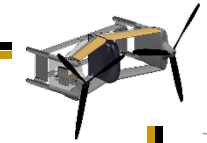
Executive Summary

2007 AHS Design Competition

Daniel Guggenheim School of Aerospace Engineering
Georgia Institute of Technology



RFP Summary

- Design a Fleet of Aircraft that are launched from a submerged submarine at periscope depth (50 ft) for the purpose of conducting sensitive covert and clandestine military mission.
- 2 Types of Aircraft
  - **Manned** Approach and Recovery Vehicle (ARV) that is operated by SOF soldiers not trained as pilots
  - **Unmanned** Escort Vehicle (UEV)
- Mission Value Metric – Number of soldiers deployed from a single submarine to an objective 140 nm away in 6 hours while maintaining continuous UEV support at the objective.
- Remain undetected throughout all phases of the mission.
- Recover all aircraft back to the submerged submarine after mission completion.

Current Submarine Layout

- 24 Existing Trident Missiles
- 20 Available for Modification
- Missile Dimensions
  - 6.92’ diameter
  - 44’ long
  - 2.83’ between missiles
- Usable Space
  16.67’ x 44’ x 95’
- Significant Submarine Modifications Allowed

Agenda

- Key Requirements
- Mission Analysis
- Submarine Modification and Launch Capsule Design Iterations
- Final Capsule (Barracuda) Design
- Aircraft Concept Selections
- Cipher (ARV) Description
- Dragonfly (UEV) Description
- Detailed Analysis Overview

Key Requirements

- ARV Payload = 800 lbs (2 SOF Soldiers)

  "Configurations with increased payload are highly discouraged"

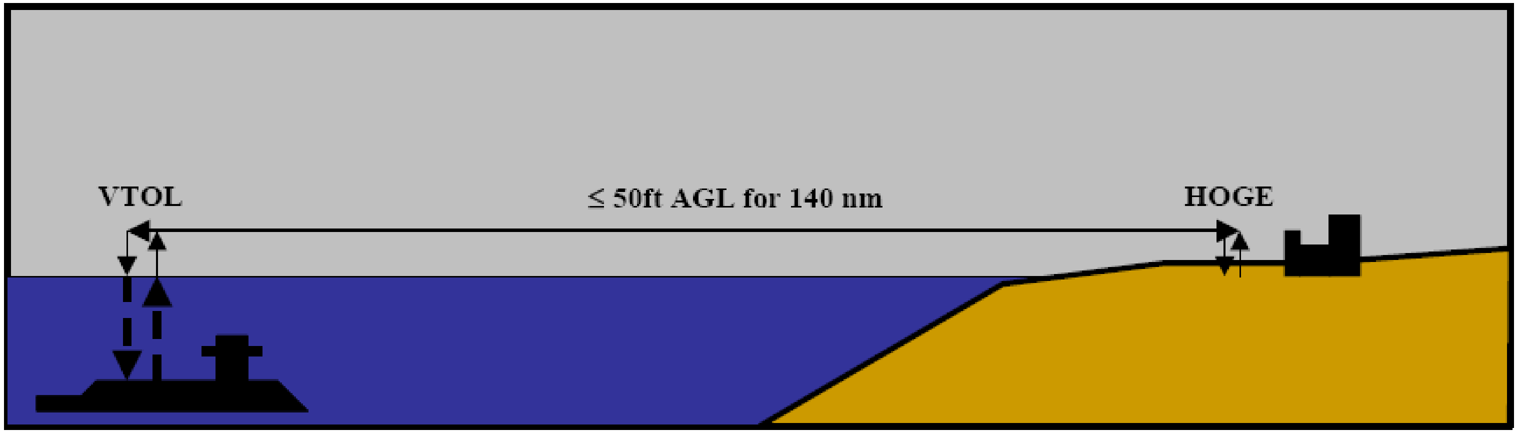
- UEV Payload = 600 lbs

- ARV should be able to conduct tactical flight (NOE).

- ARV must land at the objective (unimproved surface) in order to drop off 2 SOF soldiers.

- ARV must return to submarine fully autonomously

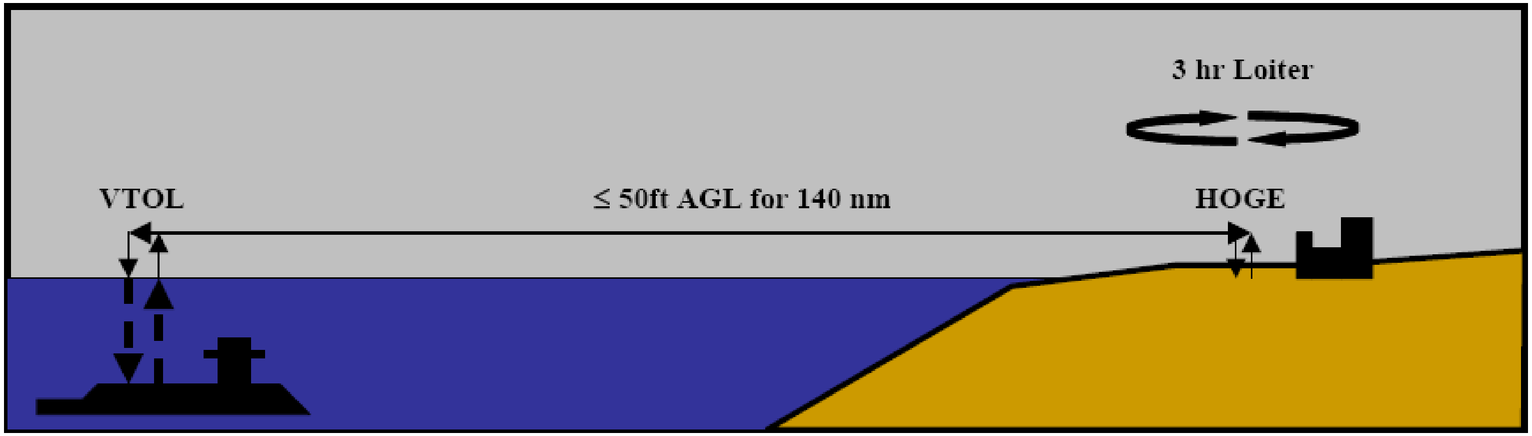
ARV Sizing Mission



ARV Mission Profile

Segment	1	2	3	4	5	6	7	Units
Type	Idle	HOGE	Cruise	HOGE	Cruise	HOGE	Reserve	-
Speed	0	0	V_{br-99}	0	V_{br-99}	0	V_{be}	ktas
Time	4	2	-	4	-	2	20	min
Range	-	-	140	-	140	-	-	nm
Altitude	0	0	0	0	0	0	0	ft
Temperature	102.92	102.92	102.92	102.92	102.92	102.92	102.92	°F
Engine Rating	IRP	MRP	MCP	MRP	MCP	MRP	MCP	-

UEV Sizing Mission



UEV Mission Profile

Segment	1	2	3	4	5	6	7	Units
Type	Idle	HOGE	Cruise	Loiter	Cruise	HOGE	Reserve	-
Speed	0	0	V_{br-99}	V_{be}	V_{br-99}	0	V_{be}	ktas
Time	4	2	-	180	-	2	20	min
Range	-	-	140	-	140	-	-	nm
Altitude	0	0	0	0	0	0	0	ft
Temperature	102.92	102.92	102.92	102.92	102.92	102.92	102.92	°F
Engine Rating	IRP	MRP	MCP	MCP	MCP	MRP	MCP	-

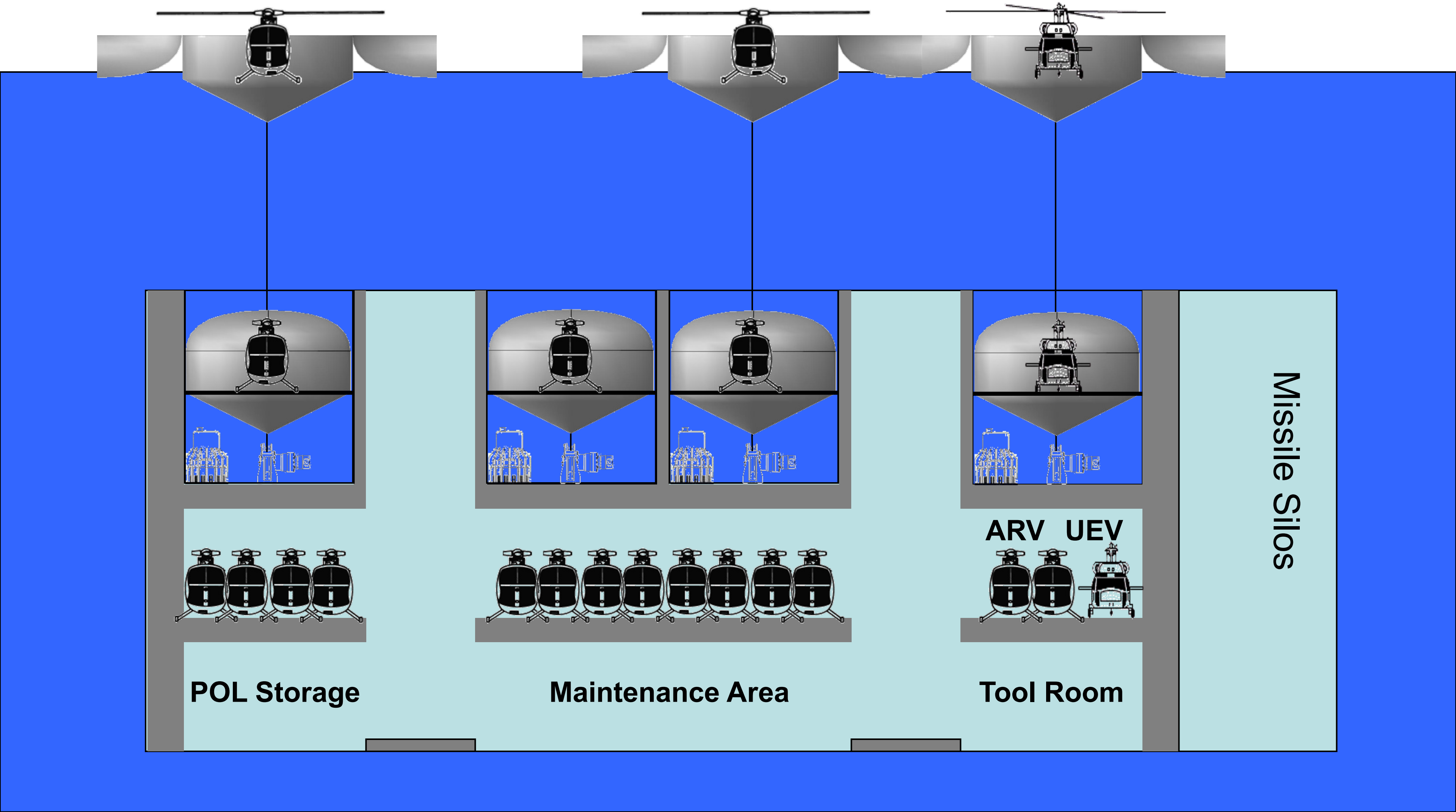
Mission Analysis

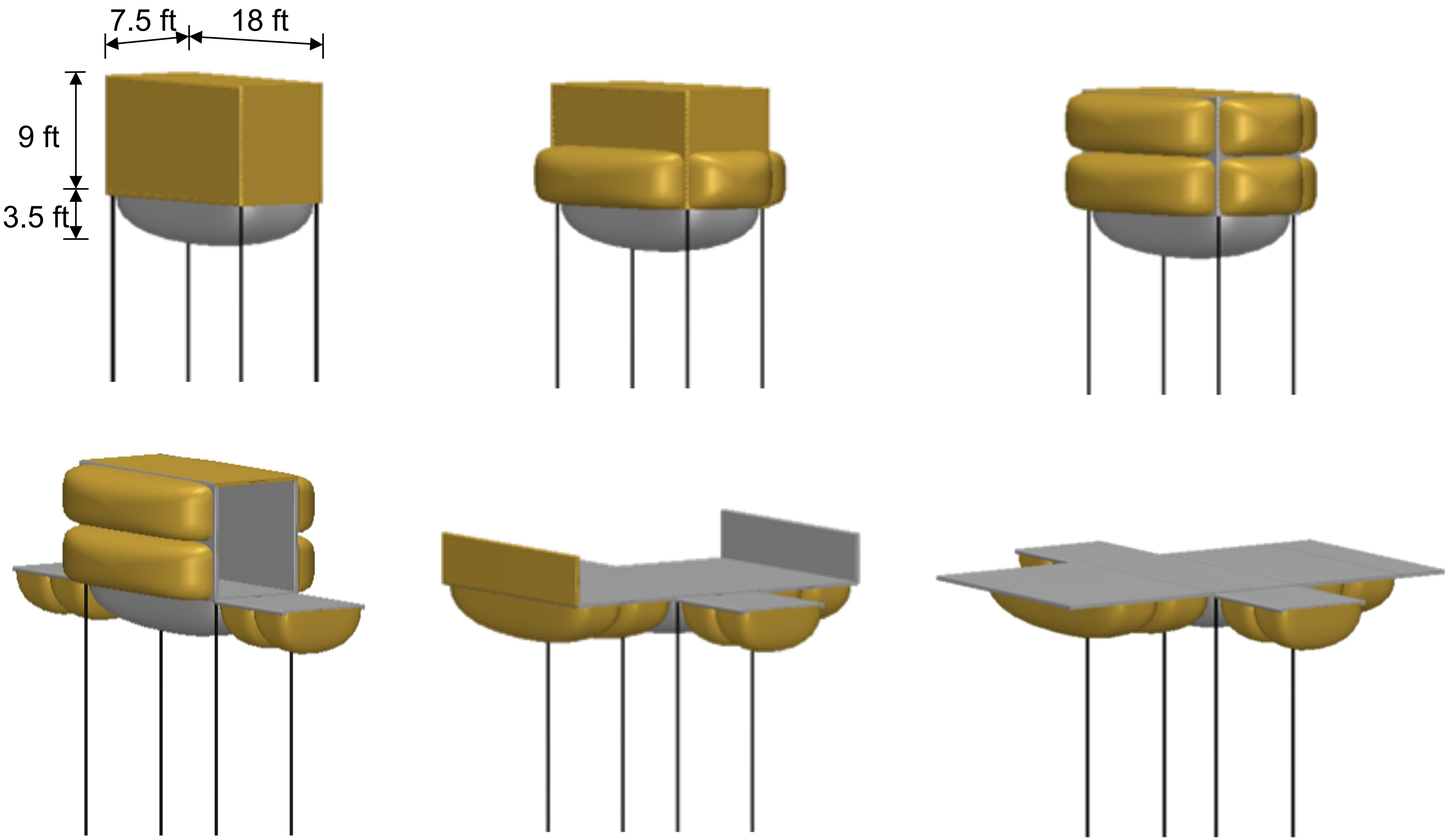
- 2 Highly Conflicting Requirements
  - Maximize Soldiers to Objective
    - **Launch Quickly**
    - **Maximize Vehicle Packing Density**
    - **High Cruise Speed = High Disk Loading**
  - Maximize Stealth
    - **Low Acoustic Signature = Low Disk Loading**
    - **Low Visual / IR Signature**
    - **Low Radar Signature**

- Minimizing acoustic signature near Objective is the most heavily weighted design consideration.

Launch Design

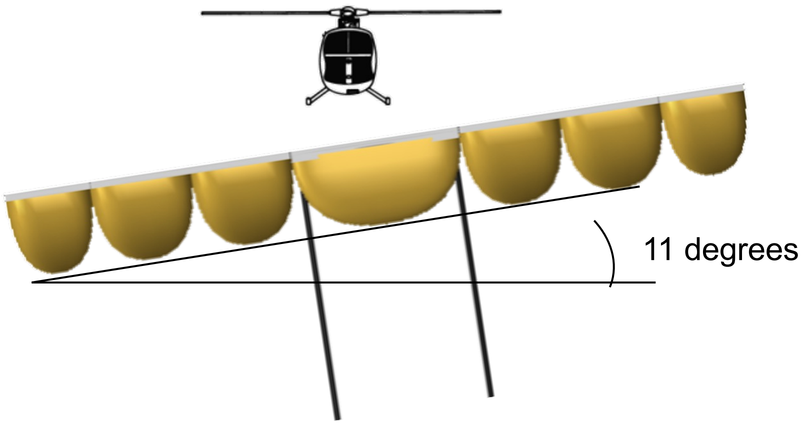
- 9 Fully Developed Launch Design Iterations Considered
- Launch System Designed in Parallel with Aircraft
- Major Trade Studies
  - Submarine Space Allocation
  - Tethered vs Free Capsule
  - Type of Surface Stability
  - Number of Missile Tubes per Capsule
  - Number of Aircraft per Capsule
  - Number of Decks Per Capsule


ARV
UEV
Missile Silos
POL Storage
Maintenance Area
Tool Room

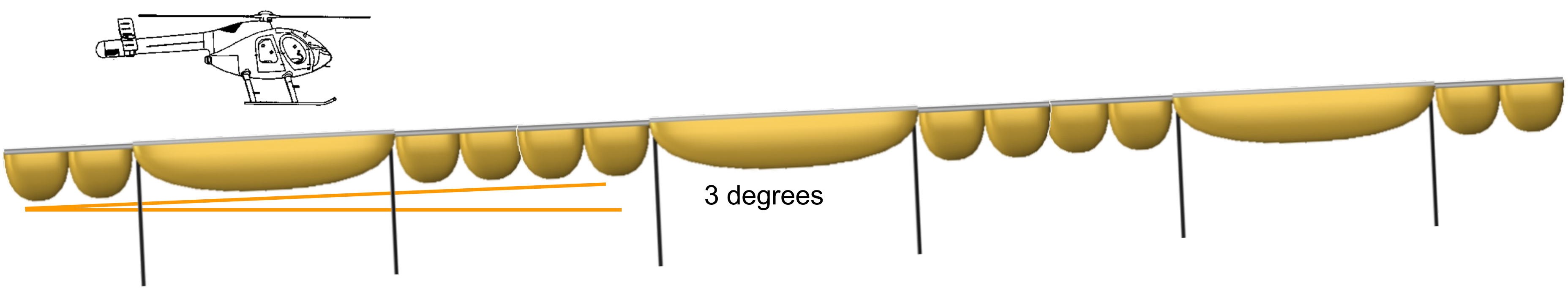

7.5 ft
18 ft
9 ft
3.5 ft

Capsule Stability Open

- Capsules unfold automatically using motors underneath Center Section
- After sections unfold, locking bars hold hinges in place, Creating a rigid structure

