SHAMU

Search and Help Aquatic Mammals UAS

Customer

Cetacean Echolocation Translation Initiative (CETI)
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University of Colorado Boulder
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Project Motivation


Image: Cetacean Echolocation Translation Initiative

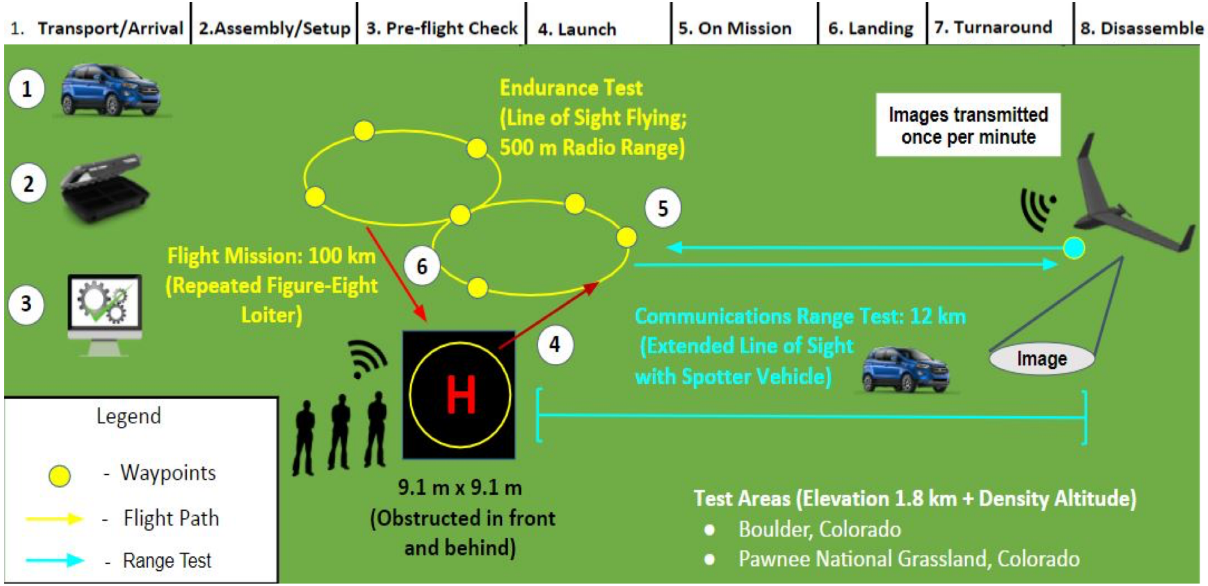
- **Cetaceans** (whales, dolphins, and porpoises) are a **vulnerable species**
- **Causes of death**: beachings, propellor strikes, disorienting marine sound pollution
- Cetaceans use **"clicks"** for **echolocation** and for **social communication**
- **Effort to understand** this click language via video and audio recording:
    - **Reveal social astuteness** to global human community
    - **Deter** from dangerous areas (ships)

Project Description & CONOPS

CETI desires:

- **improved search method**
- **increased return on research investment**

SHAMU designed an **unmanned aerial system** to carry a **future** instrument payload capable of **locating sperm whales in the ocean.** The aircraft will be **launched and recovered from a research vessel's helipad.**



SHAMU Concept of Operations (First Year)

Objectives: Levels of Success

1. The **aircraft and associated systems pass ground tests**: Aircraft has **2 kg instrument payload** with **15 x 15 x 23 cm volume**; wing loading test of **5g**; aircraft mass below **22.7 kg**. Power source endures **1 hour** simulated flight mission. Locally **downlink telemetry**; **full manual control** over control surface servos.

1. The **aircraft is airworthy and proven to fly**: piloted **takeoff** and **landing**, **5 minutes** on mission, uplink **waypoints**, **telemetry** displayed to pilot.

1. The **aircraft has improved flight performance**: **30 minutes** on mission, **full autonomy** at cruise, **500m** radio range, **images** are **saved onboard once per minute**.

1. The **UAS meets all mission objectives**: **1.4 hours** on mission, **20 m/s cruise speed, 12km radio range, images transmitted once per minute.**

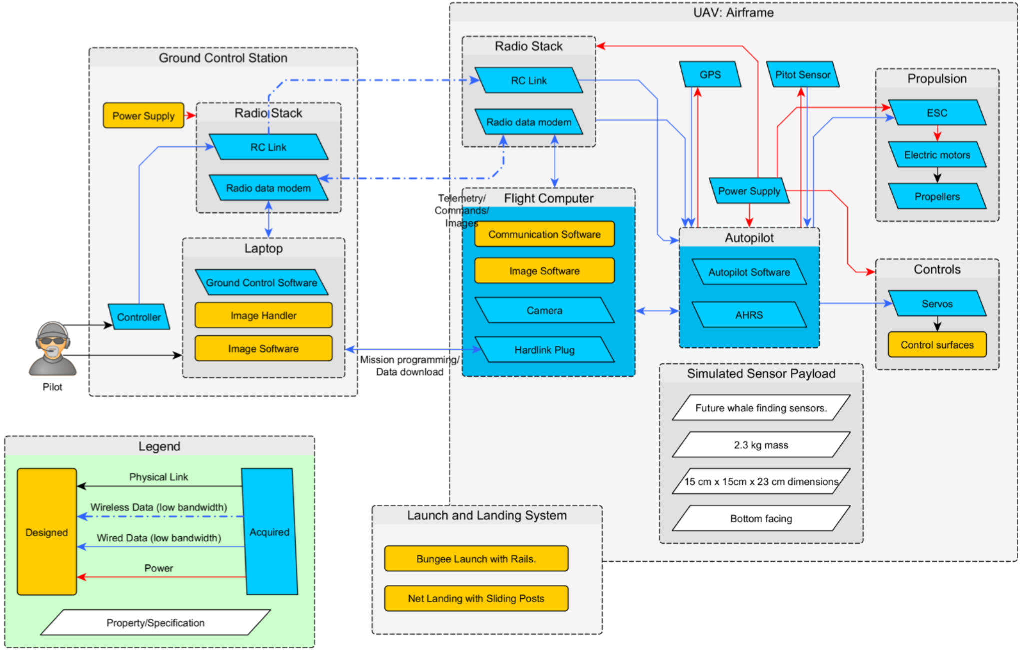
Critical Project Elements

CPE	Requirement Considerations
Aerial Vehicle	• **Stability and control** • **Future sensor payload** • **Tradeoff** between **maximizing lift-to-drag** ratio and **structural/manufacturing complexity**
Takeoff and Recovery	• Accelerate/decelerate aircraft under **maximum structural load** • Capability to transport and setup on **9.1m x 9.1m helipad**

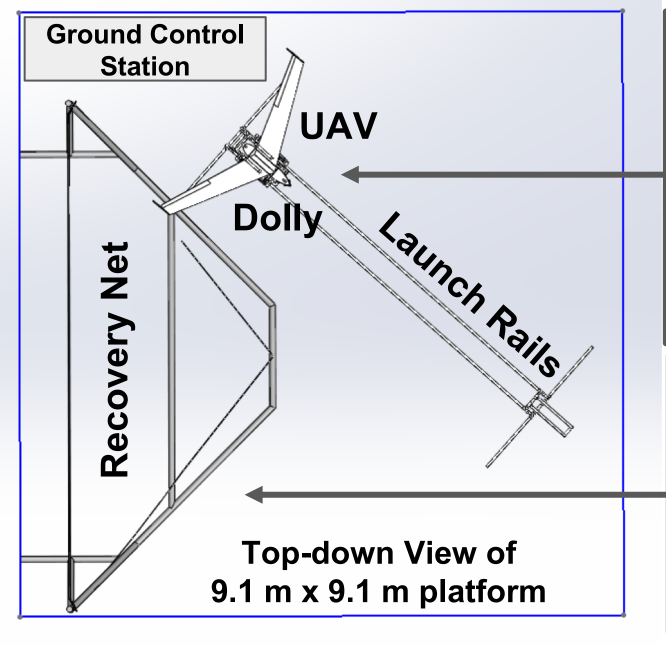
Critical Project Elements

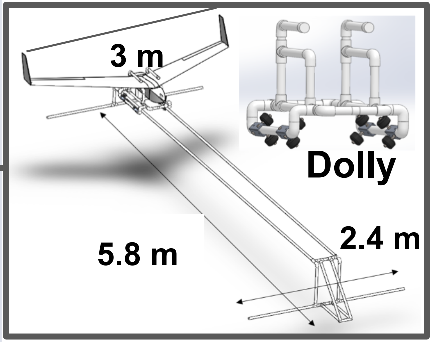
CPE	Requirement Considerations
Communication with Ground Station	• **Communication range of 12 km** from ground station • Transmit images at **one per minute** • Piloted **manual control** • Transmit **updated flight waypoints** • Transmit **telemetry** to ground station
Flight Computer / Autopilot	• Collects **sensor data** for virtual cockpit • Autopilot keeps aircraft in **steady, level flight** • Accepts **flight waypoints** and **executes**

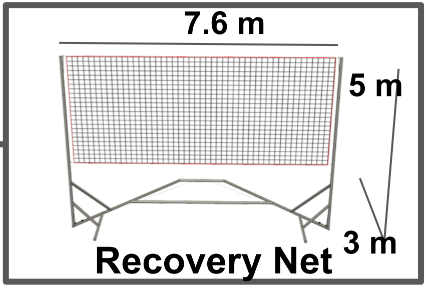
Functional Block Diagram



Baseline Design







<u>UAV on Launch Rails</u>

- Dolley rides on rails
- UAV accelerated via dolley and bungees
- UAV ejected by sudden stop of dolley via restraining rope

