Advancing Marine Renewable Energy Monitoring Capabilities

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Final Exam

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NNMREC
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Project Motivation

Sustainable development of marine renewable energy

OpenHydro turbine at EMEC

Principle Power WindFloat

Ocean Renewable Power Company RivGen

Columbia Power Technology SeaRay

Environmental Effects

Interactions between stressors and receptors that results in a detectable or measurable change of biological importance.

Stressor

Receptor

Change

Impact

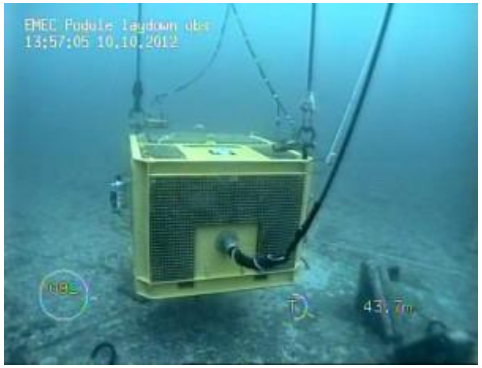
Negative effect

Benefit

Positive effect

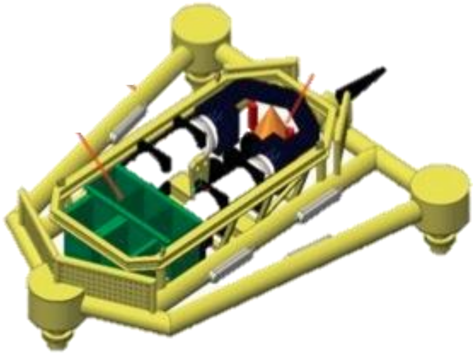
Monitoring Wish List

- **Spatially comprehensive and temporally continuous monitoring**
- **Species level identification of marine animals without behavioral changes**
- **Adaptable for evolving monitoring missions**
- **Survivable in energetic conditions**
- **Low cost, of course!**



EMEC ReDAPT

FLOWBEC



Fundy Advanced Sensor Technology (FAST) Platform

Instrumentation

AVT Manta Optical Cameras

Excelitas Strobes

BlueView Acoustical Camera

Kongsberg M3 Sonar

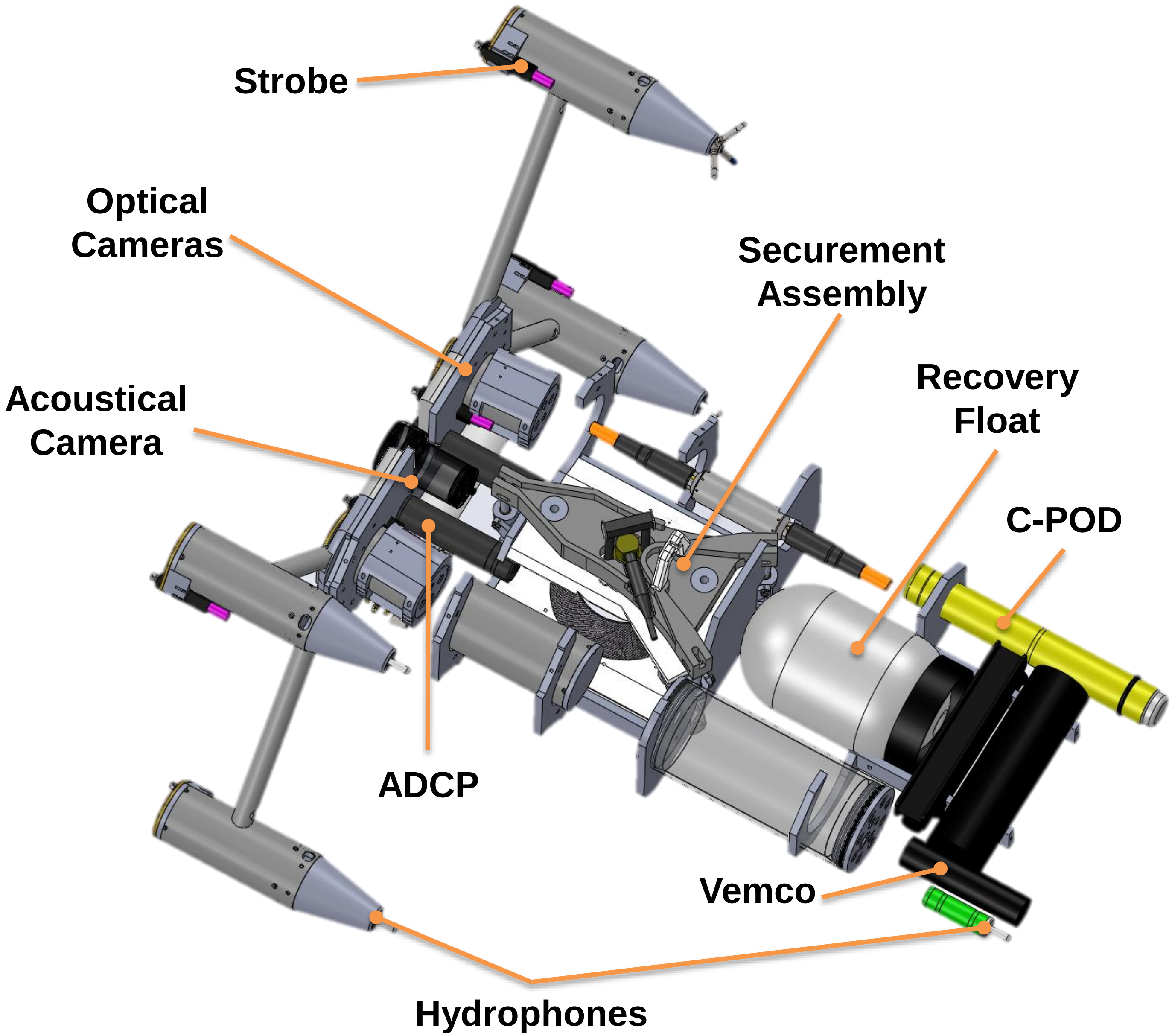
Nortek Signature ADCP

icListen HF Hydrophones

Vemco Fish Tag Receiver

C-POD Click Detector

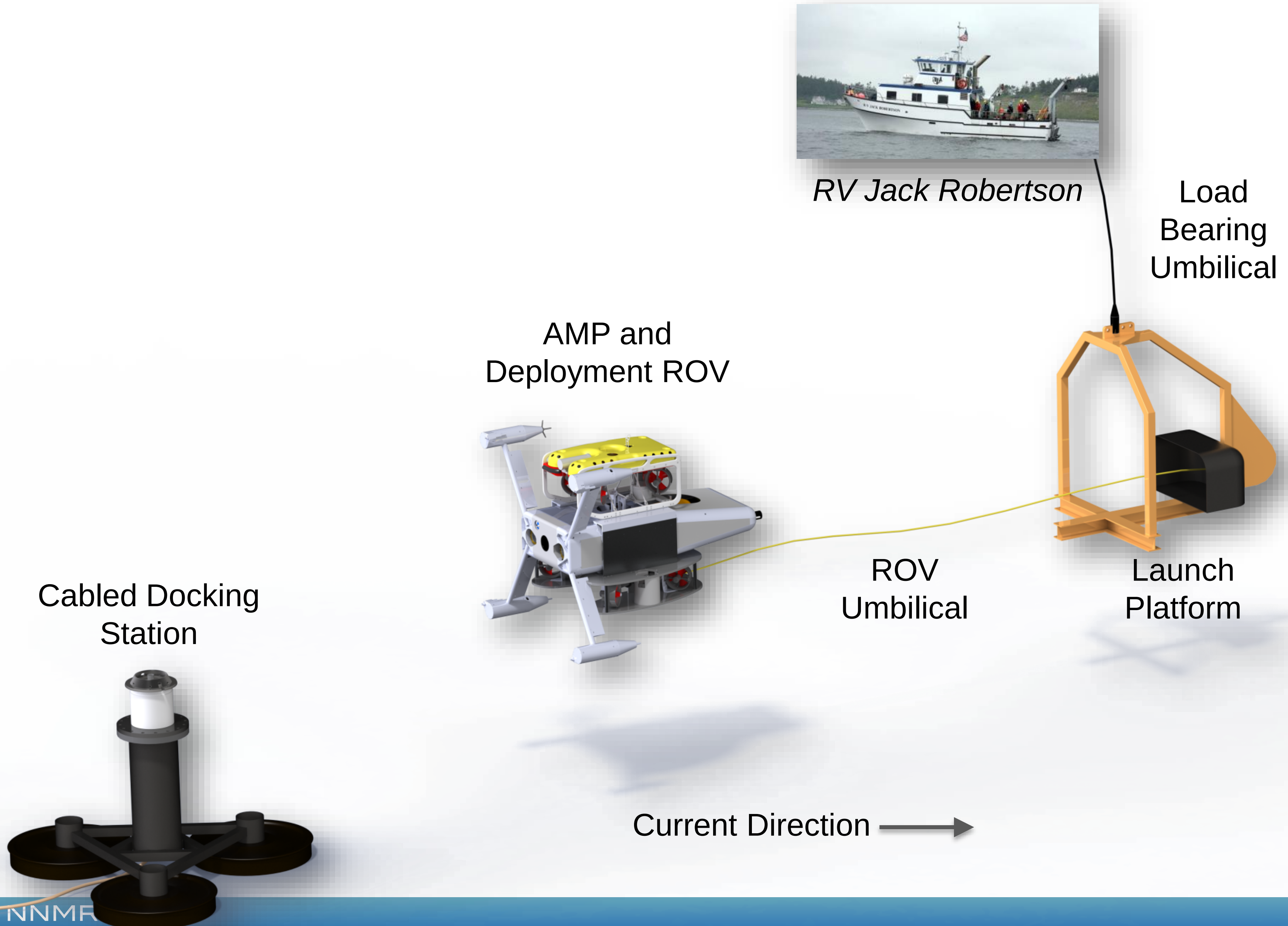
The Adaptable Monitoring Package



Cabled Instrumentation

Mechanical Design by Andy Stewart, Ben Rush and Paul Gibbs of APL

ROV Deployment

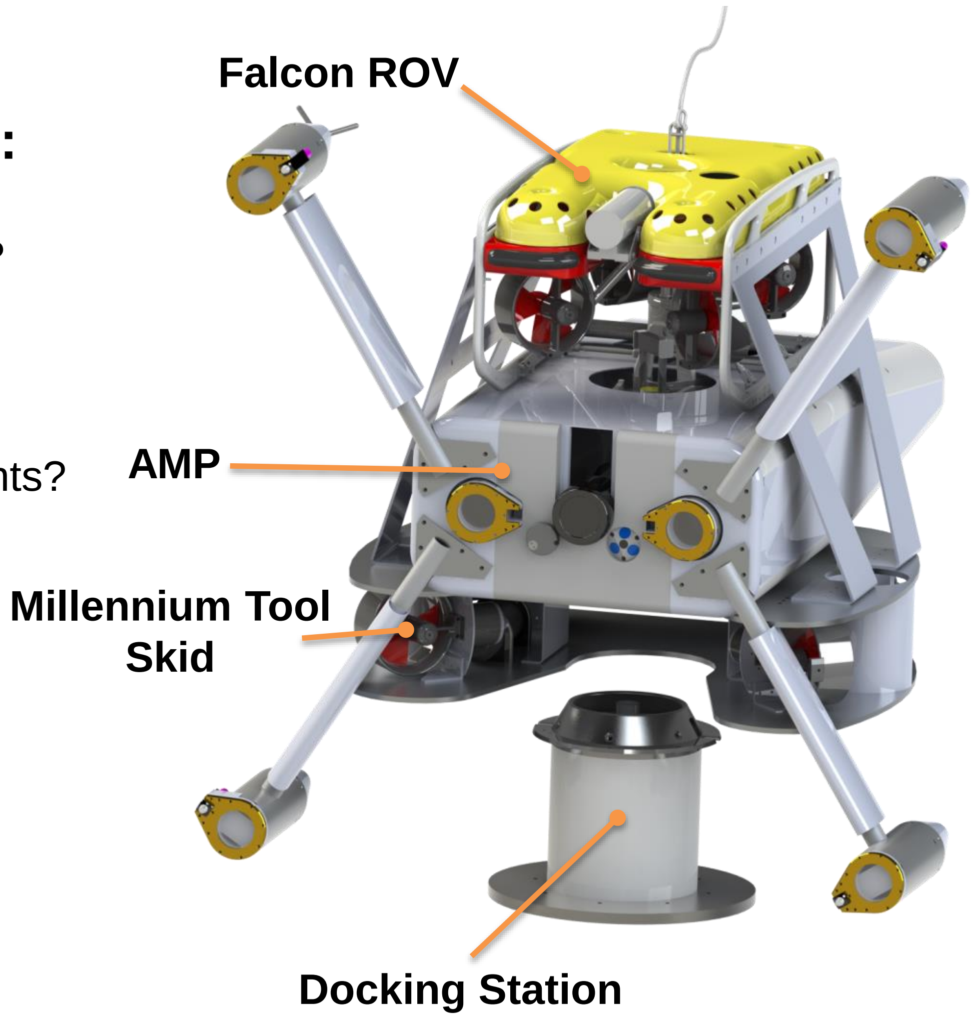


Deployment Field Trials

Field trials at Shilshole Marina, February 2015

Research Questions

- **Optical monitoring subsystem:**
  - Capabilities at marine energy sites?
  - Spacing and layout constraints?
  - Endurance for long-term deployments?
- **Hydrodynamic analysis:**
  - Added mass and drag coefficients?
  - Stability in turbulent currents?