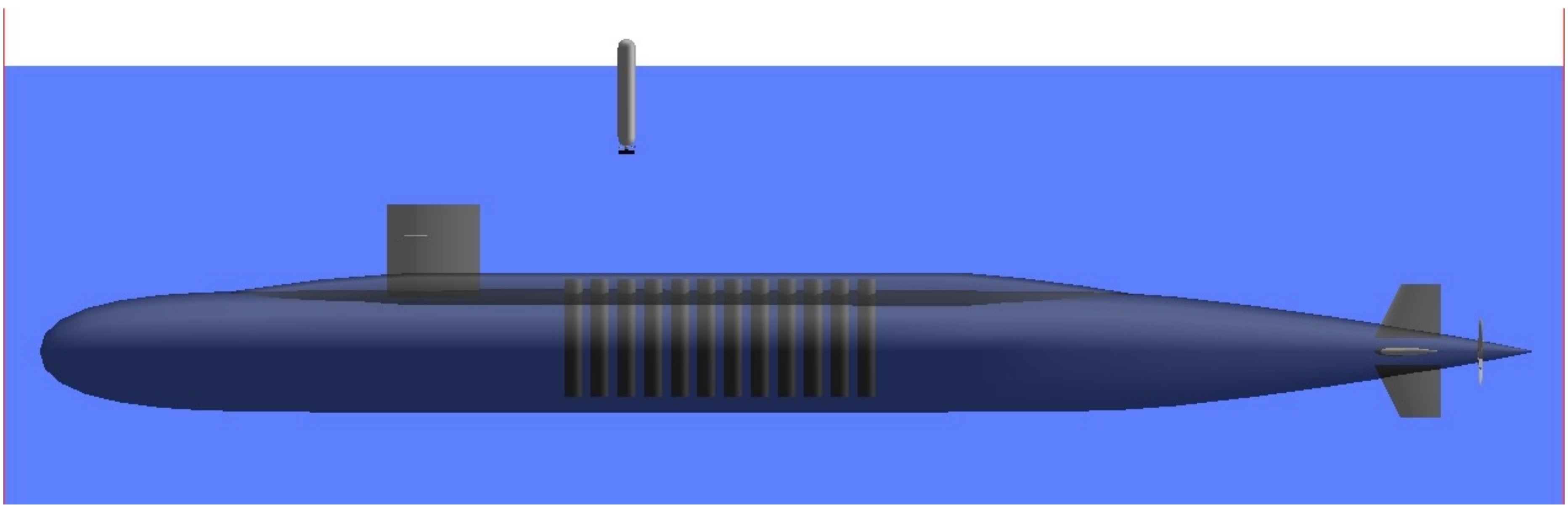


ARV Landing Orientation

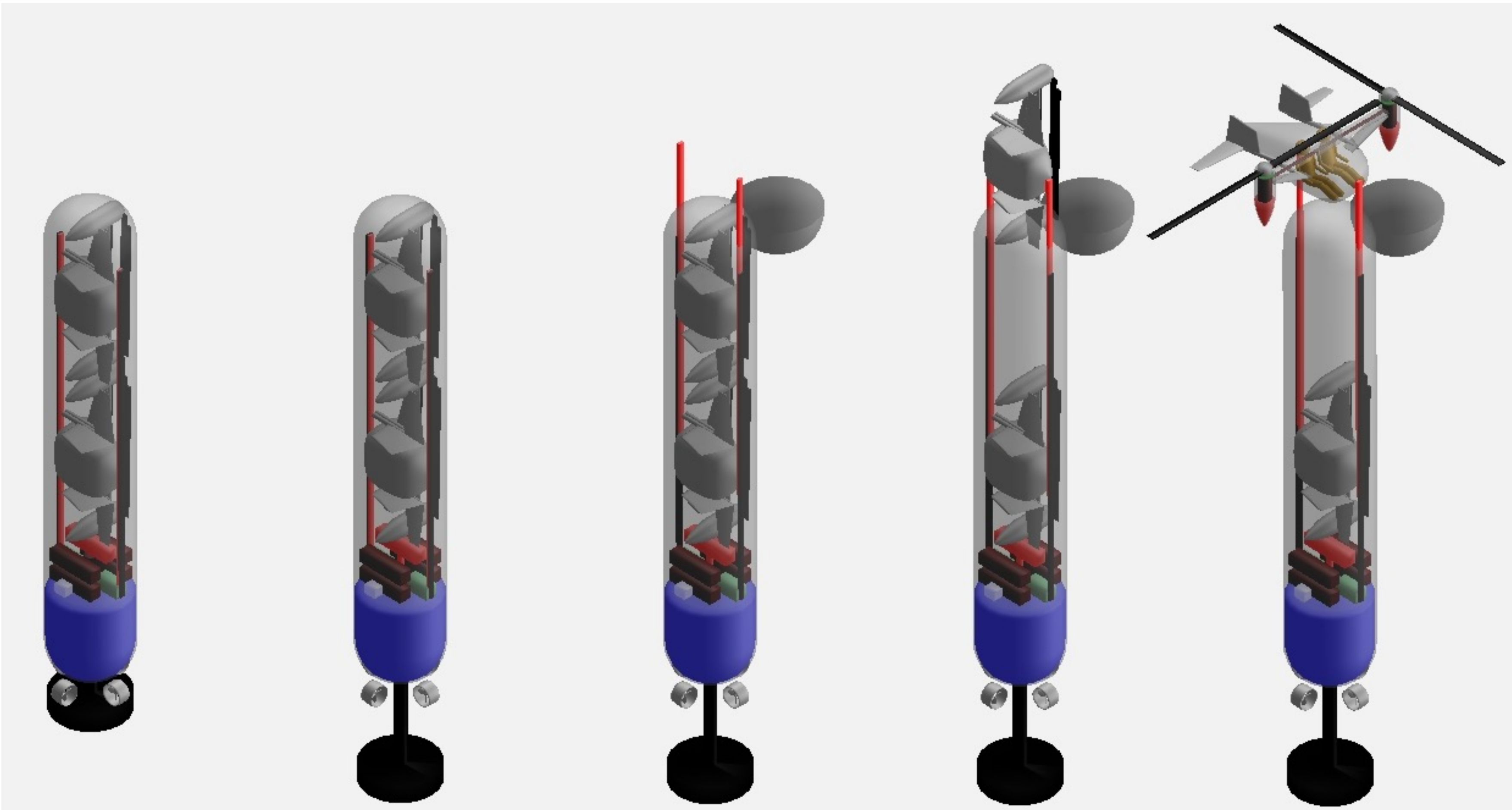


Launch System Description

– **Submarine missile tubes are unmodified.**
– **Each missile tube contains one 40’ x 6.5’ capsule, which holds 2 ARVs.**
– **The capsule is designed based on General Dynamics Vertical Sea Stabilization Concept (1963)**
– **The capsules are buoyantly launched from the missile tube and then sub leaves area (in < 10 min).**

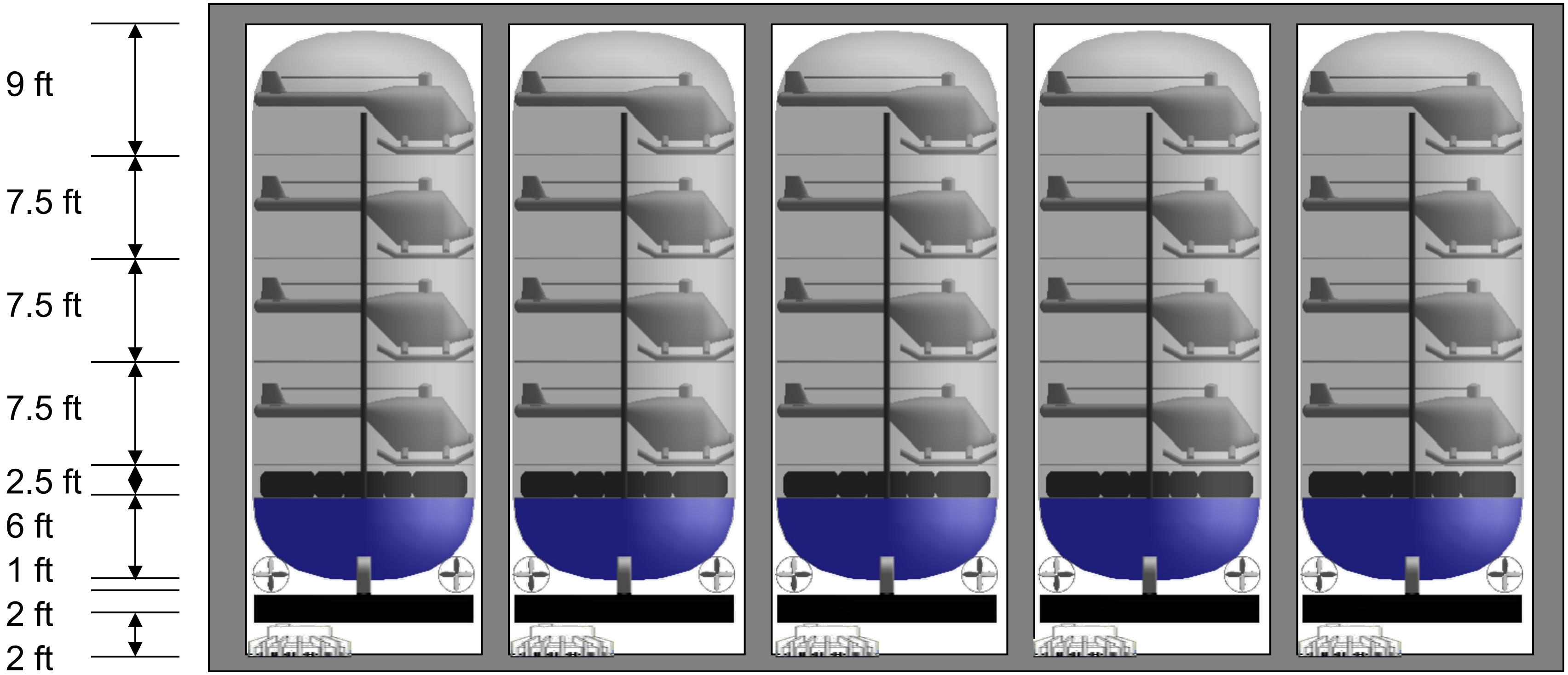


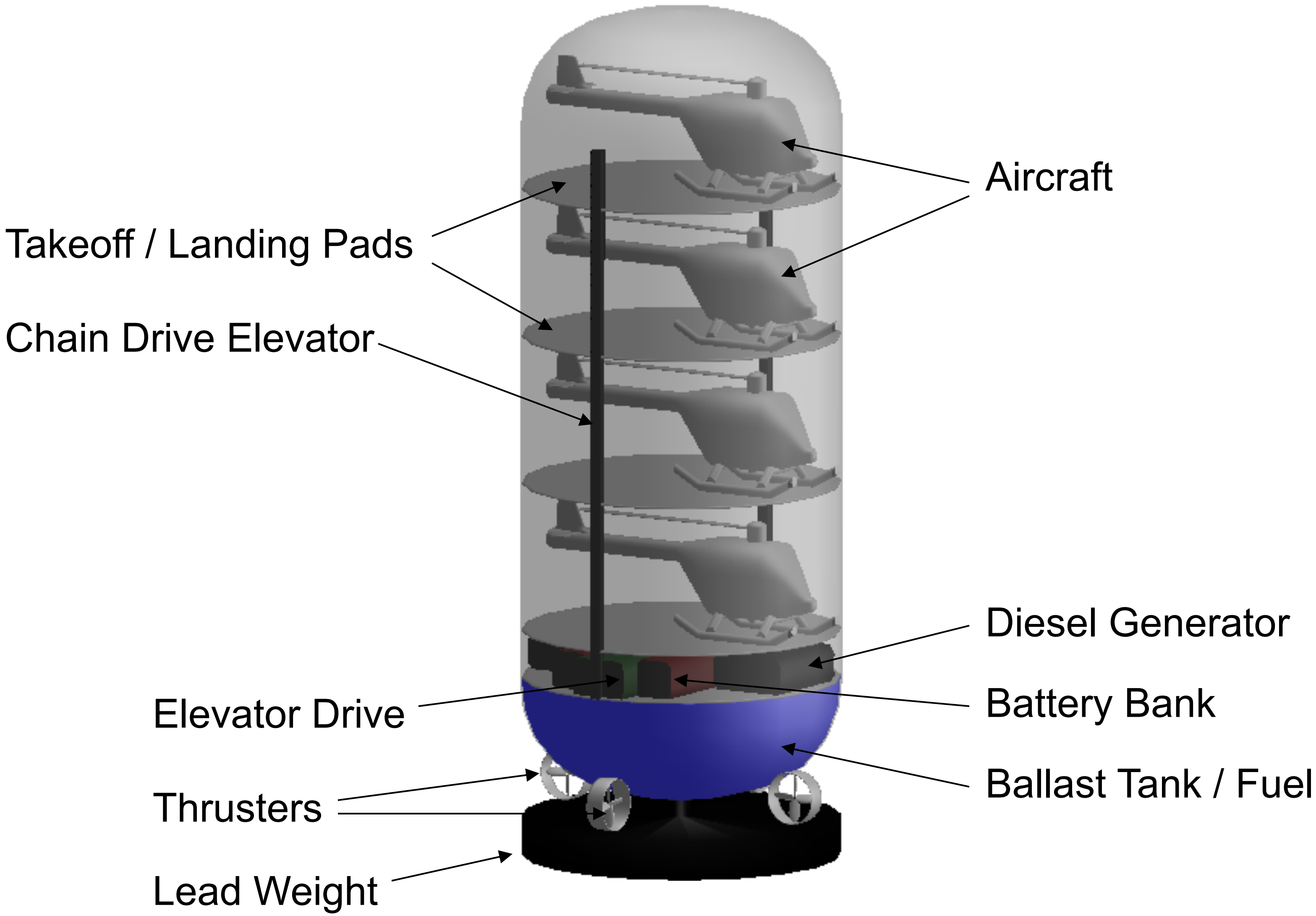
Launch System #2 Launch Sequence



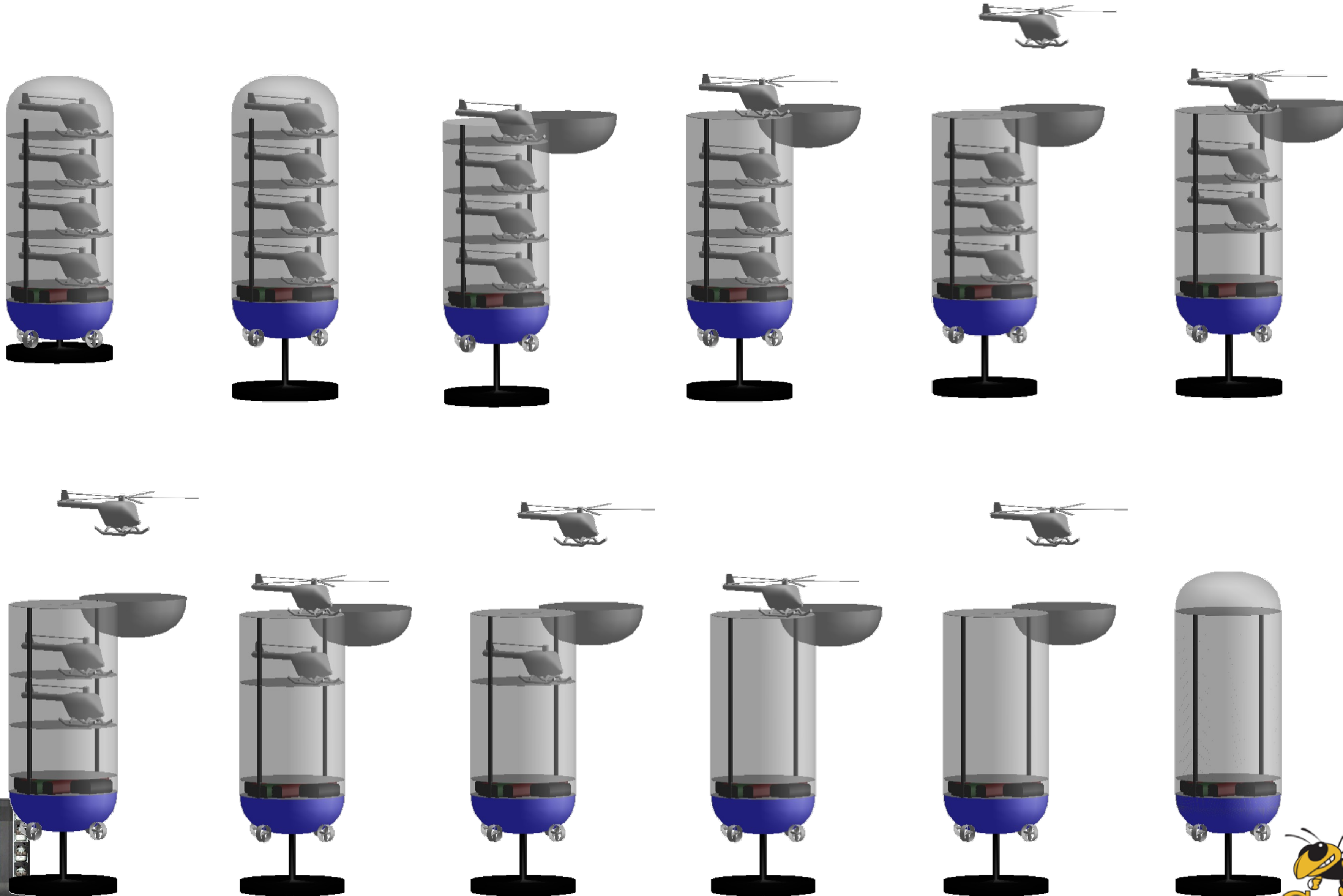
Submarine Layout

(SIDE VIEW)

