Morpheus AUV — Design of a highly maneuverable micro-AUV with on-the-fly stability-agility altering capability

- towards A-sized decoy swarming -

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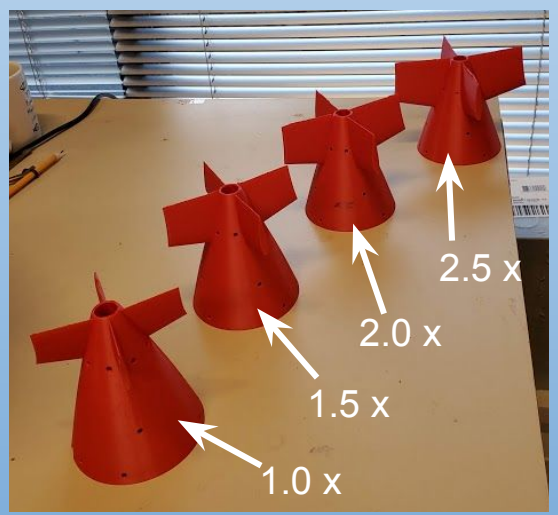
Can we improve maneuverability by increasing rudder size?

Question: Which tail section would provide a better turning rate?

(A) Size = 2.5x

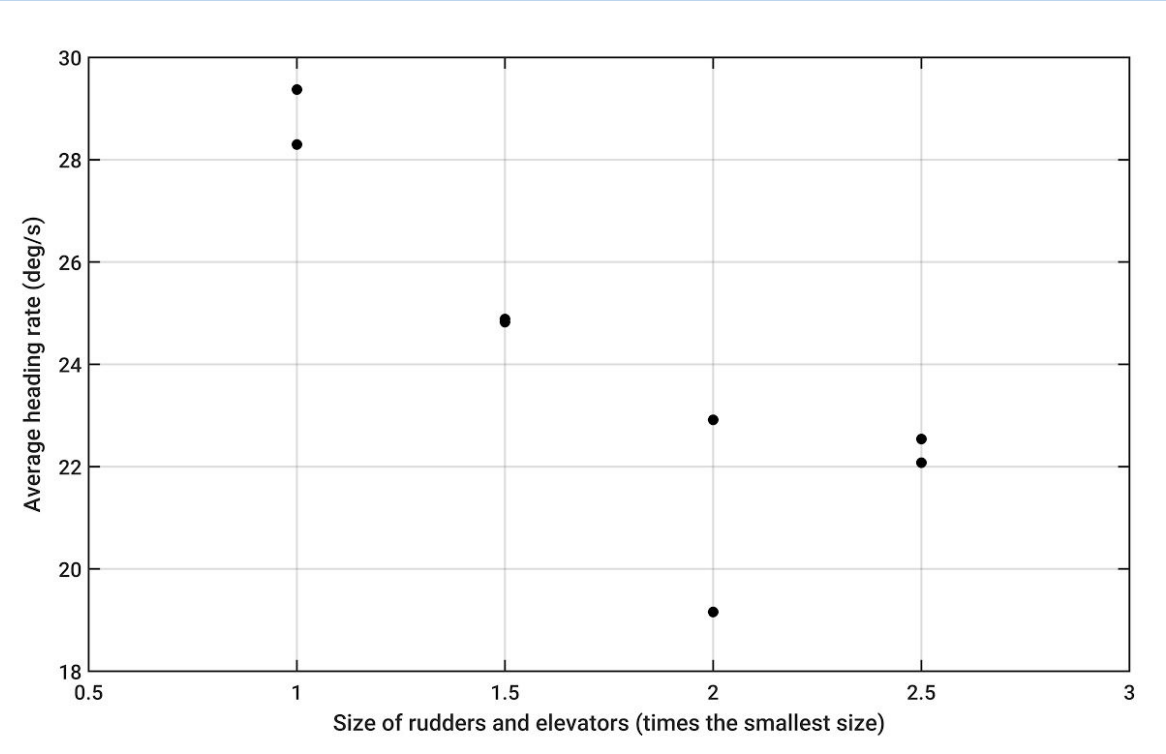
(B) Size = 1x

Rudder size vs. turning rate



Rudder size vs. turning rate

Counterintuitively, larger stern control surfaces result in a lower turning rate



Smaller vs. larger stern control surfaces

Higher maneuverability & lower stability

Pros:

- Lower vehicle stability; hence:
  - Enhanced maneuverability
  - Higher turning rate

Cons:

- Lower vehicle stability; hence:
  - Poor course keeping capability at higher speeds
  - difficulty to regain stability after a turn

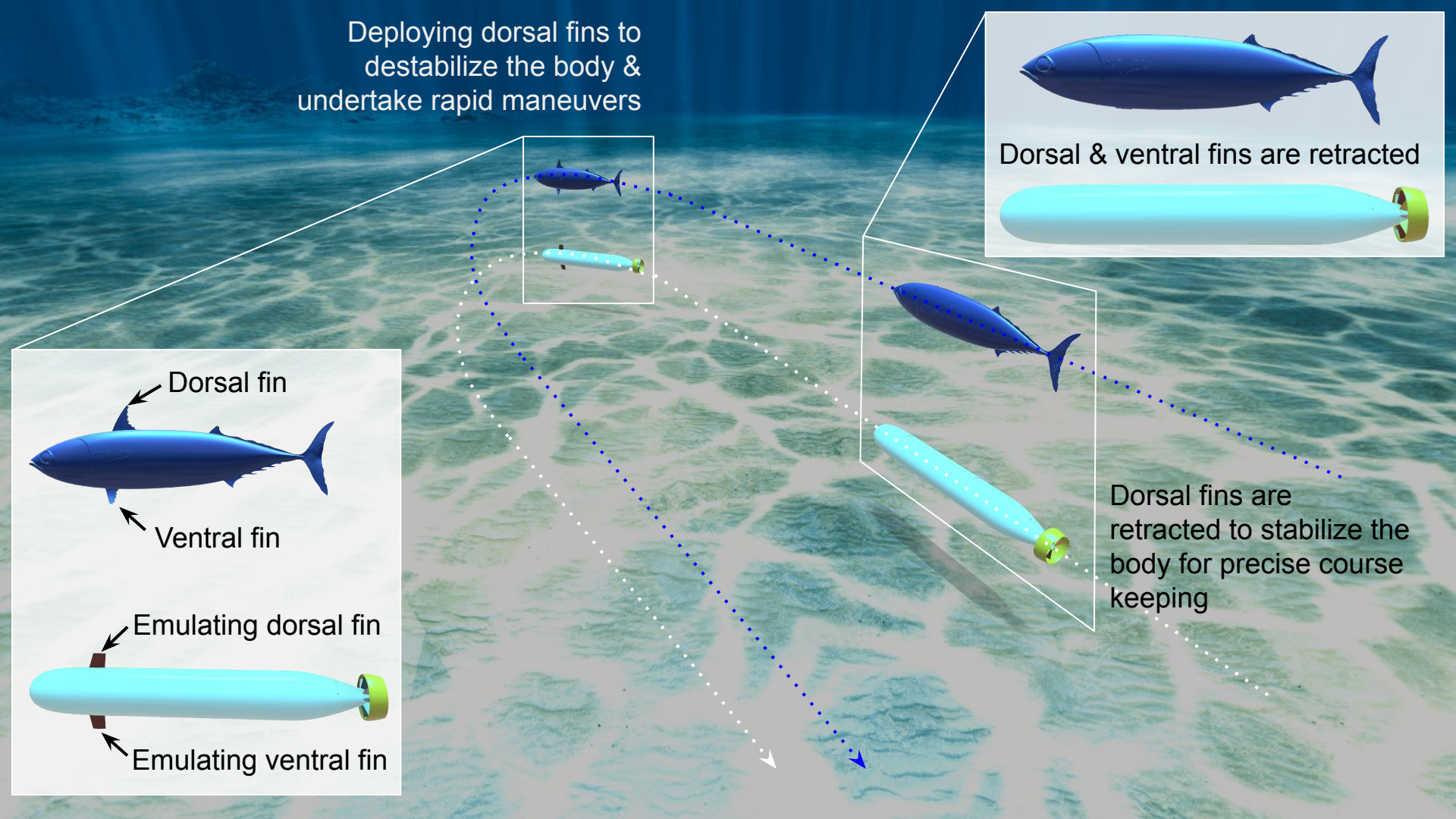
Lower maneuverability & higher stability

Pros:

- Higher vehicle stability; hence:
  - Easier to maintain course at higher speeds
  - Better survey data quality during straight-line runs
  - Ability to regain stability after a turn

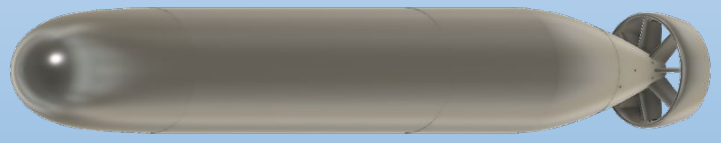
Cons:

- Higher vehicle stability; hence:
  - Lower maneuverability
  - Lower turning rate

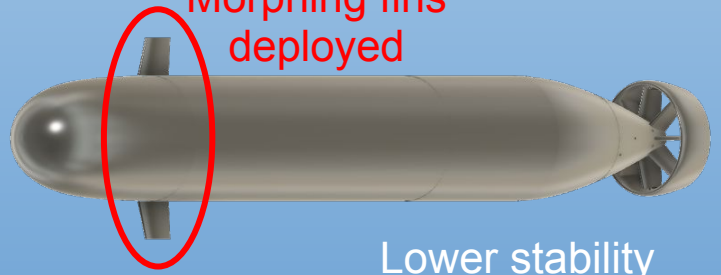

Deploying dorsal fins to destabilize the body & undertake rapid maneuvers
Dorsal & ventral fins are retracted
Dorsal fin
Ventral fin
Emulating dorsal fin
Emulating ventral fin
Dorsal fins are retracted to stabilize the body for precise course keeping

Questions that needs answers!

