NextGen Aeronautics**

  Shiv Joshi, Matt Scott, Rob Bortolin, John Flanagan, and Robbie Snyder
- **UIUC**

  Professor Girish Chowdhary and Girish Joshi
- **Virginia Tech**

  Professor Rakesh Kapania, Professor Joe Schetz, and Wrik Mallick

Agenda

- **Opportunity**
- **BASSET** (Big Antenna Small Structure Enhanced Tactical UAV)
  - Highlights
  - Limitations
- **VEARAT**
  - Objectives
  - Structure/Propulsion Modification
  - Payload Integration
  - Autonomous Operations
- **Conclusions and Suggestions**
- **Open Discussion**

Opportunity

- **The National Research Council (NRC) Identified Technology Barriers to Autonomy**
- **NASA LEARN2 Project Initiated in 2015**
  - Developing system architectures and technologies
  - Enabling experimental autonomous unmanned aircraft to easily integrate, verify and validate rapidly evolving hardware and software subsystems
- **NextGen Initiated Development Based on an Appropriate Technology Demonstrator (BASSET)**
  - Allow nontraditional technologies such as open-source software and consumer electronics products
  - Adaptive nondeterministic third party autopilot
  - Long duration autonomous operations without real-time human cognizance and control

Proposed Solution

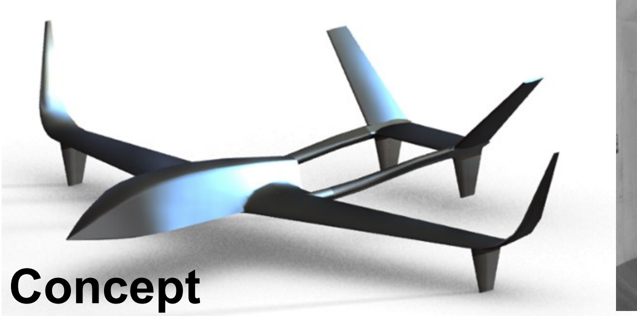
Modification of existing research vehicle (BASSET) with interchangeable and in-flight-switchable experimentalist supplied sensors, hardware and software for autonomy research and testing

Baseline UAV (BASSET) developed for communication subsystems testing by NextGen under Air Force funding (FA8650-08-C-3845) during 2008-2013. Preliminary design optimization, modification, and payload/sensors selection done under NASA LEARN2 program.

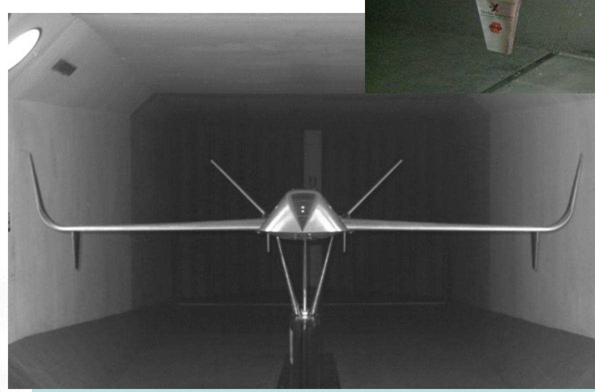
BASSET: POD-UAV for VEARAT

- Design of a small UAV (SUAV) capable of direction finding (DF) at low frequencies (30 MHz and above) using a single aircraft and with range, endurance, and overall cost comparable to or better than existing vehicles of similar size.

Show BASSET Video



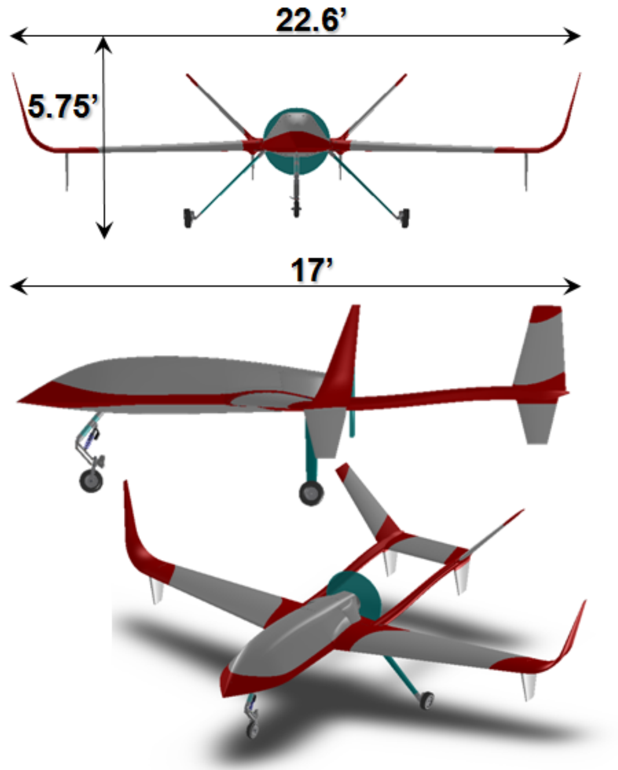
Concept

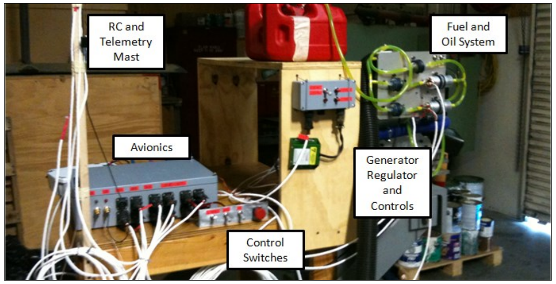


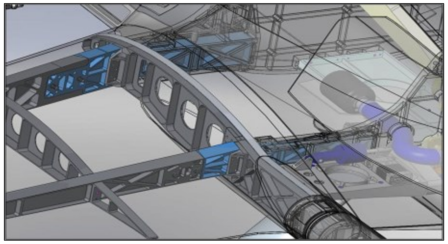
Concept to Design to Fabrication to 3 Flight Tests validating aero, structures, and antenna Geo-location performance – total budget < $4M!

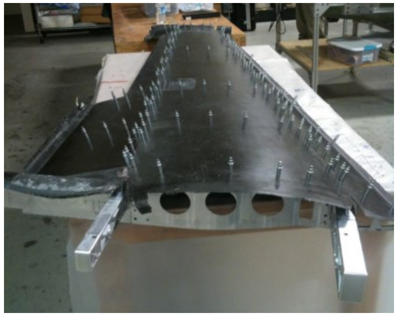
BASSET Highlights

Weight	590-700 lbs
Fuel	5 gal (67 min @ full throttle)
Takeoff Distance	< 1000 ft
Stall Speed	48-52 knots
Takeoff Speed	57-62 knots
Cruise Speed	80 knots (typical)
Max Speed	120 knots
Flight Duration	<30 minutes (typical)
Test Flight Radius	< 1 mile
Max Demonstrated Control Range (RC+Link+FTS)	2.5 Miles (TBD On-Site Test)
Test Flight Altitude	600-1200 feet AGL (typical)