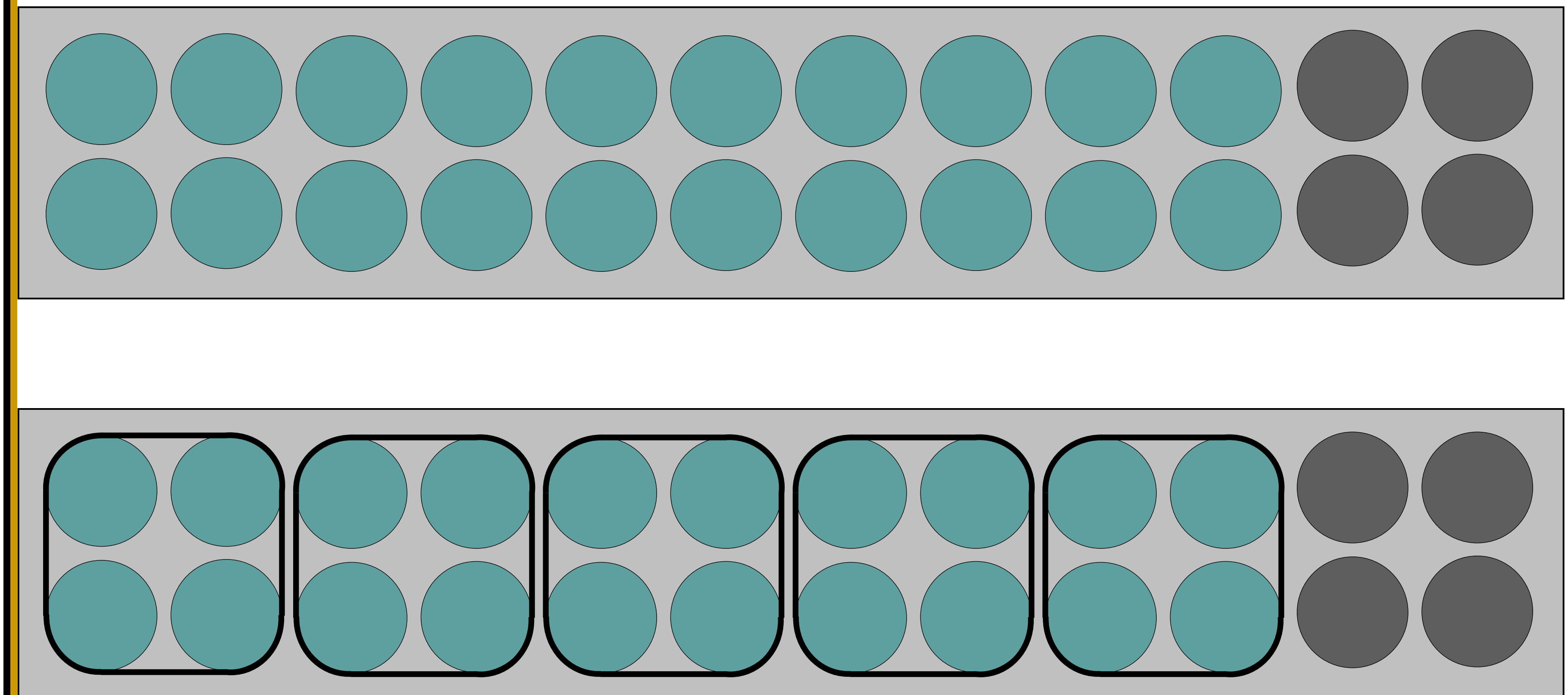



Aircraft
Takeoff / Landing Pads
Chain Drive Elevator
Diesel Generator
Elevator Drive
Battery Bank
Thrusters
Ballast Tank / Fuel
Lead Weight

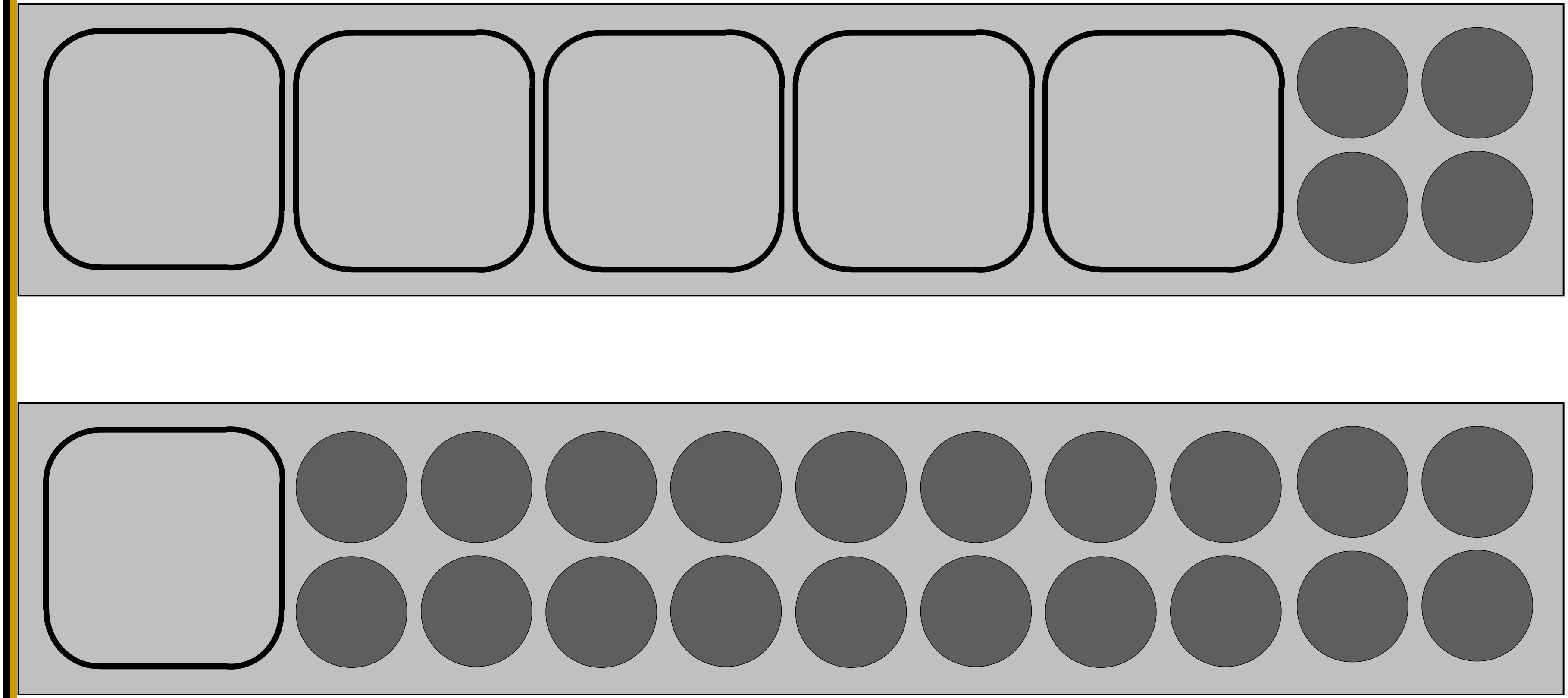
Capsule Operations

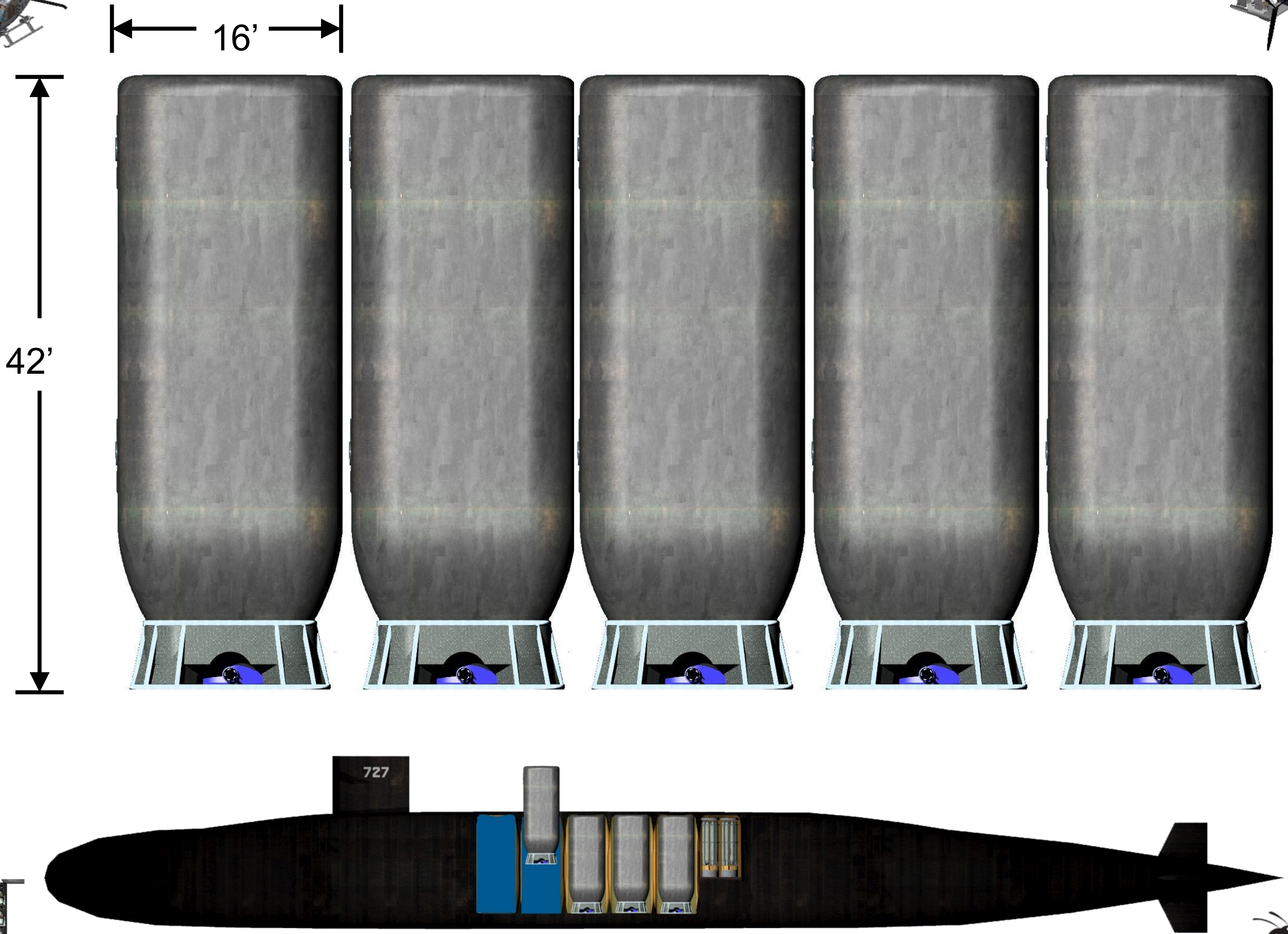


Final Submarine Modification

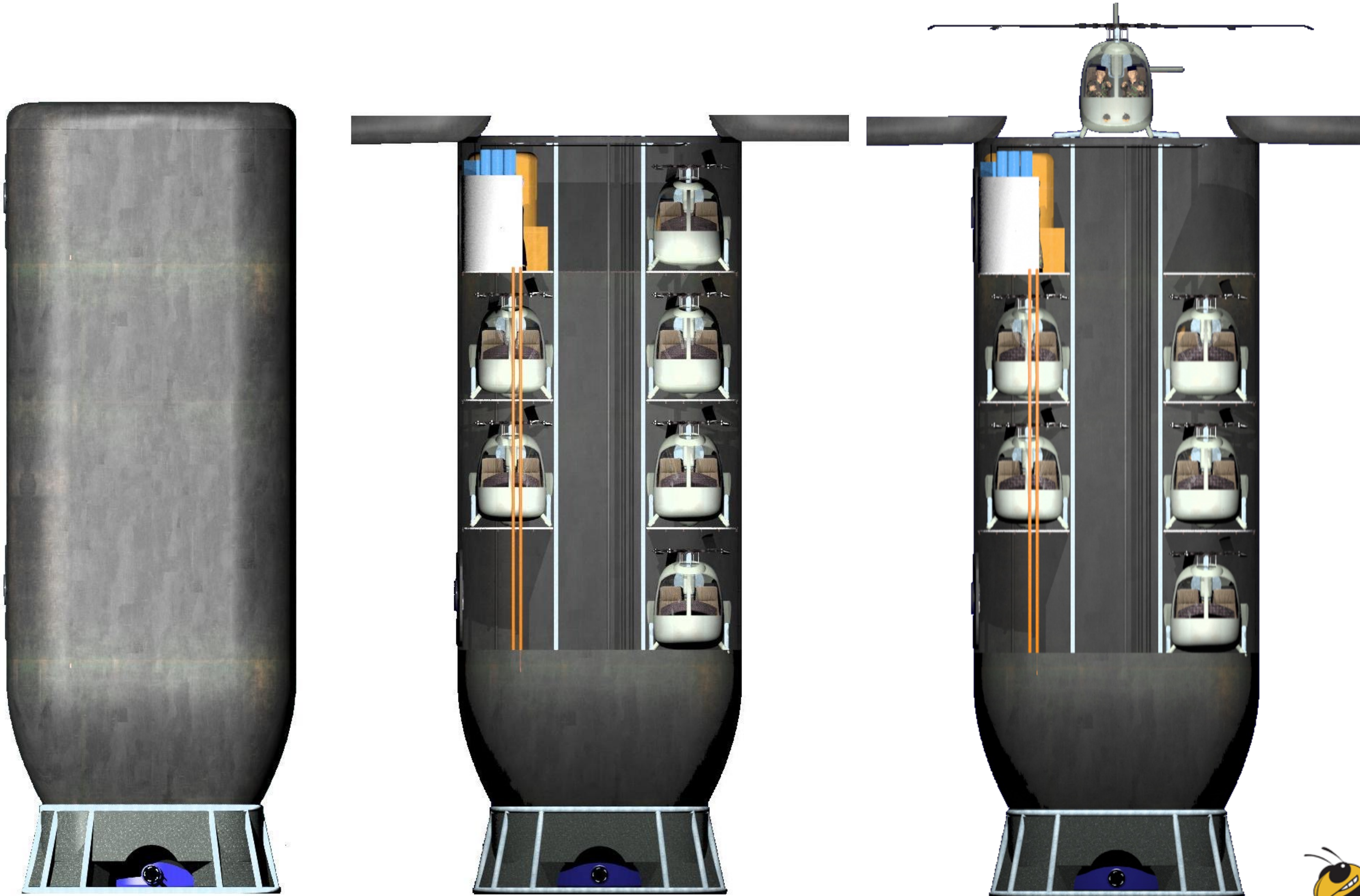


Final Submarine Modification

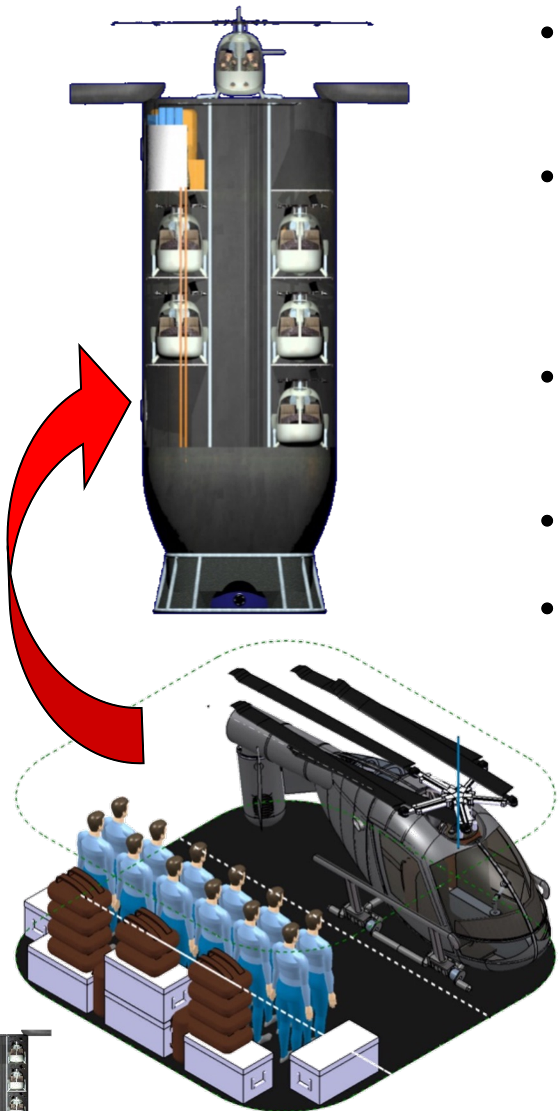



16’
42’
727

Barracuda Launch Capsule

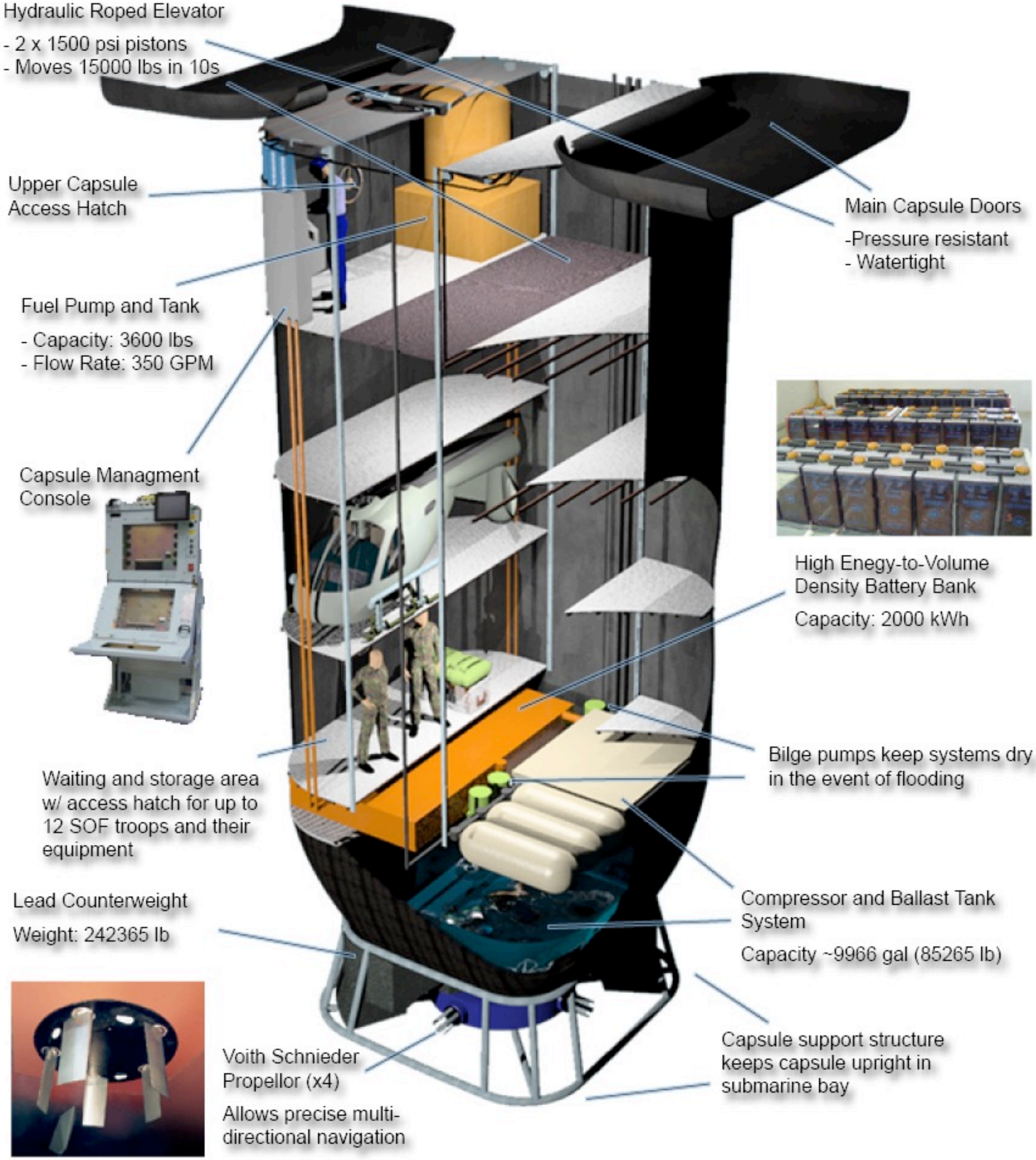


Barracuda Capsule Operations



Lower Deck

- **Barracuda has 4 storage decks plus an upper launch deck (16' x 16').**
- **One Barracuda is capable of storing 6 aircraft for a total of 30 on the submarine (28 x Cipher, 2 x Dragonfly).**
- **Center is an elevator shaft. Elevator floor becomes center of launch deck.**
- **Aircraft unfolds automatically on launch deck.**
- **Half of first storage deck is dedicated to capsule control station.**
    - **Mission equipment for first mission lift is prepositioned in the aircraft**
    - **Half of lower deck is dedicated to crew and equipment storage for second mission lift**