1. What is the optimal location for morphing fins?
2. What is the optimal size for morphing fins?
3. What is the optimal size & design for rudders/elevators?
4. What if we need to extend the vehicle length?
5. Should morphing fins articulate?



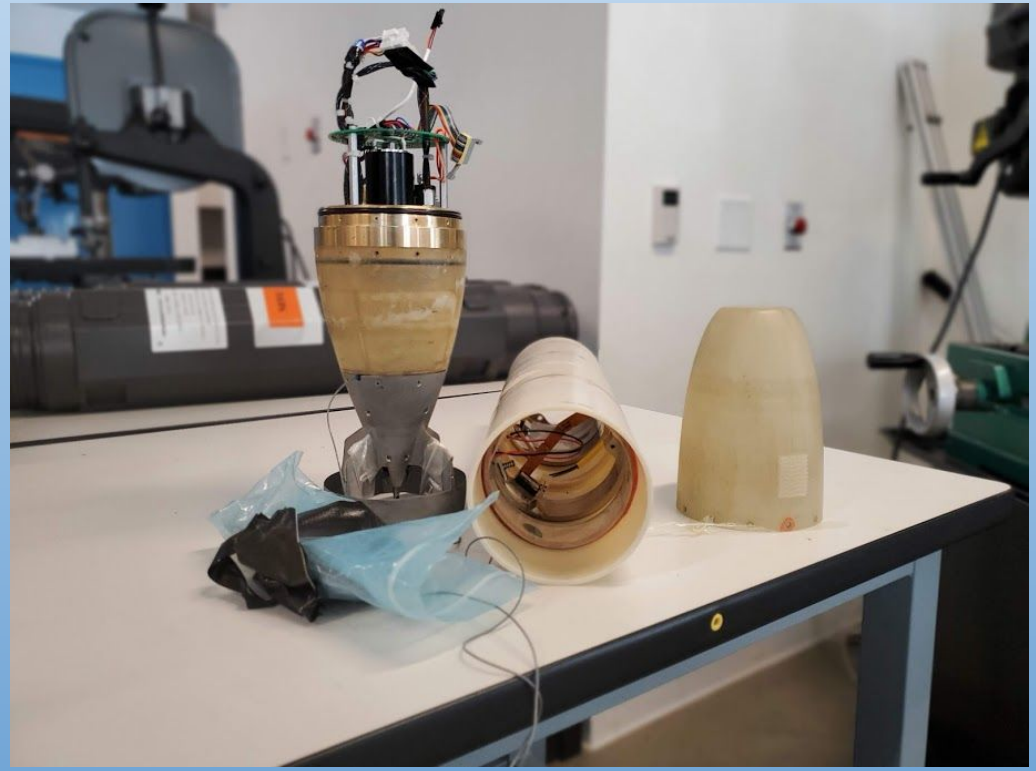
Higher stability



Lower stability

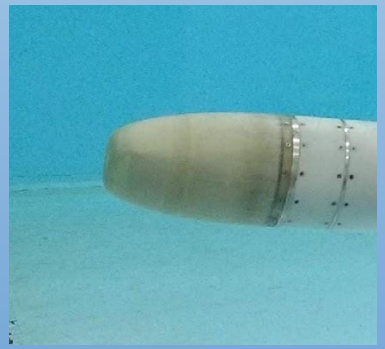
Project Morpheus - Improving Lockheed Martin's EMATT platform

MIT received three declassified EMATT shells with motor, propeller and solenoid-based rudder/elevator in Jan 2020

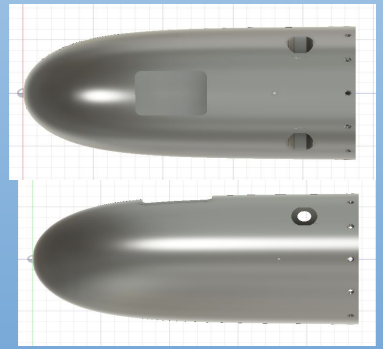


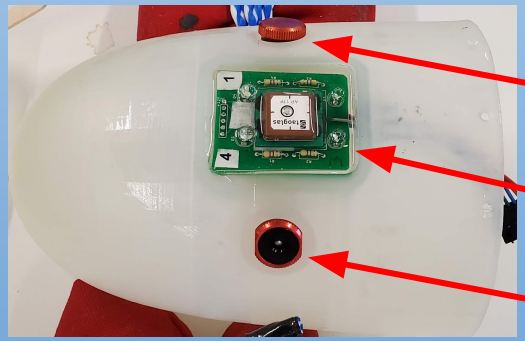
Nose-cone design

- A hydrodynamically optimized nose-cone profile was designed
- GPS & GSM antennas required for navigation and surface communication were embedded to the nose-cone, potted with epoxy
- Embedded the depth sensor (which is more capable for shallow-water ops) and vacuum vent port (ensures the water-tightness of the hull) into the nose-cone
- Manufactured the prototype nose-cone



Original EMATT nose-cone

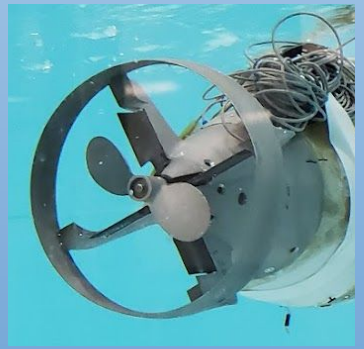




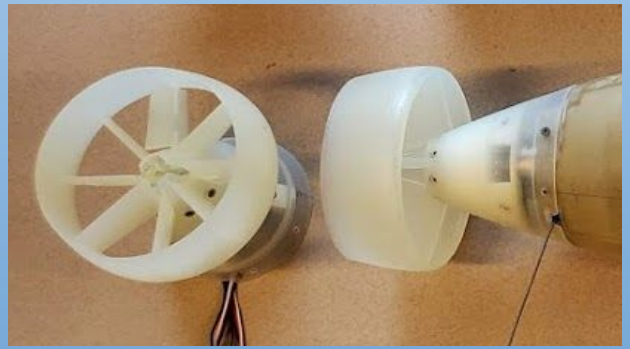
Hydrodynamically optimized Morpheus nose-cone

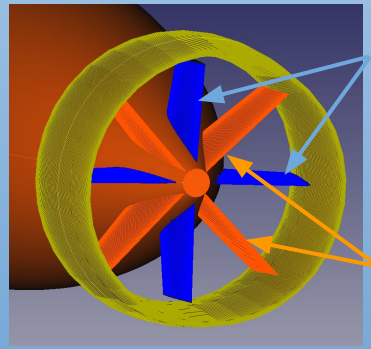
Tail-cone design

- A hydrodynamically optimized tail-cone profile was obtained by conducting theoretical analysis, maneuvering simulations and towing tank experiments
- The new tail-cone includes individually controlled, servo-based split rudders and elevons
- Included a shroud to protect the propeller and the towed hydrophone cable
- This design provide marginally stable vehicle without morphing fins



Original EMATT tail-cone

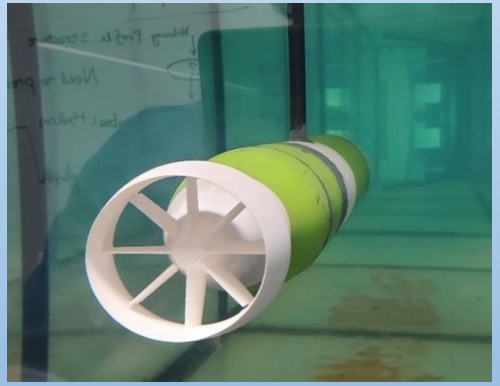


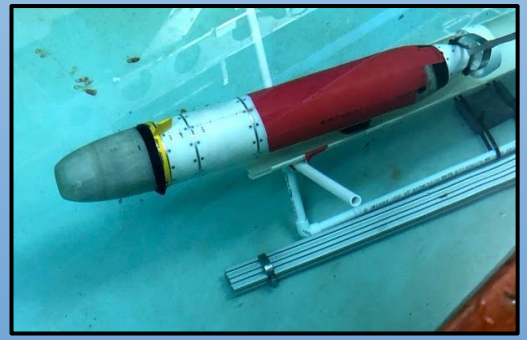


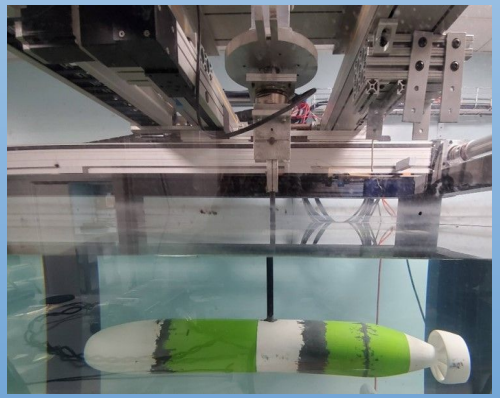
Hydrodynamically optimized Morpheus tail-cone