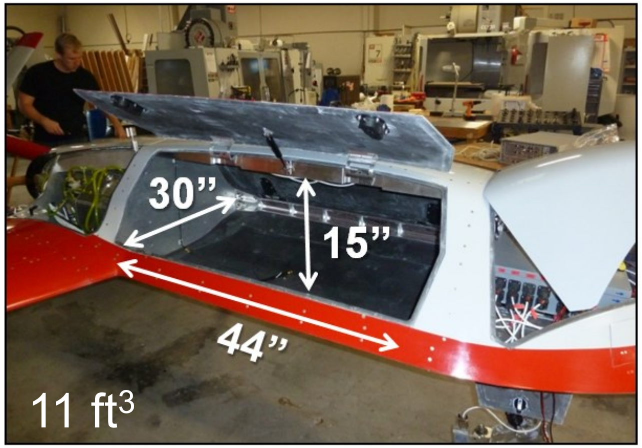


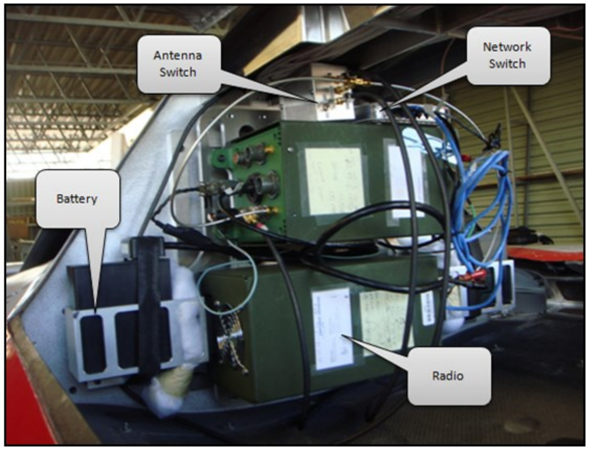






BASSET Highlights (cont'd)

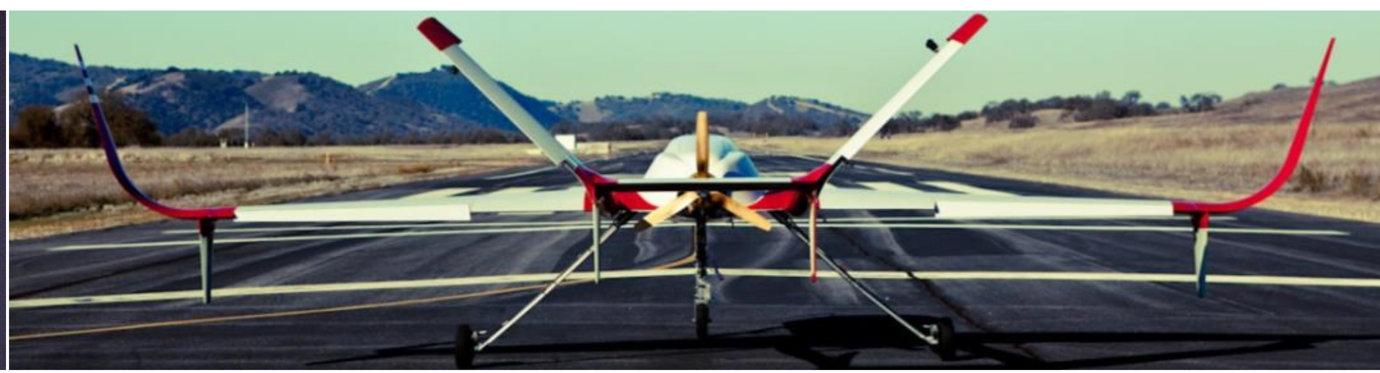




- Flight testing established basic flight characteristics, performance, and operations
- Modular major structural parts can be stored in a standard C-130 pallet
- Assembly from box to airborne in 30 minutes
- FTS and an autonomous/human switchable GNC system
- Original BASSET molds preserved - minimal retooling for manufacturing

BASSET Limitations

- Vehicle Weight Not Optimized
- Vehicle Designed With Substantial Margins of Safety
- Current Engine Performance Below Vendor-provided Data
  - Fuel consumption up to 9.5 gal/hr at 4500 RPM. Vendor test data showed 4.75 gal/hr
  - Wood propeller blades from Europe broke at low altitude necessitating emergency landing resulting in inoperable vehicle
  - Low custom designed fuel tank capacity reducing nominal flight time to half an hour
- Only LOS Communications
- Vehicle Avoidance and Weather Subsystems Not Integrated
- Requires Operator for Takeoff and Landing Operations



VEARAT Objectives (NASA LEARN2 Program)

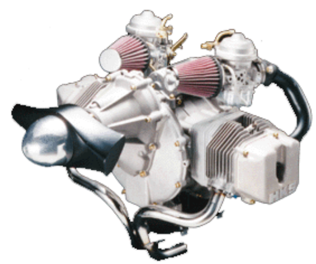
1. INCREASED ENDURANCE: 6+ hours with a payload capacity of between 50 to 100 lbs
2. Selection of new engine, along with prop redesign and improved engine/airframe integration
3. Reduce size of winglets and antennas, leading to reduced drag
4. BLOS COMMUNICATIONS: Accomplished with proposed GNC system
5. Flexibility for User to test their sensors, systems, and software
6. FULLY AUTONOMOUS OPERATIONS: Current system is capable of way-point navigation but requires an operator for takeoffs and landings; these can be automated, completely removing the pilot from the loop
7. COOPERATIVE AND NONCOOPERATIVE VEHICLE AVOIDANCE: Requires additional subsystems to be integrated in the UAV

Preliminary Specifications

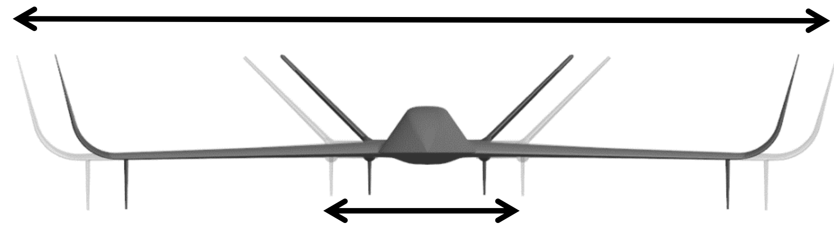
Antenna	• 3 to 8 antenna mounting locations • >50 lb of antenna payload capacity • >2 ft^3 of antenna related payload volume
[redacted]	
Operation	• Ceiling > 17,000 ft MSL standard atmosphere conditions • 15 to 150°F storage and 25 to 120°F operation • Capable of takeoff/landing on minimally prepared surfaces • Loiter speed <100 mph • 6 hr or greater mission time
[redacted]	
Features	• Plug-and-play payloads capability • Easy software uploading and HITL ground testing • Deterministic and non-deterministic hierarchical and adaptive GNC baseline hardware and algorithms • FTS • Command transfer capability • Multivehicle Collaboration • Communication Relay capability • Breakdown for storage (5 piece minimum).