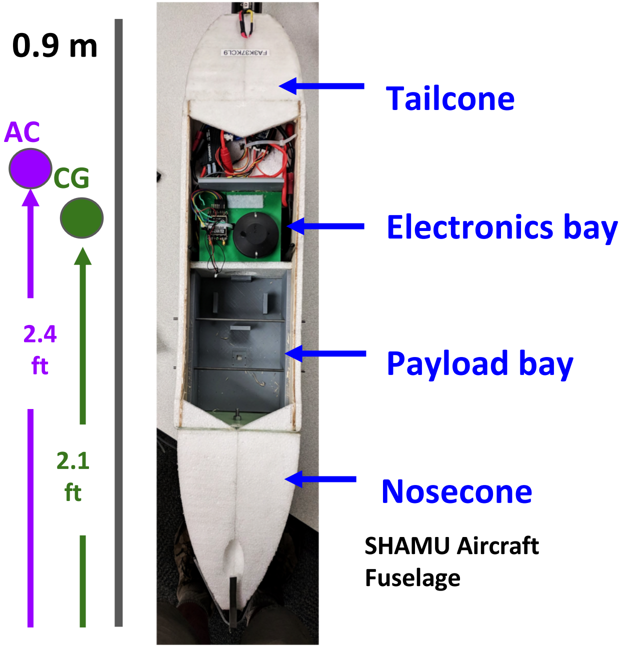
<u>Recovery Net</u>

- Net extends
- Lines, pulleys, and bungees enable net extension
- Sailing cleat prevents rebound

Baseline Design

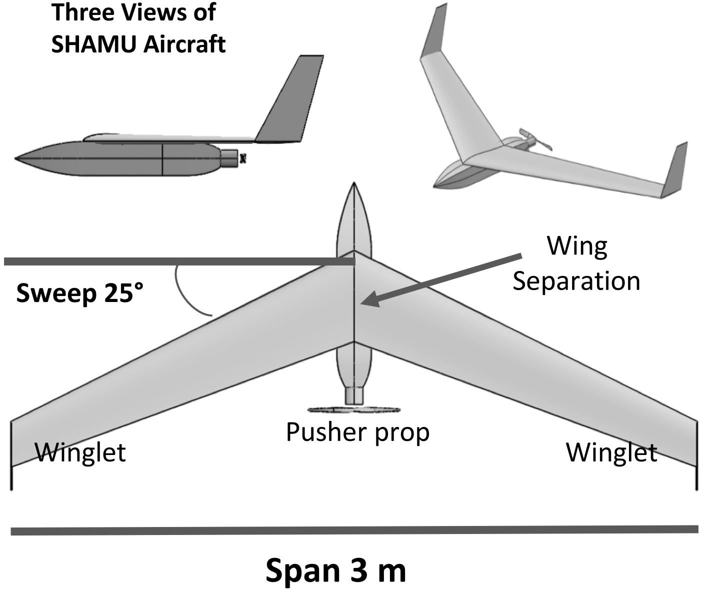
Aircraft Specifications

- Mass
  - 8.9 kg
- Static Margin
  - 22-25%
  - Positive
- Wing Span
  - 3.0 m
- Wing Area
  - 0.9 m^2
- Fuselage
  - 0.9 m length

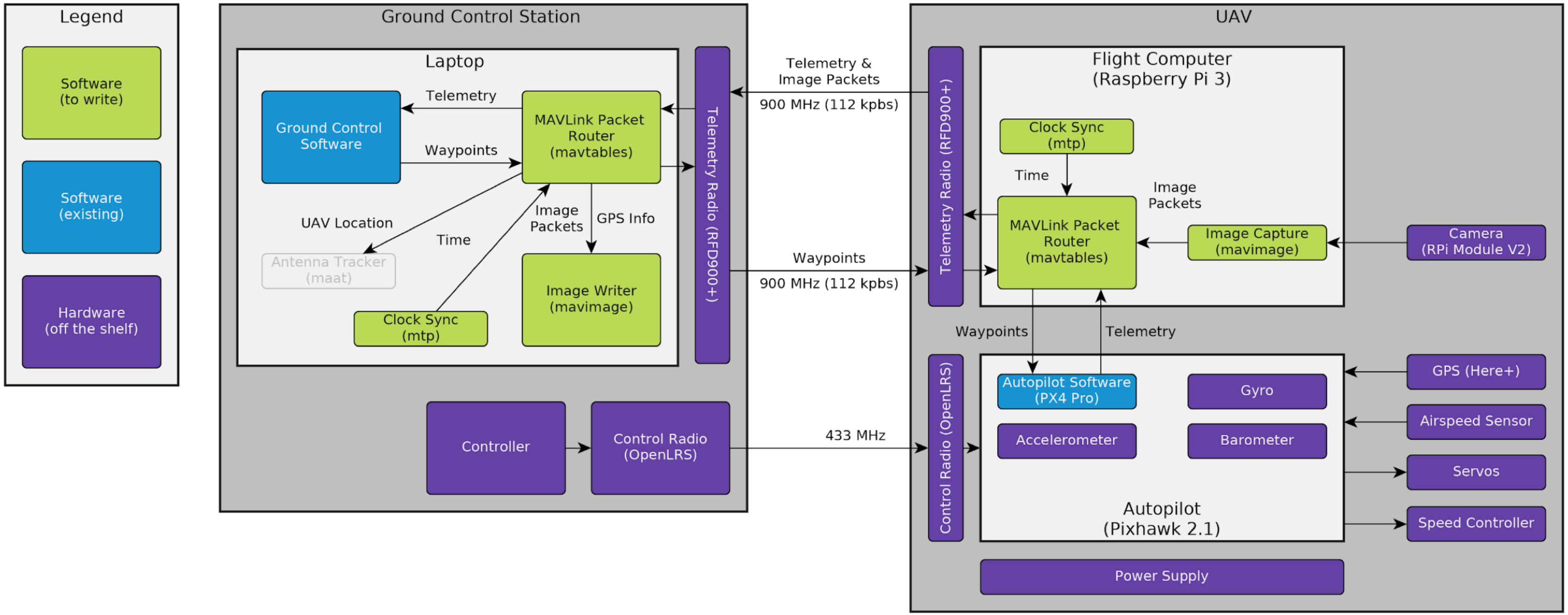


SHAMU Aircraft Fuselage

Three Views of SHAMU Aircraft



Baseline Design



Test Overview- Launch System

CPE: Takeoff and Recovery

Verification

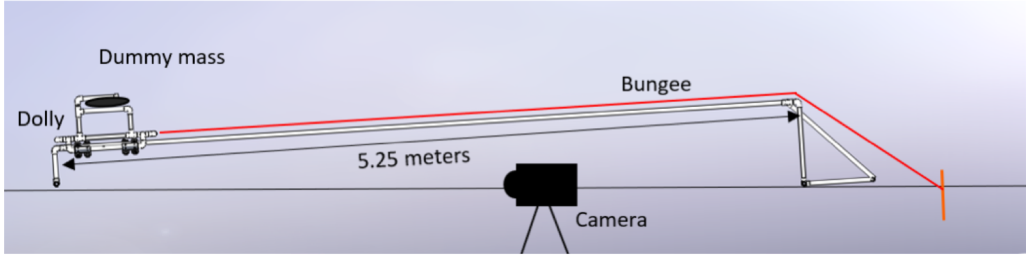
- Launch System shall accelerate aircraft to a take-off speed of 13 m/s
- Launch System shall accelerate aircraft under 5 g's

Test Setup:

- Launch system is set up to accelerate a dummy mass to 1.3 stall speed
- During launch, initial acceleration is recorded
- The final velocity of the dolly is recorded

Test Instruments & Analysis:

- Camera phone with slow motion capabilities records up to 240 FPS
- Video uploaded to LoggerPro to determine velocity and acceleration



Visual representation of Launch System test set-up

Test Results- Launch System

CPE: Takeoff and Recovery

Result:

- Experimental final launch velocity = 11.2 m/s
- Experimental initial acceleration = 7.73 g's

Discussion:

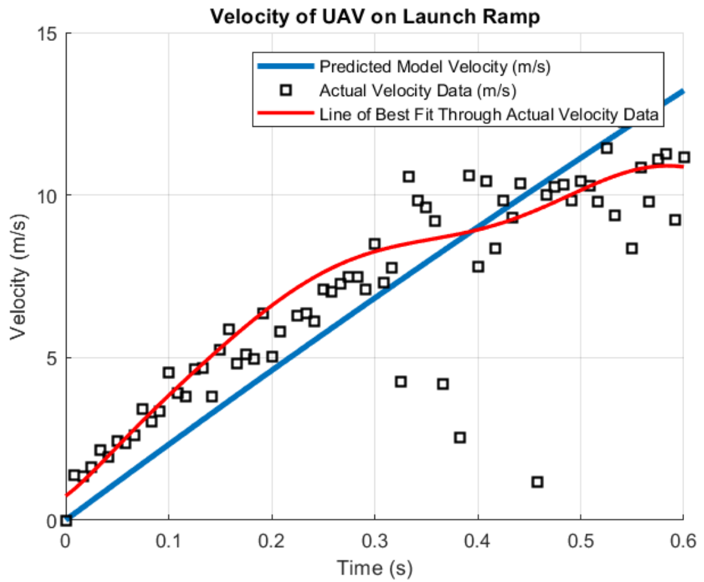
- Acceleration was not constant; decreased over time
- Velocity does not have a linear relationship with time
- Velocity should peak at smaller velocity

Requirement Satisfaction:

- 11.2 m/s < 13.2 m/s : requirement not satisfied
- 7.73 g's > 5 g's : requirement not satisfied

Recommendations

- Energy design based on flawed model
- Lower accelerations / re-design of launch (Longer rails)
- Bungees can be added to increase velocity