Forward morphing fin design

- Analytical towing tank experiments, free swimming experiments were used to determine the optimal location and size of dorsal fins
- The dorsal fin mechanism was then designed and manufactured:
  - Driven by two servos
  - housed in a free-flood compartment
  - Able to deploy, retract and change the angle of attack up to ~20 degrees



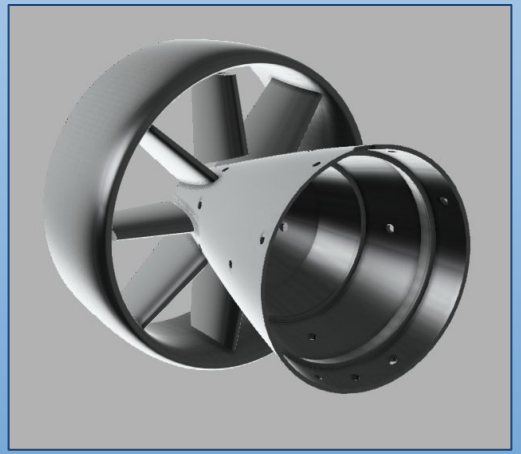




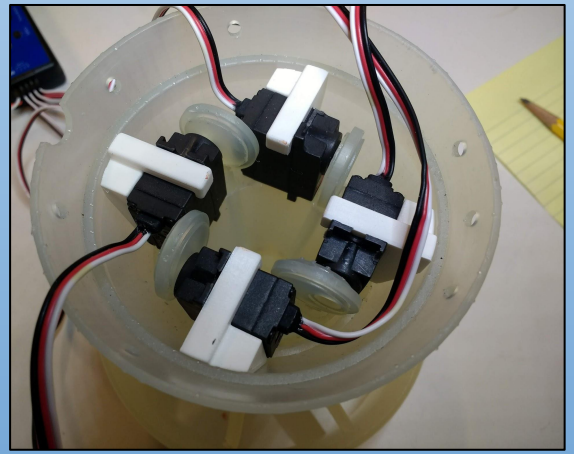
Servo-based tail-cone

Redesign the tail-cone actuation mechanism to provide multi-axis controllability for heading, pitch and roll control.

- Four waterproofed micro-servo motors are packed into the tail assembly along with linkages to drive the four control surfaces, independently (i.e. port & starboard elevons and upper and lower rudders)
- Actuator linkage mechanism was designed and manufactured by Lockheed Martin engineers



CAD design of the tail-cone

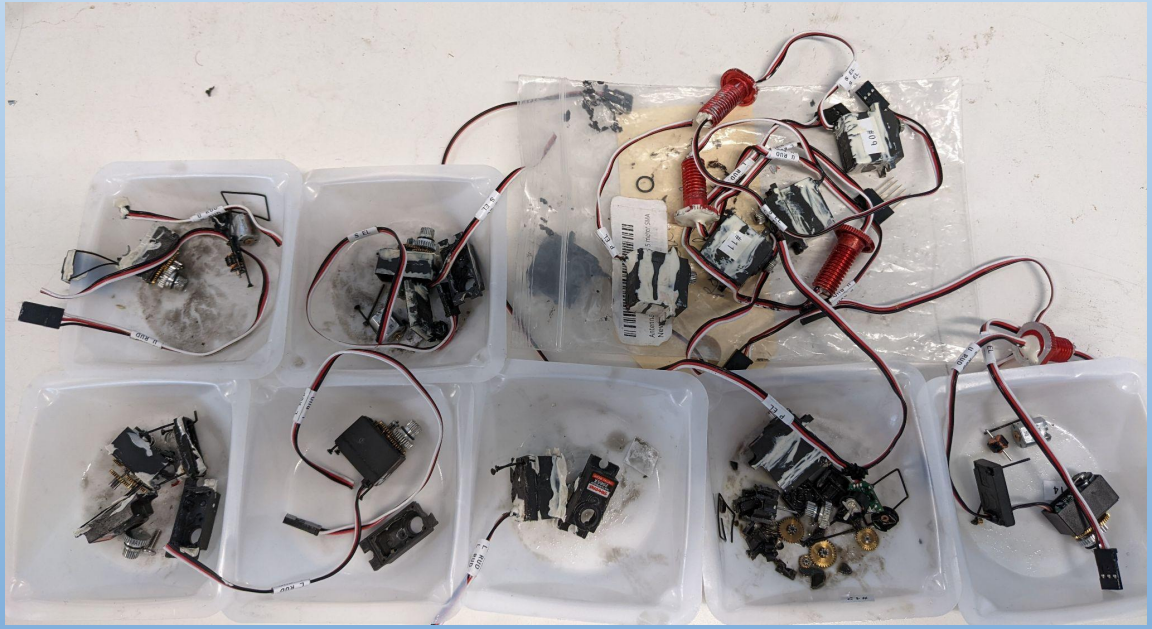


Four waterproofed servos

Tail-cones of original EMATT and Morpheus

Multiple design iterations

Improvised fin extensions



Innumerable attempts at servo compensation

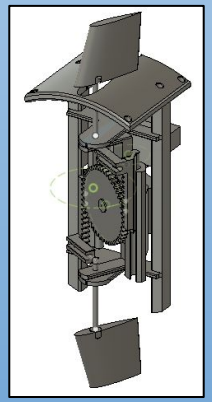
Prototype of tail-cone design

- Four servos are packed into the tail assembly along with linkages to the rudders and elevons
- Able to individually control the split rudders and elevons

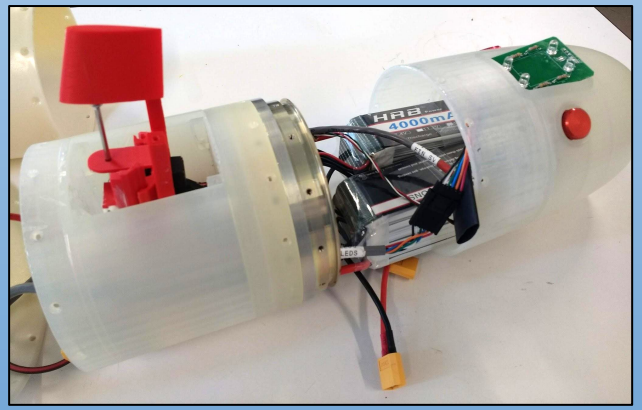
Servo-based morphing fin design

Physical design of morphing dorsal fin actuation mechanism for the Morpheus AUV

- Dorsal fin actuation mechanism was designed using two water proofed micro-servos, housed in a free-flood compartment of the vehicle
- The mechanism is able to deploy & retract the fins in a sufficiently short time period
- Able to change the angle of attack up to ~20 degrees

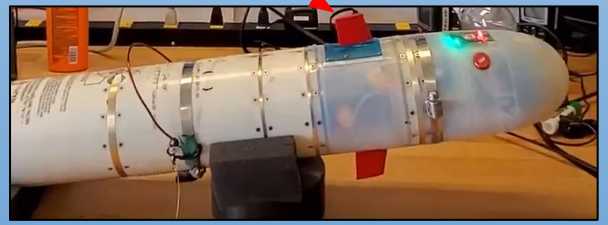


CAD design of morphing fin mechanism



Manufactured dorsal fin mechanism

Deployed and articulated dorsal fins during a hardware-in-the-loop simulation



Assembled vehicle during bench testing

Prototype of dorsal fin design

Electronics design

Developed new electronics to drive the hardware, and to add additional capabilities:

1. BeagleBone Blue single board computer
2. IMU for vehicle roll, pitch and heading
3. Wifi for wireless connectivity
4. GPS and GSM module for surface position and comms
5. Blue robotics depth sensor for depth
6. Motor driving electronics
7. External on/off key
8. Motor current and battery voltage monitors