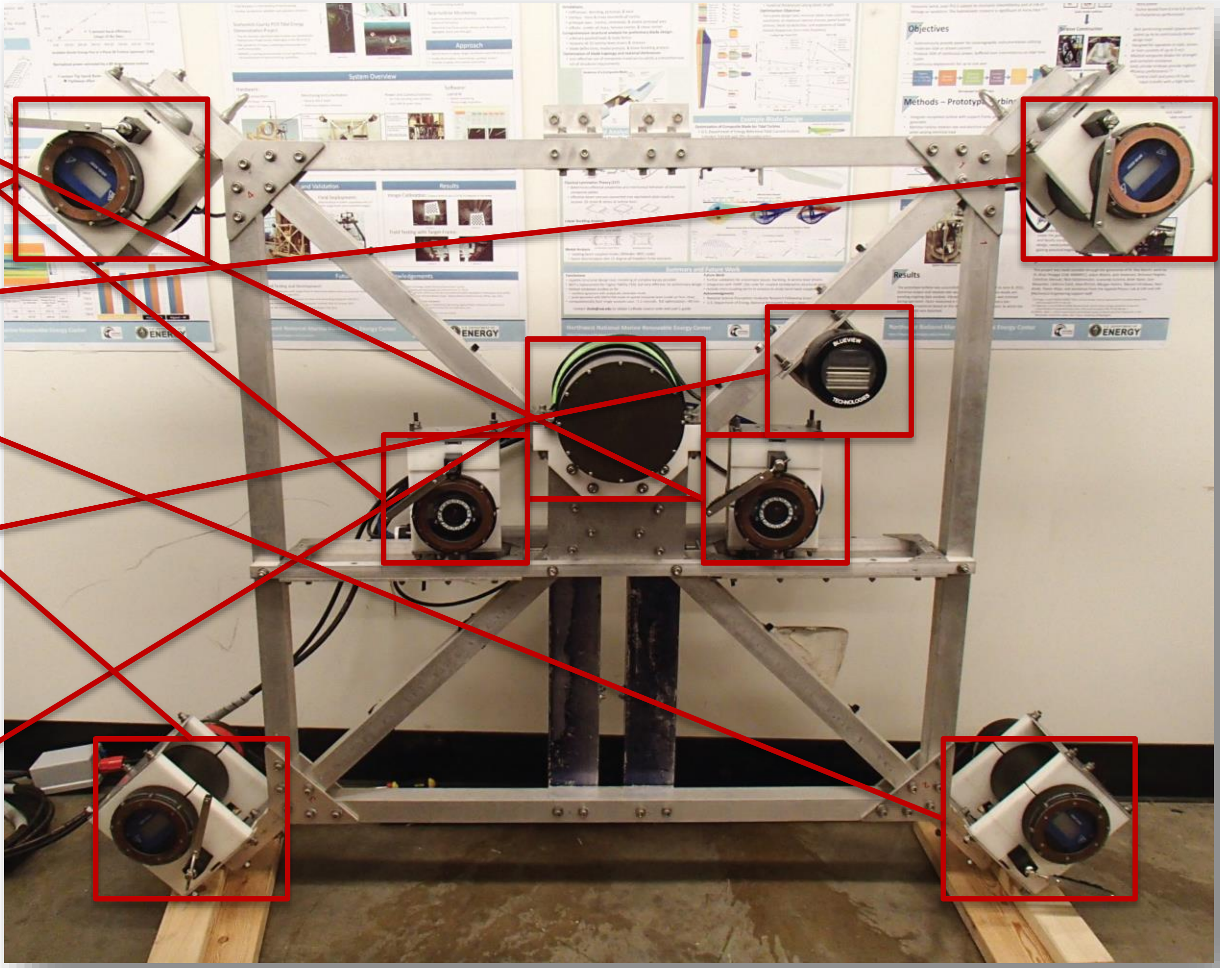
Hybrid Stereo-Optical and Acoustical Camera System

2 Optical cameras

4 Strobes

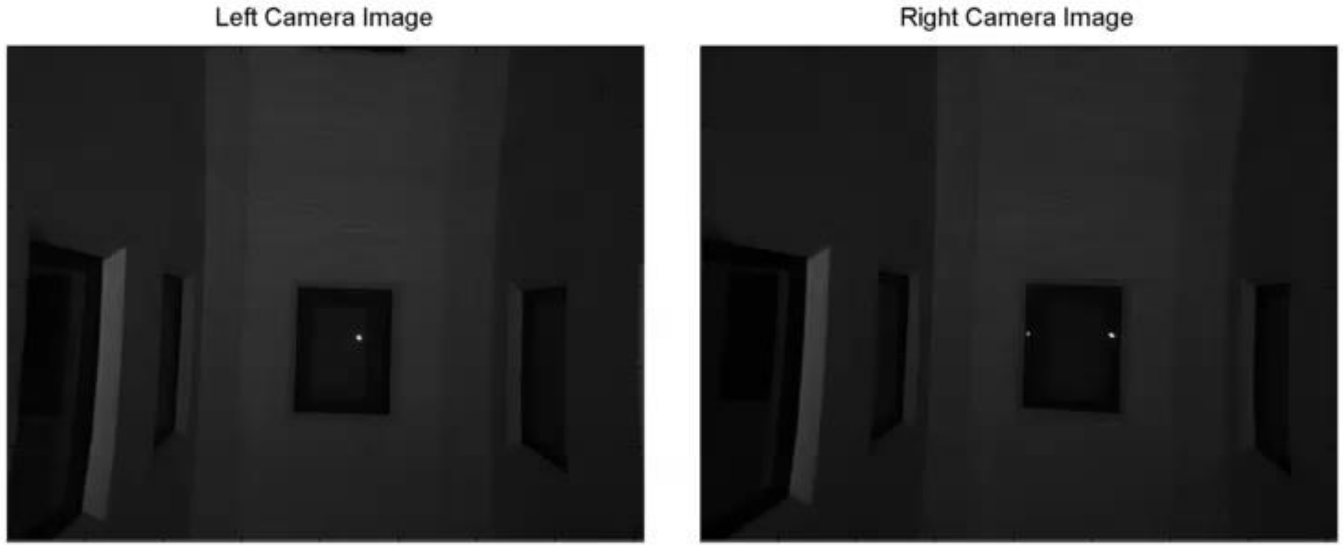
BlueView Acoustic Camera

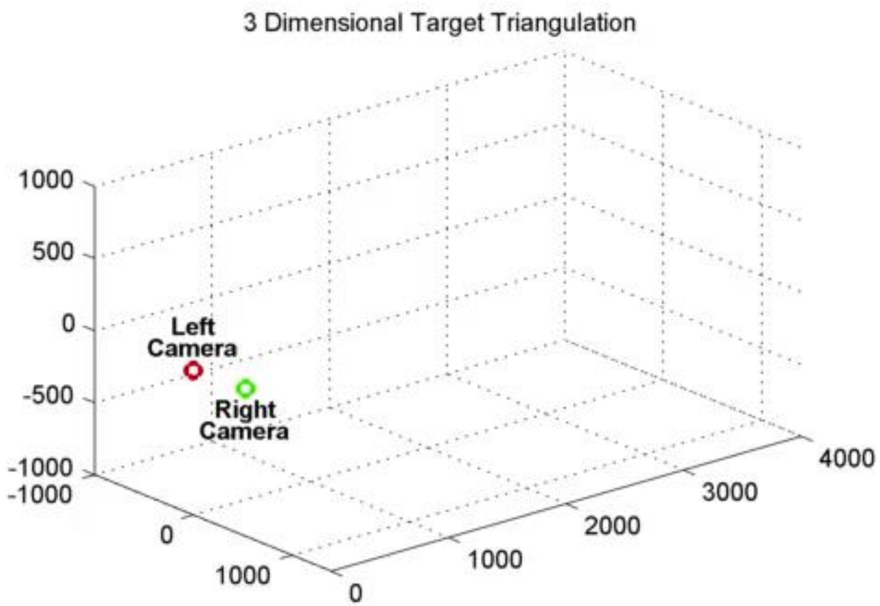
Main Electronics Bottle



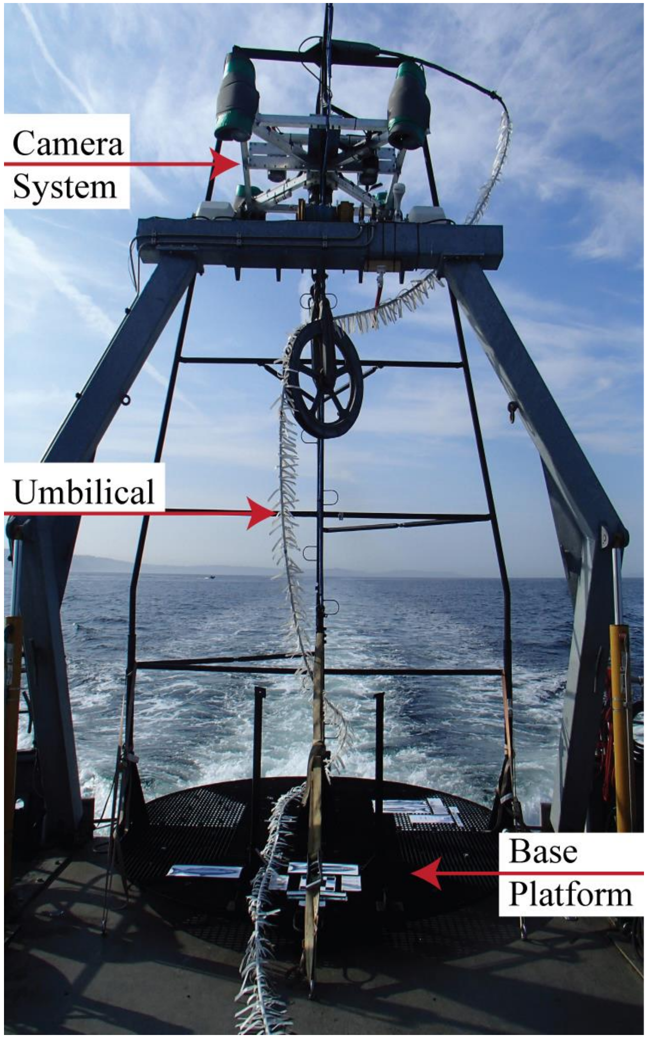
Prototype Camera System

Stereo Optical Tracking





Field Testing



Field test frame with camera system on deck of RV Jack Robertson

Stereo triangulation measurements of a target of known size.

Field deployment images with measurement target corners marked in red

Optical System Performance Summary

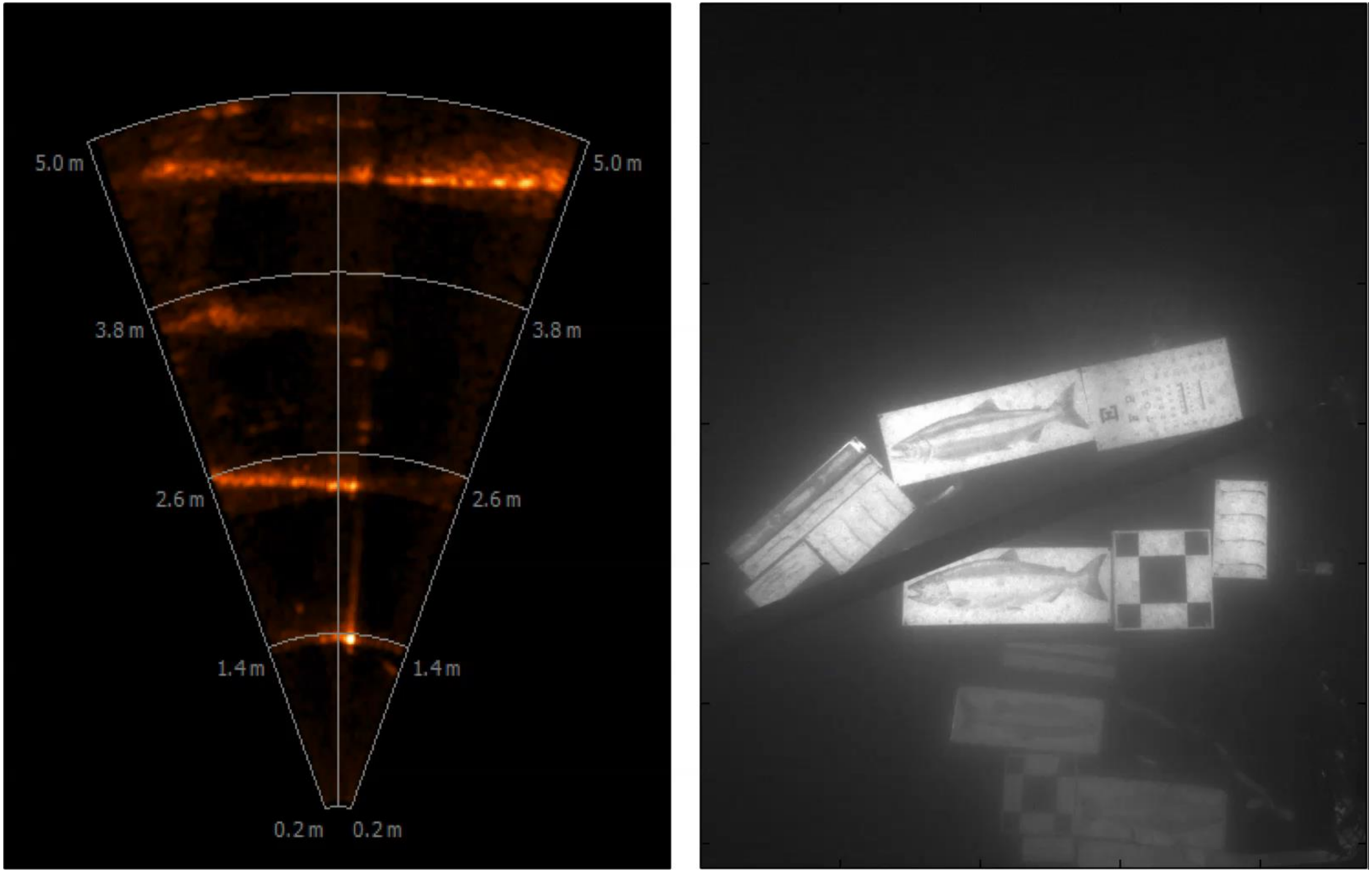
Field deployment results show good target visualization within 4 m.

Camera-Target Separation Distance	Detection	Discrimination	Classification
2.5 m	Small and large fish	Small and large fish	Small and large fish
3.5 m	Small and large fish	Small and large fish	Large fish only
4.5 m	Large fish only	Large fish only	Unlikely for any fish

Capabilities: Endurance Test Imagery

Endurance test video of a seal in a school of fish

Optical vs. Acoustical Monitoring

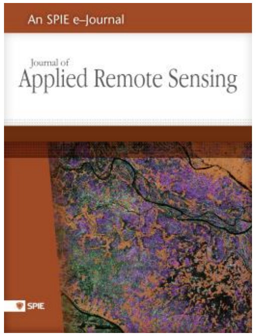


Simultaneous acoustical and optical images from field tests

Optical Monitoring Subsystem

- **Prototype system development and field evaluations**
- Published in SPIE-JARS

Joslin, J., B. Polagye, and S. Parker-Stetter (2014) Development of a stereo-optical camera system for monitoring tidal turbines, *SPIE-JARS*, 8(1), 083633.



- **Biofouling and endurance testing through long-term deployment**
- Published in MTS Journal

Joslin, J. and B. Polagye, (2015) Demonstration of biofouling mitigation methods for long-term deployments of optical cameras, *MTS Journal*, 49(1), 88-96.