Structure/Propulsion Modification

HKS 700E



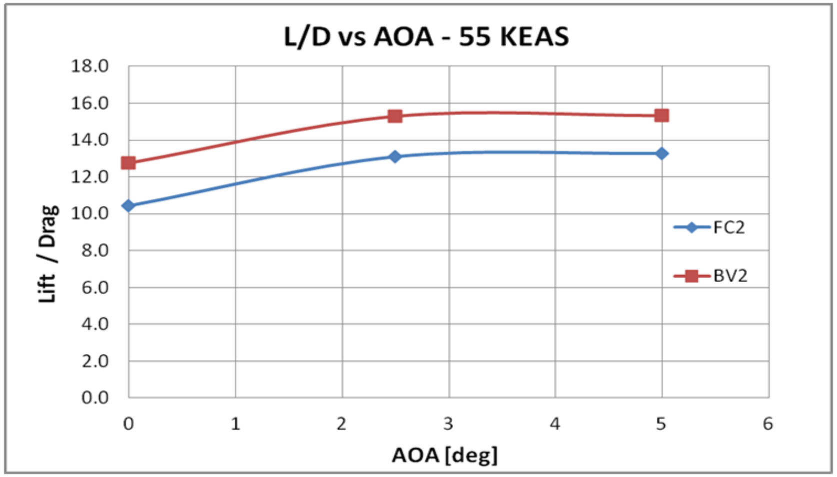
Wing Span b: 22.7' → 25'

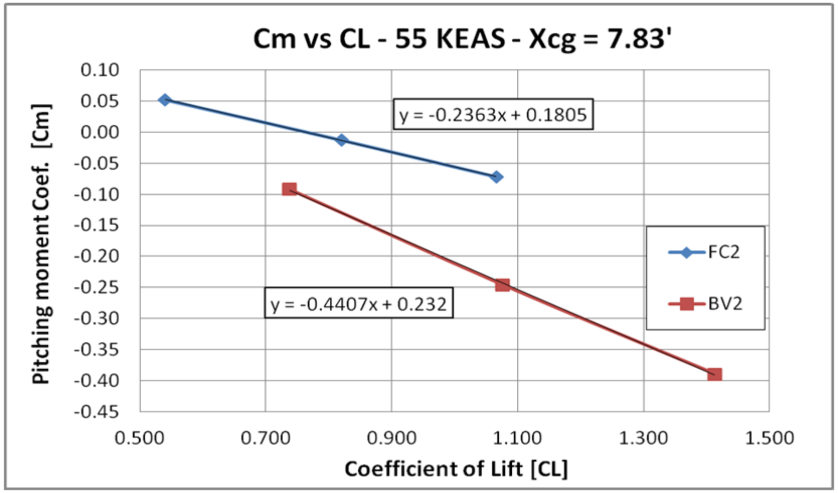


Tail Boom W: 37" → 65"

- HKS 700E engine will be integrated for the VEARAT UAS
- Reliable, efficient 4-stroke engine: 6 hrs endurance with 75 lbs payload
- Tail boom width increased for prop performance: max diameter 64" vs. 36"
- Wing span increased proportionally, providing L/D improvement >10%
- Modular wing feature retained, attachment placed outboard of tail booms
- Carry-through optimized for engine integration, structural efficiency
- Configuration enhancement maximizes use of existing tooling

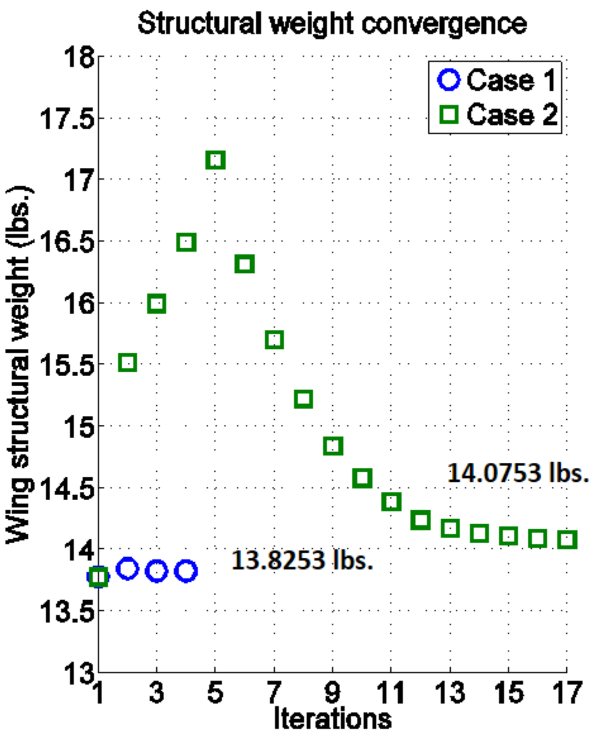
VEARAT vs BASSET Configuration

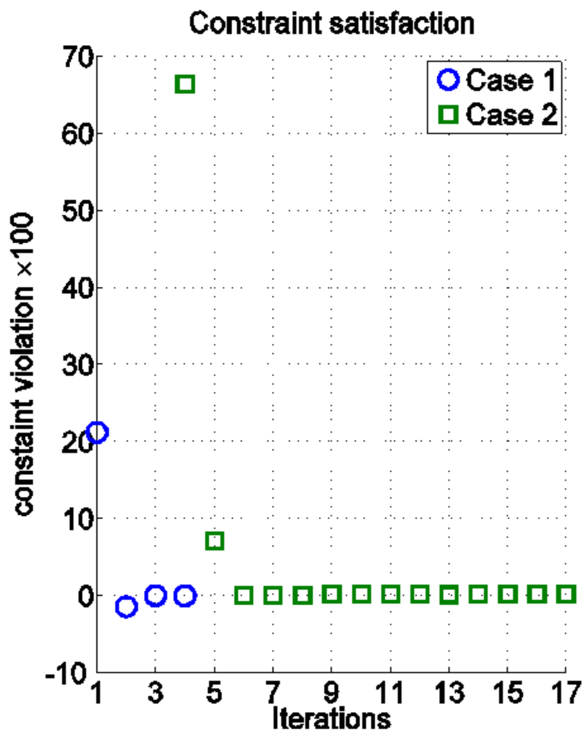


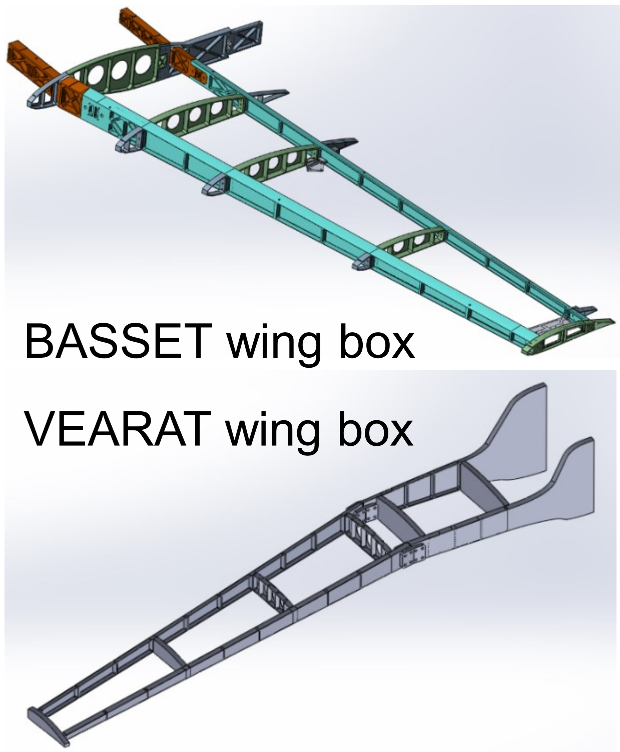


Parameter	BASSET	VEARAT	Change
Wing planform area [ft^2]	50.5	58.8	16%
Wing span [ft]	22.7	25	10%
Wing MAC [ft]	2.68	2.82	5%
Wing AR	10.2	10.6	4%
H-tail planform area [ft^2]	12.8	16.8	31%
H-tail Xac [ft]	15.7	16.1	3%
H-tail volume coefficient	0.74	0.84	14%