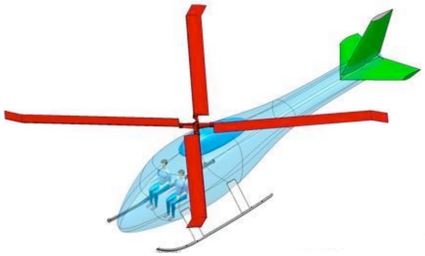
Barracuda

- **Design based on General Dynamics sea surface stability study.**
- **High length to width ratio reduces up and down bobbing motion.**
- **16’ width meets Interagency Helicopter Operations Guide (NFES 1885) for Type 3 landing zone requirements.**
- **Lead counter weight yields low C.G. resulting in minimal angular surface tilt.**

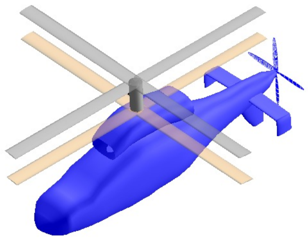
50’ Rise Time (full)	**23.89 sec**
50’ Rise Time (empty)	**18.39 sec**
50’ Sink Time (full)	**35.97 sec**
50’ Sink Time (empty)	**147.80 sec**
Surface Angular Tilt	**<2 deg**
Surface Vertical Stability (1’ Rise Time)	**4.47 sec**

Possible ARV/UEV Configurations

- Requirement to land on unimproved surfaces eliminates concepts with disk loading above 30 lb / ft^2
- Requirement to fly tactically and egress ARV eliminates Tail Sitter concept for ARV
- Low disk loading Ducted fan too bulky for submarine storage. High disk loading ducted fan too noisy.
- 3 Preferred ARV Concepts, 4 Preferred UEV Concepts

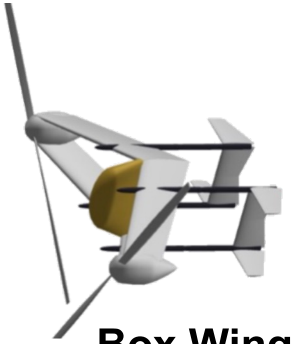


Single Main Rotor Helicopter



Coaxial With Aux Propulsion

Tilt Rotor



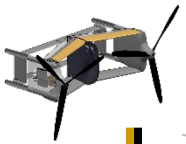
Box Wing Tail Sitter

ARV Sizing (RF Method)

Design Parameters	**Units**	**Single Main Rotor Helicopter**	**Coaxial Helicopter**	**Tilt Rotor**
Disk Loading	lb/ft^2	6	10	20
Empty Weight Fraction	ND	0.55	0.6	0.65
Equivalent Flat Plate Drag	ft^2	5	6	4
Rotor Solidity	ND	0.1	0.1	0.1
Tip Speed	ft/sec	650	650	650
Downwash Factor	ND	0.03	0.05	0.08
Aux Prop Percent Thrust	ND	NA	100	NA
Wing Span	ft	NA	NA	15
Wing Aspect Ratio	ND	NA	NA	5

ARV Sizing (RF Method)

Performance Parameter	Units	Single Main Rotor Helicopter	Coaxial Helicopter	Tilt Rotor
Minimum Gross Weight	lbs	2430	2918	4188
Hover Power 6000ft/95F	HP	293	415	990
99% Max Range Airspeed	kts	118	132	234
99% Max Range Power	HP	214	303	1148
Max Endurance Airspeed	kts	64	73	140
Max Endurance Power	HP	134	191	482
Empty Weight	lbs	1336	1751	2722
Weight of Total Fuel Required	lbs	272	336	616



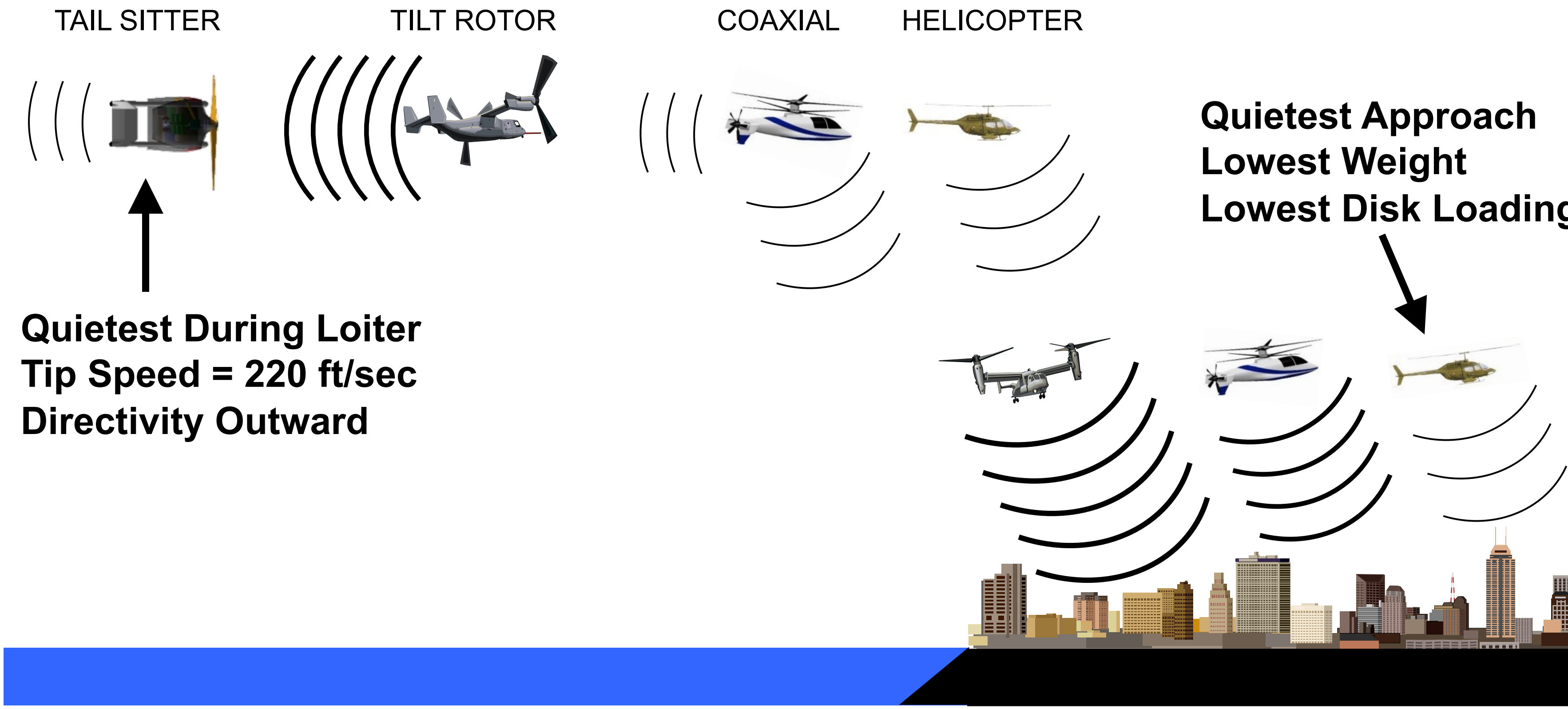
UEV Sizing (RF Method)

Design Parameters	Units	Single Main Rotor Helicopter	Box Wing Tail Sitter
Disk Loading (calculated)	lb/ft^2	6.2	9.1
Empty Weight Fraction (calc)	ND	0.56	0.61
Equivalent Flat Plate Drag (calc)	ft^2	7.1	1.15
Rotor Solidity	ND	0.085	0.115
Hover Tip Speed	ft/sec	650	600
Cruise Tip Speed	ft/sec	650	375
Loiter Tip Speed	ft/sec	650	220
Downwash Factor	ND	0.03	0.0105
Wing Area	ft	n/a	80


UEV Sizing (RF Method)

Performance Parameter	**Units**	**Single Main Rotor Helicopter**	**Box Wing Tail Sitter**
Minimum Gross Weight	lbs	2650	2606
Hover Power 6000ft/95F	HP	273	378
99% Max Range Airspeed	kts	120	142
99% Max Range Airspeed Power	HP	261	239
Max Endurance Airspeed	kts	63	83
Max Endurance Airspeed Power	HP	155	110
Empty Weight	lbs	1471	1580
Weight of Total Fuel Required	lbs	577	347

Acoustic Signature



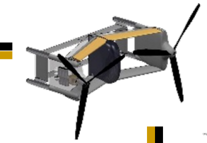
<u>Acoustic Intensity</u>
Tip Speed
Number of Blades
Weight
Disk (Blade) Loading
BVI

<u>Acoustic Directivity</u>
Orientation of Rotor

<u>Acoustic Duration</u>
ARV Egress Time

Using Different ARV and UEV Concepts

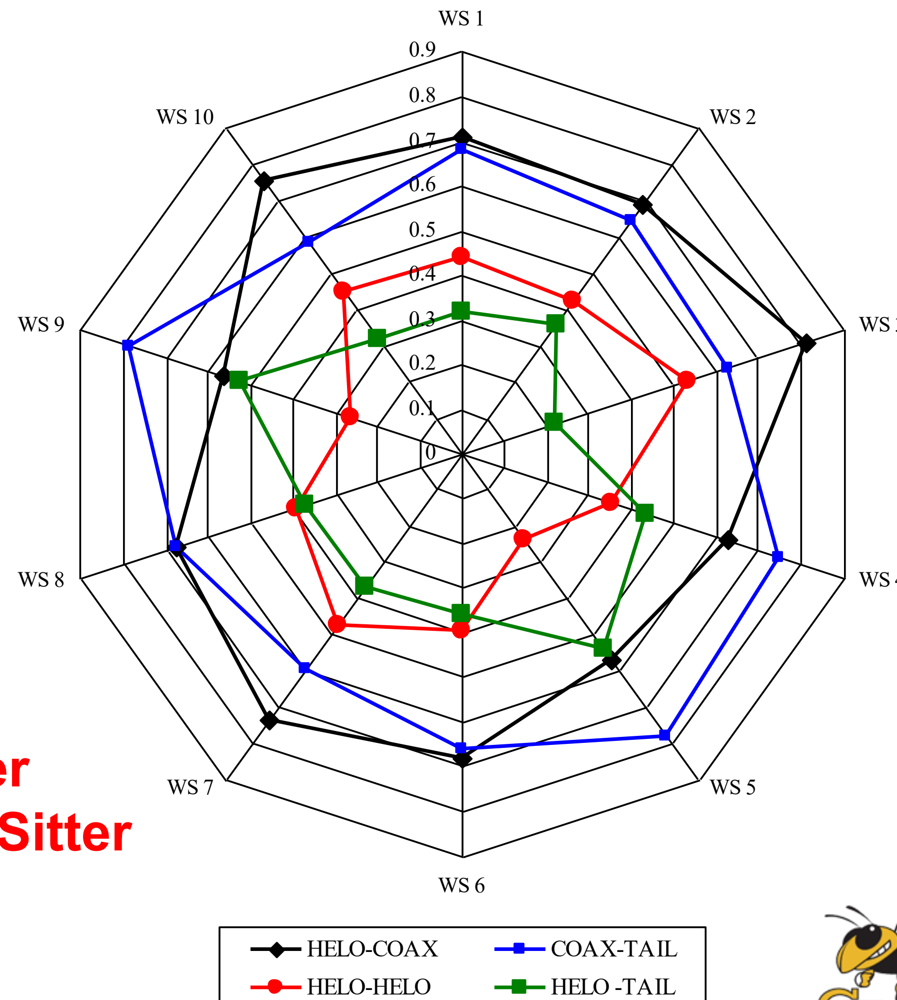
- Advantages
  - Each Aircraft Optimized for it own Mission
  - Overall Stealth Index Best (Most heavily weighted consideration)
- Disadvantages
  - High Cost
  - Commonality of Parts
- Submarine retrofit cost eclipses ARV/UEV fleet cost
- A successful compact VTOL UEV with low acoustic signature can be used for other applications other than RFP Mission



ARV / UEV Comparison

$$OEC = \frac{2.5SI + 2.0MCI_{ARV} + 1.5MCI_{UEV} + 1.5AI + 1.0ACRI + 0.5MI}{9 + LCC}$$

OEC VALUES		ARV CONCEPTS		
		Helicopter	Coaxial	Tilt Rotor
UEV CONCEPTS	Helicopter	0.83	0.70	0.61
	Coaxial	0.77	0.69	0.56
	Tilt Rotor	0.59	0.51	0.49
	Tail Sitter	**0.85**	0.73	0.59



Design Decision

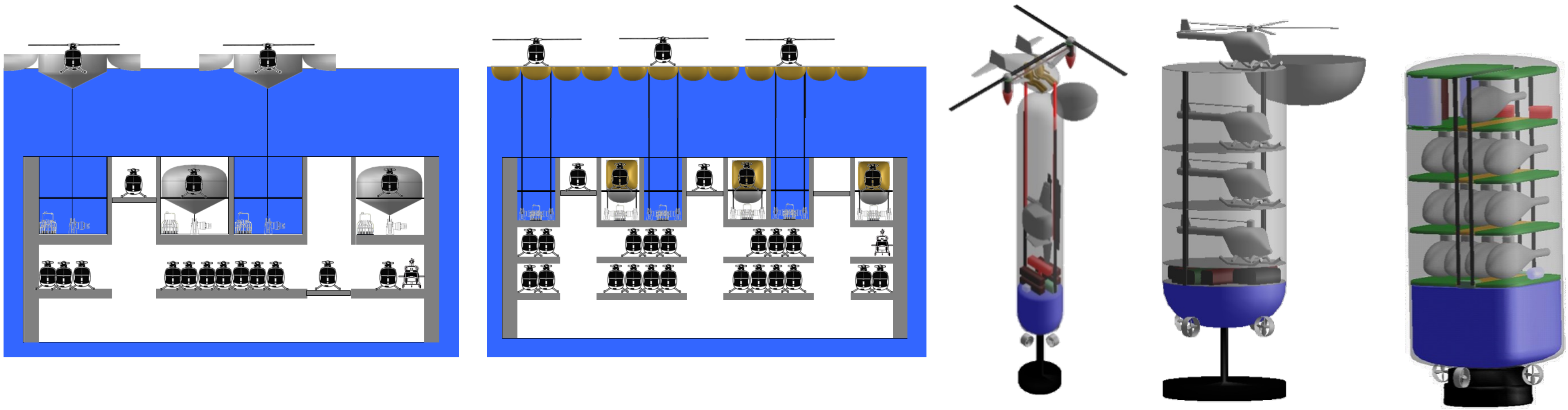
ARV Concept = SMR Helicopter

UEV Concept = Box Wing Tail Sitter

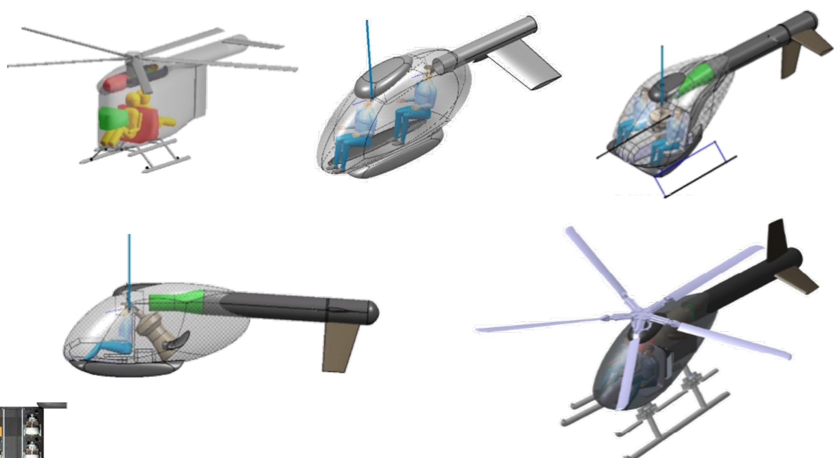
Major ARV Trade Studies

- Tail Rotor vs Fenestron vs NOTAR
- Tandem vs Side by Side Seating Configuration
  - Submarine Packing
  - Fuselage Drag
  - Crew Member Operability and Ergonomics
- Skids vs Wheels
- Number of Folding Parts (Blades, Launding Gear, Tail)
- Hub Type (Articulated vs Hingeless vs Bearingless)
- Number of Blades