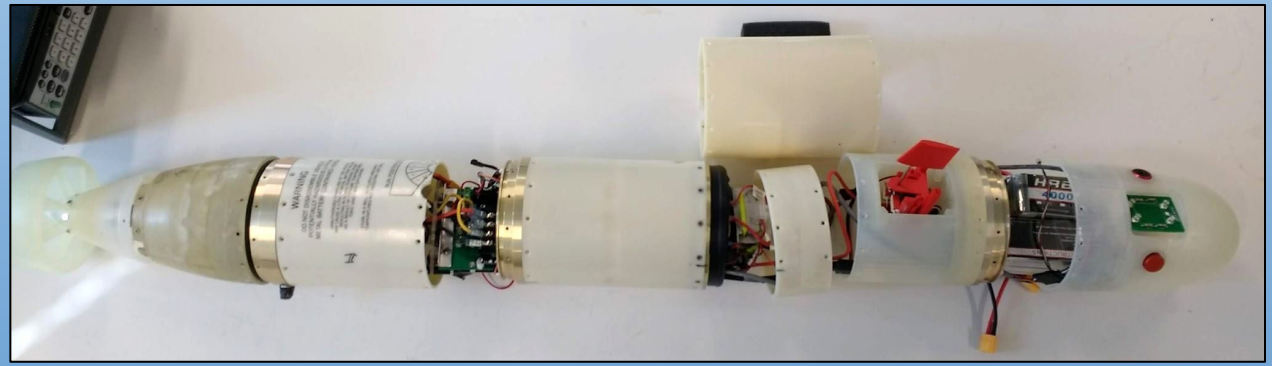
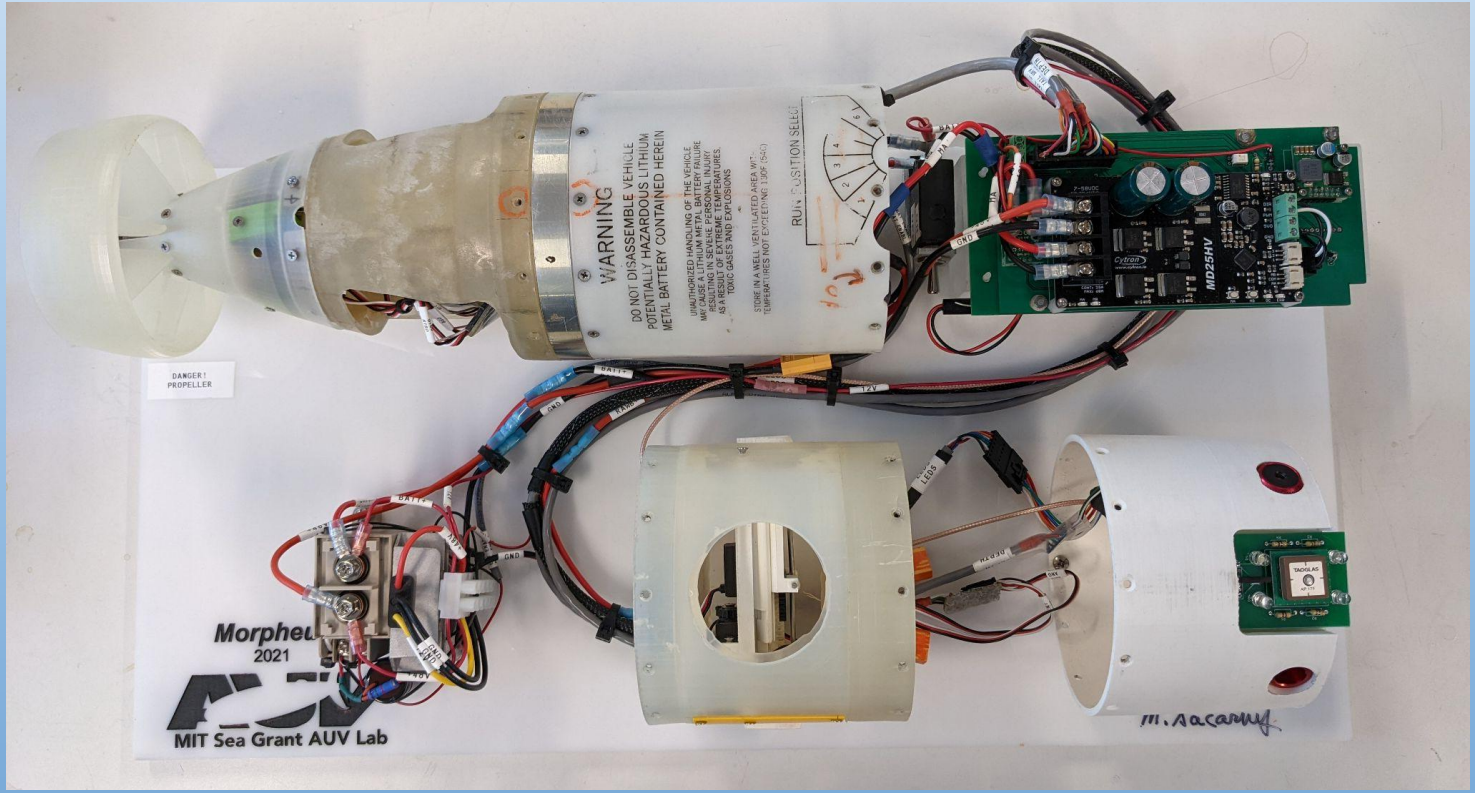
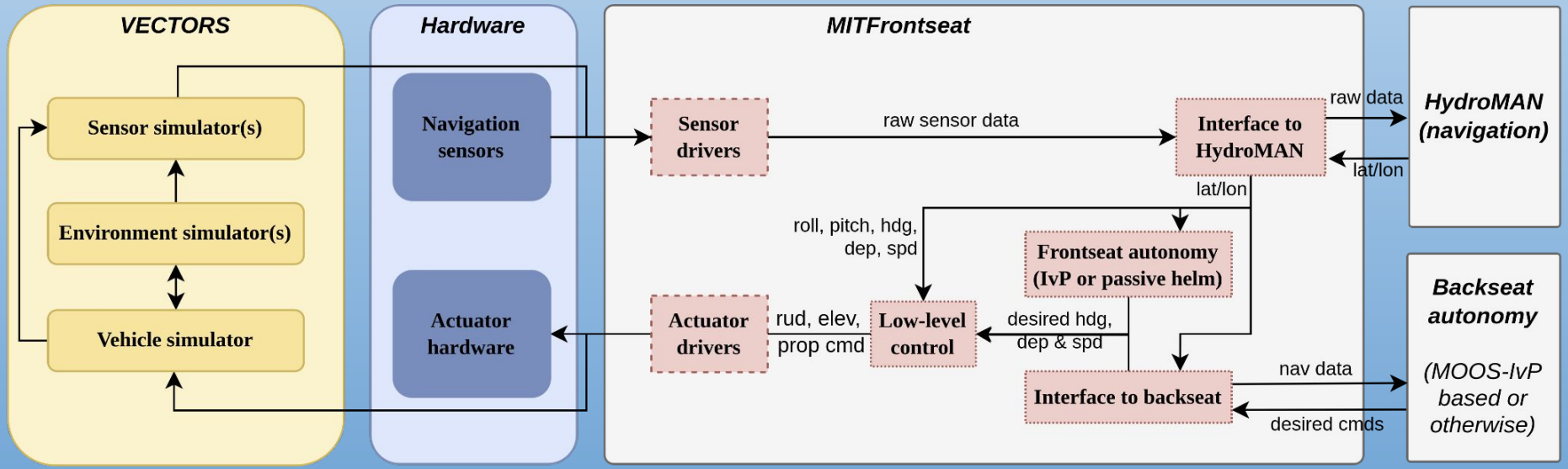