Hydrodynamic Analysis

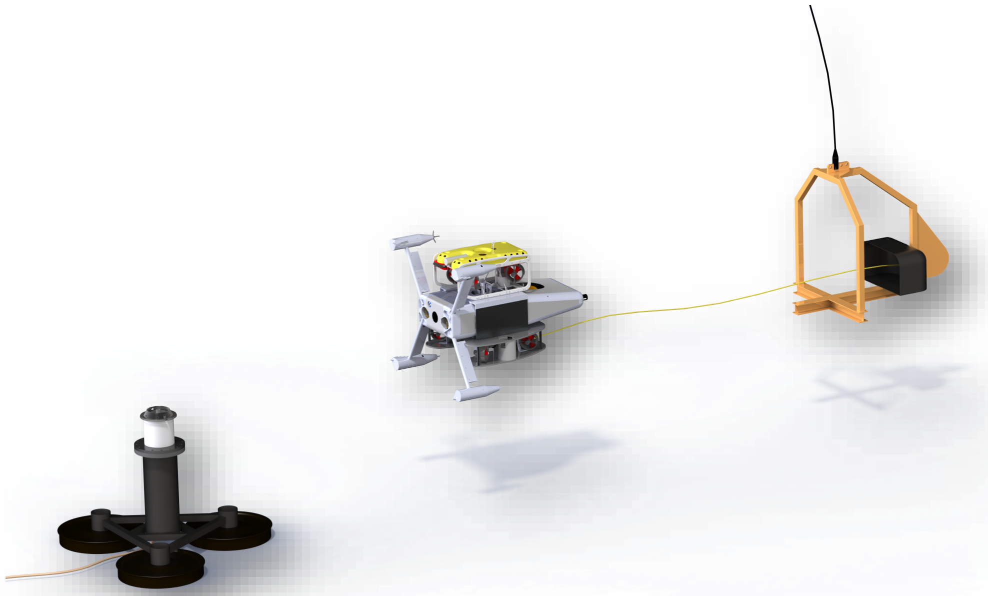
- **Question:** Can an “inspection”-class ROV deploy the AMP in currents typical of marine energy sites?
- **Motivation:**
  - Lower cost (>10x) than “work”-class ROVs
  - Thrust limitations require design optimization
- **Methods:**
  - Drag and added mass coefficient determination
  - Dynamic stability analysis

SeaEye’s largest (Jaguar on right) and smallest (Falcon on left) ROVs

Loading Conditions

Deployments

- Currents that allow for regular maintenance **< 0.7 m/s**

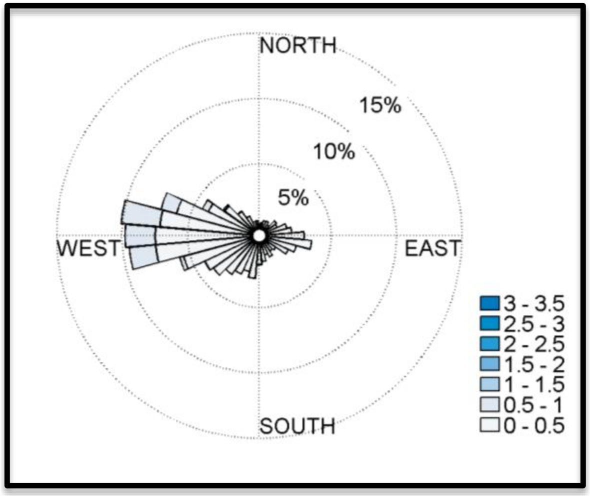


Operations

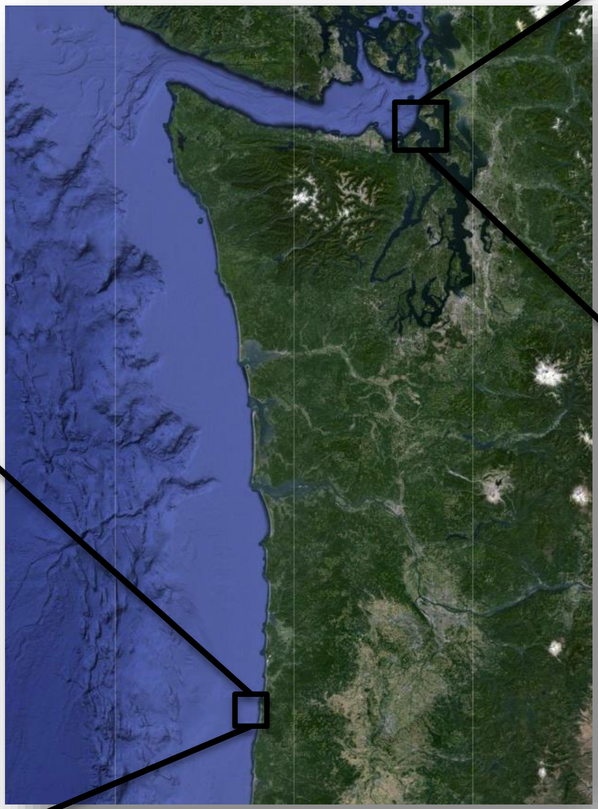
- Site extremes **< 5.4 m/s**

Marine Energy Sites

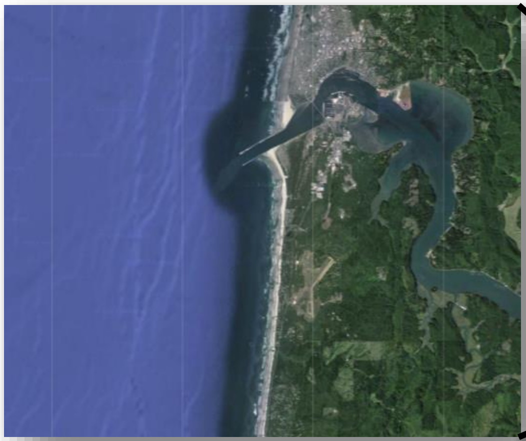
Ocean Currents



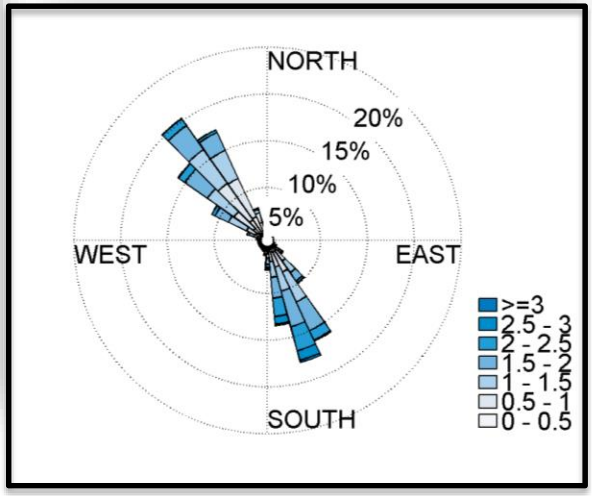
Pacific Northwest



Admiralty Inlet,
Puget Sound, WA



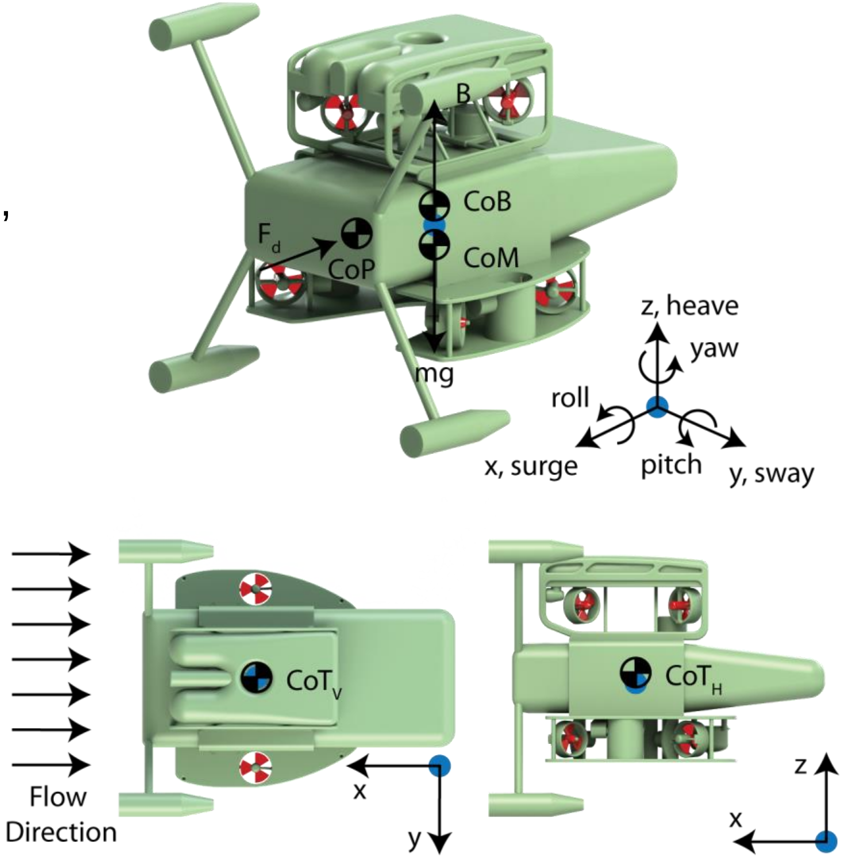
Newport, Oregon
North Energy Test Site



Tidal Currents

Underwater Vehicle Dynamics

- **6 degrees of freedom**
  - Passive control on pitch and roll
  - Thruster controlled surge, sway, heave, and yaw
- **Thrusters:**
  - 8 horizontal
  - 2 vertical
- **Primary forces and centers:**
  - Added mass and drag – CoP
  - Gravity - CoM
  - Buoyancy - CoB
  - Thrust - CoT



Simulation model free body diagram

ROV Equations of Motion

- **Dynamic equation of motion for marine robotics:**

$$M\dot{v} + F_C + F_D + F_G = F_T \qquad \in R^{6x1}$$

Inertial Forces ($M\dot{v}$), Coriolis and Centripetal (F_C), Drag (F_D), Gravity and Buoyancy (F_G), Thrust (F_T)

$$F_C \approx 0$$

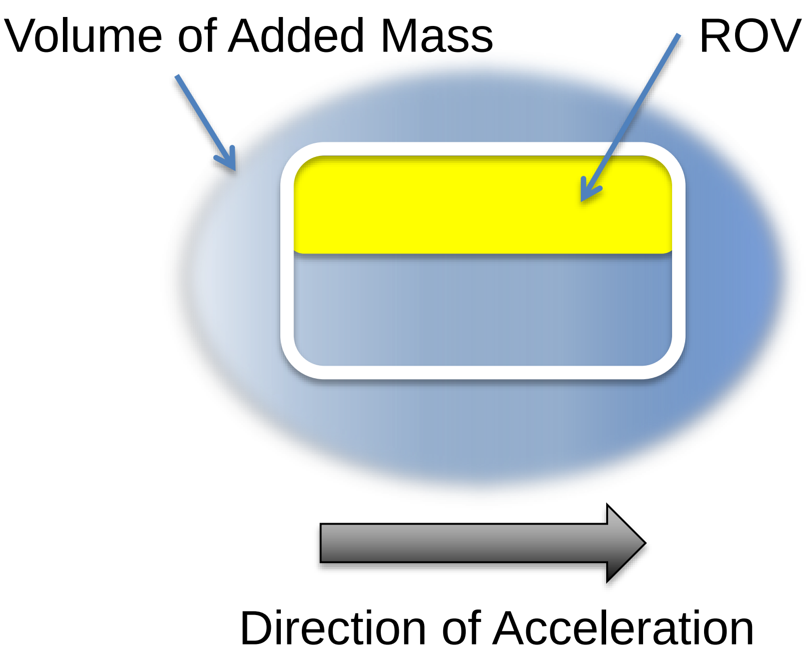
- **Simplified equation for translation on a single axis:**

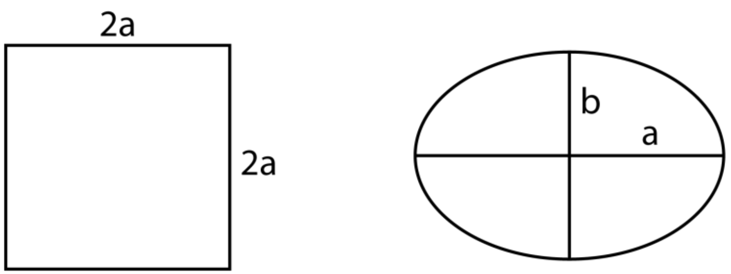
$$(m_0 + m_{ax})\dot{v}_x - \frac{1}{2}\rho A_x C_{dx}|v_x|v_x = F_{Tx}$$

Added Mass (m_{ax}), Drag Coefficient (C_{dx})

"Added Mass"

- **Definition: The inertia added to a body during acceleration or deceleration due to the fluid volume that moves with it.**





m_{11}:	$\pi\rho b^2$	$4.754\rho a^2$
m_{22}:	$\pi\rho a^2$	$4.754\rho a^2$
m_{33}:	$1/8\pi\rho(a^2-b^2)^2$	$0.725\rho a^2$

Analytical equations for added mass of simple geometries (Lamb, H., 1932)

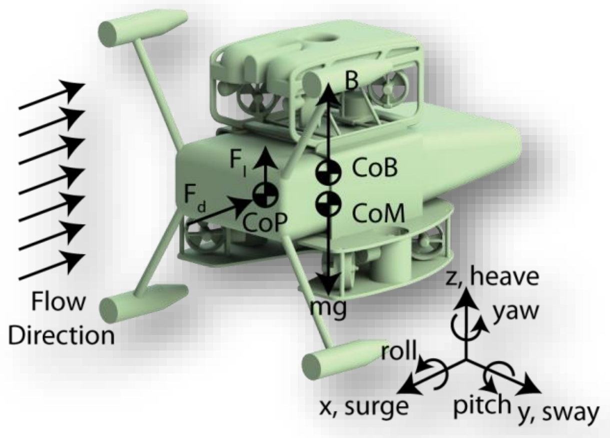
CFD Simulations

- **Steady-state simulations to determine lift and drag coefficients and center of pressure**

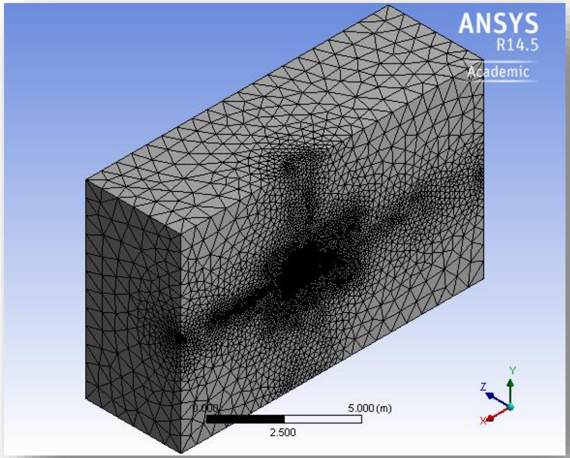
$$C_l = 2F_l / \rho A U^2$$
$$C_d = 2F_d / \rho A U^2$$

  - Unstructured tetrahedral mesh with the *k-ω SST* turbulence model.