Comparison of model and test results

Test Overview- Recovery System

CPE: Takeoff and Recovery

Verification

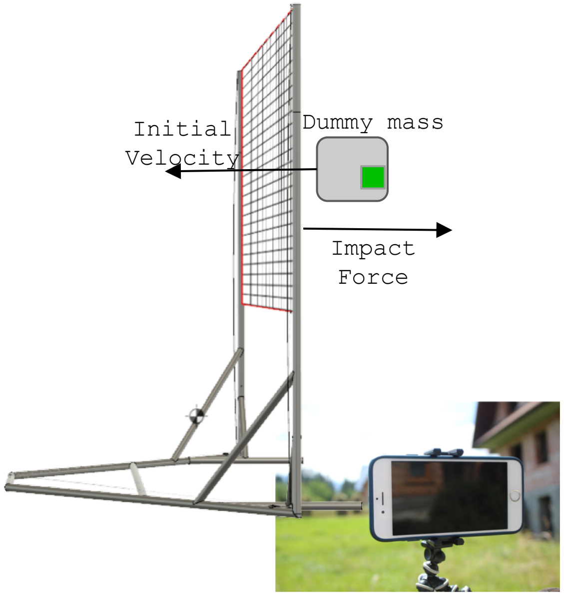
- Recovery System shall halt aircraft with acceleration under 5 g

Test Setup:

- The dummy mass is launched from the launch system directly into the recovery system
- The acceleration is measured when the dummy mass is in contact with the recovery net

Test Instruments & Analysis:

- Phone camera with slow motion capabilities of up to 120 FPS
- Acceleration of dummy mass determined with video analysis using LoggerPro



Visual representation of Recovery System test set-up

Test Results- Recovery System

CPE: Takeoff and Recovery

Result:

- Acceleration maximum is 1.88 g

Discussion:

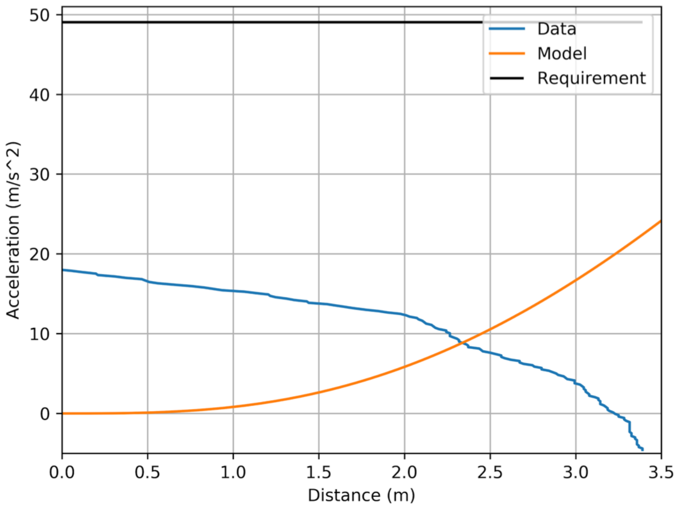
- Measured results do not match model (value/trends)
- Model assumes rigid posts (flexible in reality)
- Test was not set up to properly characterize system

Requirement Satisfaction:

- 1.88 g < 5 g: requirement satisfied

Recommendations

- Retest with correct conditions
  - Pixhawk accelerometer
  - Corrected rigging
  - LoggerPro



Comparison of model and test results

Test Overview- Communication System

CPE: 12 km Communications Range

Verification

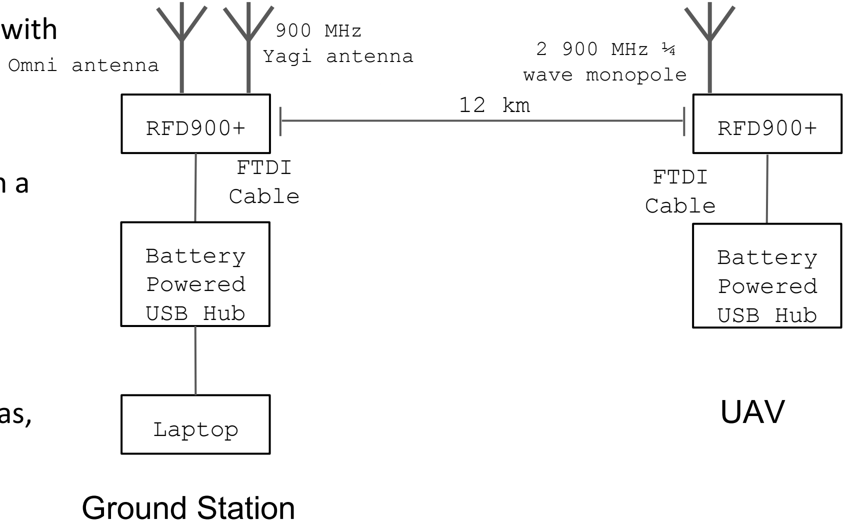
- UAV communication shall have a range of 12 km from ground station with an RSSI > 150

Test Setup:

- Two antennas are placed at a 12 km distance and attempt to establish a connection
- Received Signal Strength Indication (RSSI) is measured

Test Instruments & Analysis:

- Ground Station: Datalink radio, directional & omnidirectional Antennas, Laptop, Power Supply
- RFD900+ Modem Configuration Tool used to retrieve RSSI data



Visual representation of test set-up

Test Results- Communication System

CPE: Takeoff and Recovery

Result:

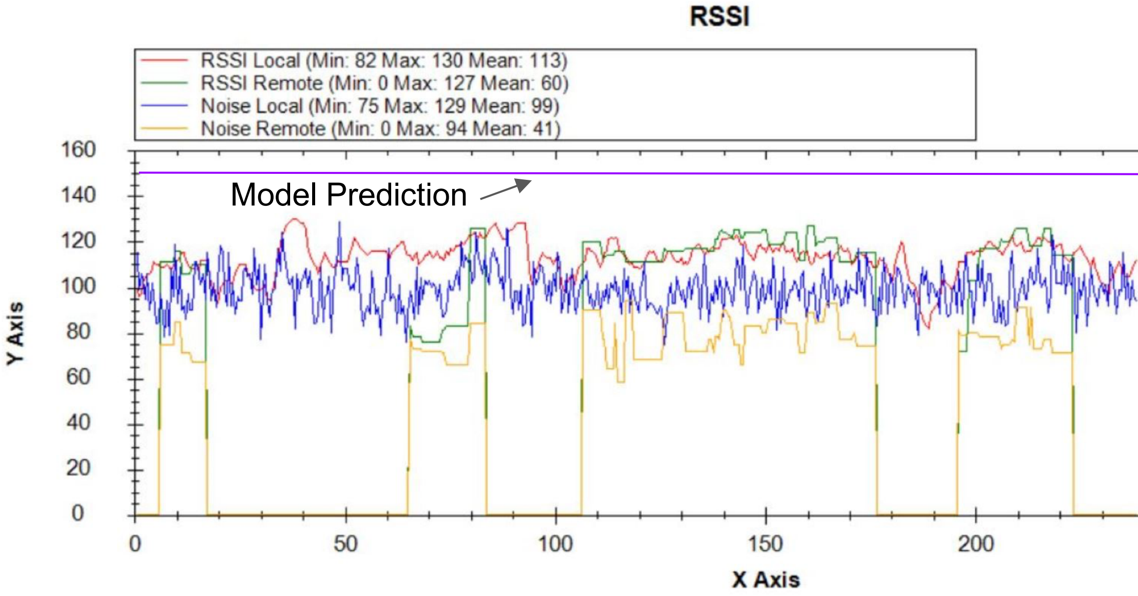
- Spotty signal with average RSSI of 120

Discussion:

- Radios were tested at ⅔ power
  - Full power = 20 dB gain increase
  - Ground interference = 10 dB loss
  - sums to ~150 RSSI
- Establishing >500 m range due to budget and schedule constraints
  - Qualified by FSPL model

Requirement Satisfaction:

- Telemetry radio has a range of >500 m
  - Success level 3 met



Comparison of model and test results

Test Overview- Software

CPE: Flight Computer and Autopilot

Verification

- Communication system delay is below 200ms for safe beyond line of site operation

Test Setup:

- Start APM Planner and mavtables on ground control system connected to telemetry radio
- Start mavtables on Raspberry Pi connected to Pixhawk (autopilot) and telemetry radio
- All systems configured to use 57600 baud rate
- Film rotation of pixhawk and rotation of APM Planner HUD

Test Instruments & Analysis:

- Pixel XL camera running at 240 FPS
- MLT for frame by frame analysis
- Python + NumPy + SciPy + Matplotlib

APM Planner behind rotated Pixhawk

Test Results- Software

CPE: Flight Computer and Autopilot

Result:

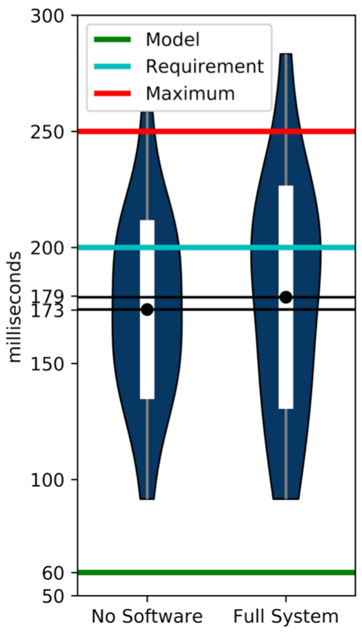
- Total communication system delay is 179 ± 48 ms
- Communication system delay without software is 173 ± 39 ms

Discussion:

- Custom software adds negligible delay (6 ms)
- 3 times greater than modeled delay of 60 ms
- Model assumes communication boundaries operate at set 57600 baud rate and capture entire packet before retransmission
- Tests show that off the shelf components have additional delays not modeled

Requirement Satisfaction:

- Communication delay exceeds 200 ms requirement.
- Communication delay is below maximum 250 ms (for safety).
- Level 3 success met



Communication System Delays

Test Overview- Software

CPE: Flight Computer and Autopilot

Verification

- MAVLink router and firewall behaves as expected and successfully establishes a MAVLink network with routing and packet prioritization
- Needed for image transmission over telemetry system

Test Setup:

- Unit testing against models with Catch 2 and FakeIt
- Integration testing against models by simulating other components with PyMAVLink and comparing against pre routed packet logs.
- All tests are automated.