VEARAT Structural Optimization



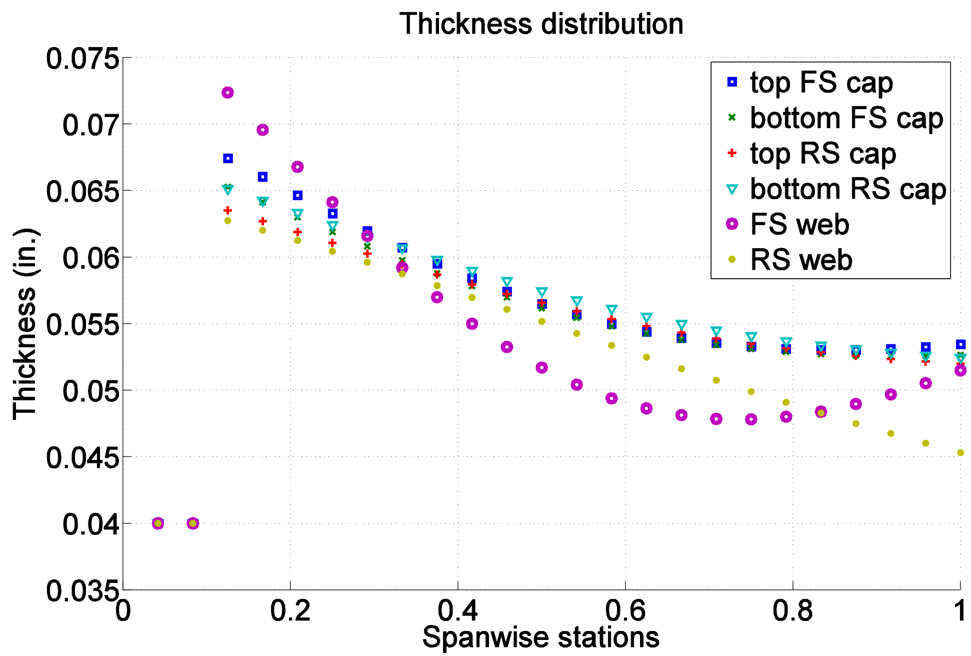




- BASSET wing was designed as a prototype
- CFD modelling is conducted to obtain updated load data following lengthening of wing at 3.35g condition
- Structural weight optimization is performed
- Design optimization study was performed using the SOL 200 module in NASTRAN
  - SOL 200 uses a gradient-based optimizer IPOPT

Optimized Wing Structure

- Optimized Thickness Distribution, 3.35 g Load Case
- Estimation of Wing Structure Resulted in Mass Savings of 55% FEM Models



Member weight	Baseline	Optimized	% Change
Front spar (lbs.)	14.861	3.6133	-75.686
Rear spar (lbs.)	7.159	2.7635	-61.398
Skin (lbs.)	6.035 (composite)	7.1000 (Al 7075-T6)	17.644
Ribs (lbs.)	8.303	2.8858	-65.569
Total (lbs.)	**36.258**	**16.3356**	**-55.07**

VEARAT Optimized Mass Savings

- By Using Weight Savings of the Optimized Wing Structure and Projecting that % Savings Onto Other Areas of the Vehicle, We Can Anticipate ~140 lbs Weight Reduction
- Added Fuel Capacity of 14.3 gal
- Expected Endurance with New Engine = 6.2 hrs

Detail Design Wing Structural Weight Savings after Optimization			
	Original BV1	BV2	% Savings
Wing Weight [lb] (Both Wings)	120.0	68.2	43%

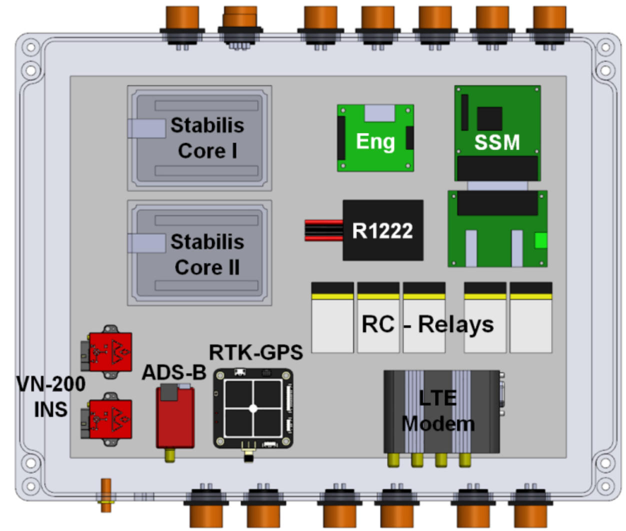
Projected Structural Weight Savings			
	Original BV1	BV2	% Savings
Fuselage Weight [lb]	91.6	52.0	43%
Tail Weight [lb]	42.3	24.0	43%
Landing Gear Weight [lb]	68.1	38.7	43%

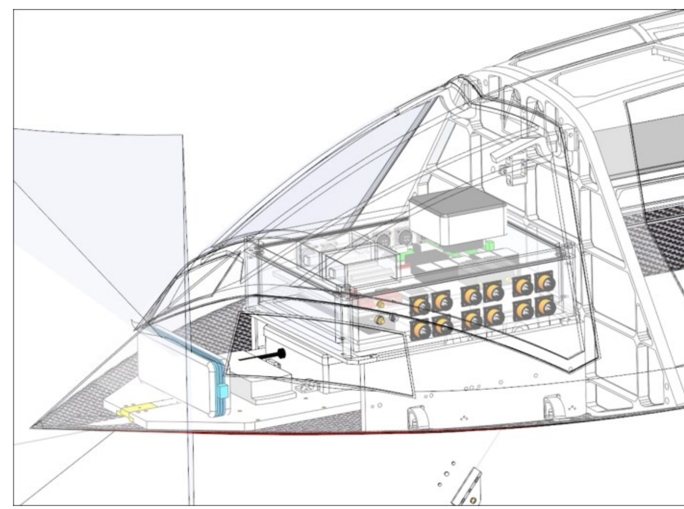
Project Total Vehicle Structural Weight Savings [lb]
139.1

Endurance Enhancement	
New Engine Added Mass [lb]	86.5
New Fuel Capacity [us Gal]	14.3
Flight Time [hr]	**6.2**