- **CFD sensitivity studies:**
  - Meshing refinements: Coarse, Medium, and Fine
  - Input velocity: 0.1 m/s to 3 m/s



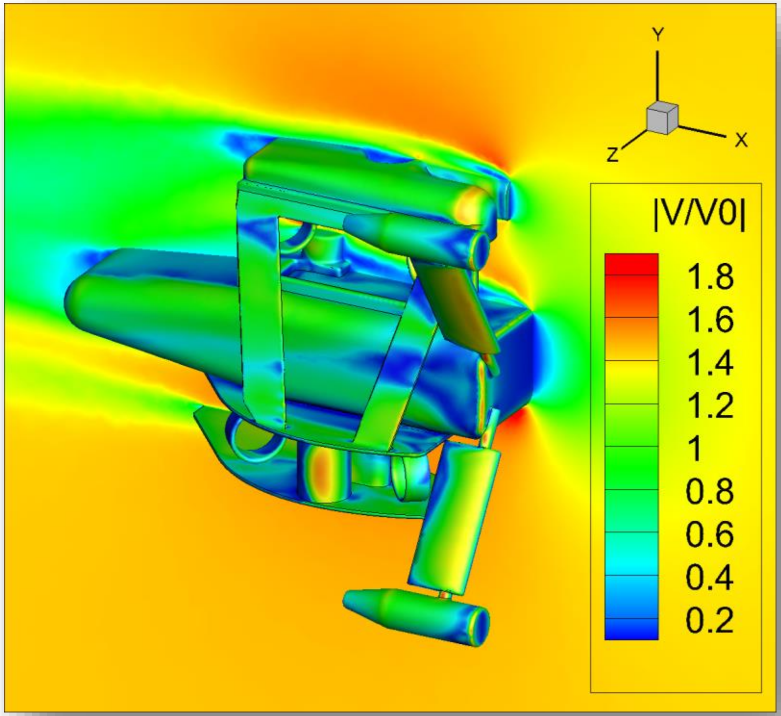
Model free body diagram



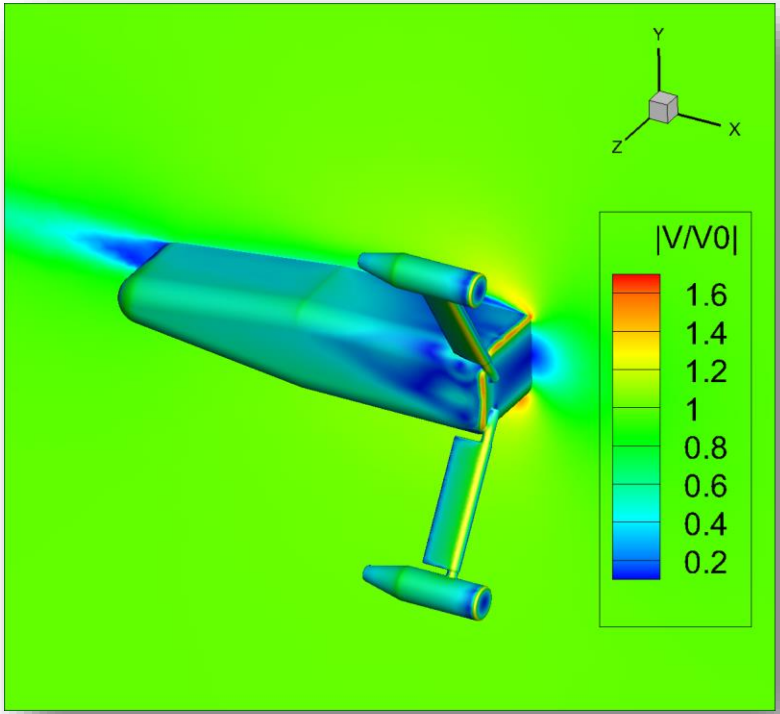
ANSYS fluid domain meshing

Sample CFD Results

- **Sensitivity study variability in drag force:**
  - Grid dependence: < 3.50%
  - Velocity dependence: < 1.1%



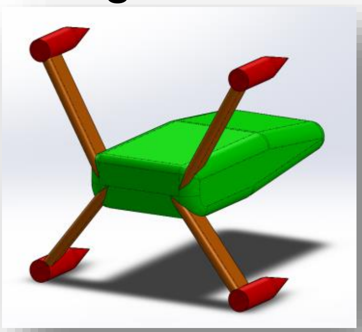
Normalized velocity around the Millennium Falcon and AMP during deployments

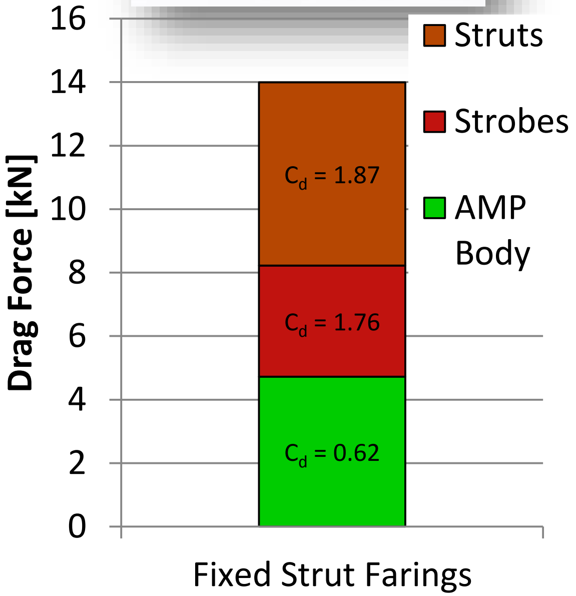


Normalized velocity around AMP during mounted operation

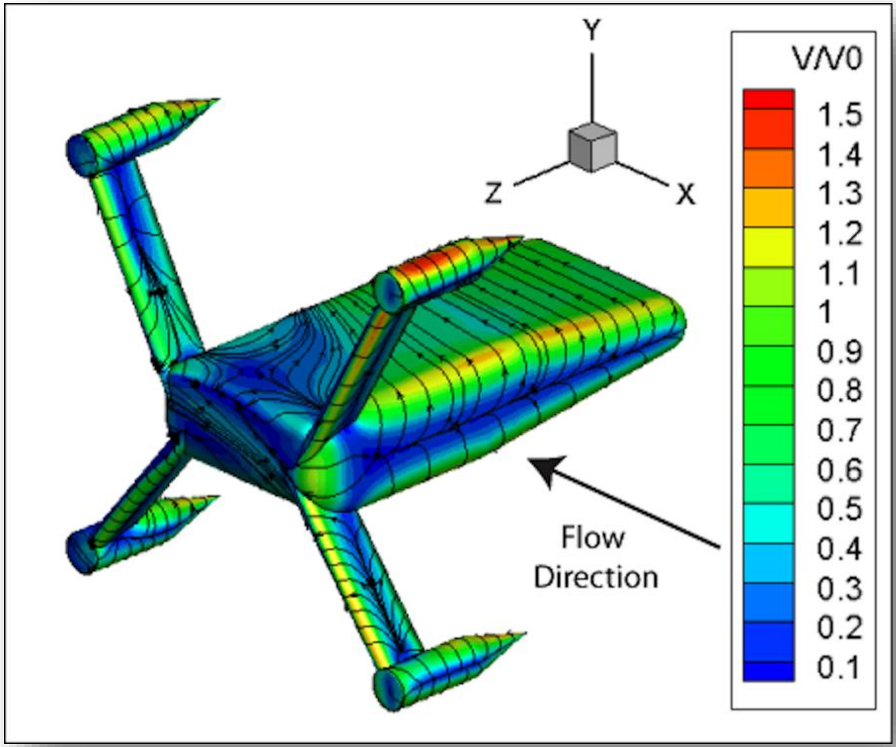
Informing Design through CFD

Case study of design improvement analysis through CFD:
Drag forces in 5 m/s side-on currents: up to 3150 lbf!





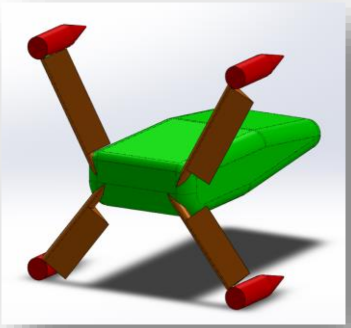
Drag forces and coefficients on AMP Components

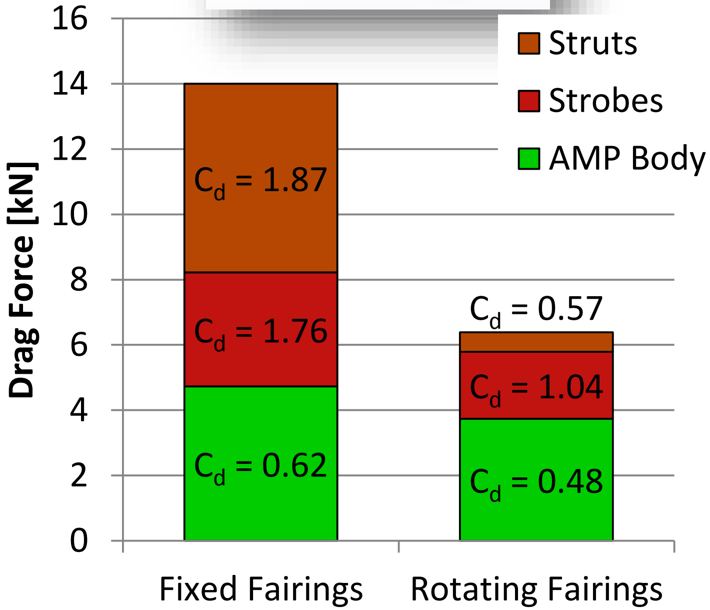


AMP with fixed strut fairings

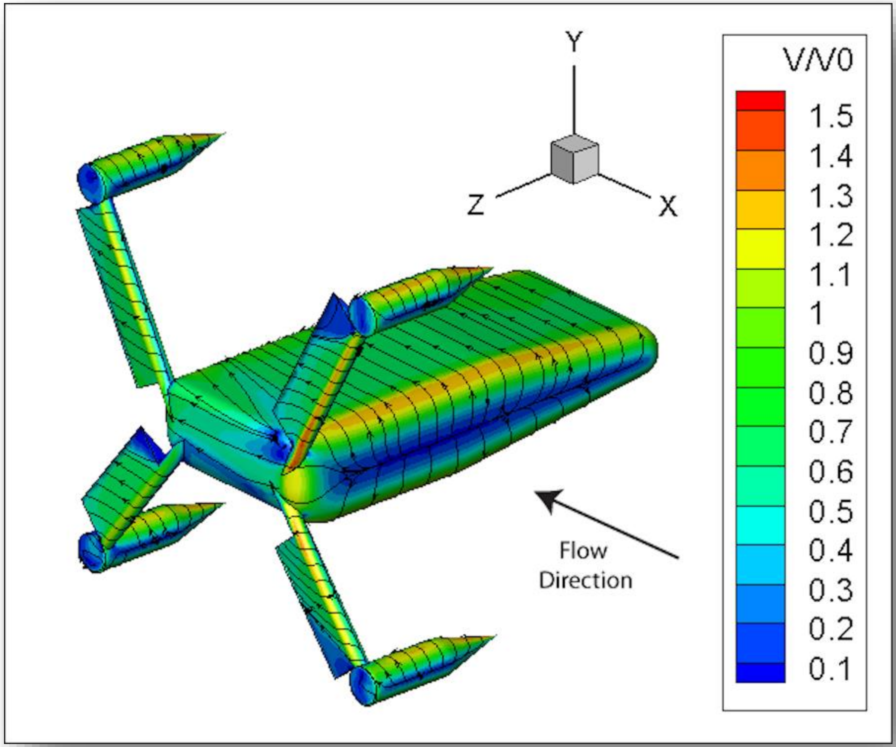
Informing Design through CFD

Case study of design improvement analysis through CFD:
Rotating struts reduces drag forces by 54% (1400 lbf)





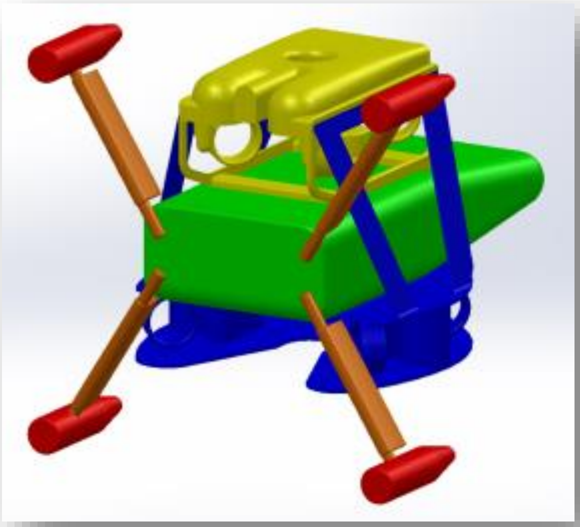
Drag forces and coefficients on AMP Components



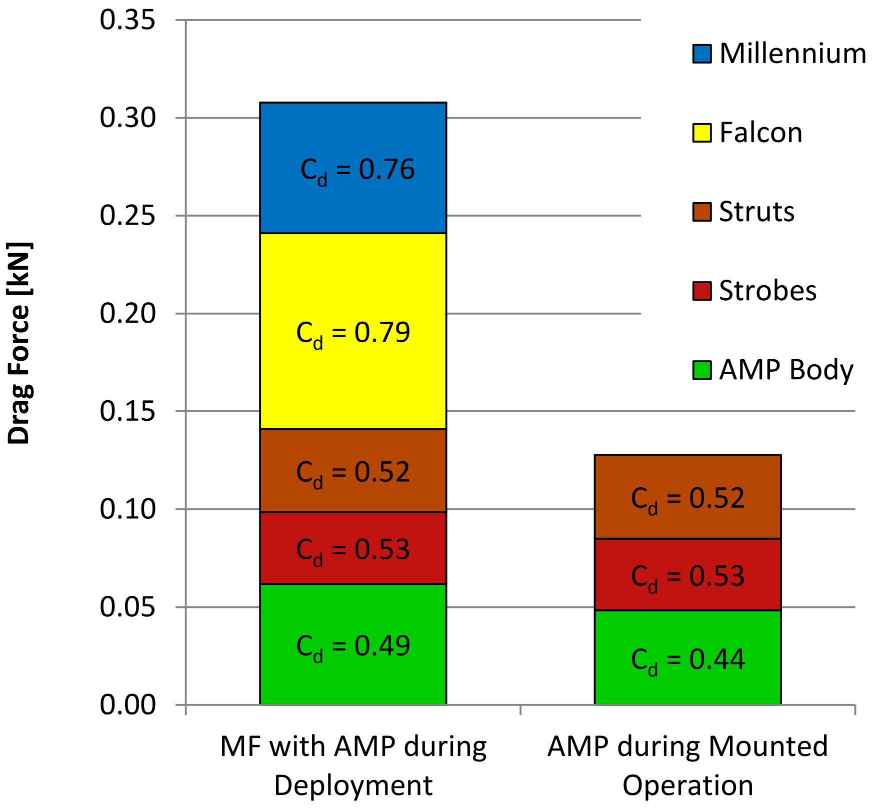
AMP with rotating strut fairings

CFD Drag Force Results Summary

- **Drag coefficient during deployments: $C_d \cong 0.67$**
- **Peak loads during mounted operations:**
  - Horizontal: 7,880 N
  - Vertical: 608 N



AMP components



Drag forces and coefficients of the AMP by component

Experimental Coefficient Measurements

- **Goal:** Verify CFD drag coefficients and measure added mass coefficients
- **Methods:** Free-decay pendulum experiments
  - Benchmark geometries
  - ¼ scale models
  - Full scale ROV

6” cube

8.5” sphere

Ohmsett Tow Tank Facility

¼ scale model

Falcon ROV

Free-Decay Pendulum Motion

- **Damped pendulum equation of motion:**

$$\sum M_p = [(B_1 - m_1 g)r_1 + (B_2 - m_2 g)r_2]\sin(\theta) + F_{D1}r_1 + F_{D2}r_2 = I\ddot{\theta}$$