Test Instruments & Analysis:

- 100% correlation with model (and zero error) is required for success.

```
*------------------------------------------------------------------------*
|                              Unit Tests                                |
*------------------------------------------------------------------------*
==========================================================================
All tests passed (3305 assertions in 295 test cases)

*------------------------------------------------------------------------*
|                          Integration Tests                             |
*------------------------------------------------------------------------*
Abstract Syntax Tree printing with --ast flag ..................... [SUCCESS]
Complex Abstract Syntax Tree printing with --ast flag ............. [SUCCESS]
All MAVLink v1.0 packets from UDP to UDP .......................... [SUCCESS]
All MAVLink v1.0 packets from UDP to serial port .................. [SUCCESS]
All MAVLink v2.0 packets from UDP to UDP .......................... [SUCCESS]
All MAVLink v2.0 packets from UDP to serial port .................. [SUCCESS]
All MAVLink v1.0 packets from serial port to UDP .................. [SUCCESS]
All MAVLink v1.0 packets from serial port to serial port .......... [SUCCESS]
All MAVLink v2.0 packets from serial port to UDP .................. [SUCCESS]
All MAVLink v2.0 packets from serial port to serial port .......... [SUCCESS]
```

Test Results (part 1)

Test Results- Software

CPE: Flight Computer and Autopilot

Result:

- All tests succeeded
- All packets routed correctly
- Packet prioritization successful

Requirement Satisfaction:

- Establishes MAVLink network with routing and packet prioritization for image and telemetry packet transmission
- Level 4 success partially met

```
Multiple senders with MAVLink v1.0 packets to UDP ................  [SUCCESS]
Multiple senders with MAVLink v1.0 packets to serial port .........  [SUCCESS]
Multiple senders with MAVLink v2.0 packets to UDP ................  [SUCCESS]
Multiple senders with MAVLink v2.0 packets to serial port .........  [SUCCESS]
Routing MAVLink v1.0 packets (part 1 - 127.1) ....................  [SUCCESS]
Routing MAVLink v1.0 packets (part 2 - 192.168) ..................  [SUCCESS]
Routing MAVLink v1.0 packets (part 3 - 172.128) ..................  [SUCCESS]
Routing MAVLink v2.0 packets (part 1 - 127.1) ....................  [SUCCESS]
Routing MAVLink v2.0 packets (part 2 - 192.168) ..................  [SUCCESS]
Routing MAVLink v2.0 packets (part 3 - 172.128) ..................  [SUCCESS]
High priority packets are transmitted first ......................  [SUCCESS]
Serial ports can be preloaded with MAVLink addresses .............  [SUCCESS]
Component broadcast fallback and MAVLink subnets .................  [SUCCESS]
Many large packets with multiple senders to UDP ..................  [SUCCESS]
Many large packets with multiple senders to serial port ..........  [SUCCESS]
```

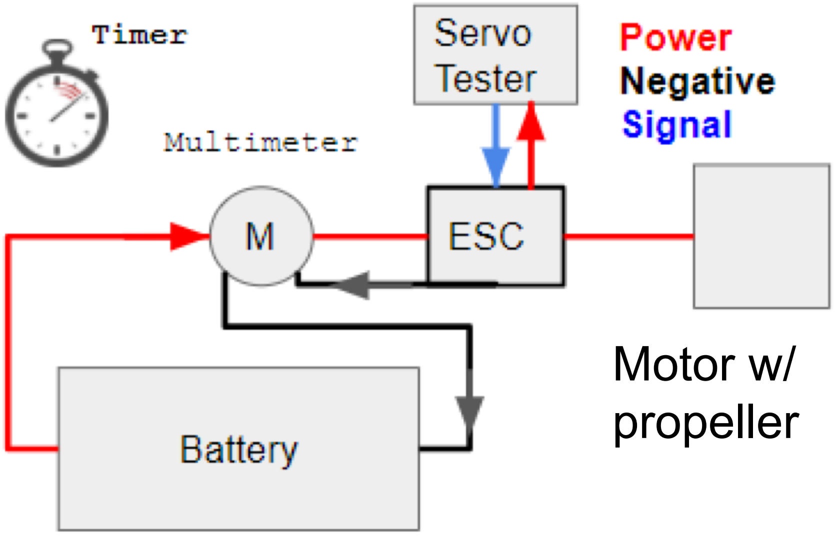
Test Results (part 2)

Test Overview- Battery Endurance
CPE: Aerial Vehicle

Verification
- Battery model

Test Setup:
- Connect battery, multimeter, ESC, servo tester, motor and propeller
- Spin up motor until multimeter reads 15 A, record time, voltage and amperage
- Stop at 84 mins, or when battery reaches cutoff voltage

Test Instruments & Analysis:
- Multimeter
- Analyze voltage and amperage over time



Visual representation of test set-up

Test Results- Battery Endurance
CPE: Aerial Vehicle

Result:

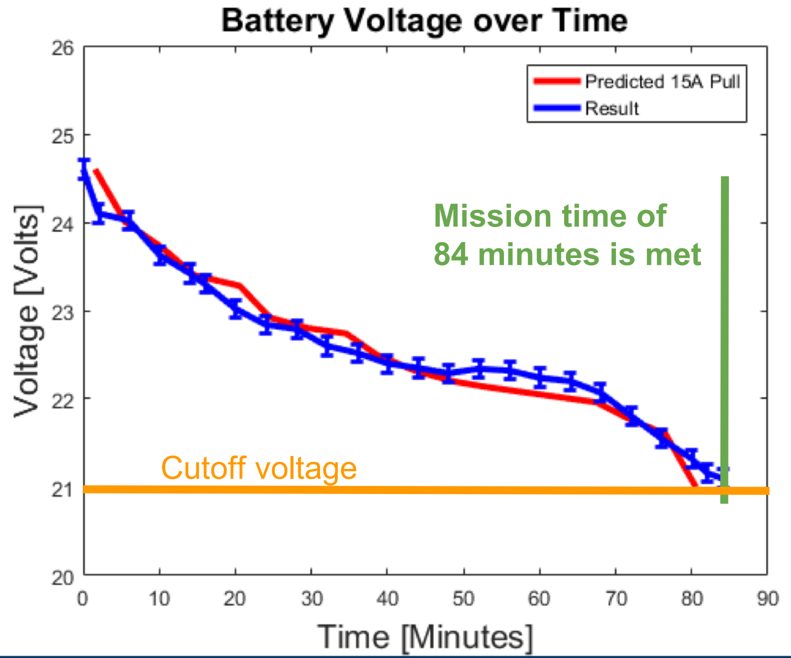
- At 15 A simulated draw, battery lasted 84 mins

Discussion:

- Prediction falls short due to newer battery
- Errors in measurement come from multimeter, accuracy of 0.01 V with 1% error

Model Verification:

- Battery lasts 1.4 hours as expected for 15 A draw
- Battery model verified



Test Overview- Motor Thrust

CPE: Aerial Vehicle

Verification

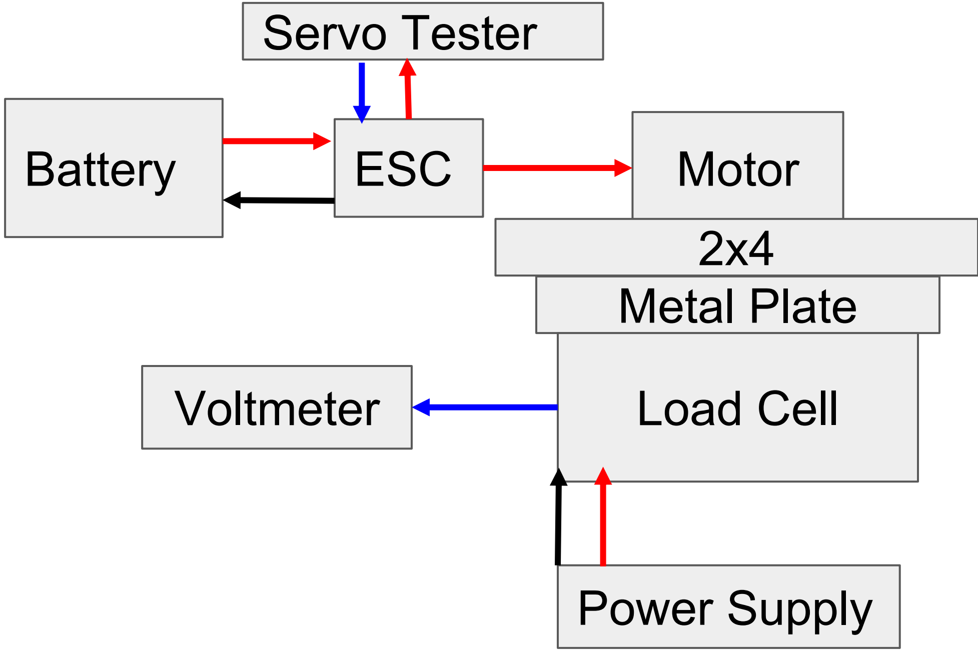
- Aircraft shall have a 5 m/s climb rate
  - 6.68 lbs of thrust

Test Setup

- Mount motor and propeller onto 2x4
- Connect battery, wattmeter ESC, servo tester, and motor
- Connect load cell to power supply, and voltmeter
- Flat plate between 2x4 and load cell
- Spin up motor every 100 W, record voltage

Test Instruments and Analysis

- Wattmeter for power, and voltmeter for voltage
- Convert voltage to lbs 10 volts per lb
- Analyze power and corresponding thrust



Test Results- Motor Thrust

CPE: Aerial Vehicle

Result:

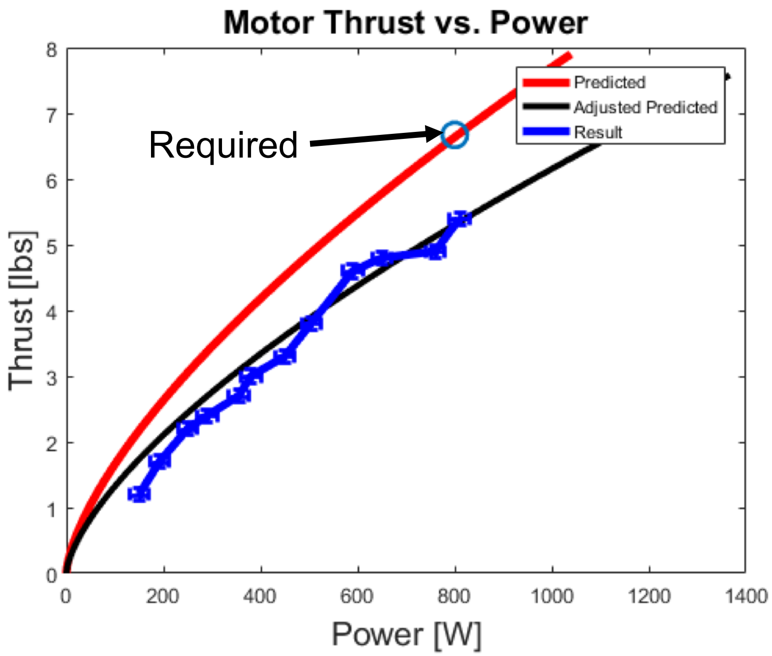
- 5.4 lbs of thrust at 810 Watts

Discussion:

- At max power, **propeller could stall**, limiting thrust output
- Results indicate **less efficient motor**
- After adjustment, deviation comes from motors being more efficient at higher power
- Errors in measurement come from voltmeter with 0.01 V resolution translating to 0.1 lbs resolution, and wattmeter with fluctuations in readings by +/- 20 W.

Requirement Satisfaction:

- With 5.4 lbs of thrust, only 3.8 m/s climb is achieved.
- Impact: **requires more power; endurance reduced to 1 hr**
  - Level 1 success met



Test Overview- Wing Loading

CPE: Aerial Vehicle

Verification

- The aircraft shall withstand flight loads of 5 g.
- Rectangular loading (i.e. recovery loads)

Test Setup:

- Wing spar incrementally loaded to 5 g using whiffletree
- Measuring deflection of wing spar

Test Instruments & Analysis:

- Whiffletree
- Scale
- Misc. weights
- Meter stick
- Vice
- Mounting block

Visual representation of wing-loading test set-up

Test Results- Wing Loading

CPE: Aerial Vehicle

Result:

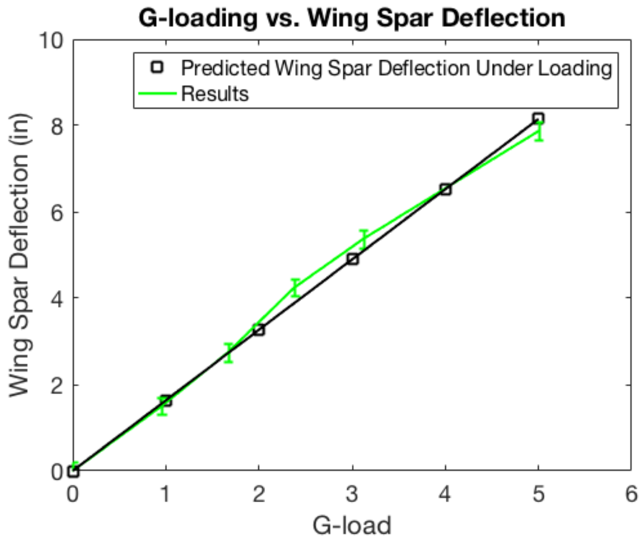
- Wing test section withstood up to 34.54 lbs of force (5 g equivalent) with a rectangular loading (recovery loads)
- Up to 7.9 inches deflection
- No detectable plastic deformation

Discussion:

- SkyCiv predicted model matches experimental loading (linear)
- Error in deflection measurement (+/- 0.2 inches)

Requirement Satisfaction:

- Achieved design 5 g rectangular loads (worst case scenario)
- Wing structure capable of withstanding maximum flight loads
- Success level 1 met



Comparison of wing-loading model and test results

Test Overview- Weight & Balance
CPE: Aerial Vehicle

Verification
- Aircraft shall be statically stable (SM > 0)
- Verify SolidWorks model used for aircraft weight and balance

Test Setup:
- Aircraft fully loaded with all equipment
- Balanced on 1 cm thick beam

Test Instruments & Analysis:
- Move 1 cm beam along length of aircraft until aircraft is balanced
- Location of beam along length measured from aircraft's nose represents longitudinal CG
- Thickness of beam corresponds to CG resolution of +/- 0.5 cm

Longitudinal CG measurement: aircraft balanced on 1 cm thick beam; location is measured from nose

Test Results- Weight & Balance

CPE: Aerial Vehicle

Result:

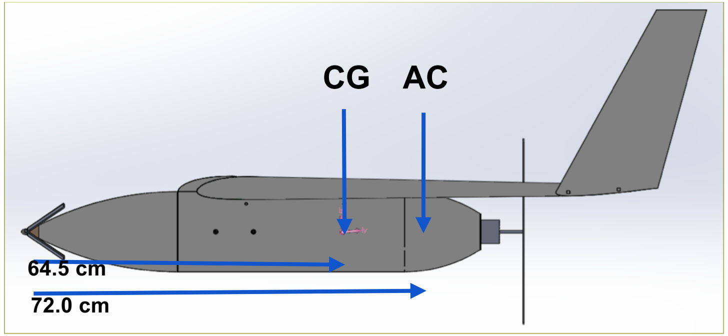
- Aircraft center of gravity (CG) along longitudinal axis is between 64 cm and 65 cm measured from aircraft's nose
  - Range captures predicted CG from SolidWorks model

Discussion:

- SolidWorks model predicted CG along longitudinal axis at 64.5 cm measured from aircraft's nose
- Test indicates that the actual aircraft's longitudinal CG differs from model at max of +/- 0.5 cm
- AC hasn't been measured, only modeled
  - AC unlikely less than 64 cm, considering large wing sweep

Requirement Satisfaction:

- Aircraft aerodynamic center (AC) is ~72 cm behind nose (modeled)
- SM range: 25.5% (7.75 cm) to 22.2% (6.75 cm) → statically stable



Labeled CG and AC on aircraft; locations indicate static stability

Test Overview- Flight Test

CPE: Aerial Vehicle

Verification

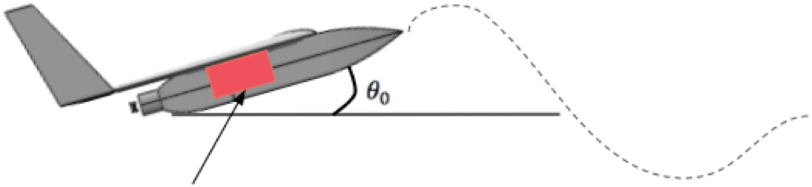
- Aircraft shall have a ground-track range of 100 km
- Aircraft dynamic stability

Test Setup:

- Aircraft placed on dolley and launched via bungee launch system
- Aircraft reaches altitude and enters cruise pattern
- Aircraft recovered into net recovery system

Test Instruments & Analysis:

- GPS
  - Coordinates used to calculate overall ground-track range
- Pixhawk 2.1
  - Logged flight data (attitude and rotation rates) to compare dynamic stability comparison with AVL model



Visual representation of aircraft's response to initial disturbance

Test Results- Flight Test

CPE: Aerial Vehicle

Result:

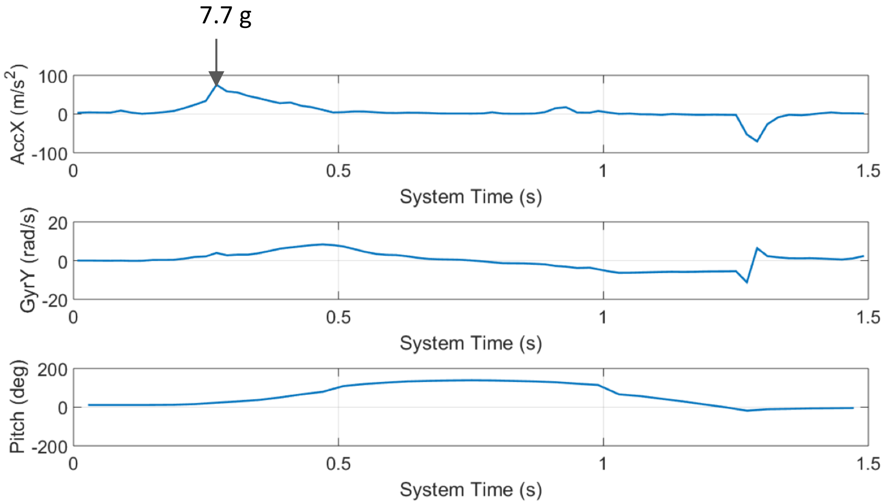
- Launch failure
- Flight data collected used to analyze launch failure

Failure Analysis:

- Launch dolley imposed a pitch-up torque
- Torque applied according to model: 70.13 N*m
- Measured pitch-up angular acceleration: 88.9 rad/s^2
  - Measured torque: 66.2 N*m
- Modeled vs. measured torque difference: 5.98 %
  - Verifies failure analysis

Failure Mitigation:

- Modify launch dolly
  - Move contact points such that launch forces pass through aircraft's CG
- Truck launch