Payload Integration

- VEARAT Offers Multiple Mounting Locations for Conventional Antennas and Communication Links
- Several Skin Panels are Replaceable and Can Be Tailored for Integrated Sensors or RF Transparency
- A Wide Variety of Onboard Power, Computing Capacity, and Programmable I/O for Data Fusion, Recording, and Autonomous Operations Will Be Available to Any Hosted Payload
- VEARAT Avionics Suite Will Feature Dual Stabilis Cores Along With Redundant INS Sensors; ADS-B Transceiver Will Be Added to Coordinate with Cooperative Aircraft
- RTK-GPS Will Be Implemented to Achieve the Spatial Awareness and Control Resolution Necessary for Automated Take-off and Landing
- Echodyne K-band Radar Will Be Installed at the Aircraft Nose; This K-band Radar Features a Metamaterial Phased Array, Which is Game-changing Technology for Radar Systems of SUAVs



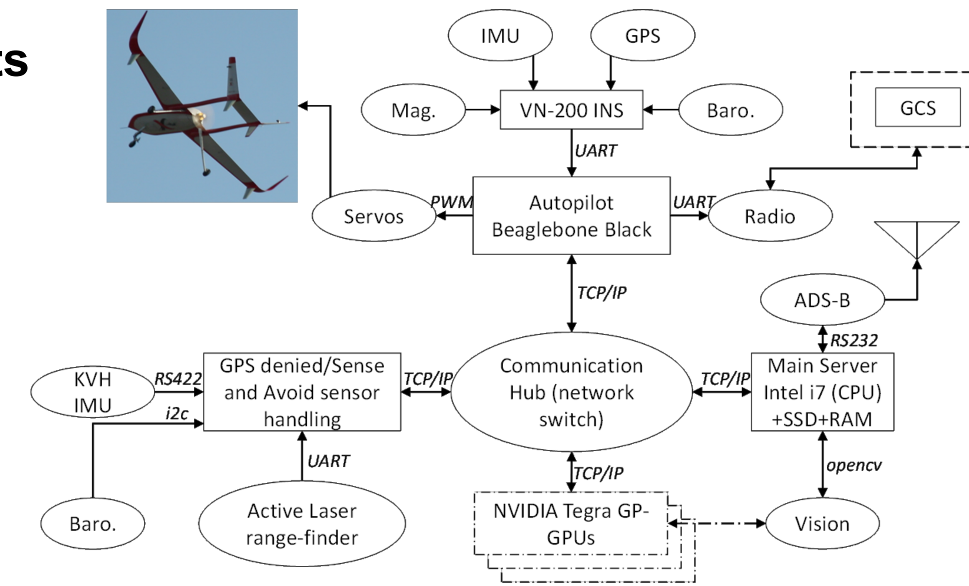


Autonomous Operations

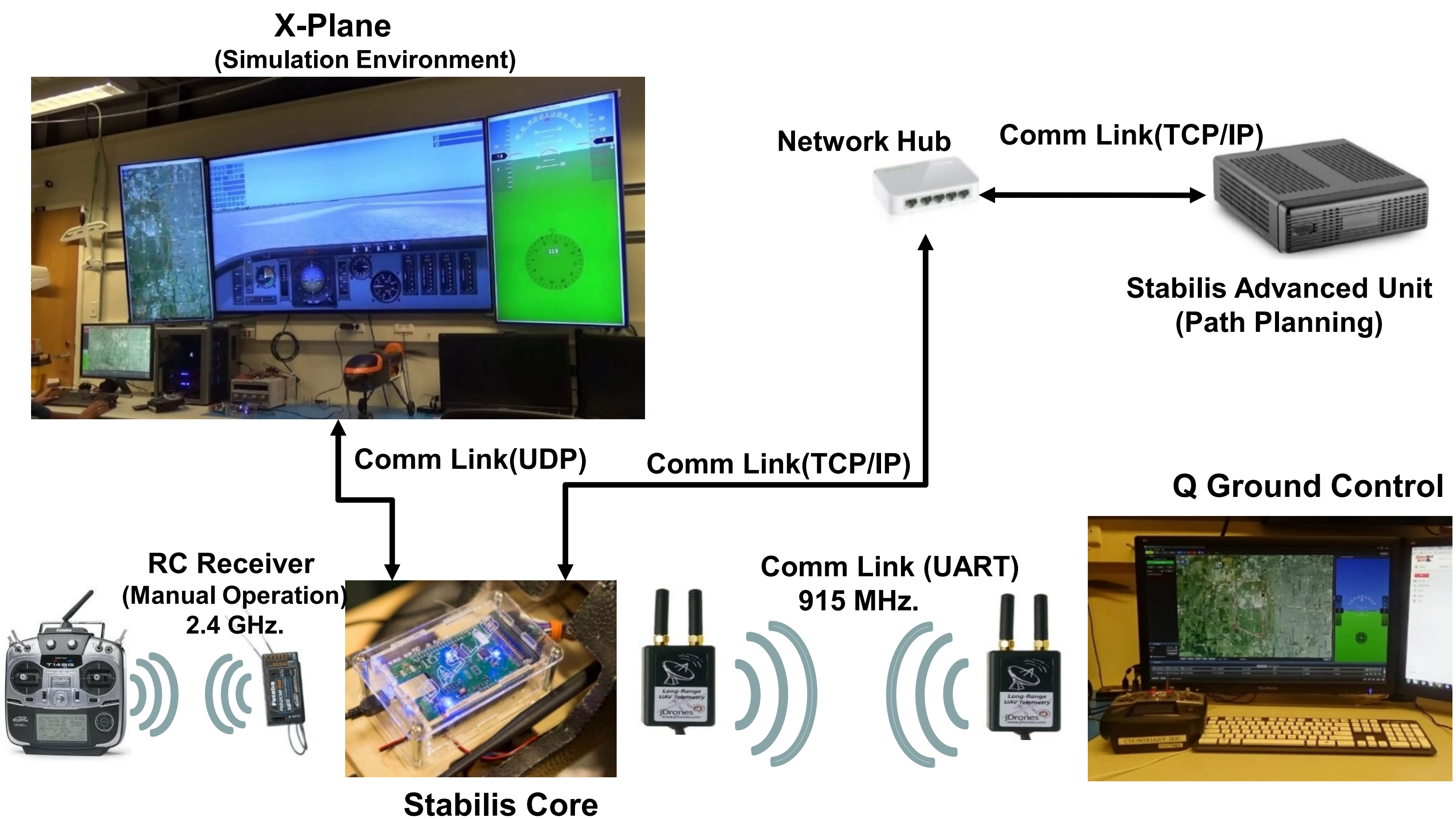
- Plug-and-adapt Autopilot Enabling Quick Adaptation to Platform and Mission Changes
- Easy Software Uploading and HITL Ground Testing
- Deterministic and Non-deterministic Hierarchic GNC Baseline Hardware and Algorithms
- FTS and Seamless Autonomous Human Control Handover

LEARN2-VEARAT Accomplishments

- SIL and HIL Testing
- Surrogate UAV Flight Testing
  - Manual Flight
  - Assistive Stable Flight
  - Autonomous Flight
  - Stall Recovery
  - Autonomous Takeoff and Landing