  - **With quadratic drag:**

$$F_D = \frac{1}{2}\rho A C_d r^2 \dot{\theta}^2$$

  - **And moment of inertia:**

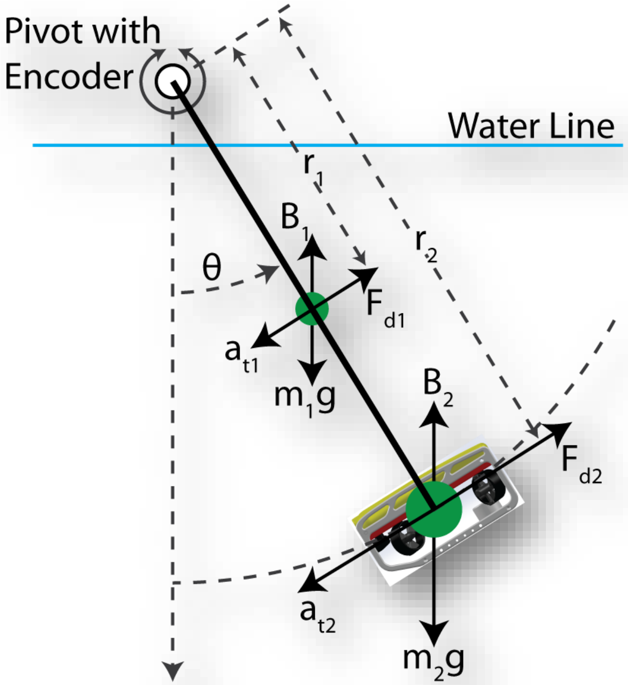
$$I = \frac{4}{3}(m_1 + m_{a1})r_1^{\ 2} + (m_2 + m_{a2})r_2^{\ 2} + I_{body2}$$

  - **The equation of motion may be written as:**

$$\ddot{\theta} = \alpha \sin(\theta) + \beta \left|\dot{\theta}\right| \dot{\theta}$$

  - **With:**

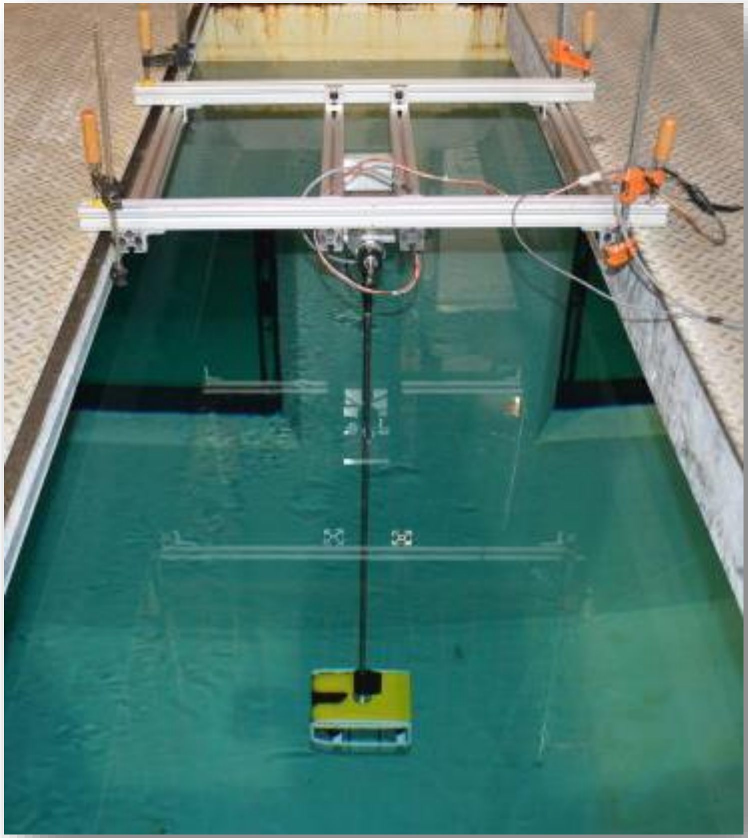
$$\alpha = \frac{(B_1 - m_1 g)r_1 + (B_2 - m_2 g)r_2}{I} \qquad \beta = -\frac{\rho(A_1 C_{d1} r_1^{\ 3} + A_2 C_{d2} r_2^{\ 3})}{2I}$$



Pendulum free body diagram

Pendulum Free-Decay Motion

¼ scale ROV mounted to pendulum arm

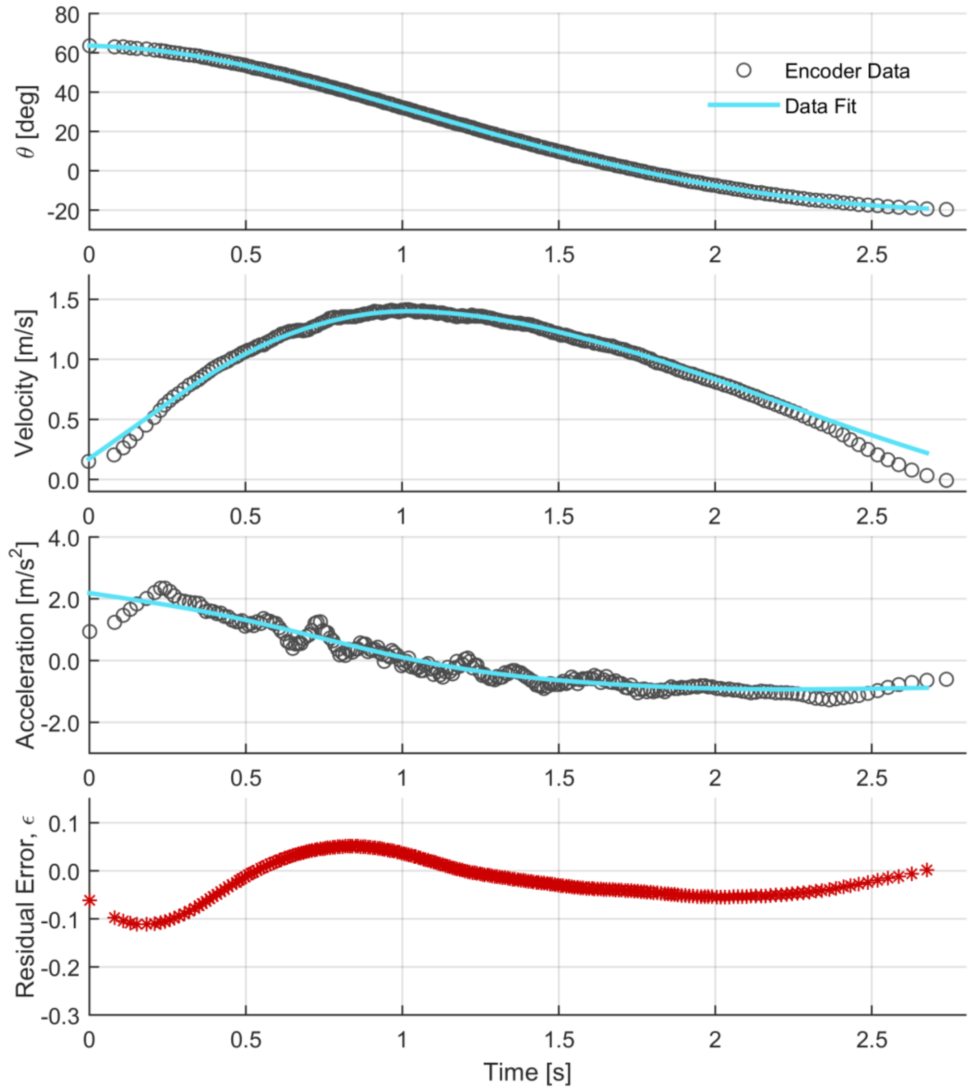


Pendulum test setup in the Oceanography test tank

- **Incremental angular encoder to measure pendulum angular position**
- **Labview interface to record encoder data and time**

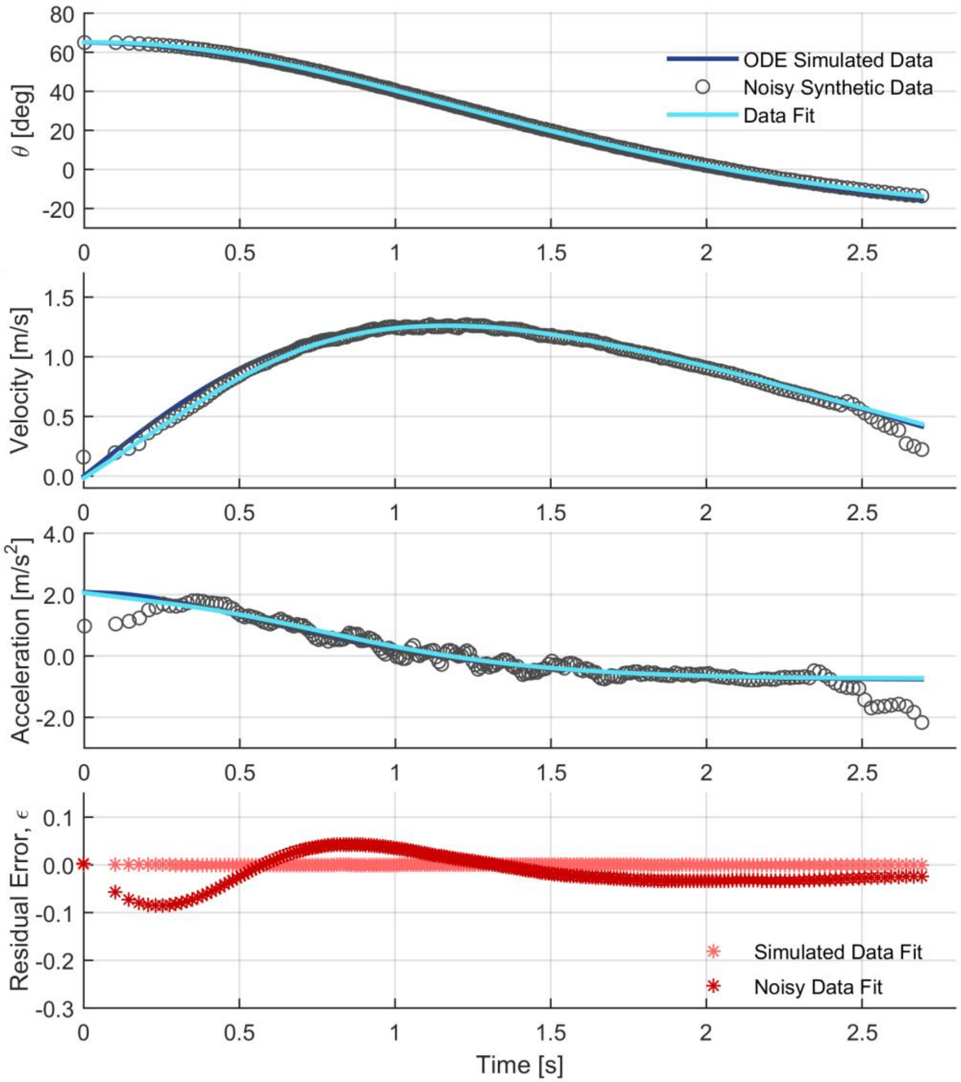
Pendulum Data Analysis

- **Collect 10 swings for each case**
- **Limit data window by velocity**
- **Spline fit to encoder data**
- **1st and 2nd order differentiation for velocity and acceleration**
- **Least squares regression to estimate *α* and *β***



Sample data from individual sphere swing

Synthetic Pendulum Data



Synthetic data with artificial noise

- **Test data processing method with synthetic data set and artificial noise**
  - Quantize data to simulate encoder output
  - Add initial decaying off axis oscillations
  - Add Gaussian noise
- **Added mass +6%**
- **Drag coefficient +3%**