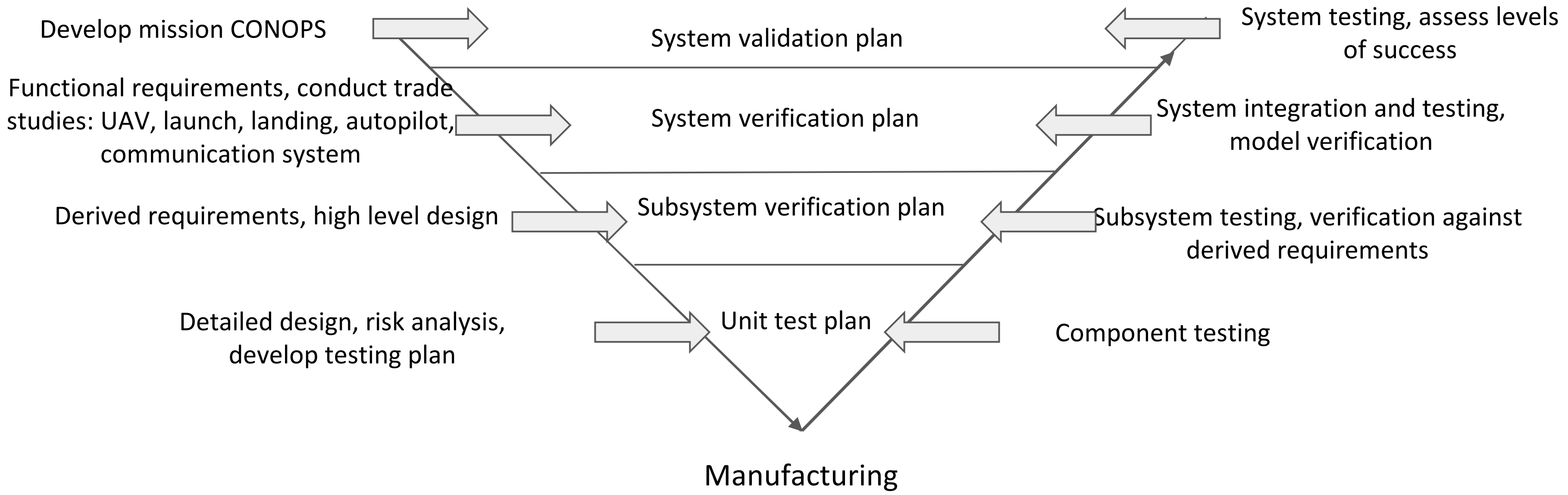


Launch failure as recorded by the aircraft; linear acceleration (m/s^2), pitch-up angular rate (rad/s), pitch-up angle (deg)

Level of Success

	Aircraft Design	Guidance, Navigation, Control	Structures	Communications/ Radio	Ground Control System	Electrical
Lvl 1	. Aircraft accommodates 2 kg instrument payload with 15 x 15 x 23 cm volume.	Full manual control over servos via RC link while on the ground. Hardware-in-the-loop (HIL).	Weight below 22.7 kg. Wing loading test of 5g.	Downlink Telemetry (, Range: local, external power. (Ground test)	Log incoming telemetry to files. Mission/ waypoints programmable via files outside of flight operations.	Powered for 1 hour on ground for mission simulated power draw.
Lvl 2	Aircraft is airworthy and proven to fly. Performance- 5 minutes on mission time at 15 m/s - 20 m/s cruise speed with 8.45 kg mass and size payload.	Piloted takeoff and landing. Full manual control over servos and control surfaces via RC link while in the air.	Survive flight up to 2 g in RC flight conditions.	Uplink mission elements, Range: local, external power. (Ground test)	Display telemetry to pilot on laptop for beyond line of sight operations.	Eendure 1.4 hours on ground for mission simulated power draw.
Lvl 3	Performance - 30 minutes on mission time at 18 m/s - 20 m/s cruise speed on a moderate day. (0-5 m/s winds)	Full autonomous in flight mission commands/ waypoints including in-flight mission reprogramming.	Survive takeoff and aircraft recovery with up to 4.4 g accelerations using systems designed for shipboard use.	Uplink commands at 8kbps/Downlink telemetry at 90kbps. Line of sight range flight test on aircraft power (500 m range).	Graphical User Interface for displaying telemetry and sending commands/waypoints in flight.	Using only onboard power sources, equipment shall endure 1 hour in flight.

Systems Engineering



Systems Engineering

Predicted Risks	Actual Challenges	Lessons Learned
Manufacturing delay	Manufacturing delays - 3 weeks	Manufacturing should start earlier, daily work required. Delays should be expected
Crash during flight test	Crash during flight testing	Data acquisition methods should characterize system in case of failure (video, accelerometers)
N/A	Subsystem scheduling	Work early and often
N/A	Timely integration of subsystems	System integration should be emphasised early
N/A	Project scope	Proper scope is vital to project success. Should be established early

Project Management Approach

Successes

- Quadcharts
  - Tasks, Accomplished, Issues, Next Steps
- Gantt Chart
  - Track sub-team progress (12 members)
- Meeting schedule fall/spring
  - Fall more frequent; group design work
  - Spring once a week; individual/subteam manufacturing
- Communication with PM on conflicts
  - Understanding/Prevention/Honesty
- Appreciation for individual accomplishments

Lessons Learned

- Project management tools are effective if taken seriously and understand limitations
- Engineers tend to dislike non-technical/logistical discussions
  - Planning and updates are necessary
  - Be efficient and aware of time
- Conflict prevention requires a leader
  - Feel safe and understood
  - Track record of handling conflict successfully
- Engineers work hard and deserve praise
  - Method of motivating high and under performers

Project Management Approach

Difficulties

- Leveling team member contributions
  - Motivation / skill level / initiative
- Authoritative leader
  - Gain respect or lose respect (risky)
  - Preferred members to develop own responsibility (not always effective)
- Lateral communication between team members
  - Lack of technical knowledge sharing
  - Behind schedule
  - Increased errors

Lessons Learned

- Team needs PM to hold all team members accountable and encourage improvement
  - Full-time job / difficult with technical requirement in syllabus
- People require different management styles
  - Increased authority could have motivated some students
- PM's responsibilities must be well-defined
  - PM depends on system engineer to monitor design and requirements
  - PM monitors team progress and team dynamics

Budget

CDR Prediction

Airframe w/ motor:	$1230
Communications:	$530
Electronics:	$800
Launch system:	$295
Recovery system:	$510
Software:	$320
Total:	**$3685**

Actual To Date

Airframe w/ motor:	$1374
Communications:	$900
Electronics:	$800
Launch system:	$700
Recovery system:	$550
Software	$500
Shipping:	$340
Miscellaneous:	$250
Total:	**$5414**

Project Management

Source	Rate	Cost
Fall - 2567 Hours	$65,000/2,080hr = $31.25/hr	$80,218
Spring - 3107 Hours	$65,000/2,080hr = $31.25/hr	$97,094
Materials/Parts	N/A	$5,250
Overhead	200% Labor Costs	$354,625
Total Cost	N/A	**$537,188**

Acknowledgements

The SHAMU team would like to thank our crowdfunding supporters, Dr. Gerren, Dr. Koster, Dr. Lawrence, Trudy Schwartz, Bobby Hodgkinson, Matt Rhode, PAB, Tim Kiley, Lee Huynh, Mr. Norman, Trimble Inc., James Nestor, and David Gruber.

Thank you

Questions?

Backup Slides

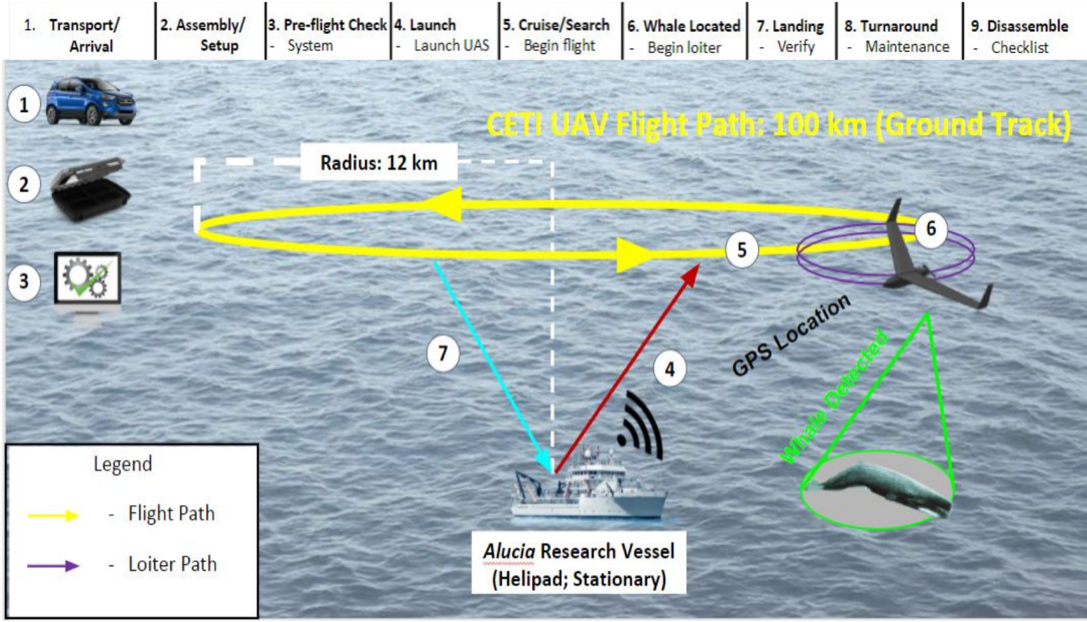
Project Motivation

Image: Cetacean Echolocation Translation Initiative

- **Cetaceans** (whales, dolphins, and porpoises) are a **vulnerable species**
- **Causes of death**: beachings, propellor strikes, disorienting marine sound pollution
- Cetaceans use **"clicks"** for **echolocation** and for **social communication**
- **Effort to understand** this click language via video and audio recording:
  - **Reveal social astuteness** to global human community
  - **Deter** from dangerous areas (ships)

Project Description & CONOPS

- Cetacean Echolocation Translation Initiative (CETI) is **decoding cetacean click communication**
- CETI requires an **improved search method** for locating surfaced whales to **increase return on research investment**
- $5000 budget to develop an **unmanned scouting aircraft** to be **launched and recovered from research vessel**



Project Scope

Functional Requirements:

Aircraft shall...