HIL- Setup


X-Plane
(Simulation Environment)
Network Hub
Comm Link(TCP/IP)
Stabilis Advanced Unit
(Path Planning)
Comm Link(UDP)
Comm Link(TCP/IP)
Q Ground Control
RC Receiver
(Manual Operation)
2.4 GHz.
Comm Link (UART)
915 MHz.
Stabilis Core

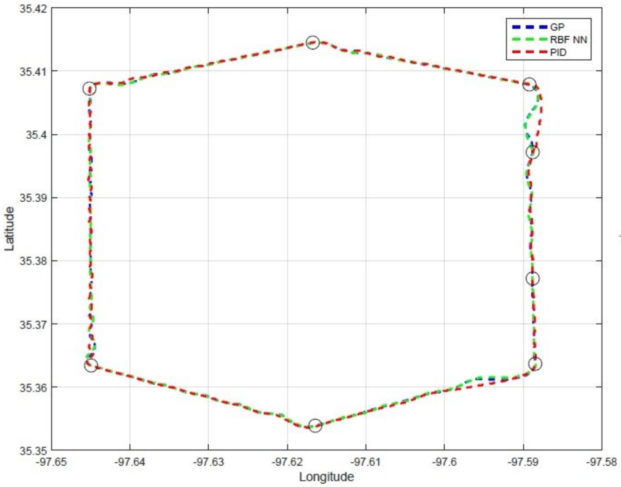
Stable Flight: Assistive Stable Mode

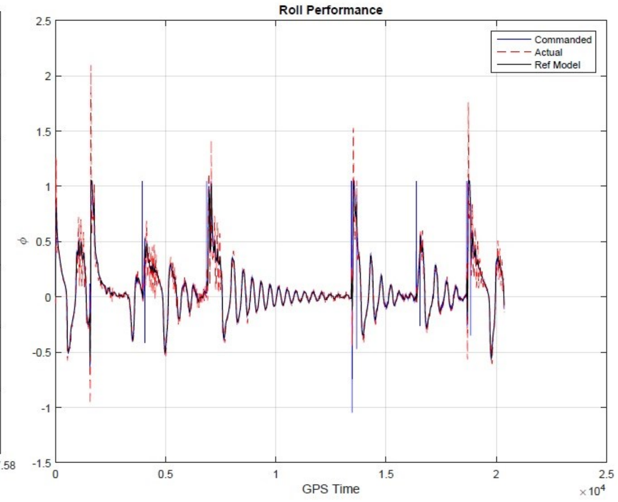
- Adaptive Control Performance: Online Disturbance Approximation in Roll and Pitch
- Adaptive Control Cancels the Actual Disturbance Using Approximated Disturbance, Thereby Enforcing the Reference Model Behavior Onto Plant
  - Autopilot commands the UAV to track the pilot stick command
  - In absence of pilot signals, the UAV holds zero attitude and maintains steady flight
  - Stable mode autopilot defines performance limits in roll and pitch to ensure safety
  - RTL capability in case of telemetry loss
  - Failsafe mode and switch to manual in case of spurious behavior of autopilot

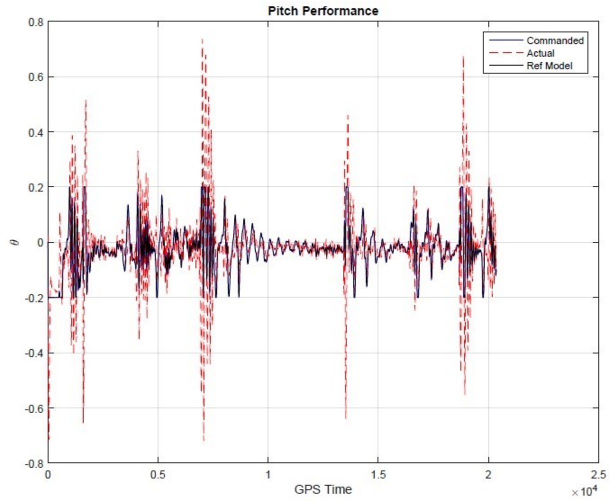
A novice operator could fly the plane in near impossible flight conditions with cross wind of 23 knots.

Autonomous : HIL Results

- Roll and Pitch Command Tracking for Waypoint Guidance
- No Cross Wind
- HIL Tests Validate Control Design and Aid in Controller Parameter Tuning