Table-top demonstration model

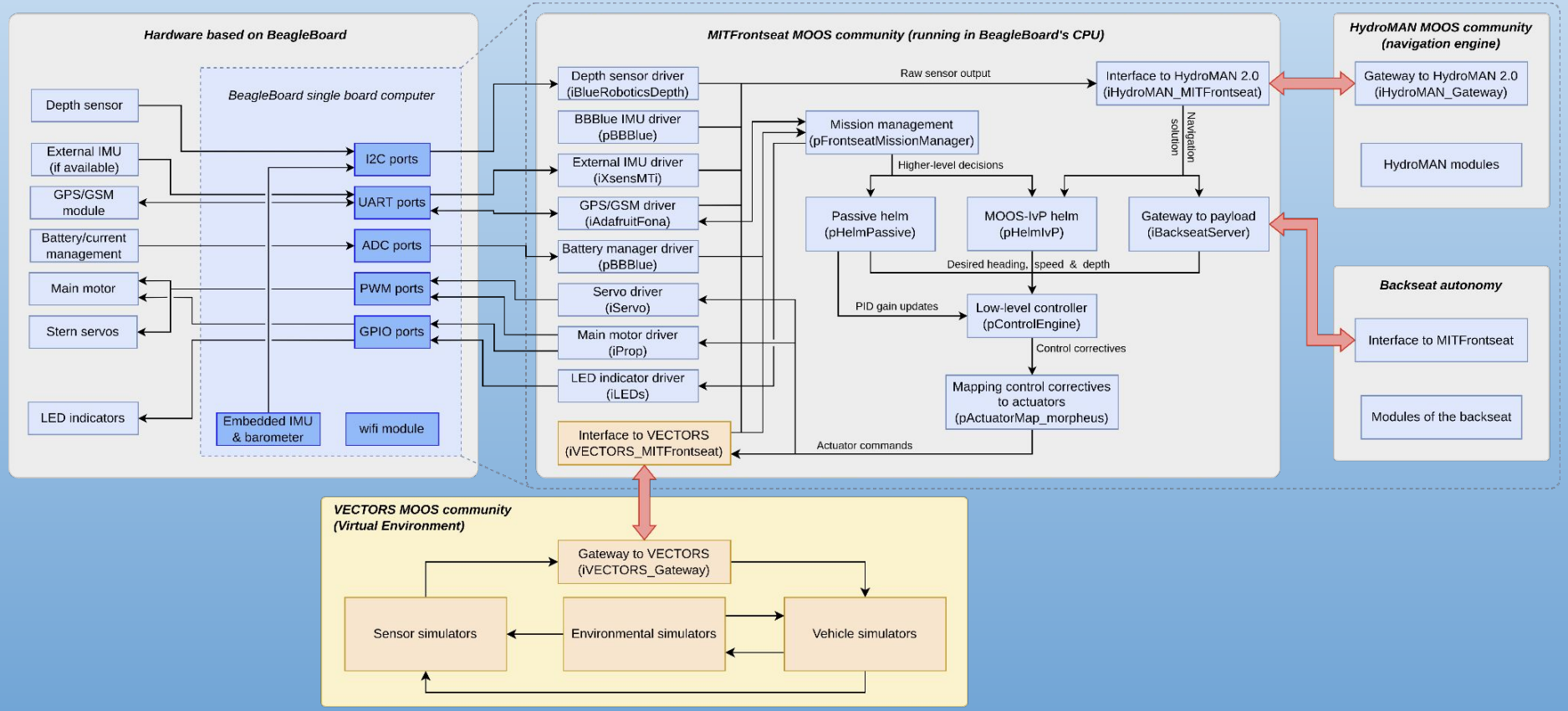


Morpheus software design

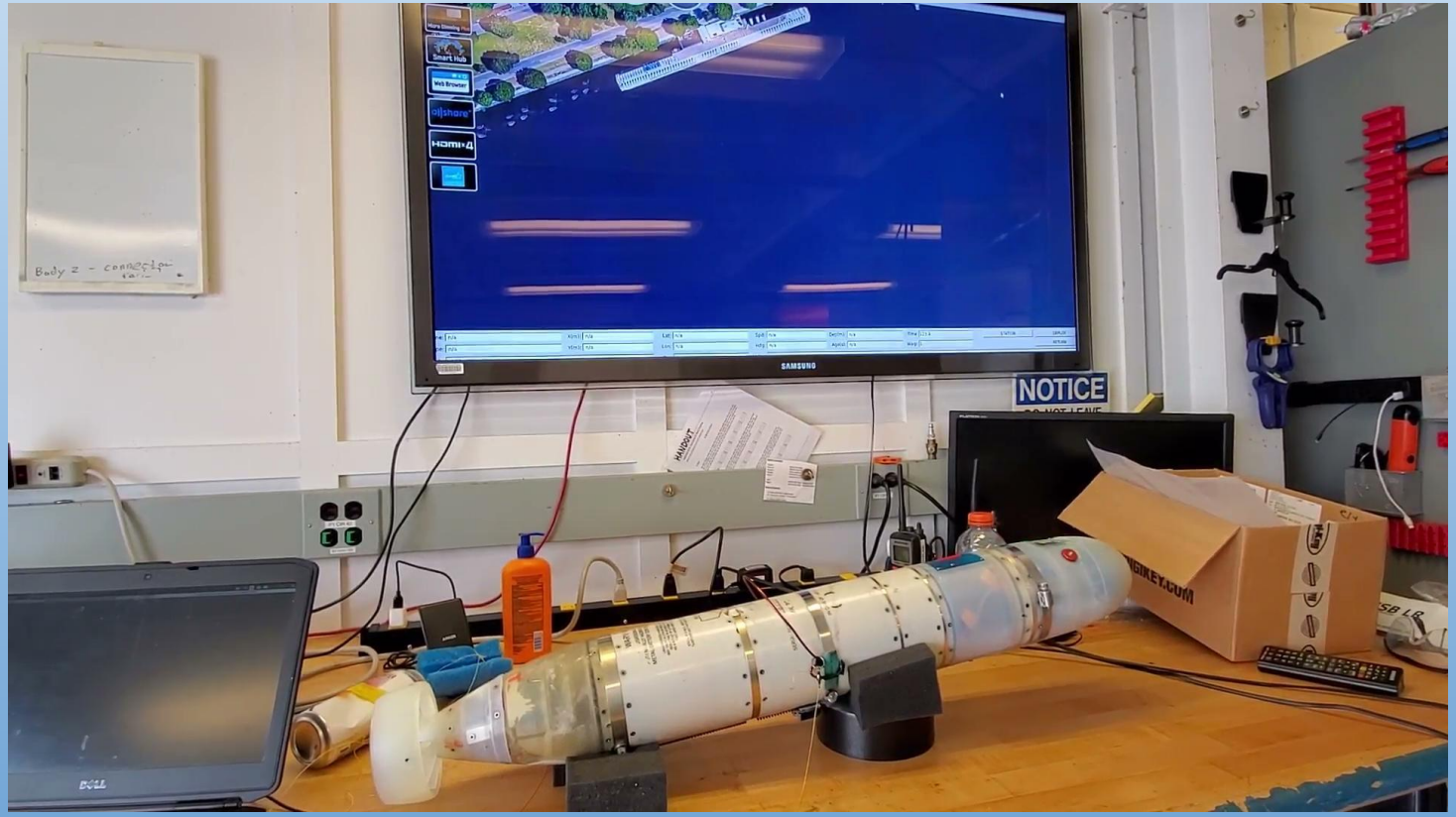
- **MITFrontseat** - Frontseat software of the vehicle
- **HydroMAN** - Self-learning, vehicle flight dynamic model-aided navigation engine
- **VECTORS** - Virtual environment for construction and testing of oceanic robotics systems



Morpheus software design

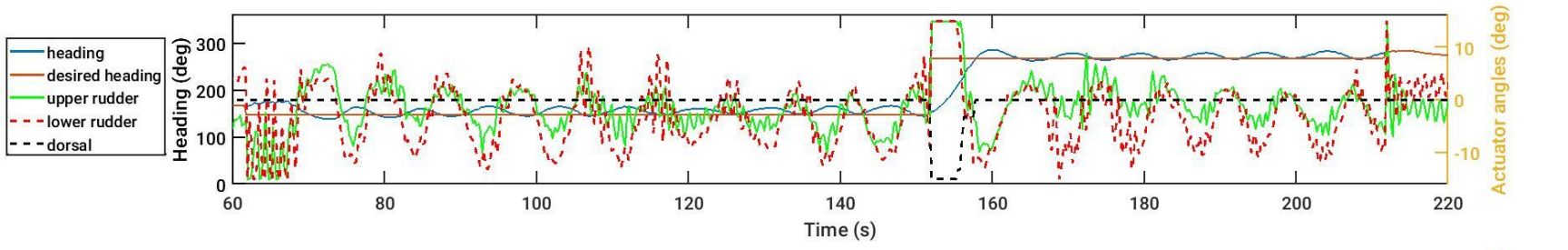


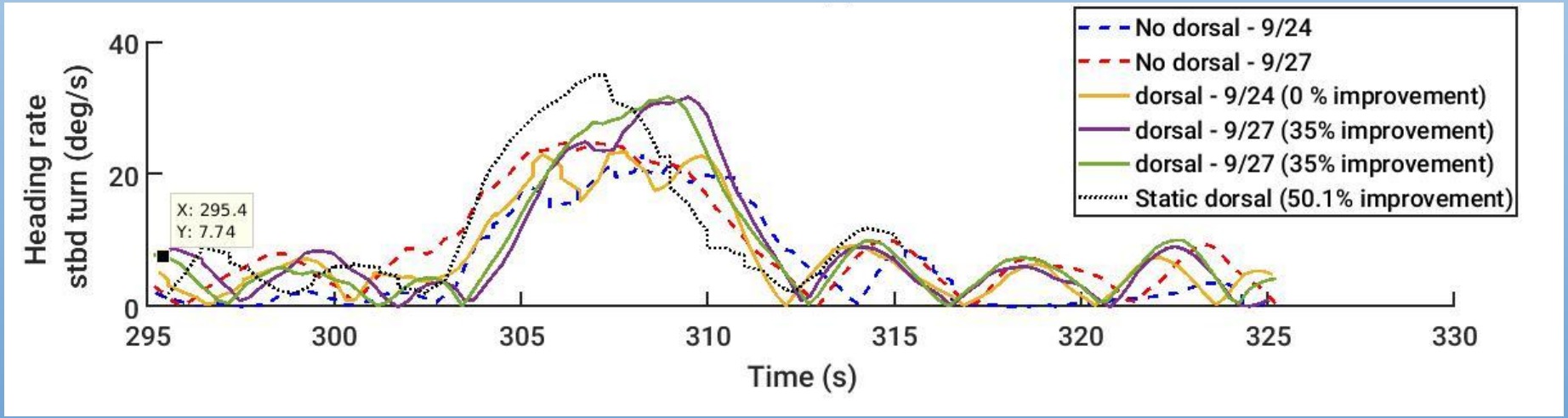
A hardware-in-the-loop simulation



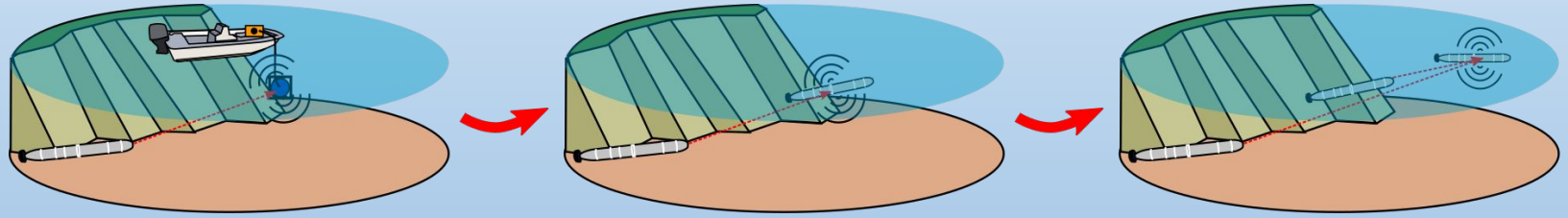
In-water experiments

Results from in-water experiments





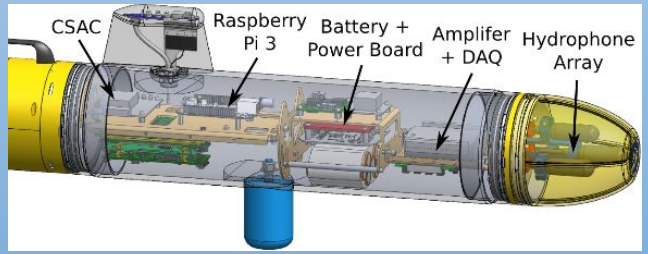
Acoustic navigation toward multi-AUV behaviors