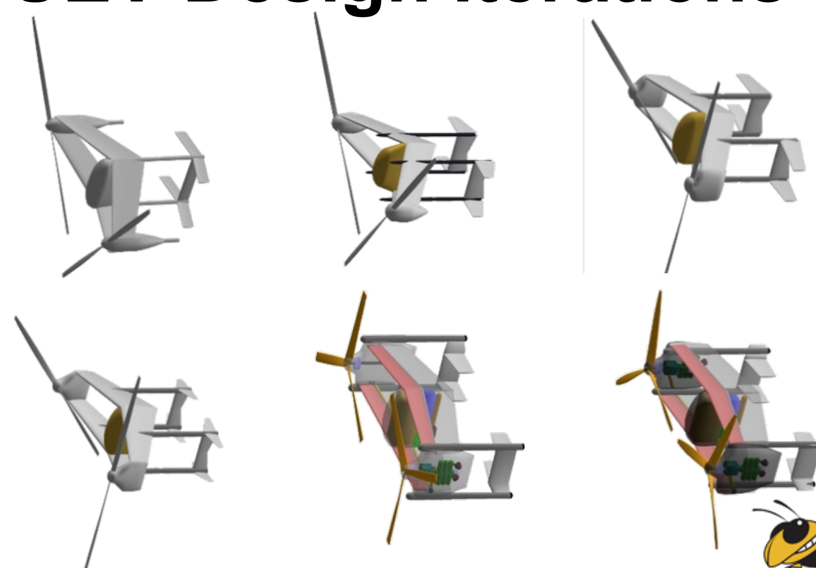
Submarine/Launch Design Iterations



ARV Design Iterations



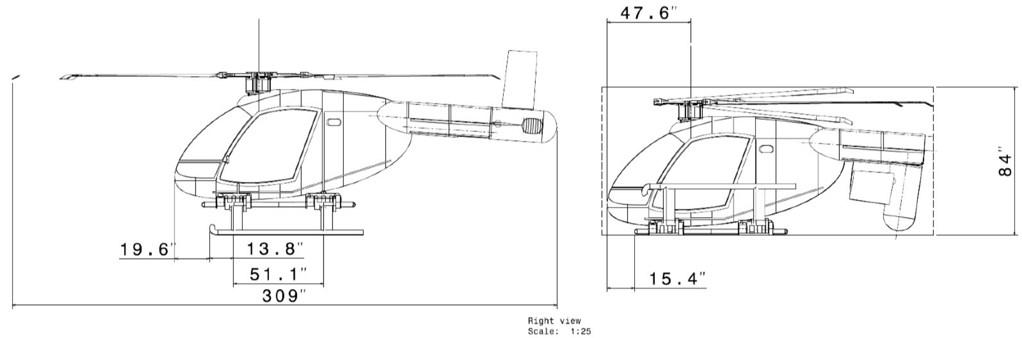
UEV Design Iterations

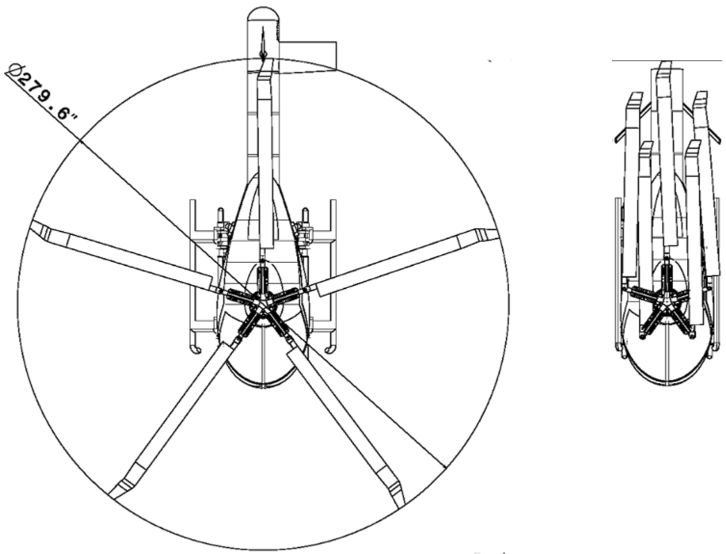


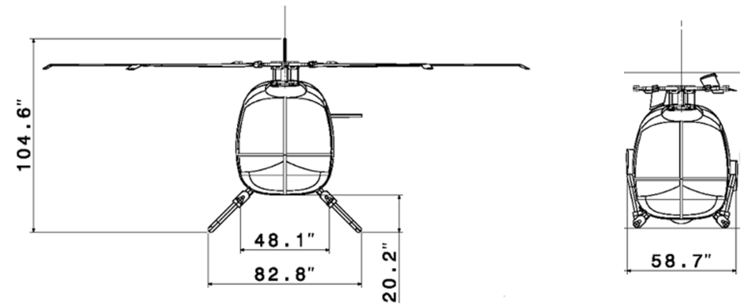
Cipher (ARV)

- Gross Weight = 2817 lbs
- Empty Weight = 1683 lbs
- Disk Loading = 6.6 lb/ft^2
- Payload = 800 lbs
- Fuel Weight = 334 lbs
- 99% Best Range Speed = 122 knots
- Max Speed = 132 knots
- Rotor Radius = 11 ft 8 in
- Tip Speed = 650 ft/sec
- Engine = 385 HP

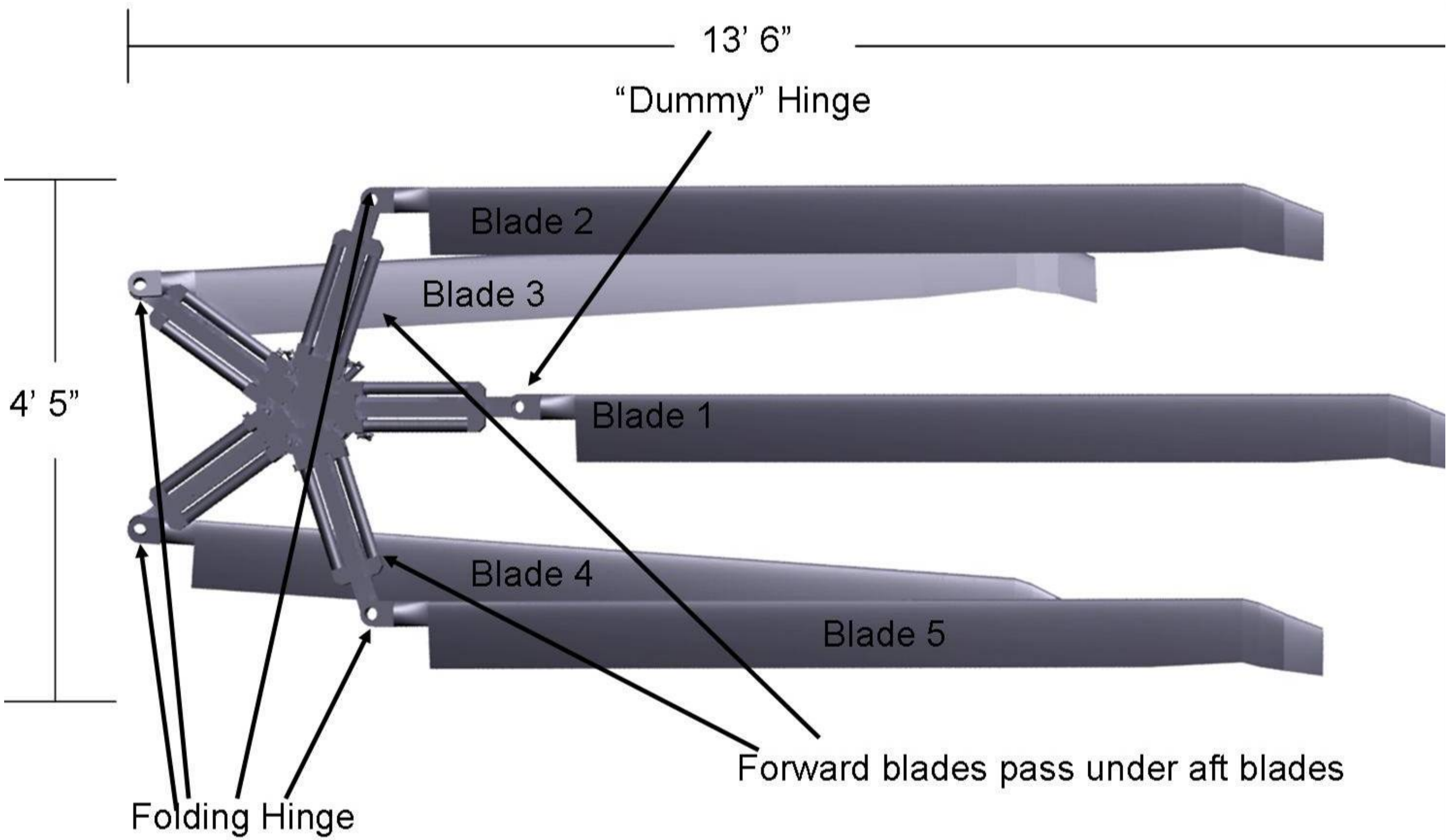
Cipher - ARV


47.6"
84"
19.6"
13.8"
51.1"
309"
15.4"
Right view
Scale: 1:25


Ø279.6"

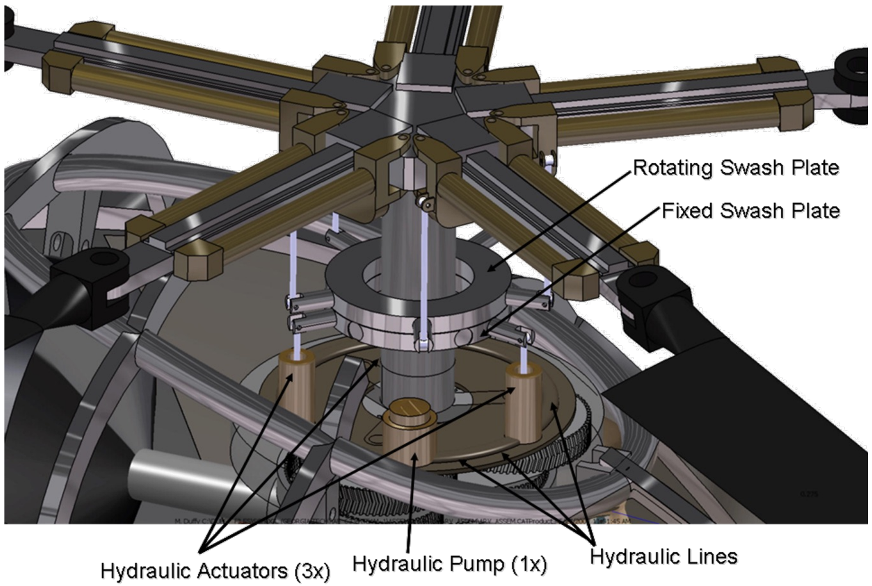

104.6"
48.1"
82.8"
20.2"
58.7"

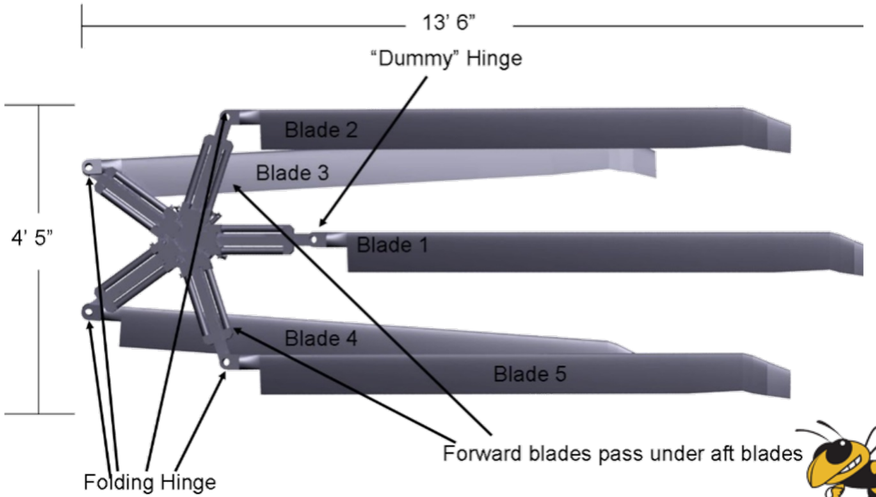
Cipher Blade Folding



Hub Design

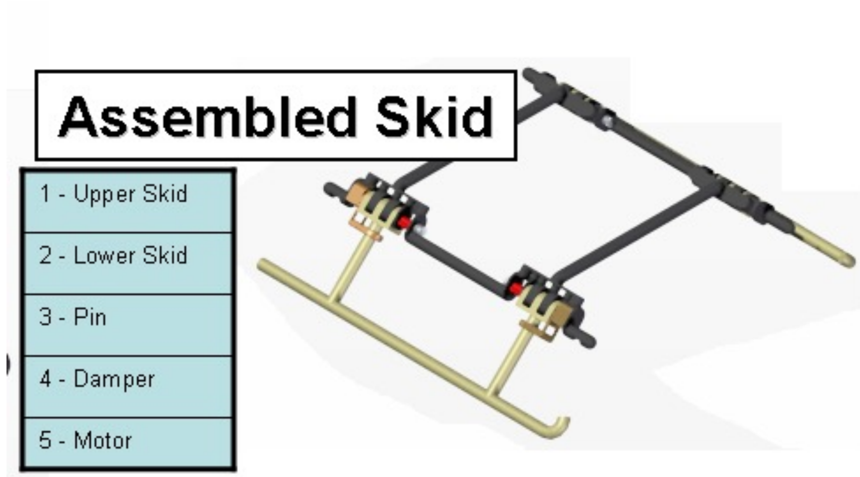
- Bearingless rotor design based on Hanson hub
- Folding hinge outboard of flex beam allows for compact storage
- Folding hinges rigidly lock in storage and in flight
- Rotor folds/unfolds in ~10 seconds
- SC1095 and SC1094R8 airfoils with non-linear twist improves performance
- Swept, Tapered, Anhedral tip decreases acoustic signature
- Low inertia rotor decreases weight

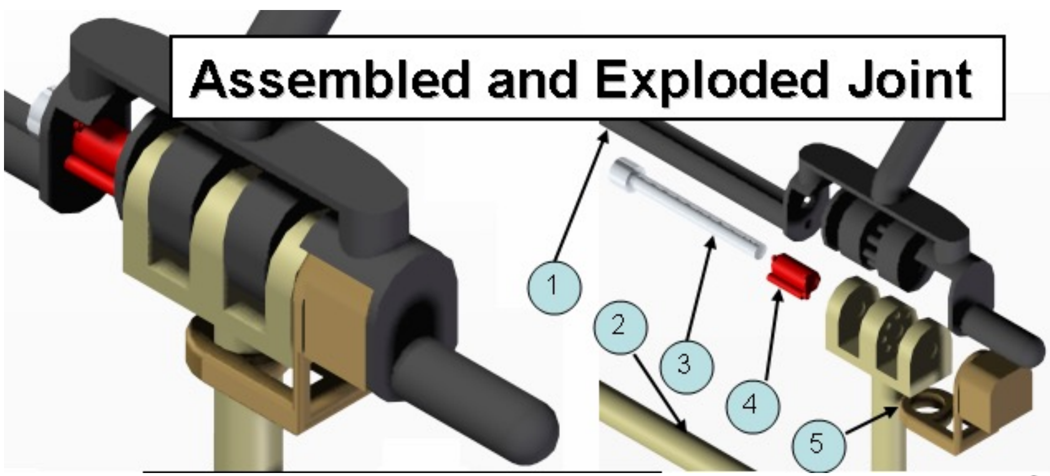




Cipher Landing Gear Folding

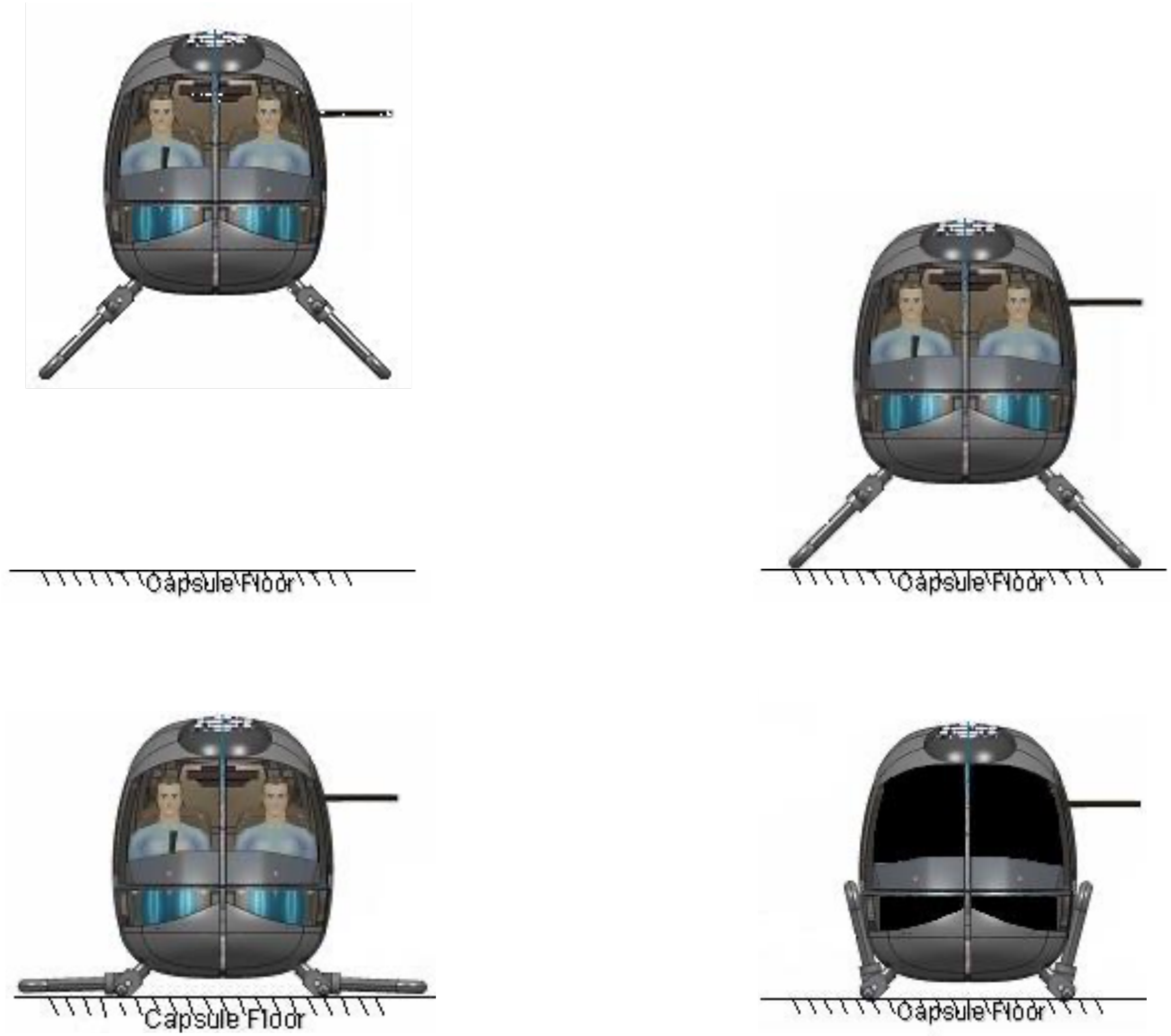
- Rotational Damper to allow motor less decent
- Small NEMA 34 Stepper Motor
- 8 hydraulically actuated pins to lock gear