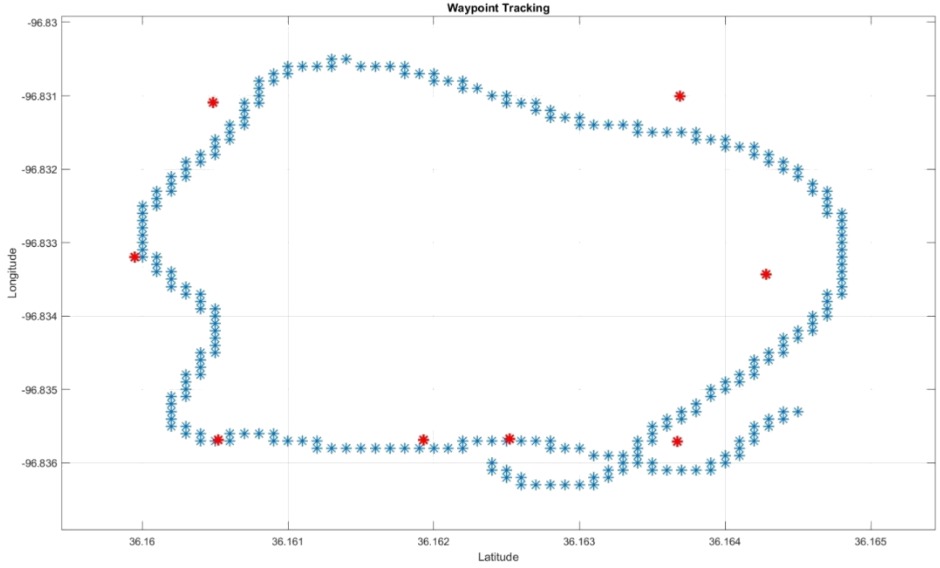






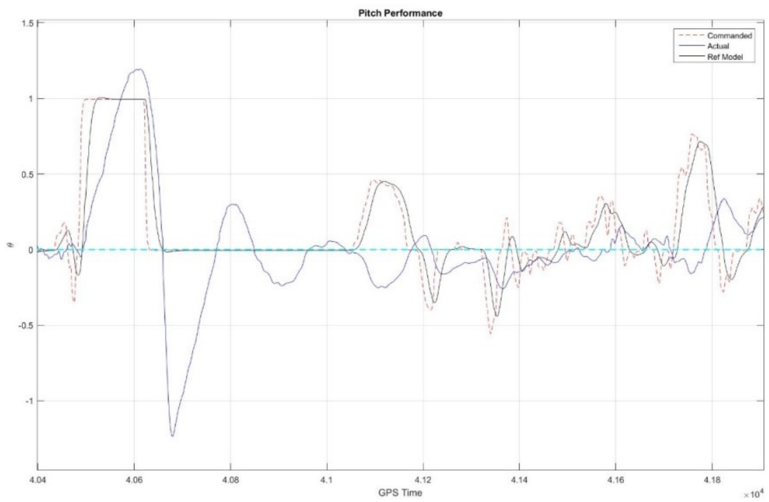
Autonomous Flight

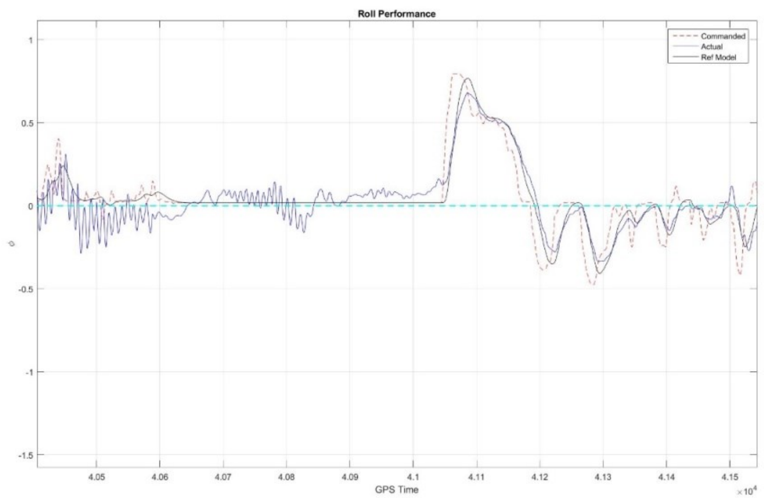
- Autonomous Waypoint Guidance
  - Autonomous Trajectory Tracking Defined by Waypoints
  - UAV Maintains Airspeed and Altitude Defined at Waypoints
  - HIL and Flights Tests are Conducted to Demonstrate Performance and Robustness of Controller
- Flight Condition
  - No. of Waypoints: 8, in hexagonal pattern
  - Cross winds: 23 knots



Stall Recovery

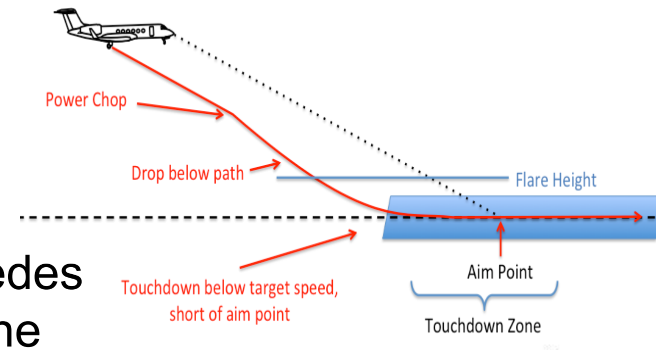
- In Stable Mode, Aircraft Was Made to Stall By Pitching Up Heavily Followed By Engine Cutoff
- Aircraft Recovered Successfully From Stall and Maintained Its Attitude Post-stall

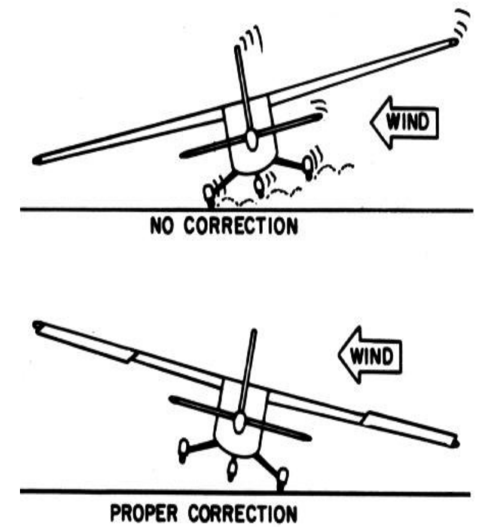




Autonomous Landing Control

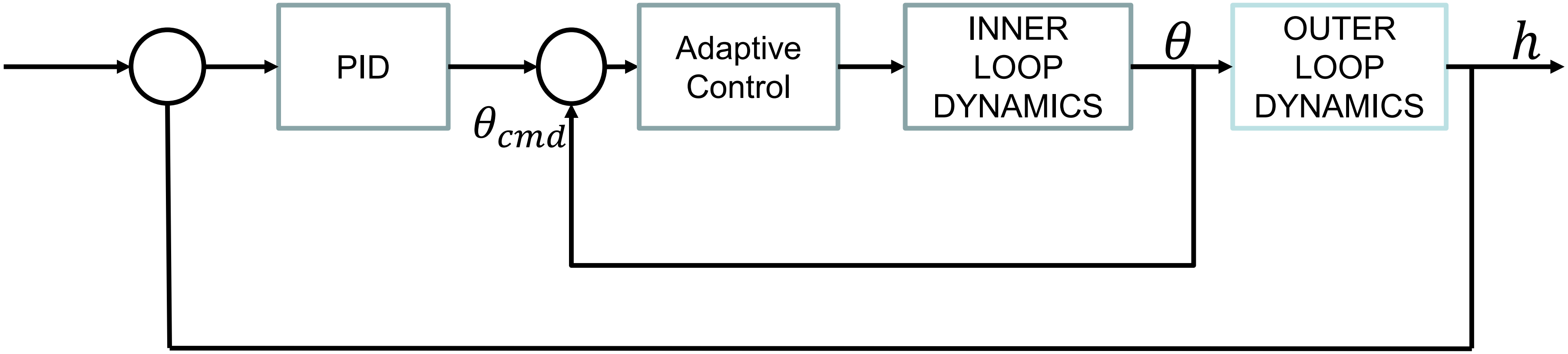
- Phases in Landing Maneuver
  - Cruise (Constant Altitude Phase)
  - Descent Phase
  - Flare: Follows final approach phase and precedes touchdown and roll-out phases of landing; in the flare, the nose of the plane is raised, slowing the descent rate, and the proper attitude is set for touchdown
    - At start of flare, throttle is set to minimum
- Landing Control: Aim of Controller
  - Controller Portability Across Different UAV Platforms
  - Online Adaption and Control in Presence of
    - Cross wind
    - Ground effect