Benchmark Geometries

- **Cube Results:**

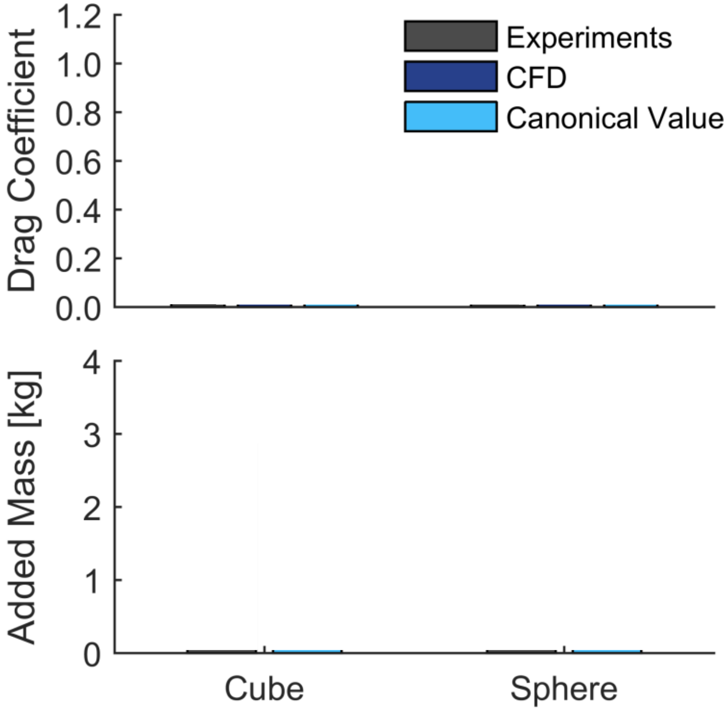
$C_d = 1.05$

$C_d = 0.690$

$C_d = 0.723 \pm 0.035$

$m_a = 0.7\rho a^3 = 2.4\ kg$

$m_a = 2.86 \pm 0.35$



- **Sphere Results:**

$C_d = 0.20$

$C_d = 0.197$

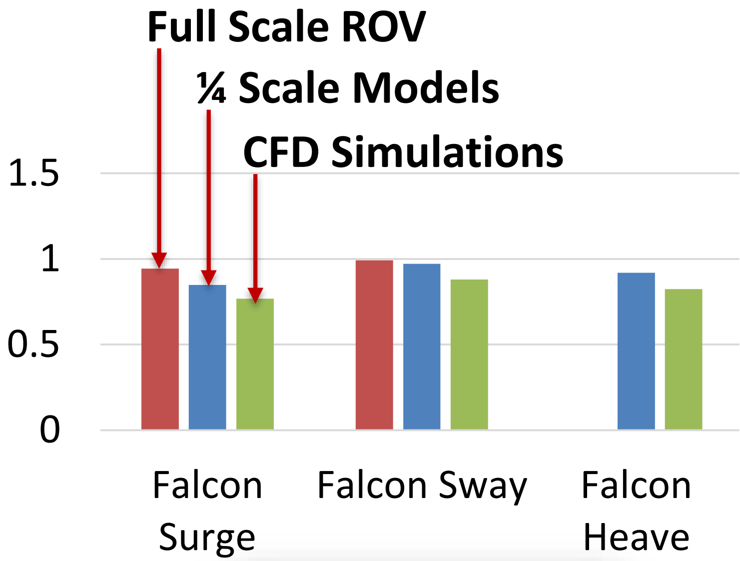
$C_d = 0.217 \pm 0.015$

$m_a = \frac{2}{3}\rho\pi r^3 = 2.7\ kg$

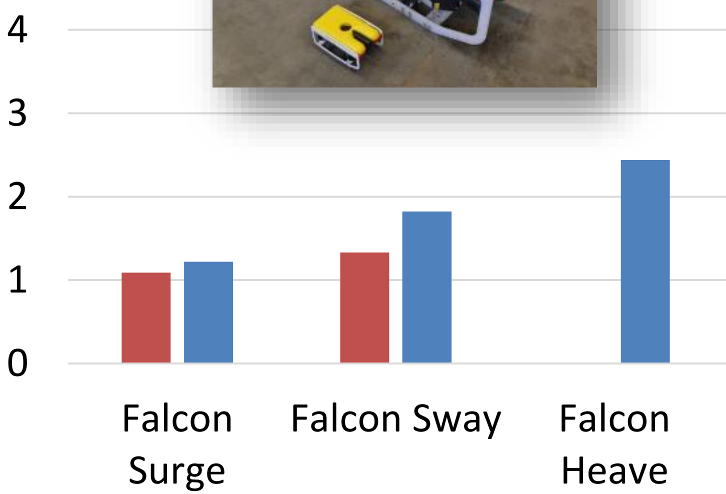
$m_a = 2.62 \pm 0.34$

Coefficient Results Summary

Drag Coefficients

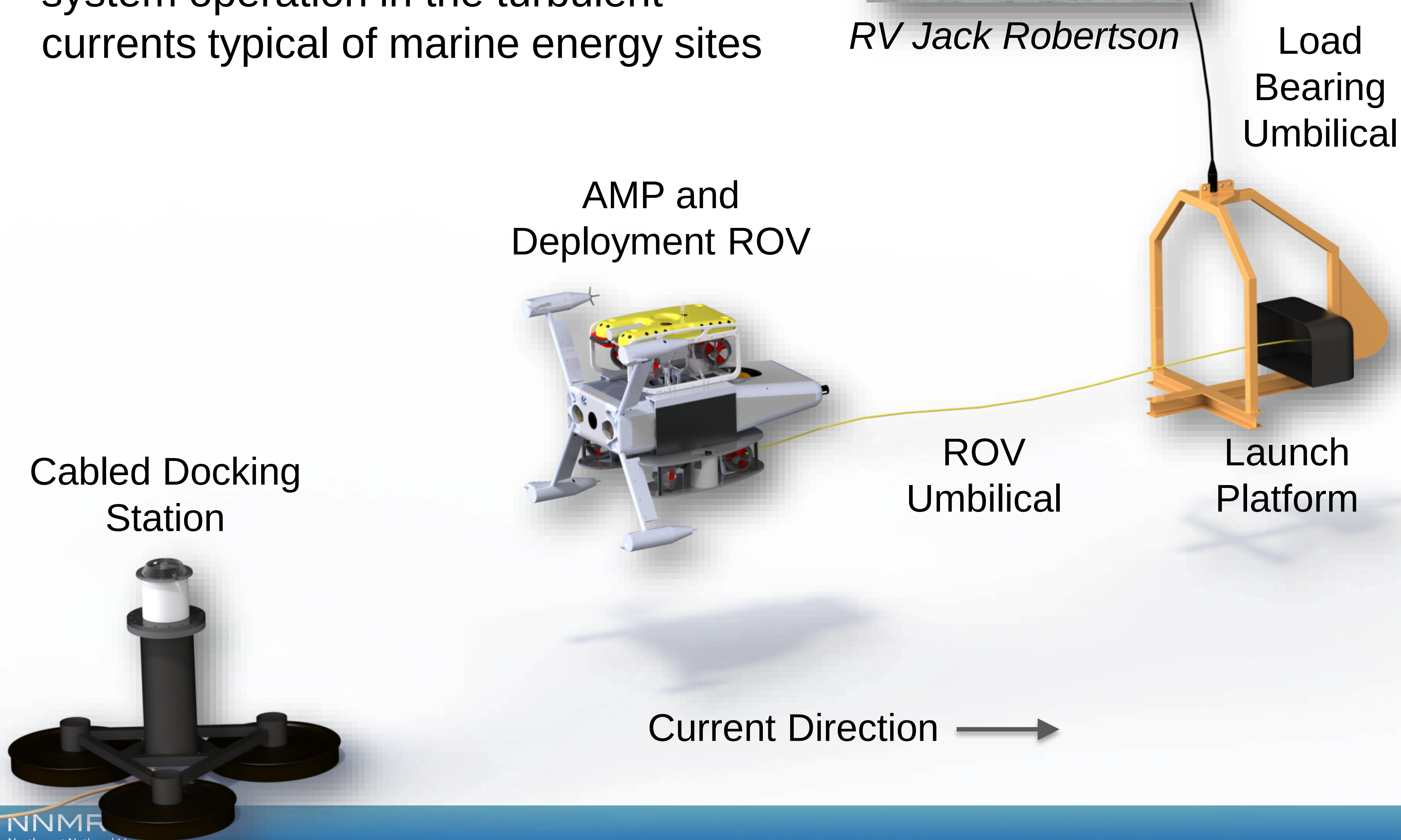


Added Mass Coefficients

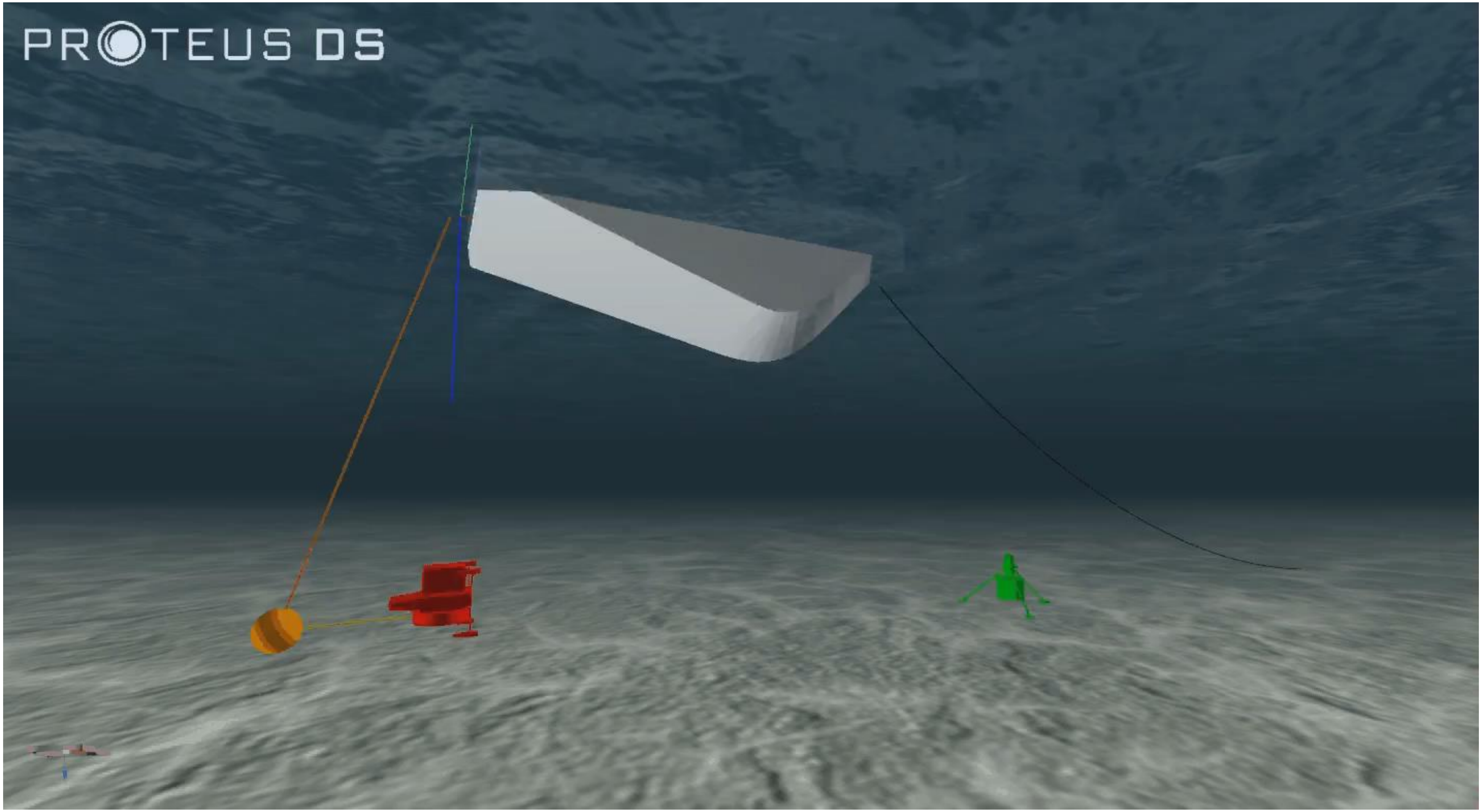


Dynamic Stability Analysis

Goal: Determine the stability limits for system operation in the turbulent currents typical of marine energy sites



Simulated AMP Deployment



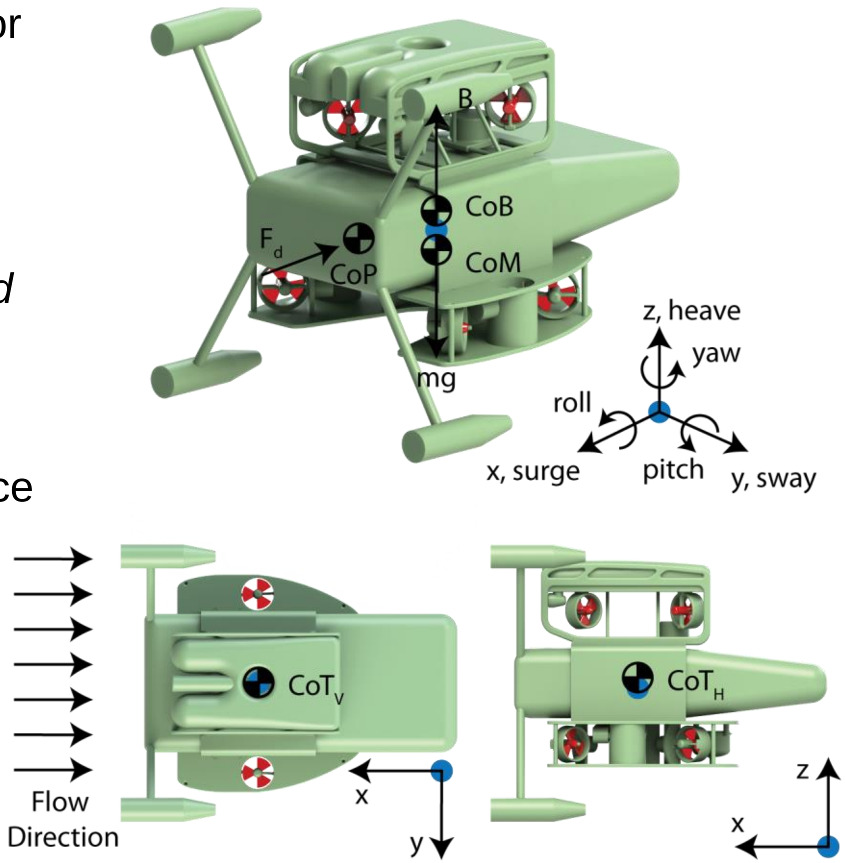
Dynamic simulation of AMP deployment from an anchored vessel with a launch platform in 1 m waves and 0.7 m/s mean turbulent currents (4x speed)

Dynamic Simulations

- **ProteusDS:** Time-domain dynamic simulator
- **System model:**
  - Surface mesh from simplified solid model
  - Inputs variables: C_a, C_d, *m, B, I,* F_{Tmax}, *and centers of mass, buoyancy, and thrust*
- **Fluid forces:** Drag and added mass forces summed for relative fluid motion on each surface polygon

$$f_d = \frac{1}{2}\rho C_d A_{proj} v^2 \qquad f_i = \rho C_a V_{disp} \dot{v}$$

- **Limitations:**
  - No fluid interaction calculations
  - Simplified hydrodynamic coefficients
  - Simplified thruster dynamics

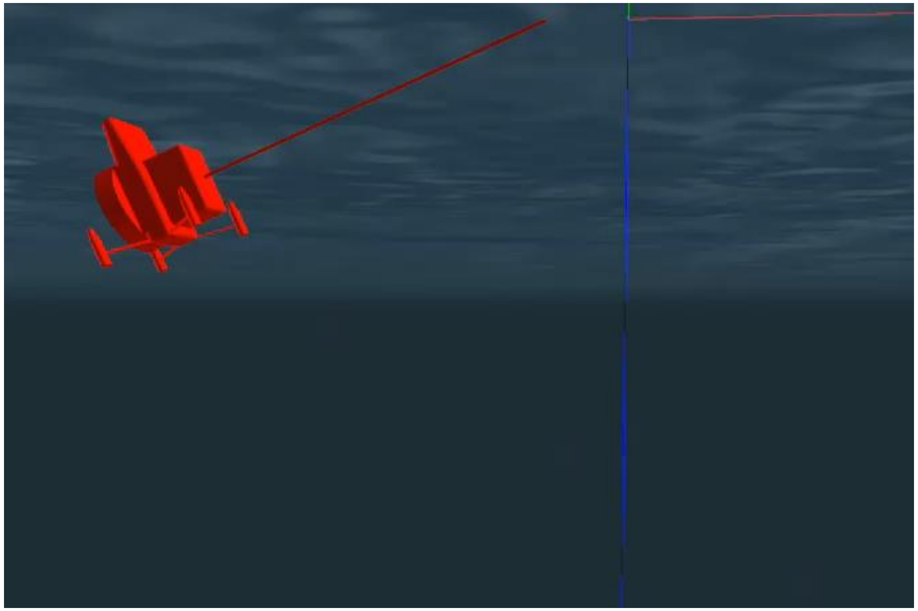


Simulation model free body diagram

Hydrodynamic Model Verification

- **Dynamic simulations of free-decay pendulum experiments to verify hydrodynamic coefficients:**