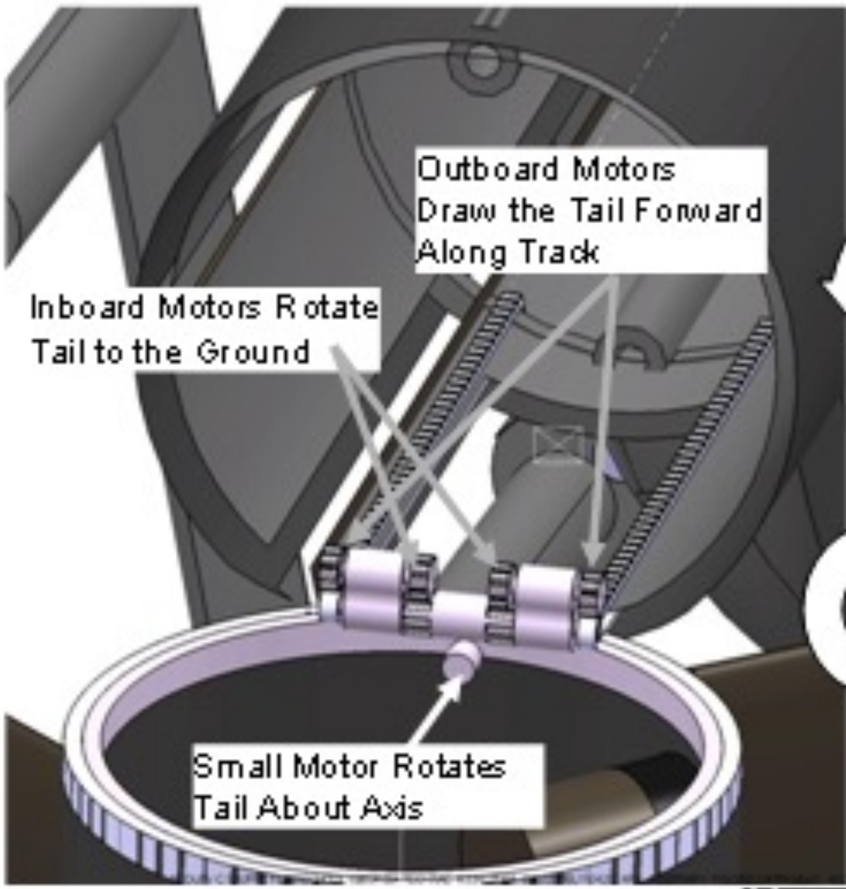


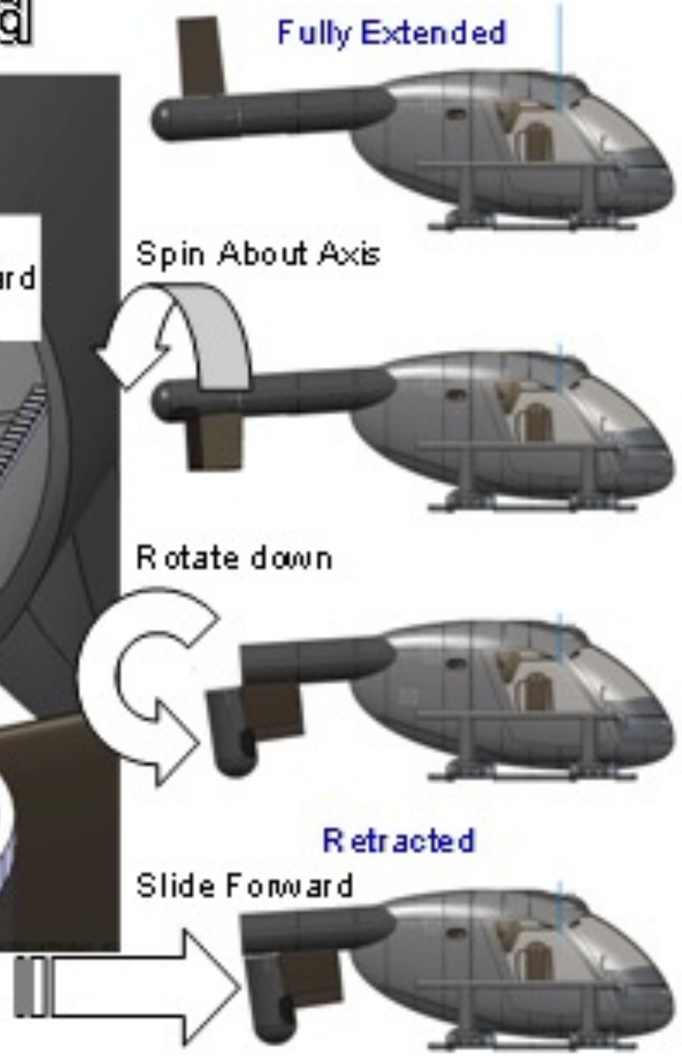
Landing Gear Operation During Takeoff

Landing Gear Operation During Landing

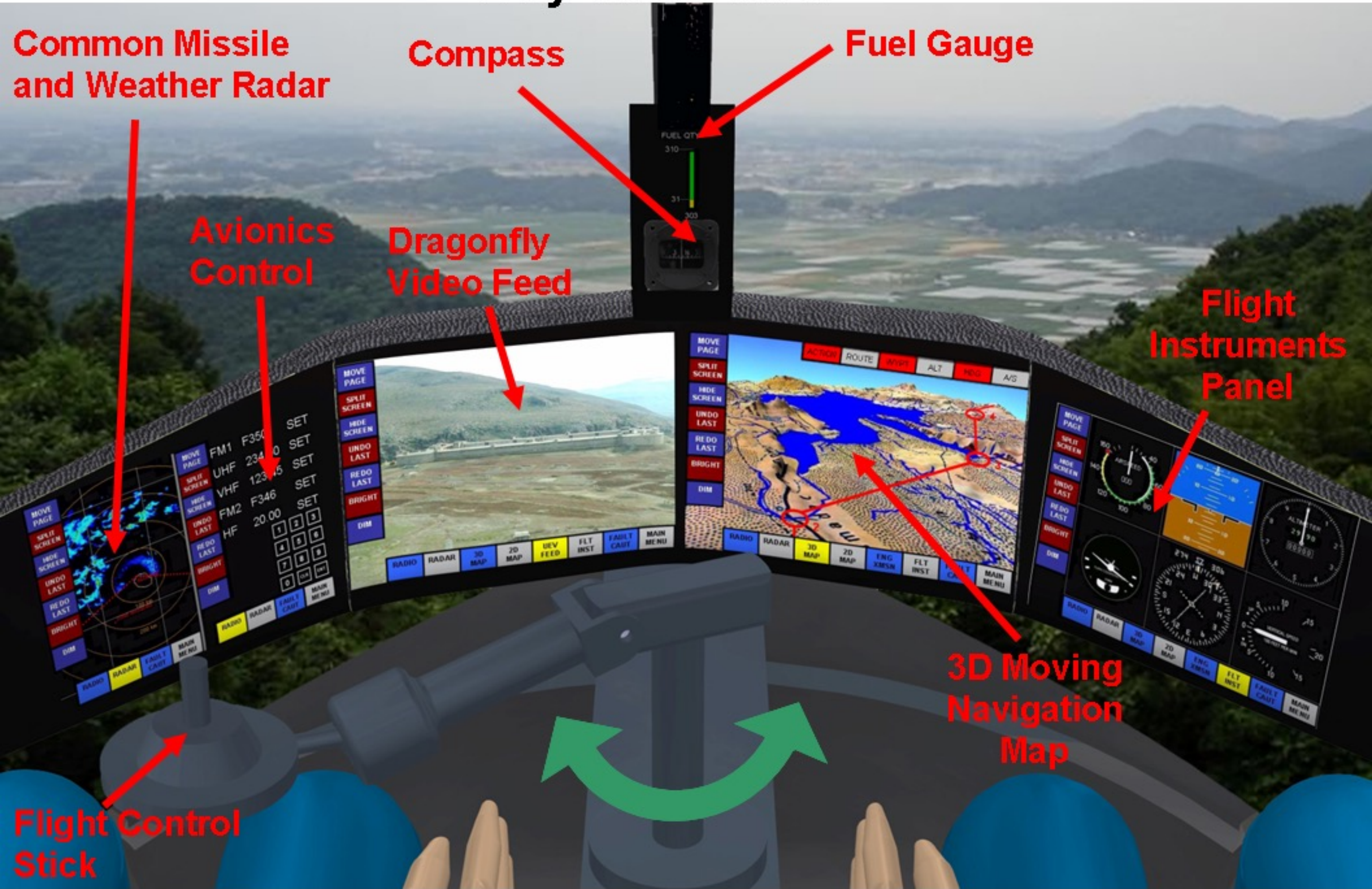


Tail Fold


Outboard Motors
Draw the Tail Forward
Along Track
Inboard Motors Rotate
Tail to the Ground
Small Motor Rotates
Tail About Axis

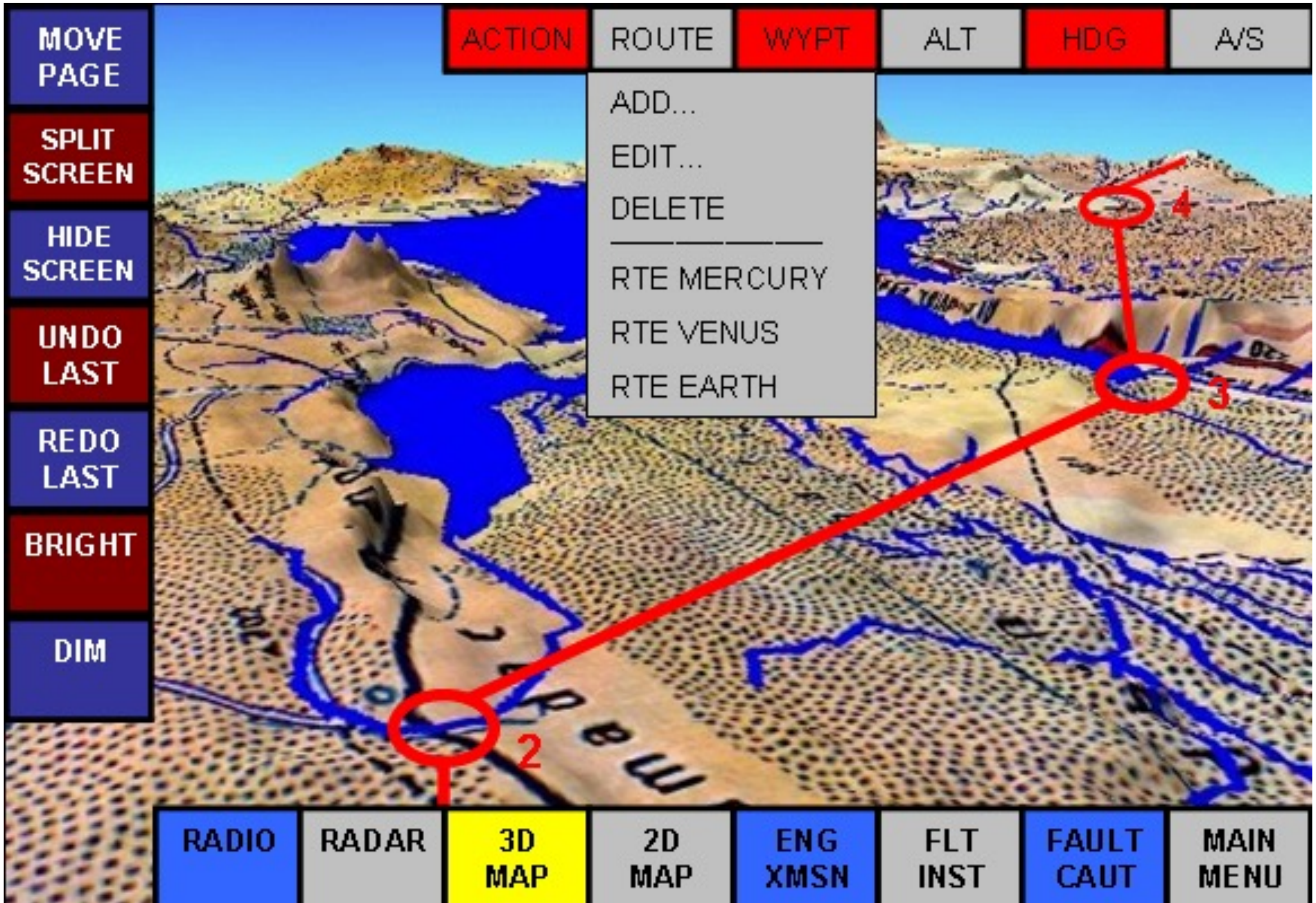

Fully Extended
Spin About Axis
Rotate down
Retracted
Slide Forward

Day Time View



Night Time View
(NVG Compatible)

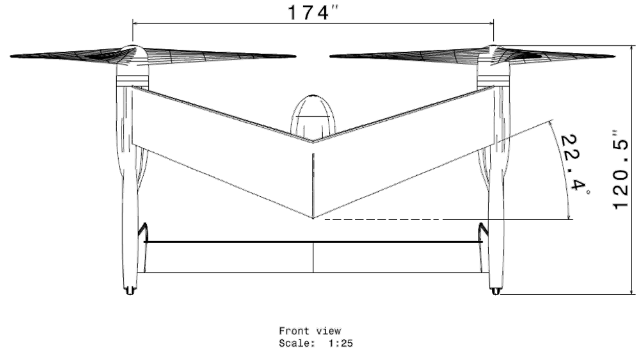
User Interface

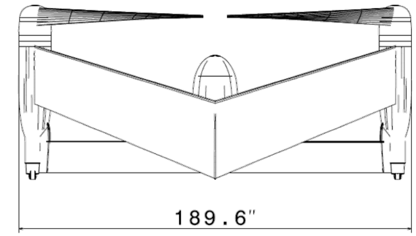


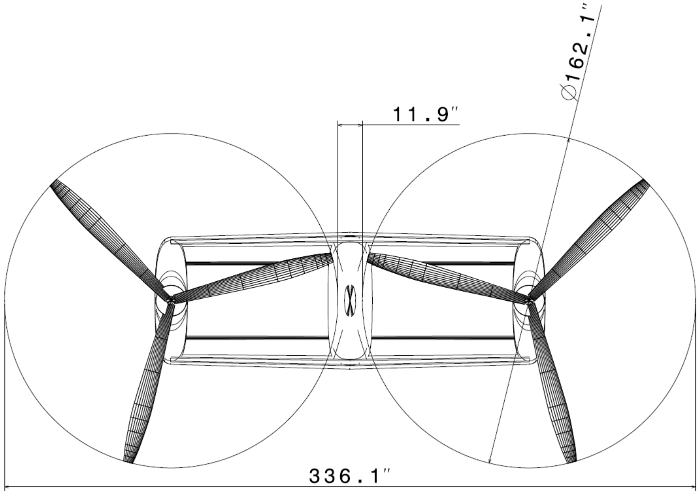
Dragonfly (UEV)

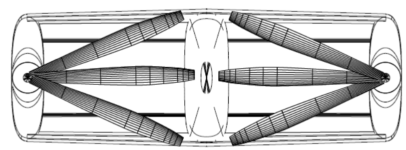
Gross Weight	2760 lbs
Rotor Radius	6.75 ft
Wing Area	80 sqft
Tail Area	26 sqft
Engine	2x205 HP Turbo-Diesel Engines
Cruise Speed	142 knots
Max Speed	146 knots
Endurance Speed	83 knots
Gross Weight	2760 lbs
Loiter Tip Speed	220 ft/sec

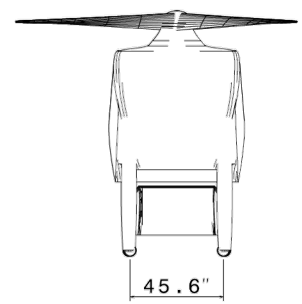
Dragonfly - UEV

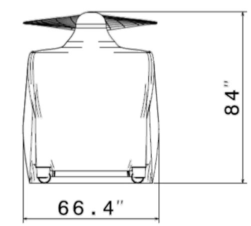


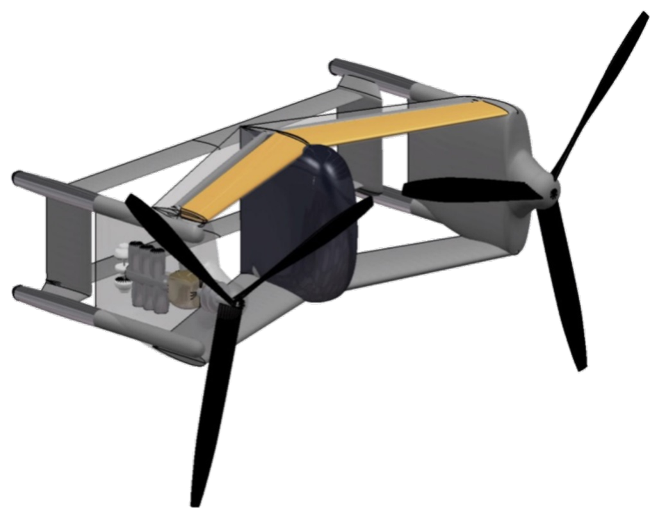










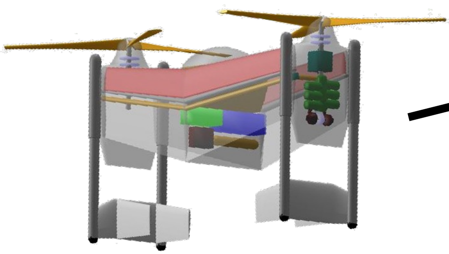


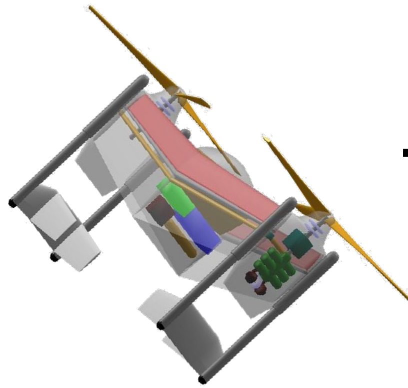
Dragonfly Transition

Hover

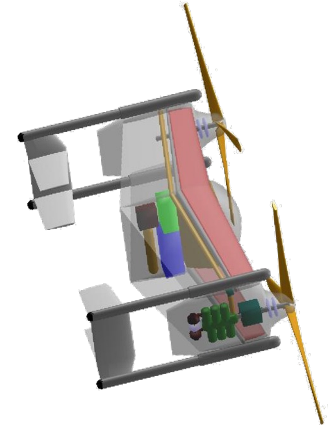
V_∞=0 kts

α_s= 0 deg

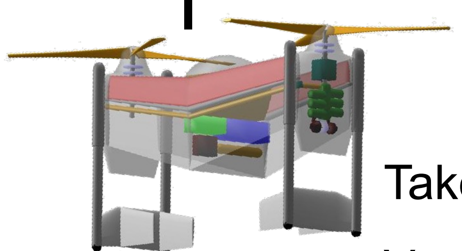




Transition
V_∞=0- V_{br} kts
α_s= 0-90 deg



Forward Flight
V_∞= V_{br}
α_s≈ 90 deg



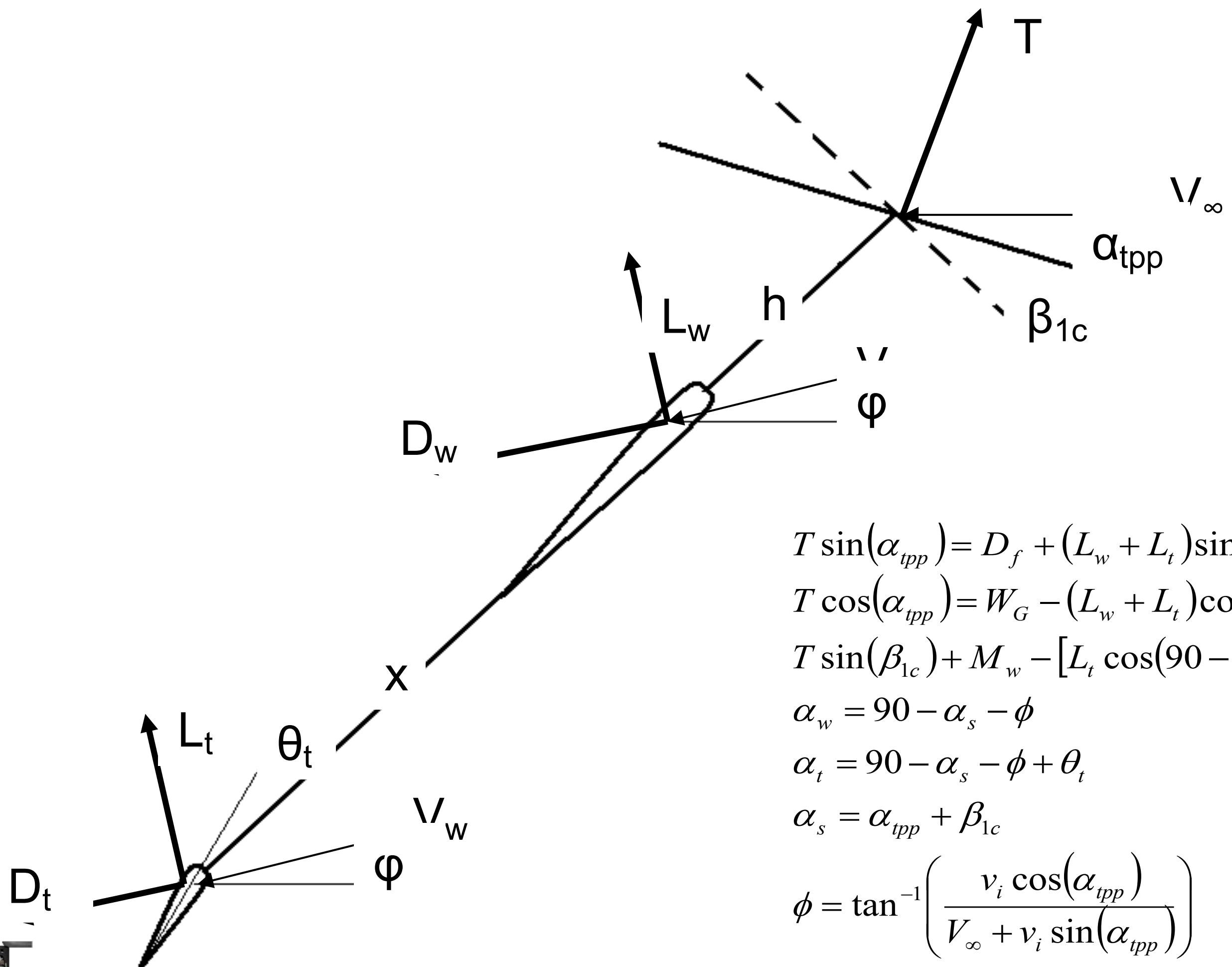
Take-off

V_∞=0 kts

α_s= 0 deg

- Tail articulates to balance forces and moments
- Longitudinal cyclic limited to seven degrees