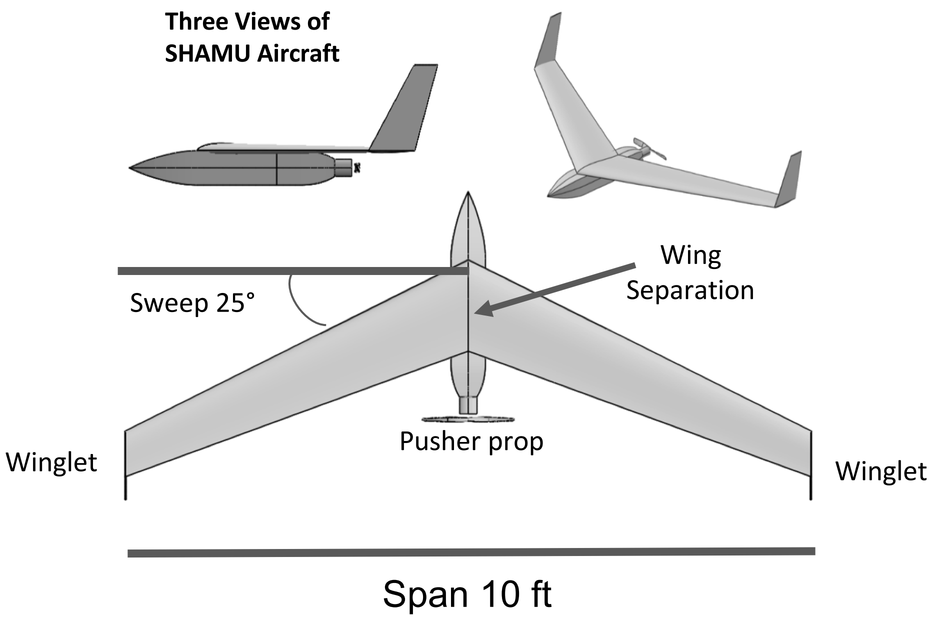
- launch and recover from **9.1 m x 9.1 m platform**, obstructed fore and aft
- have **100 km ground track range**
- have a **1.4 hour mission endurance**
- have a **12 km communications range**
- include a payload bay with **15 cm x 15 cm x 23 cm dimensions** to support **2 kg** of whale-scouting instruments

Deliverables:

- **Conceptual Design** (Trade Studies, Derived Requirements)
- **Preliminary Design Review** (Feasibility Study, Baseline Design Selection)
- **Critical Design Review** (Detailed Design Report)
- **Manufacturing & Procurement**
- **Verification and Validation**

Design Solution: Aircraft Configuration

- **Flying wing**
  - Weight
  - Durability
  - Manufacturing Complexity
- **Pusher configuration**
  - Recovery - prevents landing on the motor
- **Separable wings**
  - Easier transportation
- **Magnetically fastened winglets**
  - Designed to detach upon landing



Design Solution: Wing Design

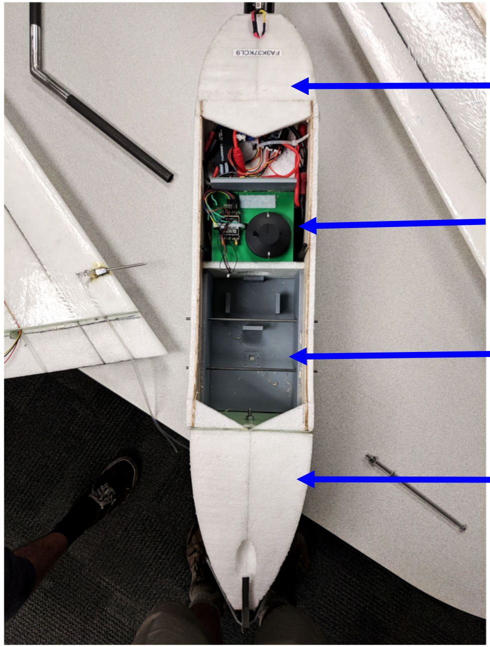
$$S = \frac{W}{1/2 \rho V_S^2 C_{L_{max}}}$$

1.	**Area**		10 ft^2
2.	**Span**	Limited for portability	10 ft
3.	**Sweep**	From similar aircraft	25°
4.	**Taper Ratio**	Drag, structure	0.5
5.	**Twist**	From other aircraft	3° washout
6.	**Dihedral**	Structure	0°
7.	**Incidence/Airfoil**	Drag, Structure	0°/mod. Joukowski

Manufactured SHAMU Aircraft

Design Solution: Fuselage Design

- **Tailcone**
  - Attached permanently
  - Fiberglass firewall to anchor motor
- **Electronics bay**
  - Houses power source and avionics
- **Payload bay**
  - Removable, 3D-printed
  - Supports downward-facing camera
  - Accommodates 2 kg of mass for future whale-scouting instrument
- **Nosecone**
  - EPP foam with aluminum pronged hook
  - Removeable for replacement

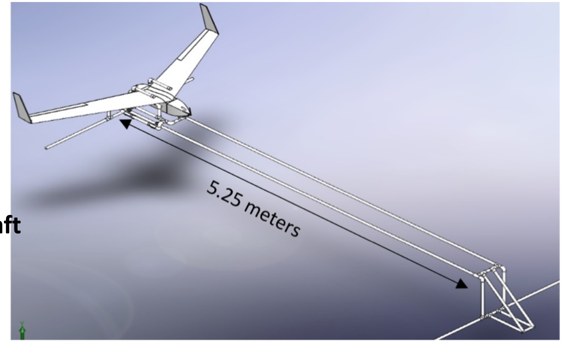


SHAMU Aircraft Fuselage

Launch System

Relevant Requirements

- Launch system shall fit on a 9.1 m x 9.1 m platform
- Launch system shall not exceed forces of 5 g
- Launch system shall accelerate aircraft to 13 m/s



SHAMU Aircraft on Launch System

Considered Options:

- **VTOL**
  - High risk
  - High complexity
- **STOL**
  - Risky with only 9.1 m x 9.1 m of area
- **Ramp**
  - Effective and simple
  - Needs propulsion method
  - Requires large area
- **Bungee**
  - Inexpensive materials

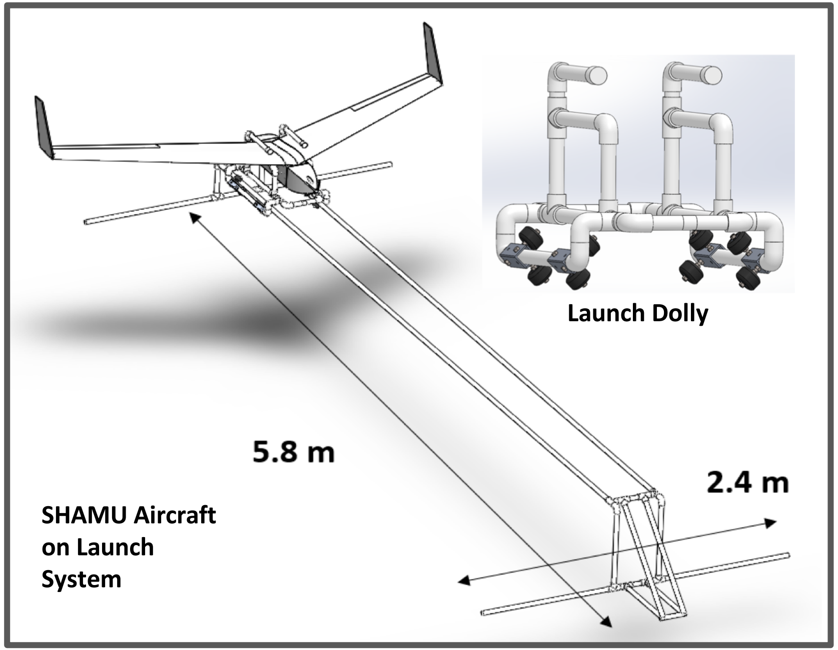
Design Selection: Launch System

System Design: Rail guided dolly propelled by bungees

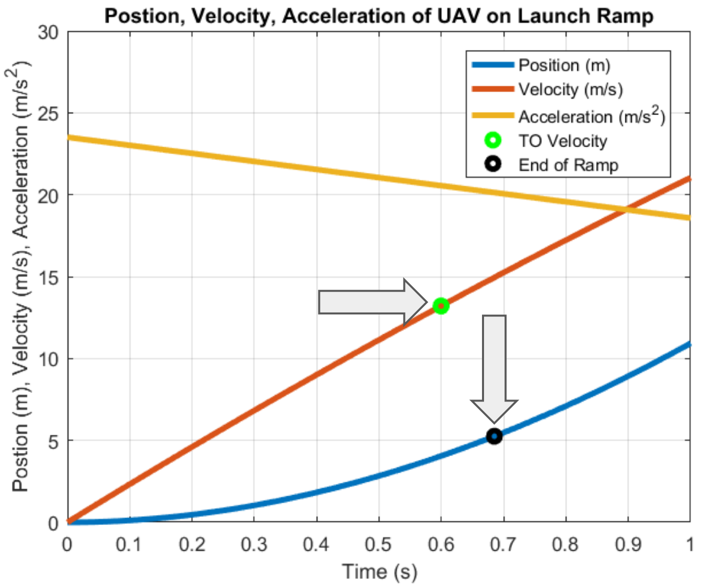
- Dolly rolls on rails via roller coaster wheel design
- Ramp system launches aircraft at 5 degree angle of attack

Reasoning for Design Selection

- Relatively simple design
- Assembly < 20 minutes
- Inexpensive materials
- Capable of delivering aircraft to desired velocity