ProteusDS model

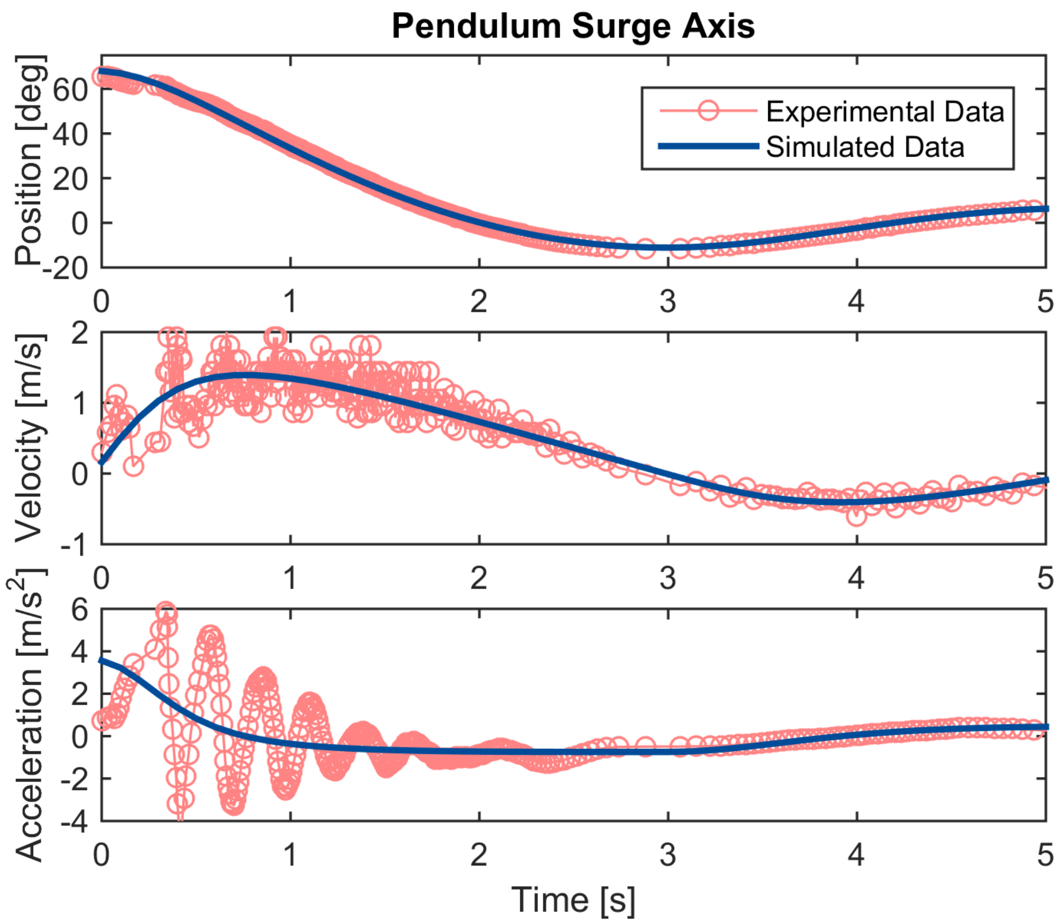


Simulated pendulum motion

Free-decay pendulum experiment

Hydrodynamic Model Validation

- **Comparison of simulation and experimental results:**



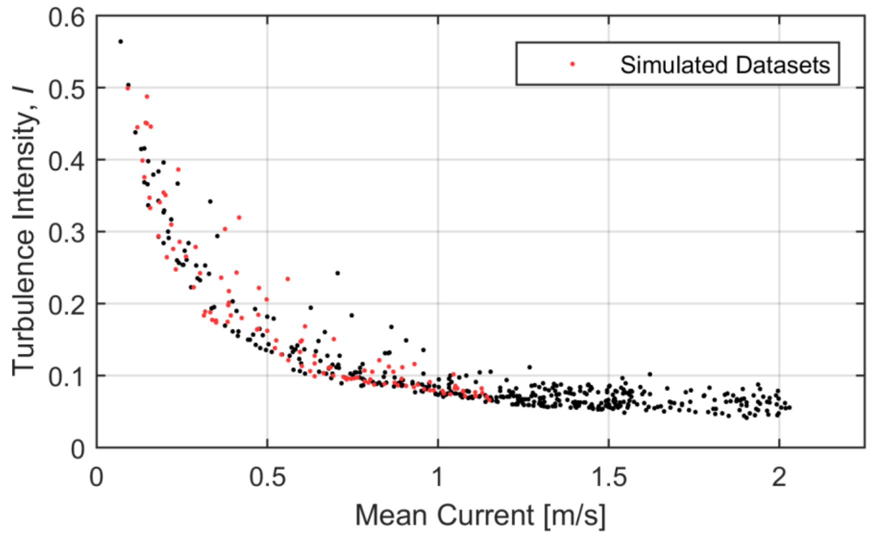
Simulated pendulum experiments

Turbulent Current Forcing

- **Data from tidal turbulence mooring deployment in Admiralty Inlet**
  - Corrected for mooring motion
  - Split into 5 minute bursts for consistent mean velocity
  - Binned by mean velocity: 0 to 1.1 m/s
  - Low-pass filter *u, v,* and *w components to constitute "engulfing gusts"*

$$f_c = \frac{\bar{u}}{L}$$

  - Where *L* = 1.5 is the system length scale

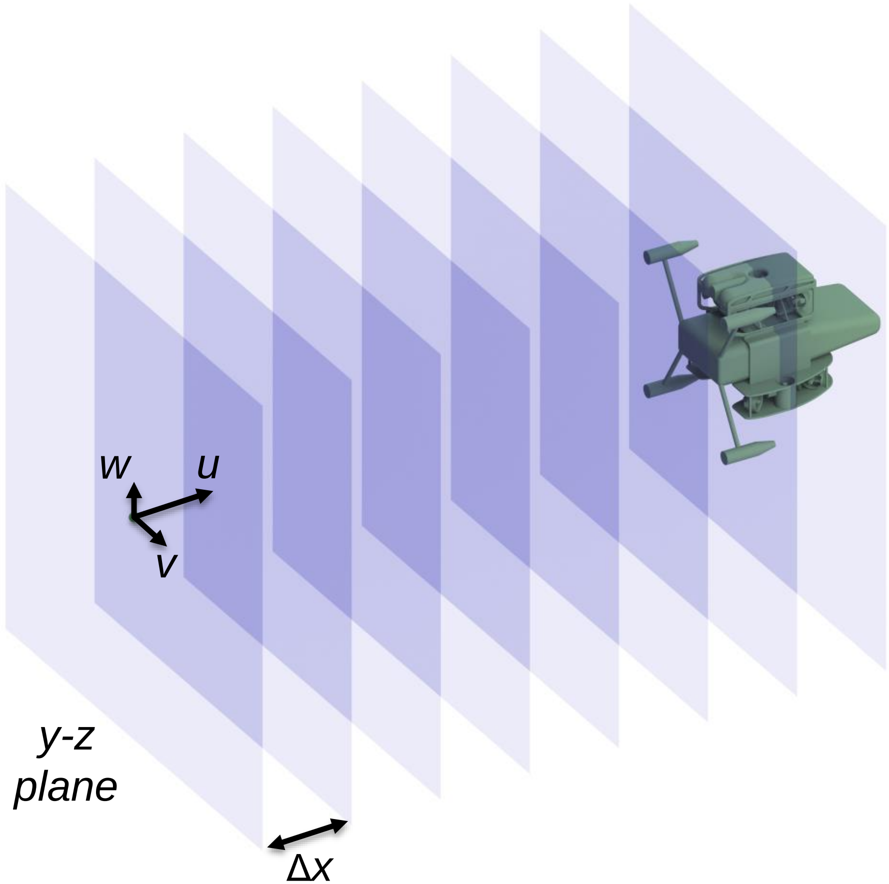


Admiralty Inlet turbulent current data

Turbulent Current Forcing

- **5 minute ADV files used to generate time-varying 3D current fields**

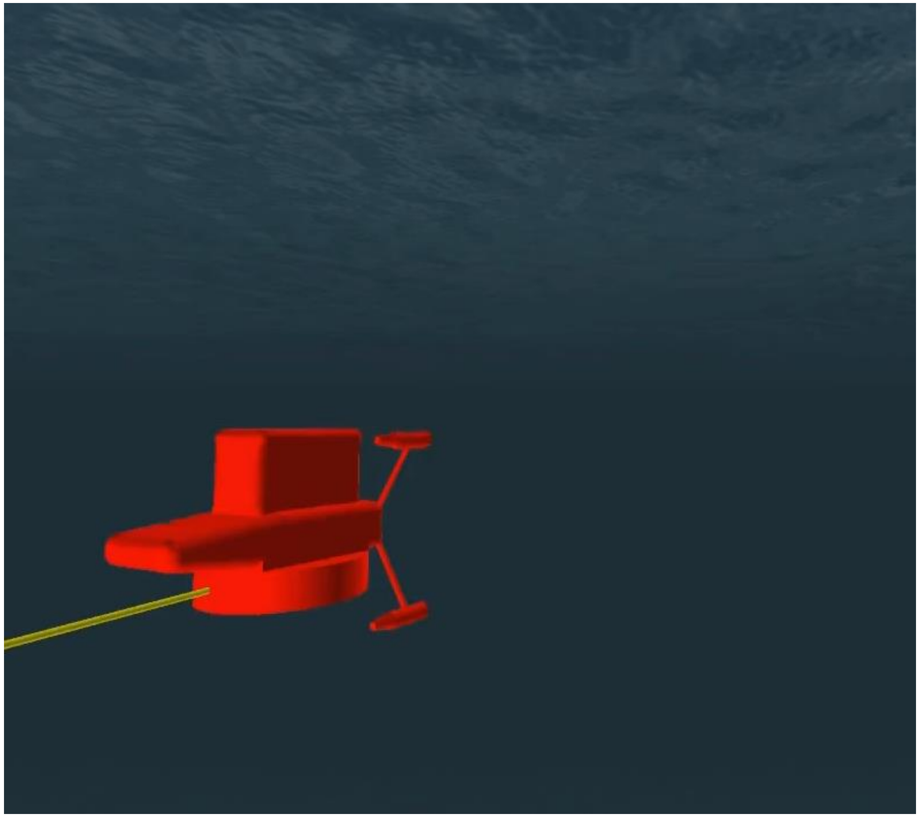
  - Define grid of *y-z* planes spaced by Δ*x* = 1 m
  - Assign *u*, *v*, and *w* current components to *y-z* planes
  - Propagate turbulence downstream at mean current velocity
  - ProteusDS linearly interpolates between planes and over time



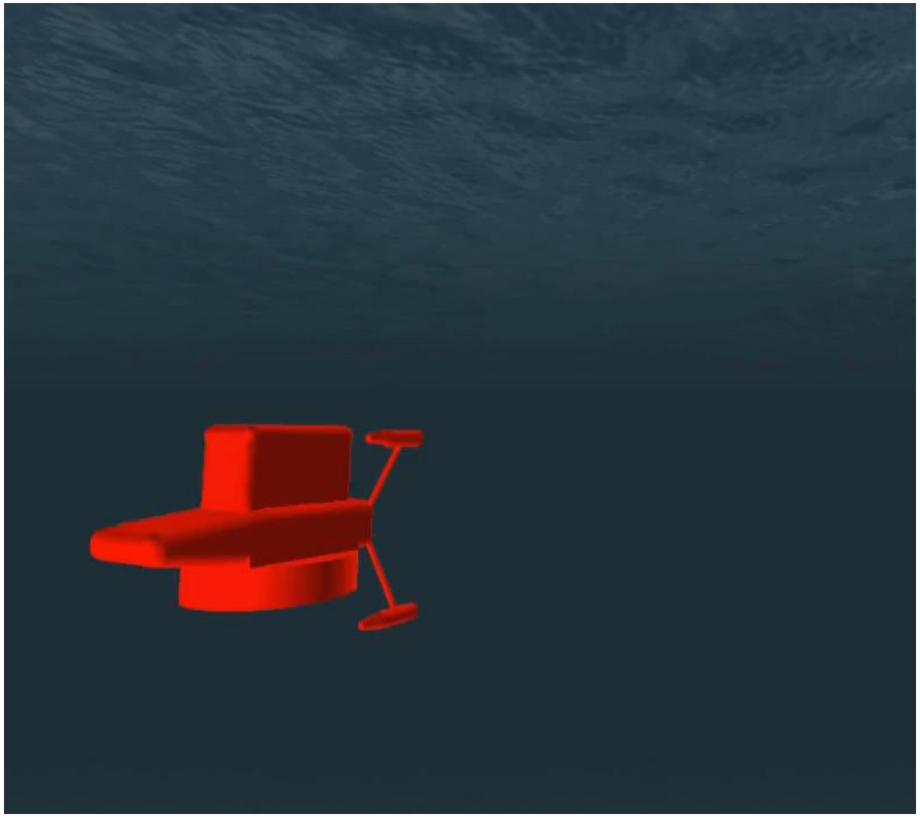
Time-varying "3D" current forcing

Simulated Operations

- **Simplified deployment operations with system driving against the turbulent current forcing**



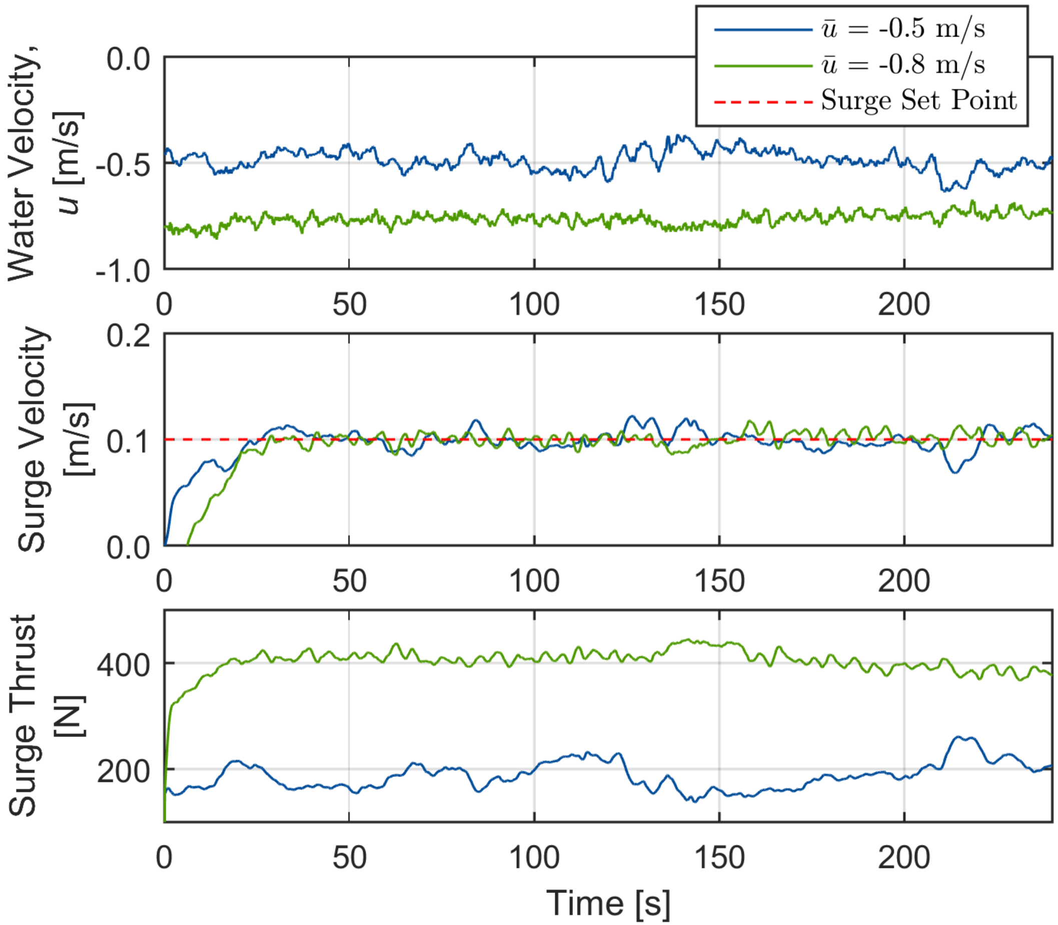
Simulation with umbilical (4x speed), Run time = 47 hrs