Dragonfly Transition



$$T\sin(\alpha_{tpp}) = D_f + (L_w + L_t)\sin(\phi) + (D_w + D_t)\cos(\phi)$$

$$T\cos(\alpha_{tpp}) = W_G - (L_w + L_t)\cos(\phi) + (D_w + D_t)\sin(\phi)$$

$$T\sin(\beta_{1c}) + M_w - [L_t\cos(90 - \alpha_s - \phi) + D_t\sin(90 - \alpha_s - \phi)]x$$

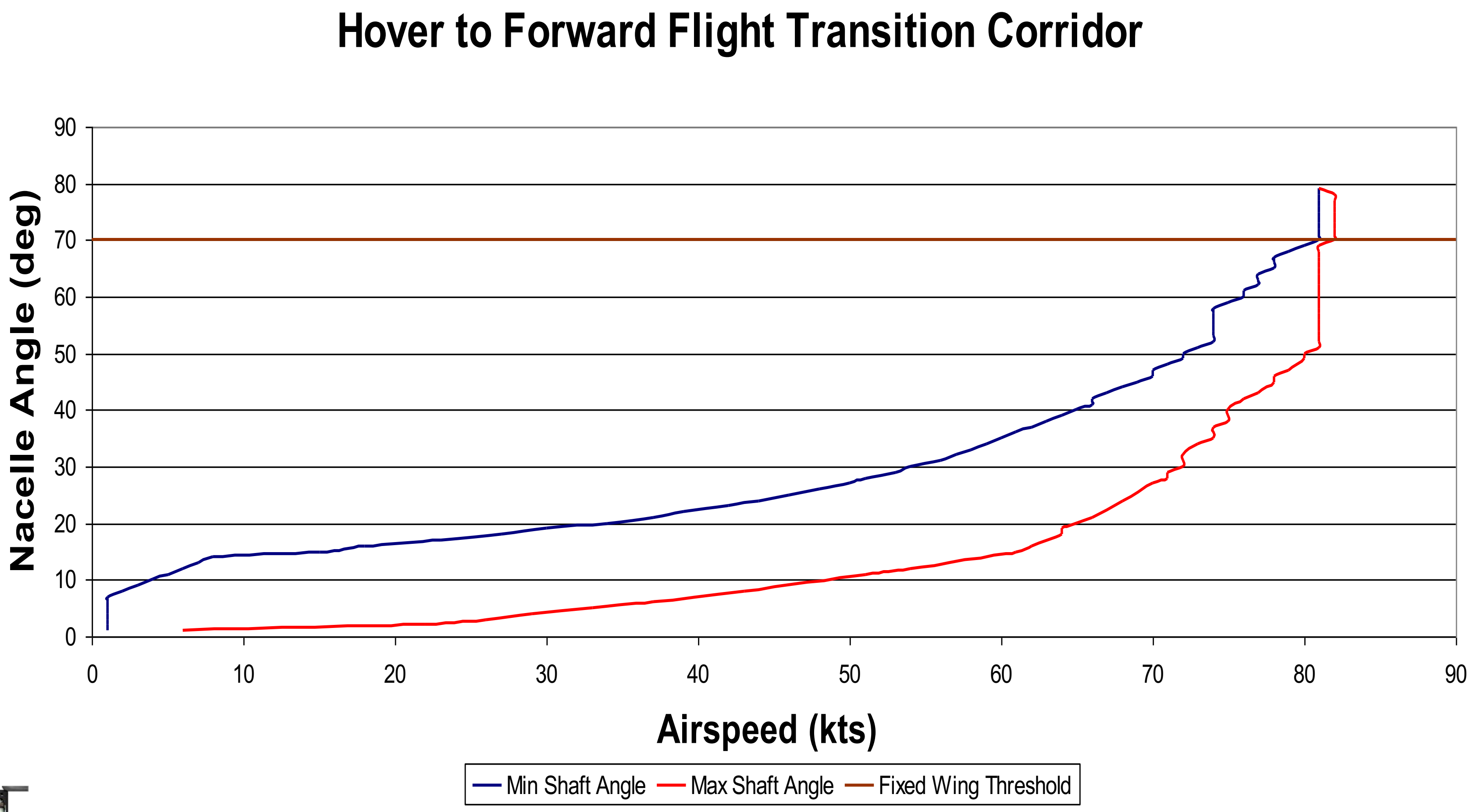
$$\alpha_w = 90 - \alpha_s - \phi$$

$$\alpha_t = 90 - \alpha_s - \phi + \theta_t$$

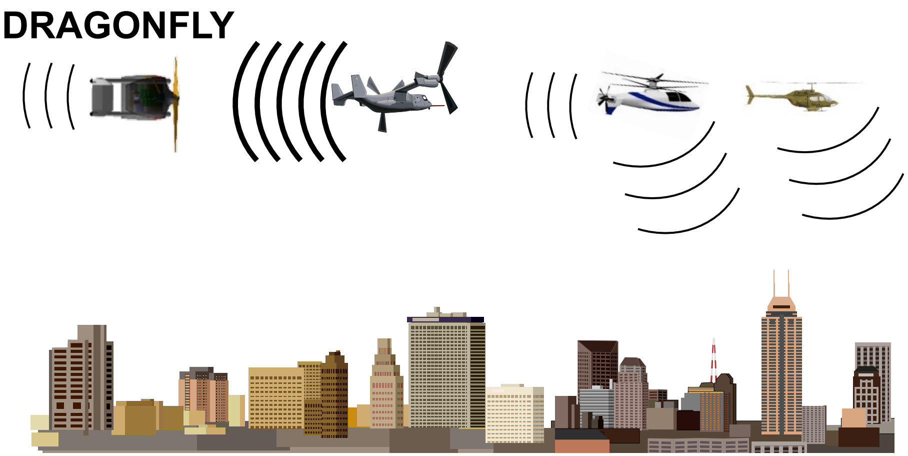
$$\alpha_s = \alpha_{tpp} + \beta_{1c}$$

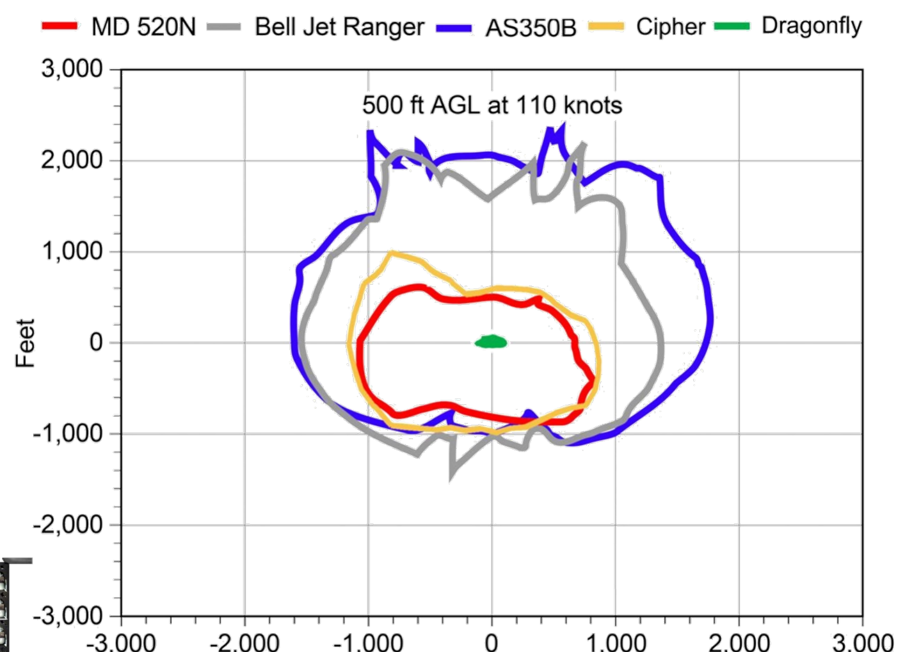
$$\phi = \tan^{-1}\left(\frac{v_i\cos(\alpha_{tpp})}{V_\infty + v_i\sin(\alpha_{tpp})}\right)$$

Dragonfly Transition Corridor



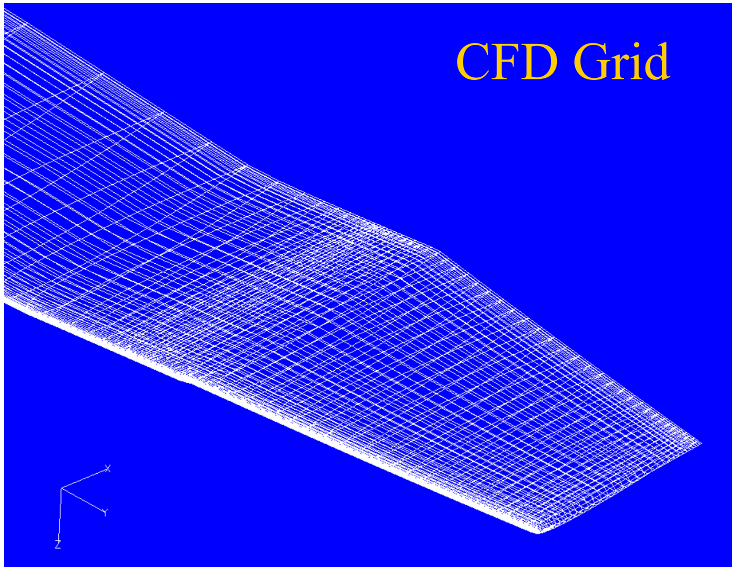
Acoustic Signature



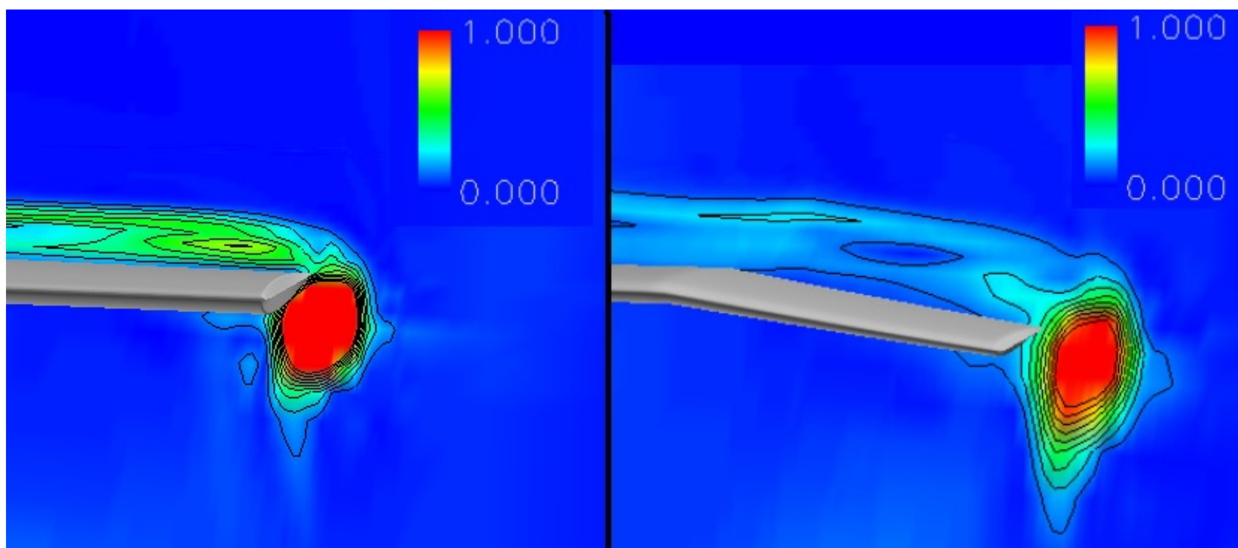


- **Reducing acoustic signature for the UEV is most important during the loiter over the objective.**
- **Dragonfly cruises in airplane mode during loiter, so noise is directed primarily outward instead of downward towards the objective.**
- **Rotor tip speed is reduced to 220 ft/sec during loiter.**
- **Low gross weight and low drag allow for 89 kt loiter speed (only 138 HP required) for 6 hours.**
- **Box wing configuration allows for increased wing area and aero-propulsive efficiency with minimal submarine storage footprint.**