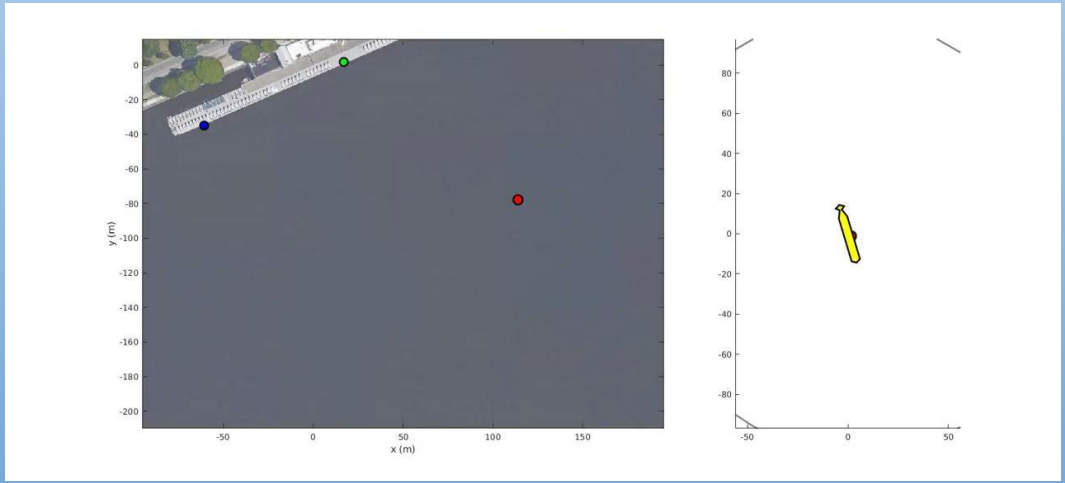


AUV trailing towed acoustic beacon

AUV trailing leader (DVL-equipped) AUV

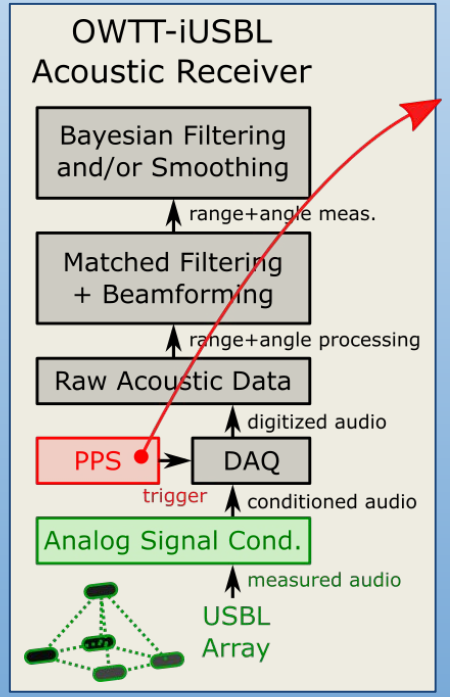
Multi-AUV behaviors with 1 leader AUV





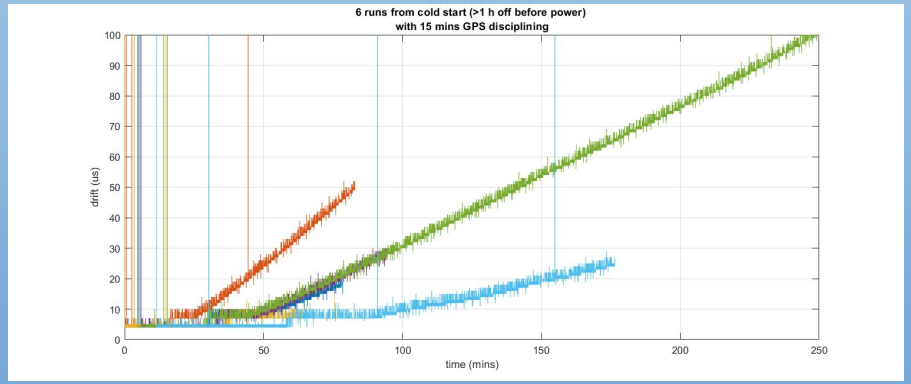
Receiver electronics stack improvements

Prior iUSBL receiver used expensive CSAC for precise OWTT ranging - replaced with Syrlinks OCXO



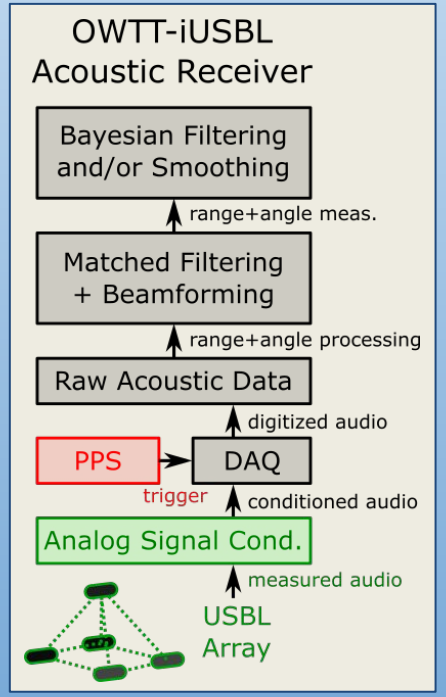
CSAC:
approx. $7k
Power: 120mW
Drift: < 100us/day =
1m per 160 hours
Size: 2.5 x 3.0 inches

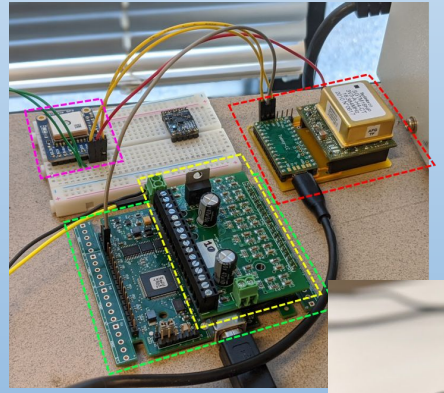
OCXO:
approx. $1k
Power: 150mW
Drift: < 1.5ms/day =
1m per 11 hours
Size: 1.5 x 2.6 inches

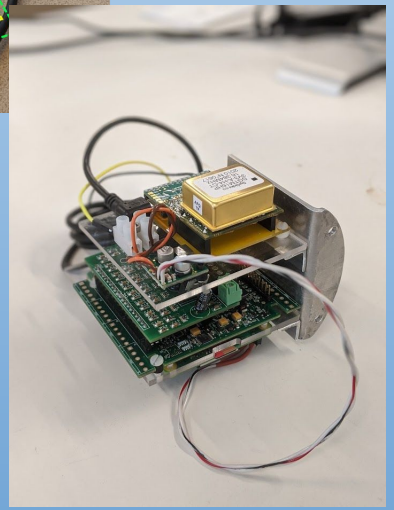


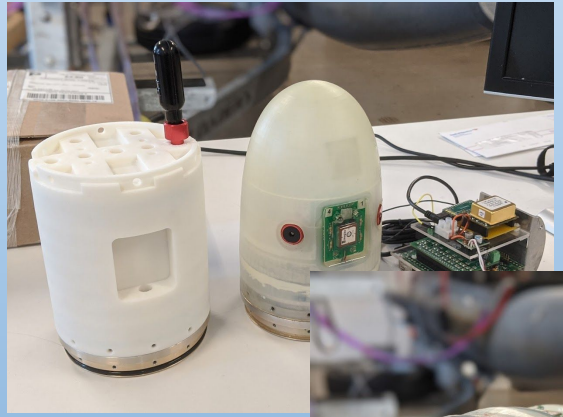
Receiver hardware - current progress

Electronics stack assembled/validated, mounting cradle and replacement nose-mounted housing fabricated