Autonomous Landing Control

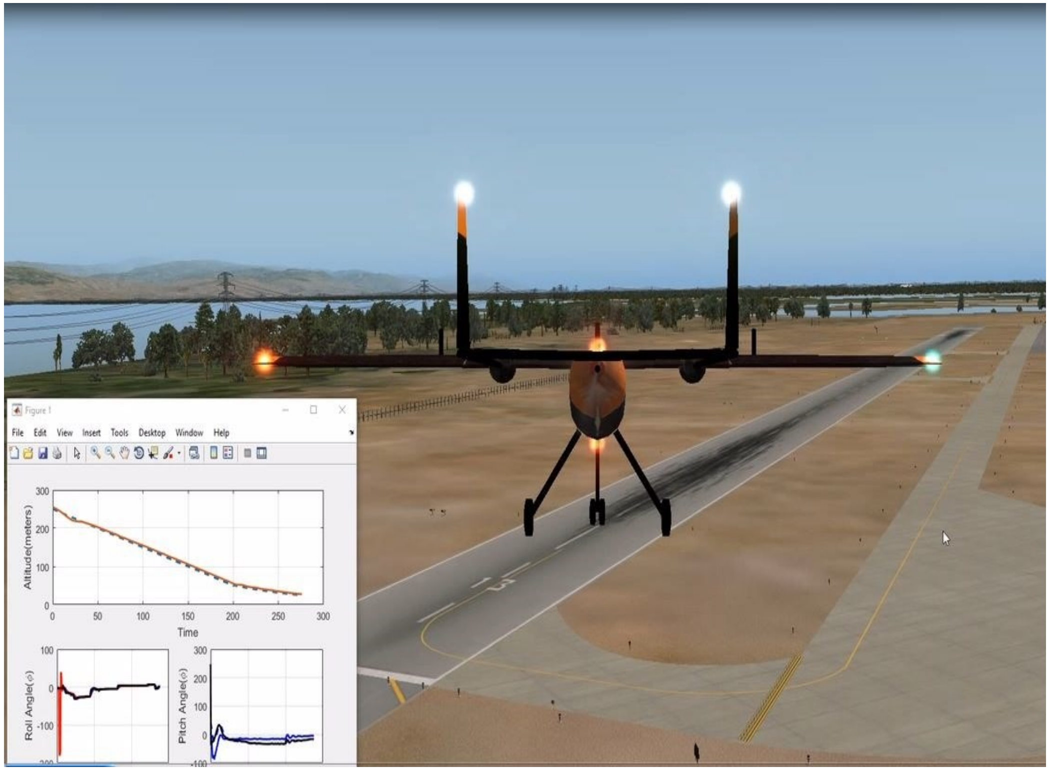
- Flow Diagram Shows Control Architecture
- Altitude h and Altitude Drop Rate $\dot{h}$ is Commanded, Required Pitch Angles are Evaluated and Controlled as Follows
- Outer Loop Uses PID and Inner Loop Uses Adaptive Control to Achieve Autonomous Landing



Autonomous Landing Control

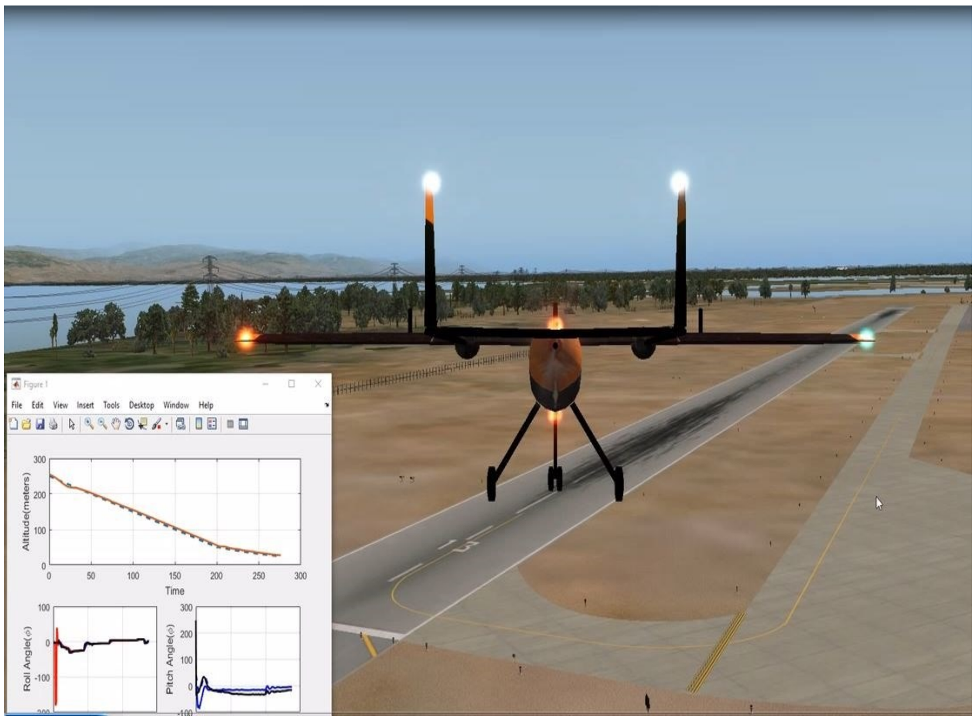
- SIL Results: X-plane + MATLAB
- Crosswinds: 10 knots, No Ground Effect

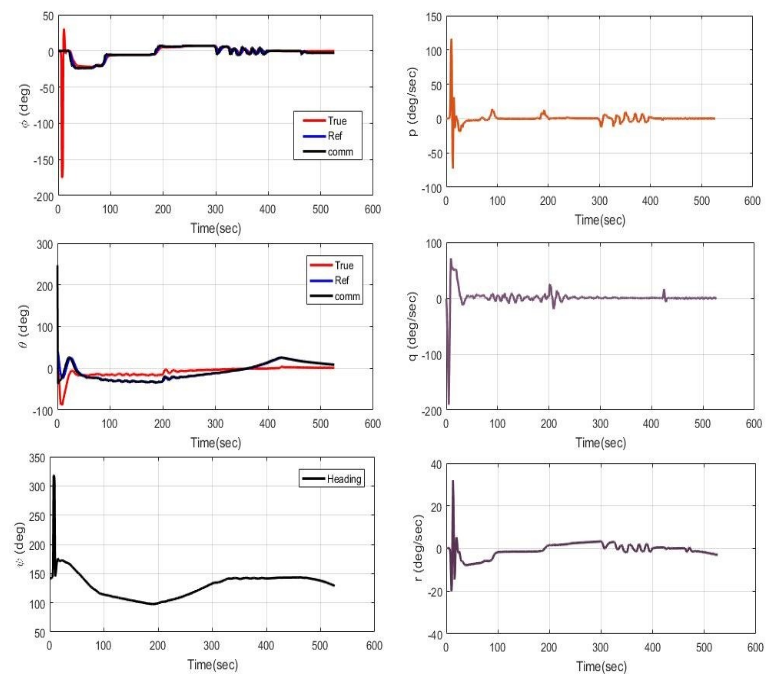
Vehicle Specification	
Vehicle	Skyhunter
Vehicle Mass Airframe + Payloads	<10lbs
Wing Span	1.8m
Body Length	1.4m
Wing Area	$3.9ft^2$
Engine	Electric
Prop	9-12" prop



Autonomous Landing Control

- UAV Attitude Angles and Body Rates While Executing Landing Maneuvers





Conclusions

- Newly Selected Engine and Larger Propeller Diameter Provide Higher Fuel Efficiency and Weight Optimization Resulting in
  - 6+ hour endurance
  - Reduced number of flights needed to complete experiments
- Autopilot with Modularized Subsystems
  - "Plug-and-Play" logic for switching subsystems with units supplied by experimenter
  - Default "sense and avoid," weather, peripheral sensors
  - Multiple communication channels
- GNC Software
  - Multi-threaded design
  - Deterministic and non-deterministic hierarchical and adaptive GNC baseline algorithms
  - Easy software uploading, HIL ground testing, and SIL inflight predictions

Suggestions

- NextGen Aeronautics, working cooperatively with NASA, can provide versatile experimental autonomy research UAV(s) available to research community at the fraction of cost needed for autonomy hardware/software verification and validation

Open Discussion