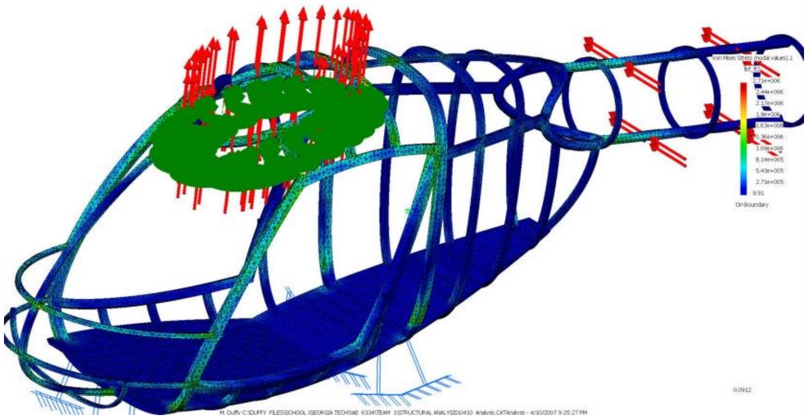
Acoustic Analysis

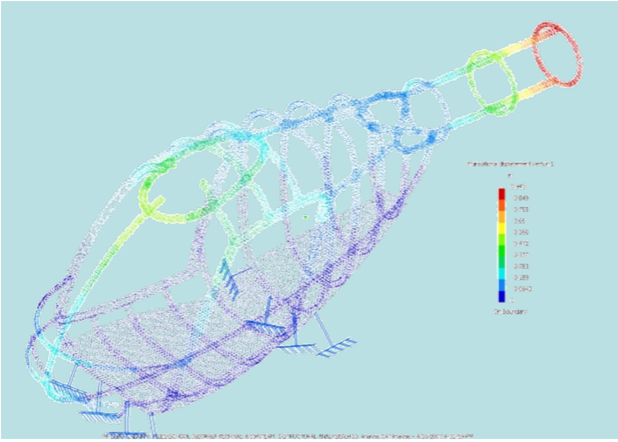


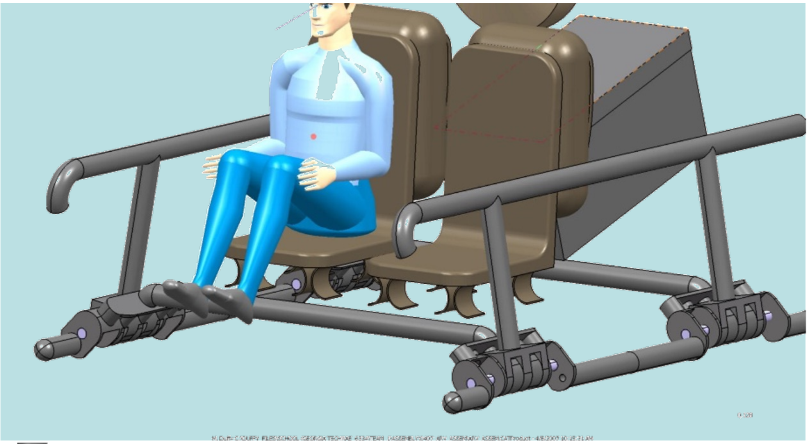
Vorticity Contours

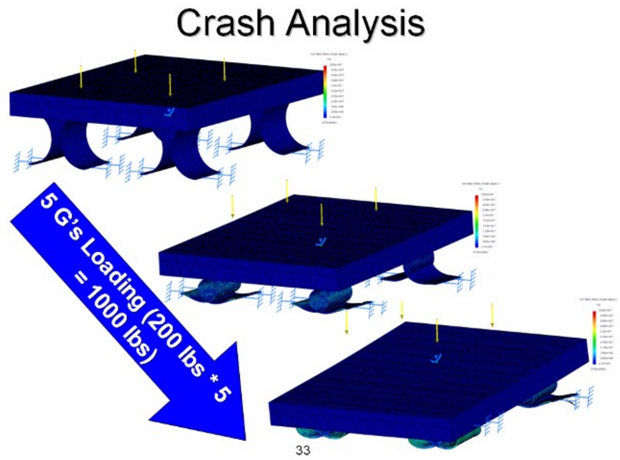


Structural Analysis

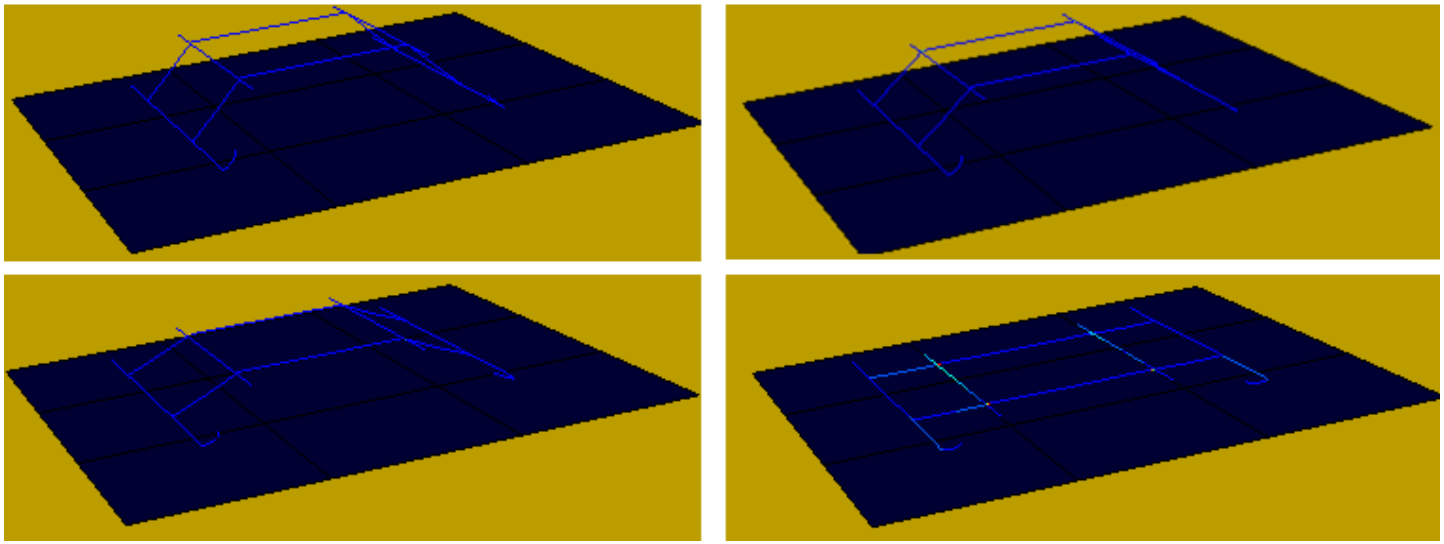






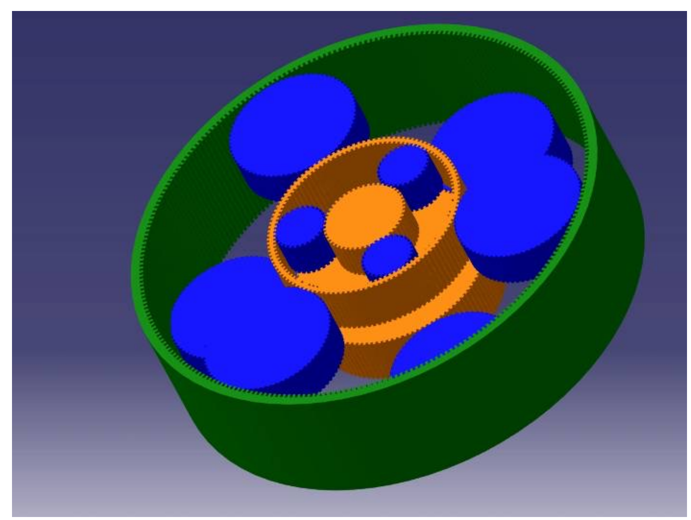


Structural Analysis

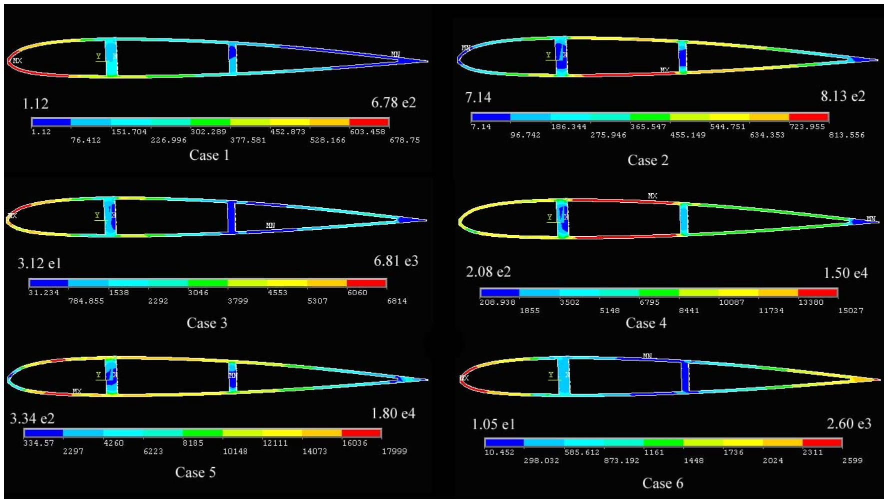


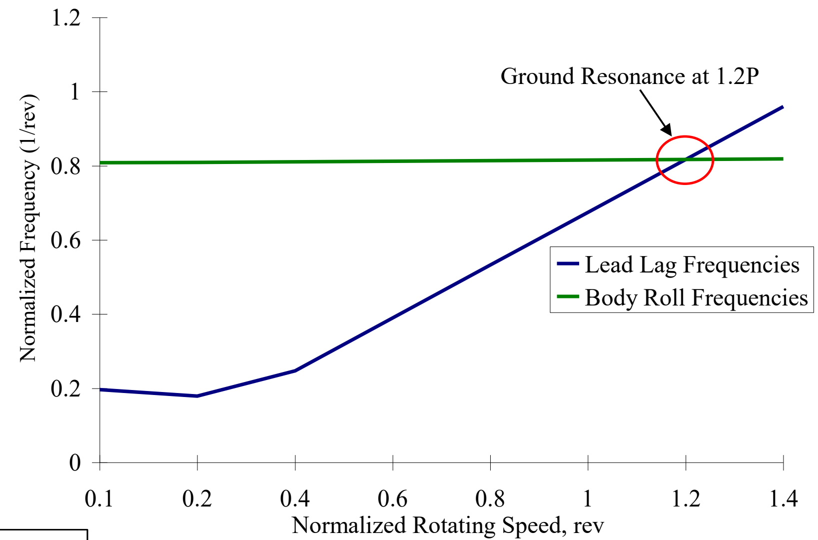
ABAQUS model of morphing landing gear

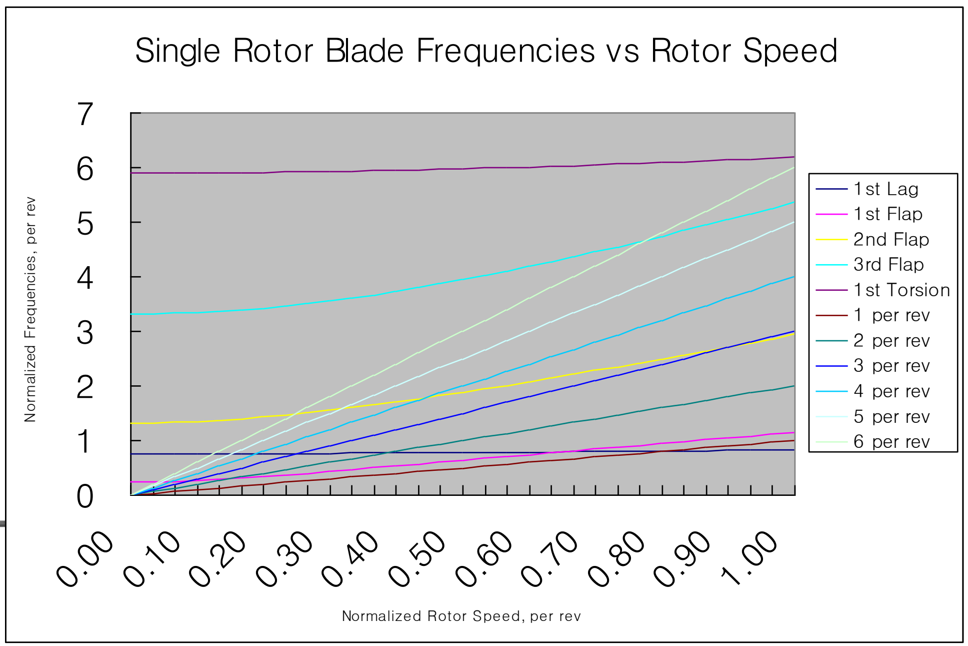
Transmission Design

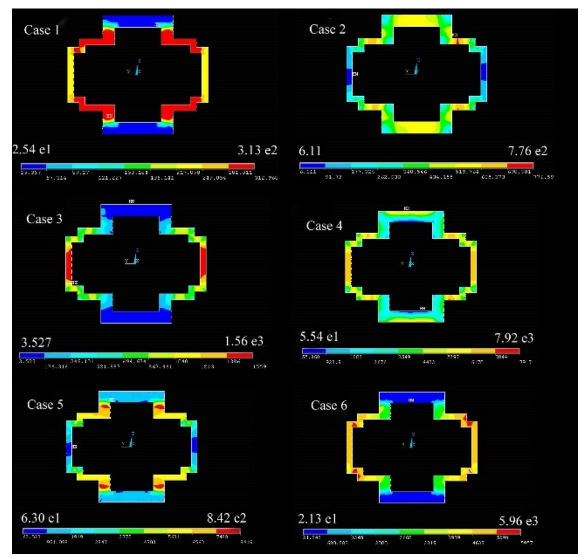


Rotor Dynamics Analysis

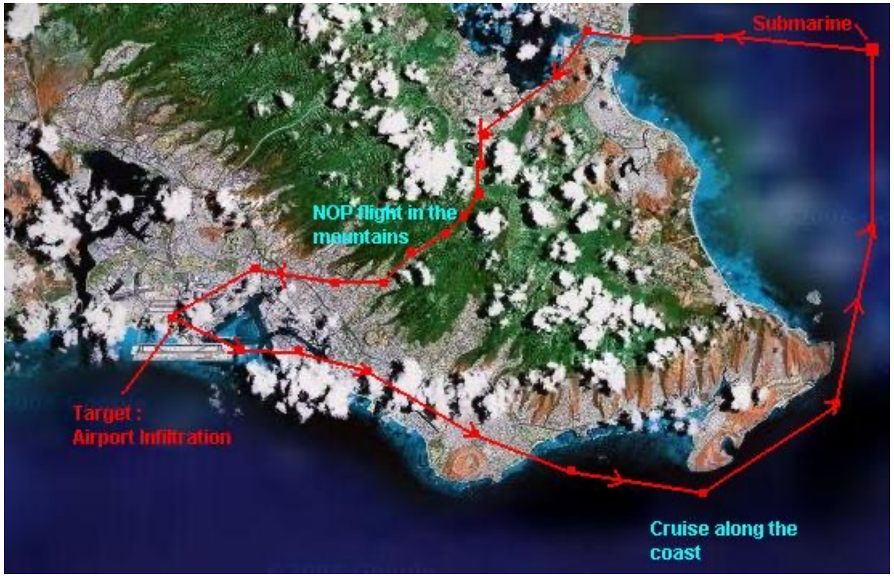


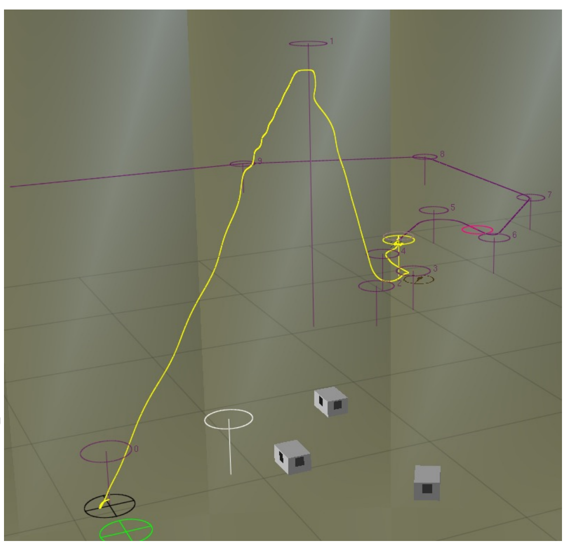


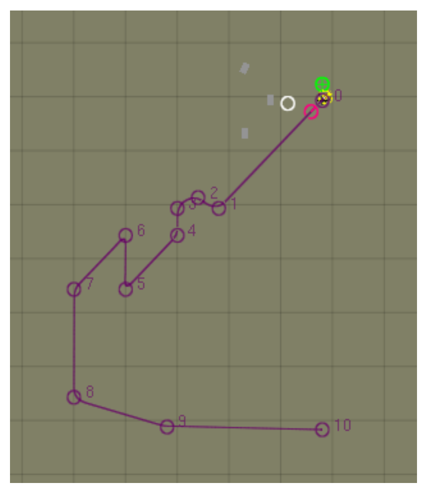


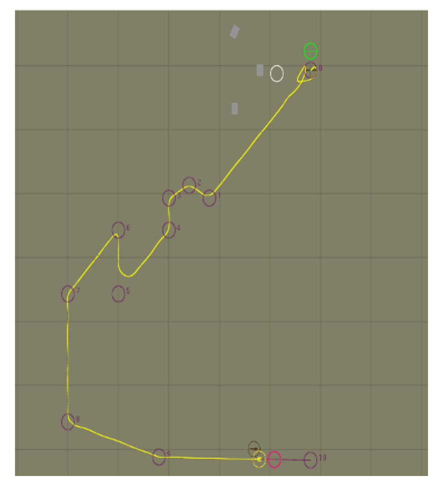


Control Analysis

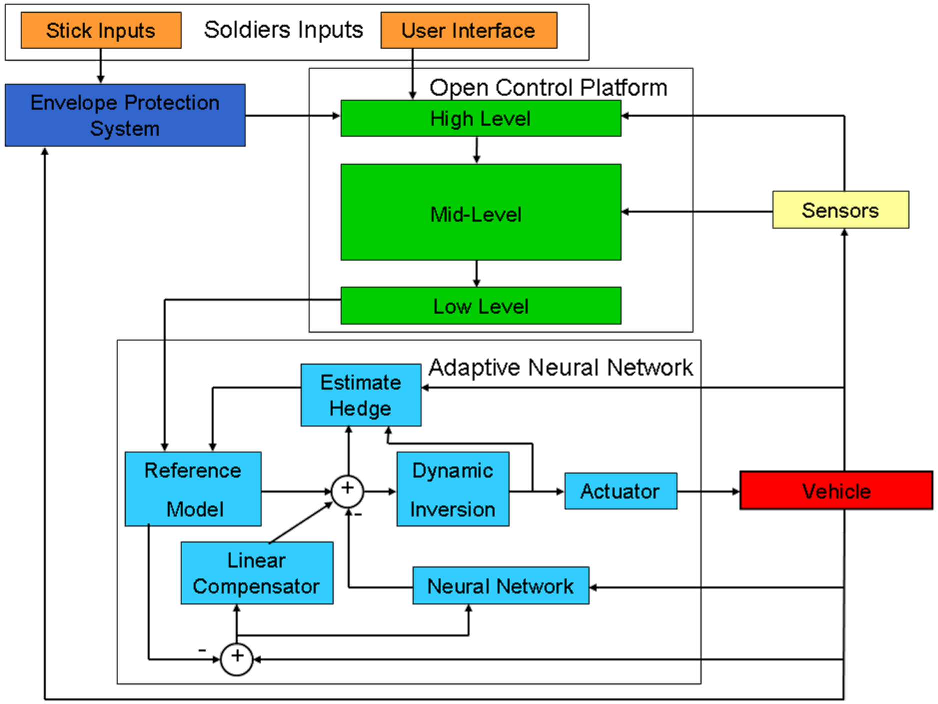








Autonomous Control System



- Soldiers inputs are entered via cockpit touch screens and flight stick
- The open control platform interprets soldiers inputs and creates a flight plan.
- The adaptive neural network adjusts control sensitivity to keep the aircraft on the flight plan
- The envelope protection system adjusts the soldiers' flight stick inputs in order to maintain aircraft safety

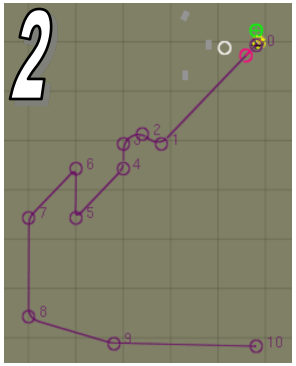
Level	Descriptor	Observe	Orient	Decide	Act
6	Real-Time Vehicle Coordination	On-board sensing supplemented by off-board data	Tactical Assigned Goals	Coordinated Trajectory Planning and Execution	Goal Accomplishment with minimal supervision

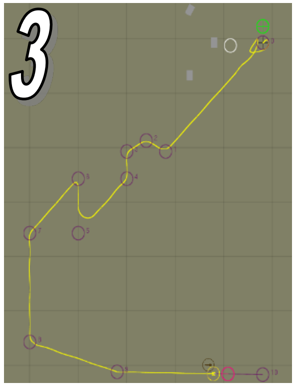
Aircraft Autonomy Level

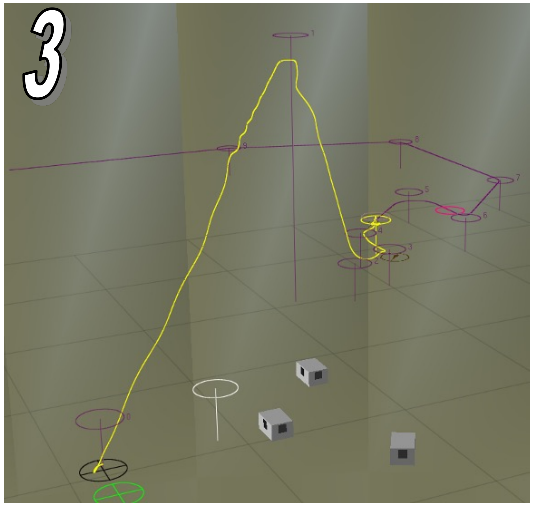
GUST Modeling

- **The Cipher autonomous control system was modeled in the GUST autonomous control simulator to test the maneuverability and stability**
  1. **A sample mission was planned based on actual geography**
  2. **The flight plan was brought into the GUST simulator**
  3. **The Cipher autonomous control system then went through the flight plan automatically**

- **The results from the GUST modeling show that the autonomous control system can accurately follow a given trajectory**







Overall Mission Layout

- 5 Barracuda capsules launch from submarine and reach surface 23 minutes after mission start
- The first serial consisting of 4 Ciphers and 1 Dragonfly takeoff for the objective 32 minutes after mission start
- Subsequent Serials (2-6) takeoff every 10 minutes
- Each Cipher takes 67 minutes to reach the objective 140 nm away
- After soldiers are deployed at objective, each Cipher returns to Capsule to refuel and transport additional soldiers to the objective
- The Dragonfly stays on the objective for entire 6 hour mission
- Each Serial makes two trips to the objective and back during 6 hour mission