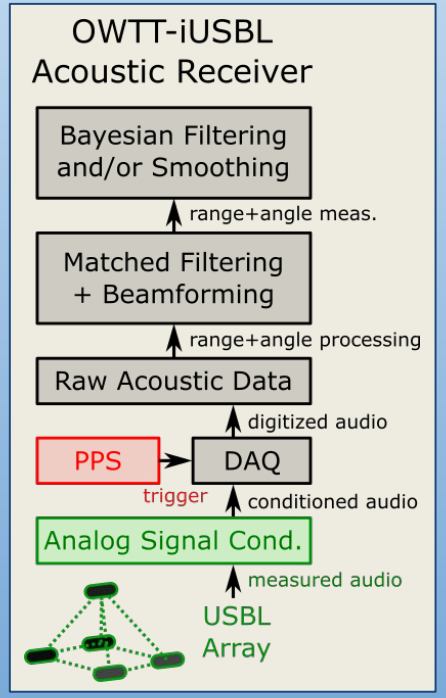


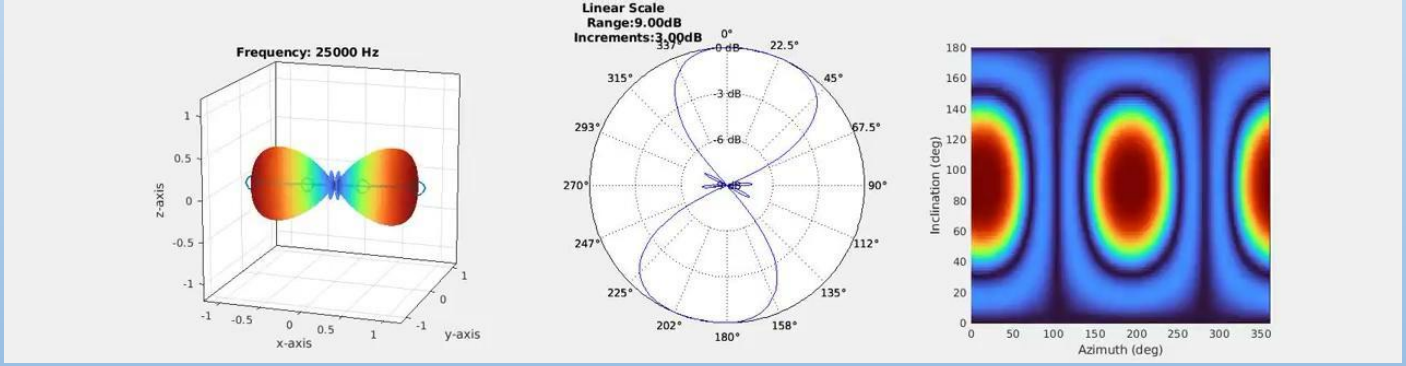


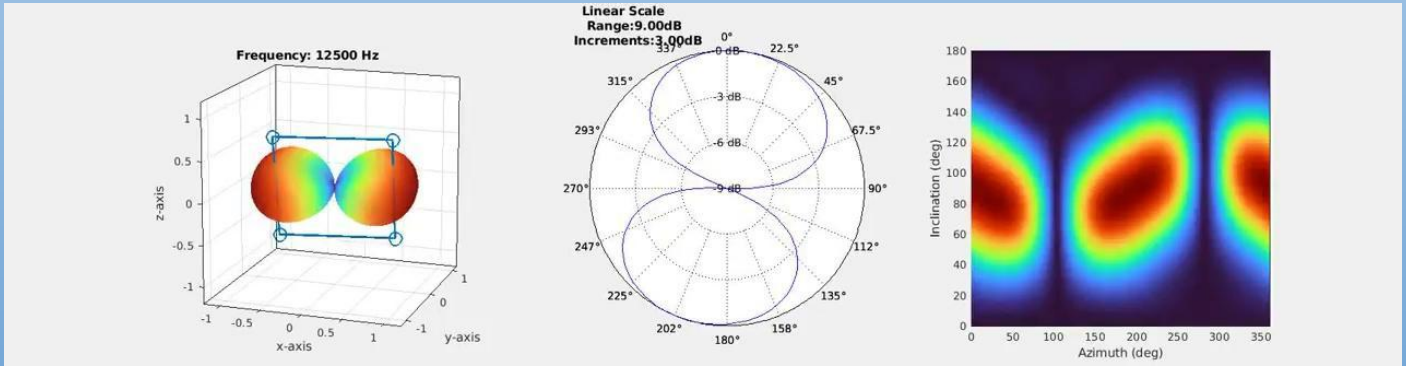


Receiver hardware - array design

Various array geometries simulated to downselect ‘optimal’ design for source tracking within mission context







Receiver hardware - array design

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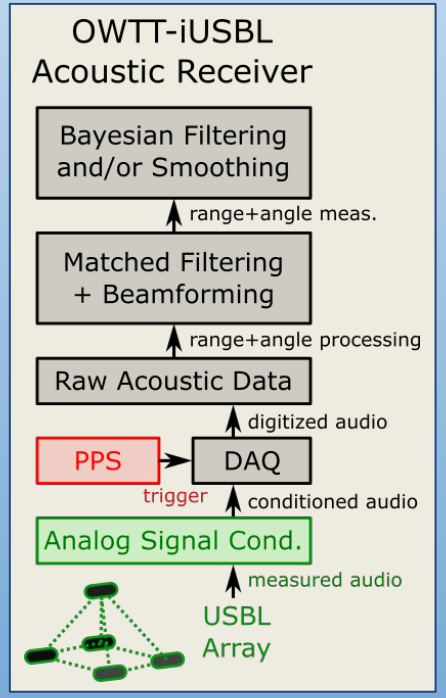

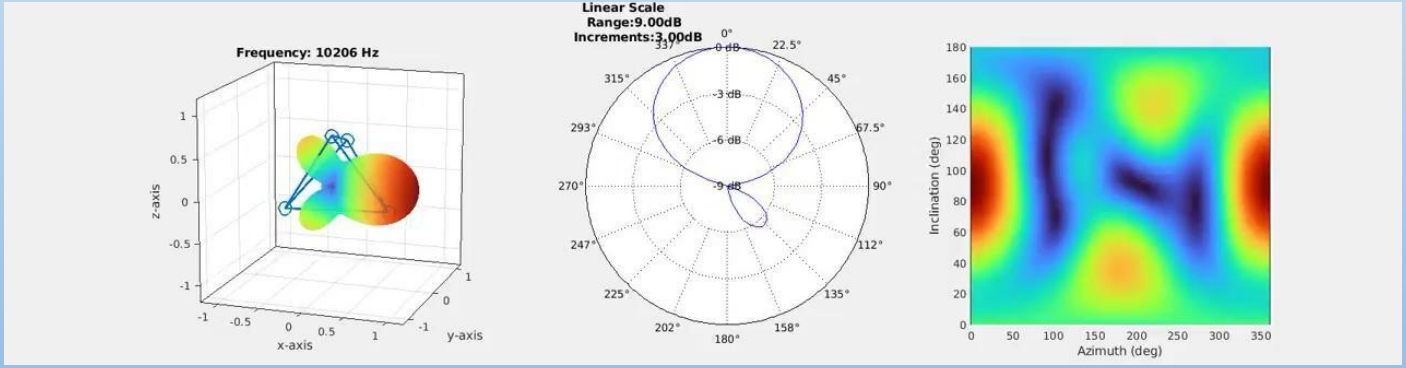

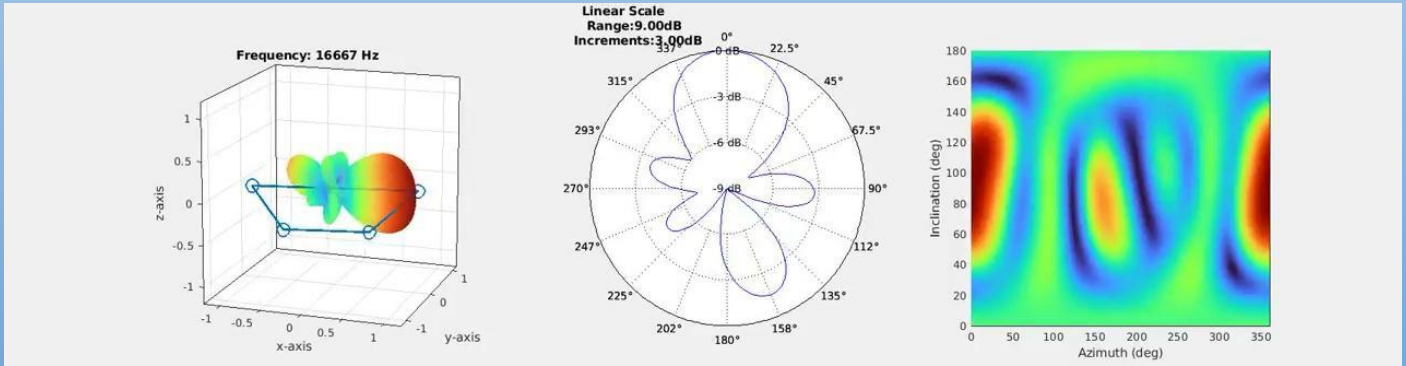

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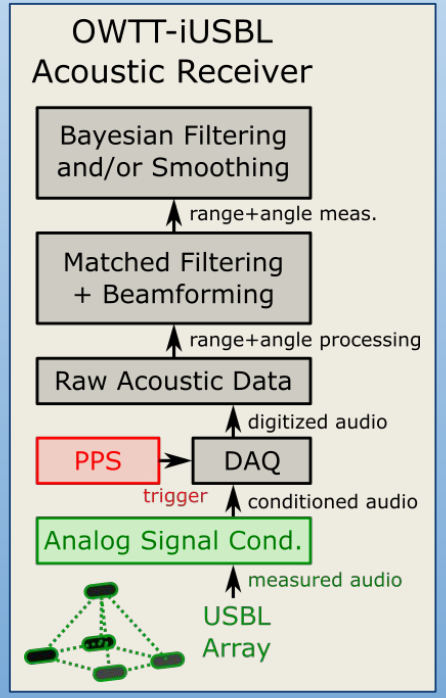
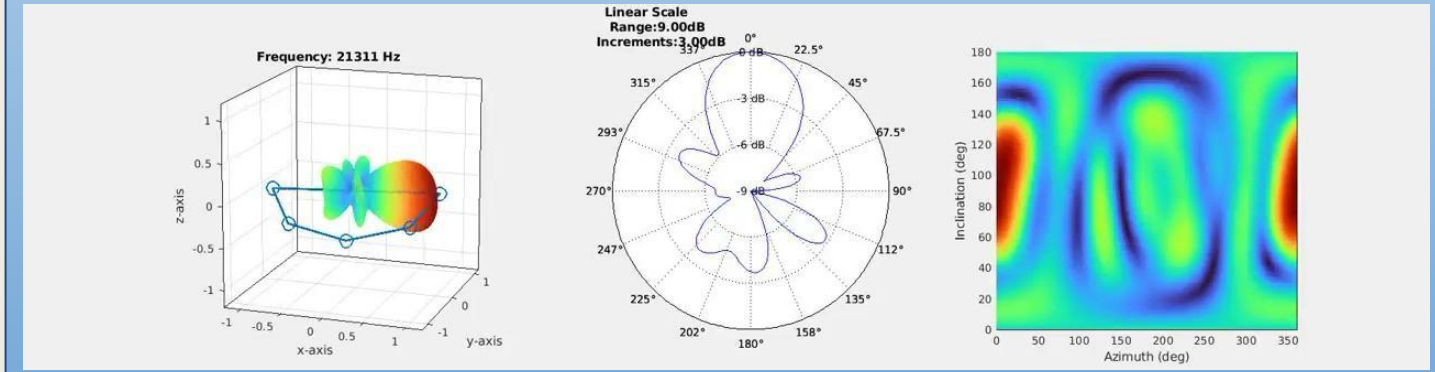