Launch System: Bungee and Rail Design

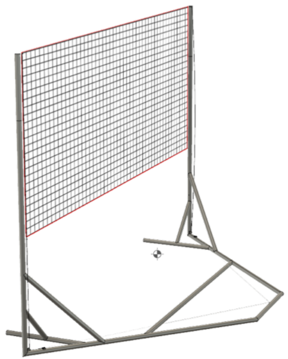


- **Concerns:**
  - G-force on launch needs to be **< 5 g**
  - UAV/Cradle speed **≥13.2 m/s by 5.25 m** (End of ramp)
- **Solution:**
  - Acceleration spread out across a long ramp
- **Assumptions:**
  - Newton's 2nd law / Conservation of Energy
  - Mass of UAV/Cradle is 14.0 kg
- **Results:**
  - UAV/Cradle speed of **13.2 m/s at 5 m < 5.25 m**
  - UAV/Cradle experiences max **2.44 g**

Recovery System

Relevant Requirements:

- Recovery system shall halt aircraft under 5 g
- Recovery system shall fit on a 9.1 m x 9.1 m platform



Rendering of Recovery Net

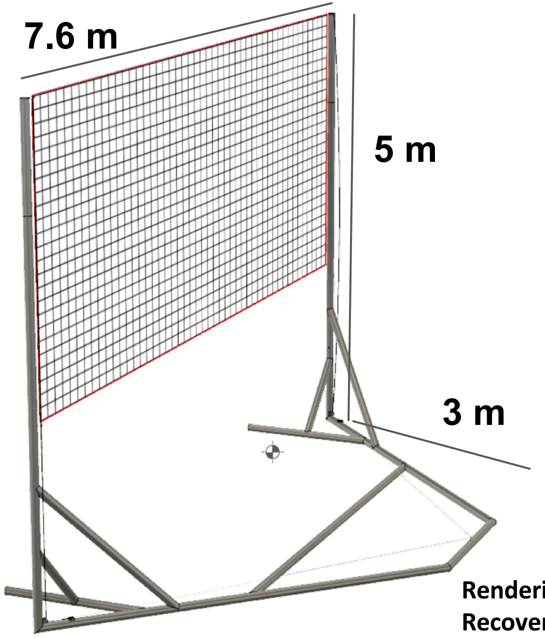
Considered Options:

- **Parachute**
  - High risk: winds can alter trajectory
- **VTOL**
  - High risk
  - High complexity/weight
- **STOL**
  - Risky with only 9.1 m x 9.1 m of area
- **Deep stall**
  - High risk: low controllability
- **Net**
  - Low complexity, medium risk
  - Large volume

Design Selection: Recovery Net

System Design: Recovery net with extending lines

- **Net** suspended between two poles
- **Pulley connections to extend upon impact**
- **Extension** of net **reduces forces** upon landing and **closes the net** to **capture aircraft**
- **Impact forces** are **reduced** by an extending **bungee** attached to the pulley line
- **Sailing Cleat** prevents line from rebounding
- **Hook on nose** of aircraft will **catch** the net to **prevent impact** with **ground**



Rendering of Recovery Net

Communications System

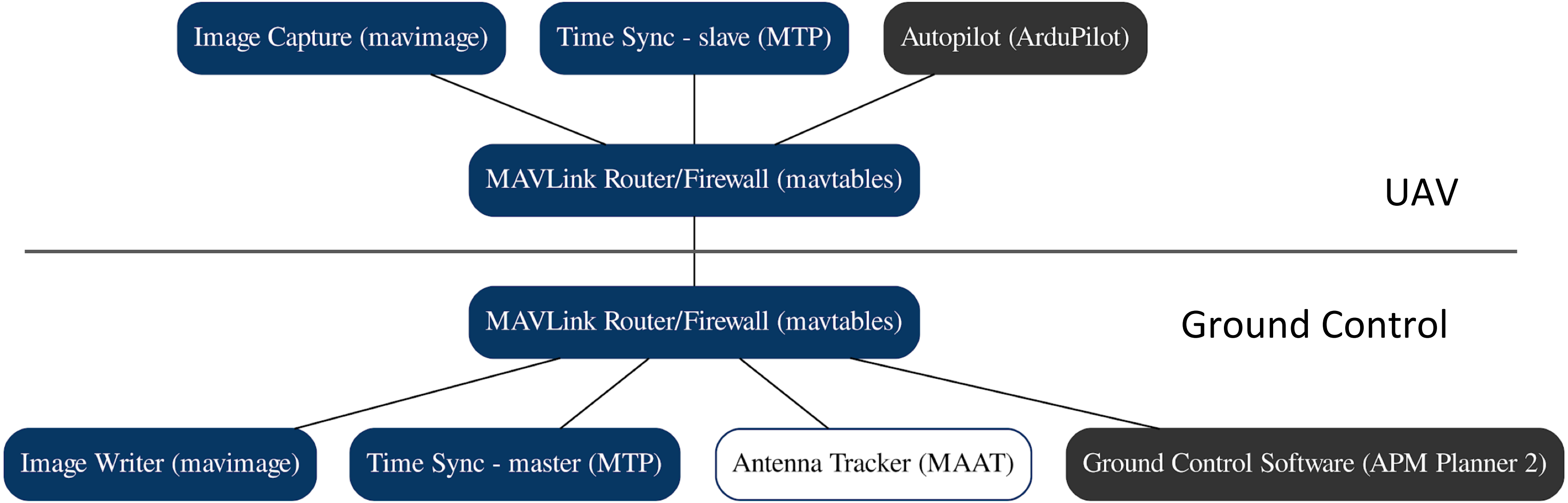
Relevant Requirements:

- Aircraft shall have 12 km communication range at 90+ kbs
  - Communications system transmits real time telemetry
  - Communications system transmits images at 1 image per minute
- Aircraft shall have 12 km communications range for manual remote control

System Design:

- 900 Mhz - Sik RFD900+ Datalink Modem
  - MAVLINK protocol for telemetry & images
  - Long range directional Yagi antenna
  - Short range omnidirectional antenna
- 433 Mhz - Hawkeye OpenLRS RC Modem
  - Long range directional Yagi antenna
  - Short range omnidirectional antenna

MAVLink Network

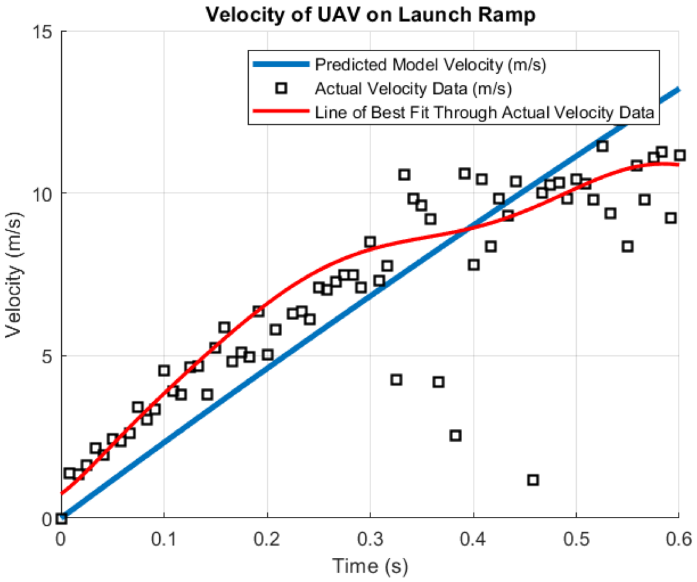


Verification

- **Aircraft stability predicted via AVL**
  - Aircraft's response to disturbances compared to predicted response
- **Half-Scale Aircraft Model**
  - Validate aircraft configuration in a real flight environment
- **Launch velocity and acceleration**
  - Measure velocity and acceleration via video analysis in LoggerPro
- **Recovery deceleration**
  - Measure deceleration via video analysis in LoggerPro

Half-Scale Flight Test

Verification



Requirement

Launch system shall accelerate aircraft to 13 m/s

Discussion

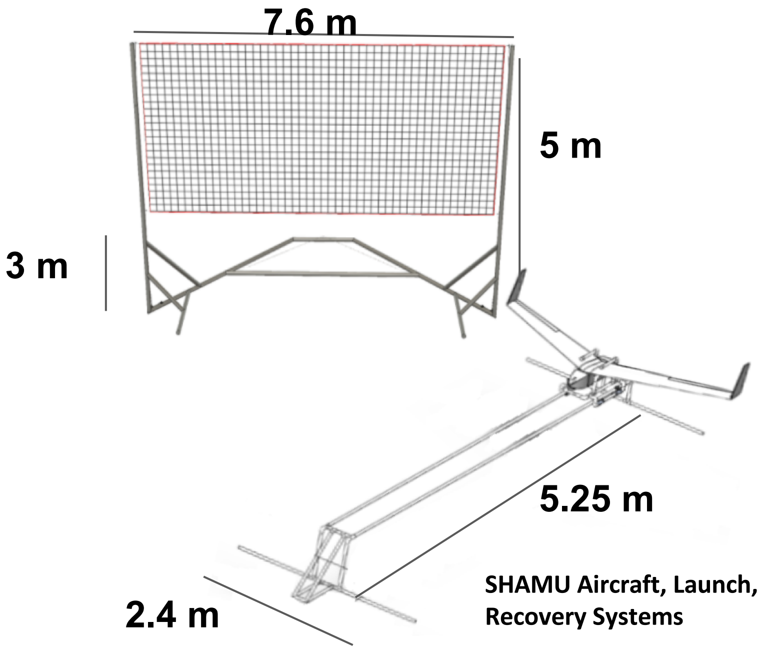
- Predicted to launch at 13 m/s
- Experimental results show 11 m/s
- Launch system modified to convert additional potential energy into kinetic energy to meet 1.3 stall speed requirement (13 m/s)

Conclusion

Non-linear behavior of latex/rubber surgical tubing must be accounted for in model

Validation

- **Full-scale simulated mission test**
- **Aircraft system range and endurance**
  - Flight time, speed, and range on-mission compared to predicted values
- **Launch system Validation**
  - Capable of delivering required kinetic energy to UAV
- **Recovery System Validation**
  - Capable of recovering aircraft after mission without overstressing airframe



SHAMU Aircraft, Launch, and Recovery Systems