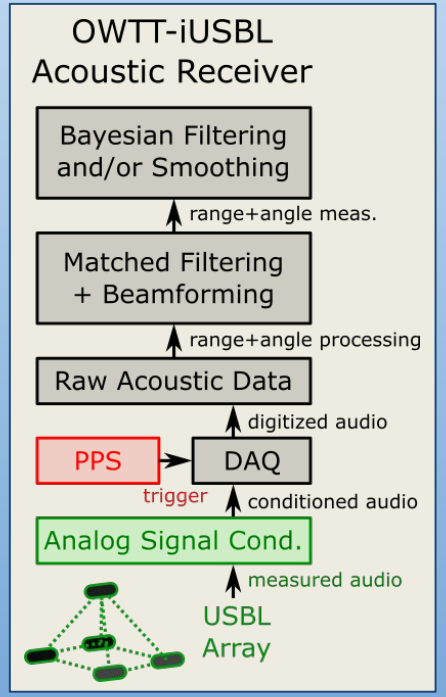
Selected 5-element uniform semi-circular array:

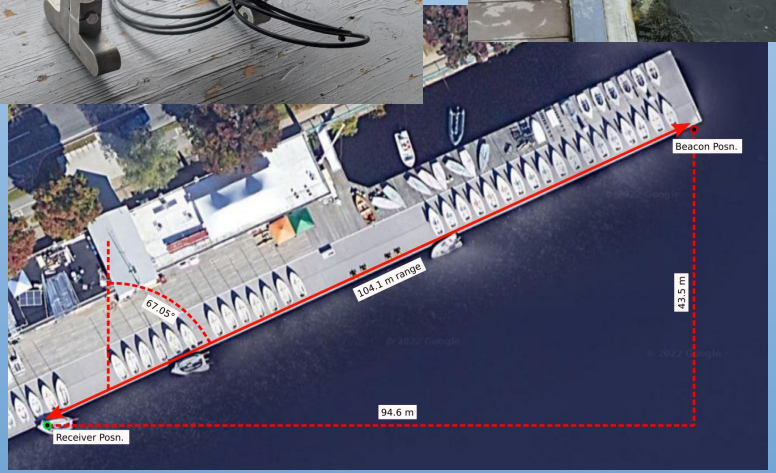
- nearly as narrow beamwidth as 4-element uniform linear array at optimal frequency (~34 deg vs. ~32 deg) at azimuths directly ahead
- better response than uniform linear array at port/stbd sides
- has some ability to discriminate in elevation



Initial testing - river experiments

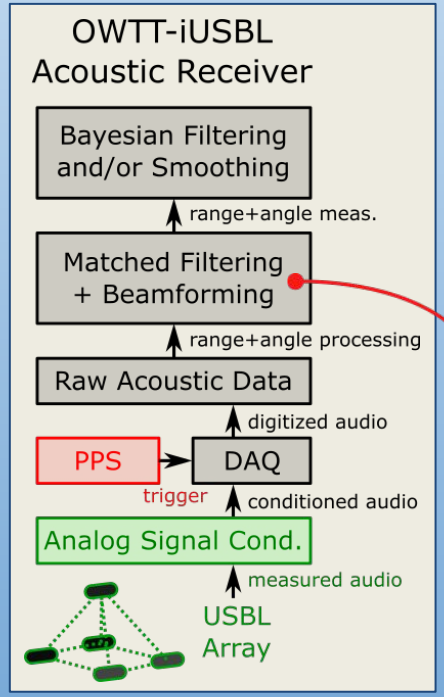
Receiver housed in a BlueRobotics 4” bottle, clamped and attached to differential GPS rig for evaluation

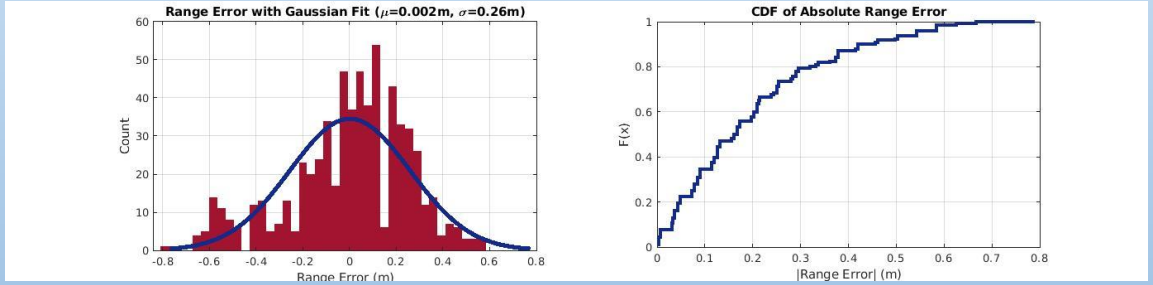


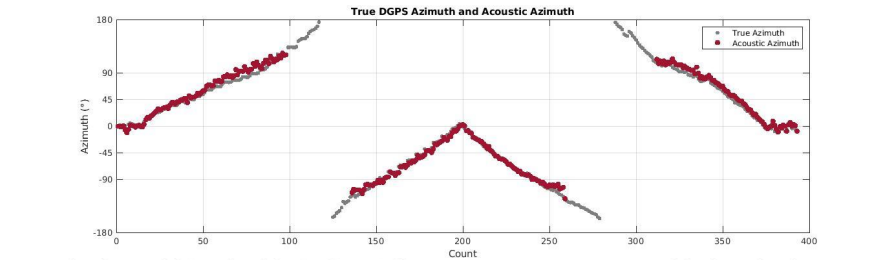


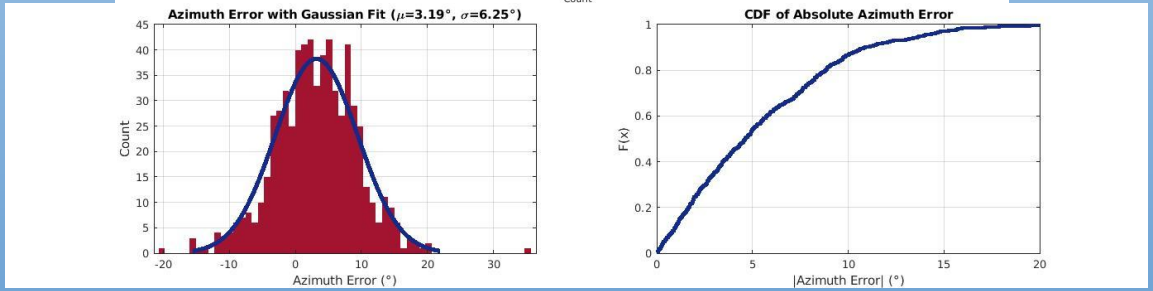
Initial testing - receiver measurement statistics

OWTT ranging via matched filtering, and azimuth (relative bearing) measurement via beamforming



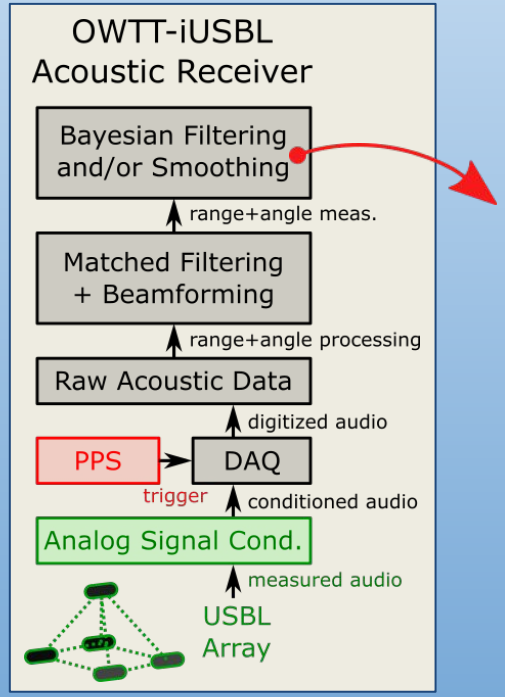






Initial testing - particle filtering

‘Factored’ particle filter used to fuse acoustic range/angle measurements with IMU orientation - range and angle integrated separately, then element-wise combined for computational tractability



Morpheus AUV — Design of a highly maneuverable micro-AUV with on-the-fly stability-agility altering capability

- towards A-sized decoy swarming -

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