Simulation without umbilical (4x speed), Run time = 0.5 hrs

Navigation Controllers

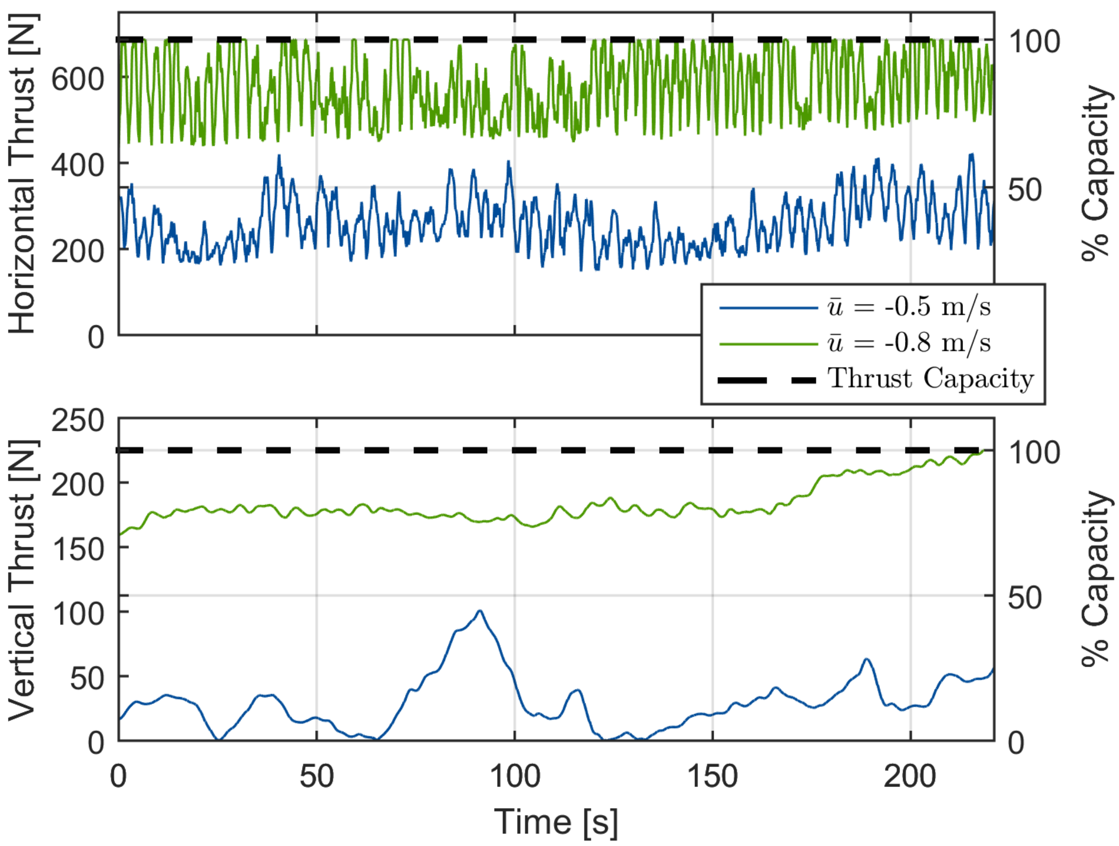
- **PID controllers for:**
  - Yaw (heading)
  - Surge (forward velocity)
  - Heave (depth)
- **Simulate thruster forces at centers of thrust**
- **Limited to ROV thrust capacity**
  - Horizontal thrust limit = 70 kgf
  - Vertical thrust limit = 22 kgf



Representative simulation data for surge controller

ROV Thrust Capacity

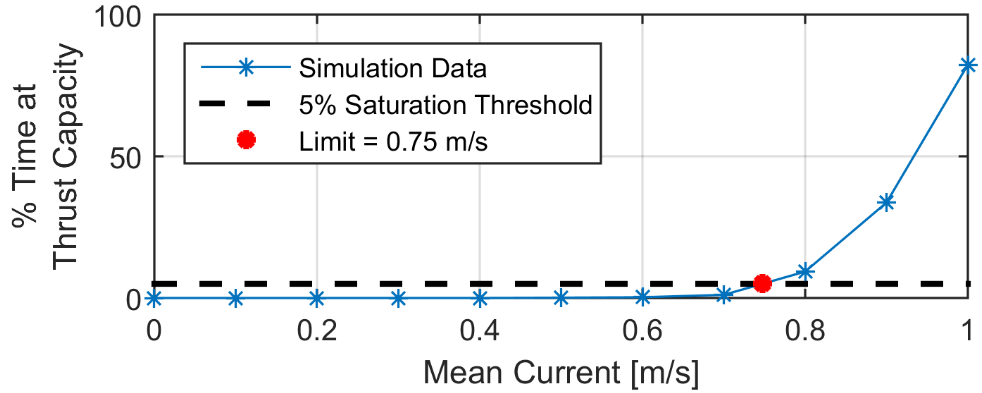
- **Horizontal thrust is the sum of the yaw torque and surge force**



Representative controller thrust forces for 0.5 and 0.8 m/s mean currents

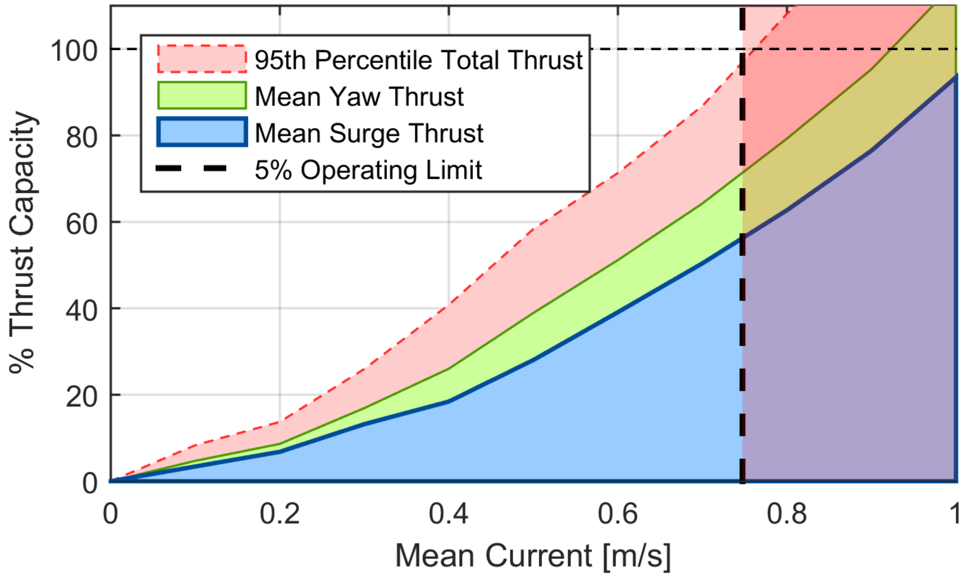
Operational Limits

- **Limit determined by a 5% threshold for thrusters operating at capacity**



Thruster time operating at capacity for simulations without the umbilical

- **Predicted limits:**
  - 0.75 m/s without umbilical
  - 0.74 m/s with umbilical



Horizontal thrust allocation to yaw and surge

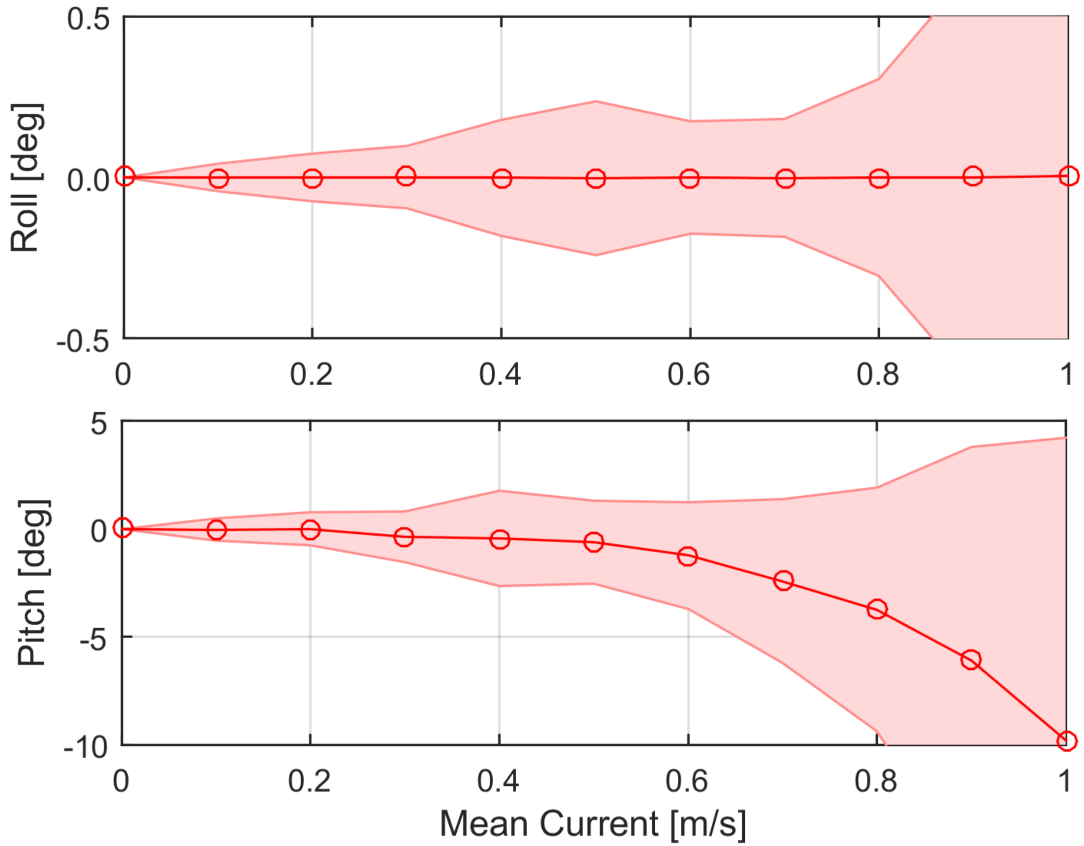
- **Thrust allocation:**
  - Without umbilical: 21% yaw, 79% surge
  - With umbilical: 19% yaw, 81% surge

Passive Stability

- **Pitch and roll stability maintained by buoyant righting moment**

- Less than ± 0.5° roll at the operational limit

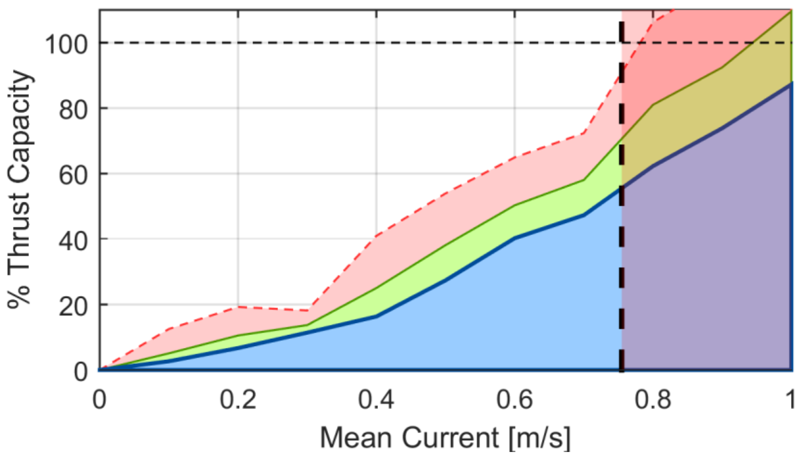
- 3.3° forward pitch due to offset between centers of thrust and pressure



Passive stability from simulations without the umbilical

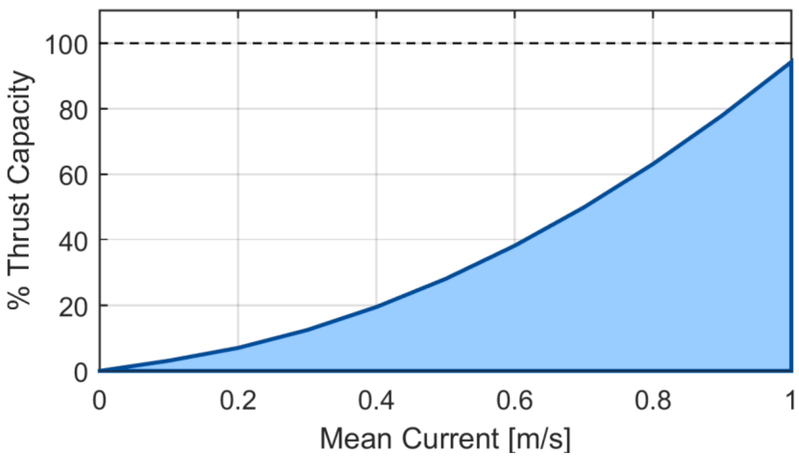
Parameter Sensitivity Studies

- **Mesh resolution, turbulence length scale filtering, and controller update rate:**
  - < 6.7% (0.05 m/s) difference in predicted limit
  - < 10% difference in thrust allocation



Baseline simulation thrust allocation

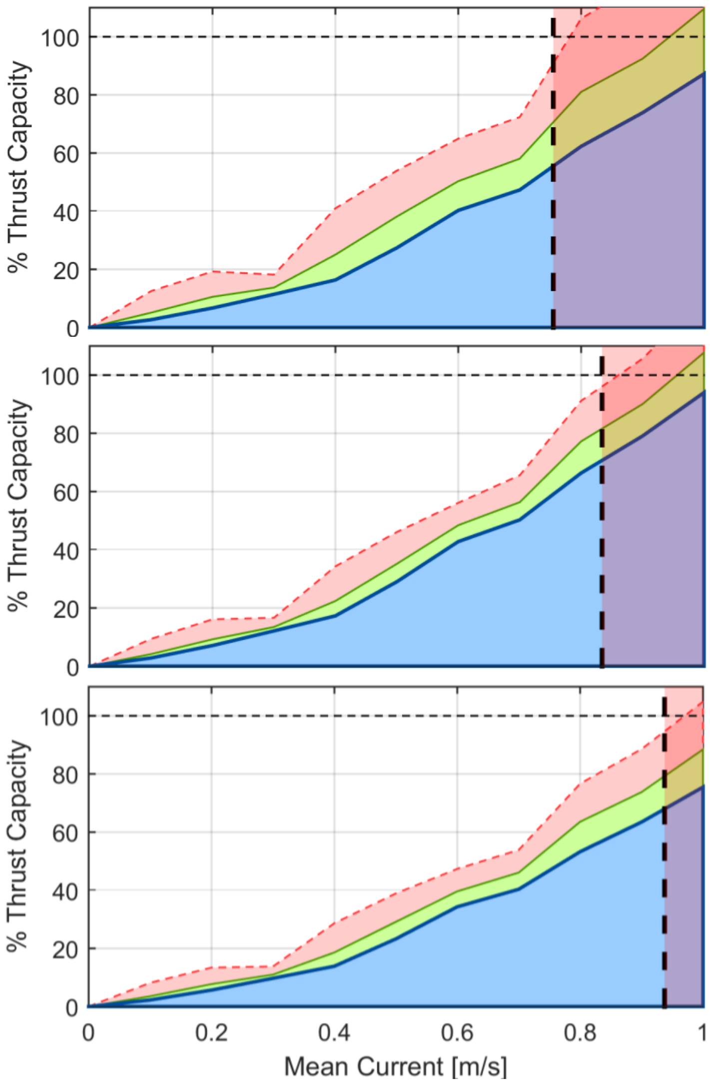
- **Uniform current fields:**
  - 35% (0.26 m/s) over prediction in current limit
  - No allocation for yaw thrust
  - No variation in control forces



Simulation thrust allocation without turbulence

Parameter Sensitivity Studies

- **Hydrodynamic coefficients:**
  - Measured values
  - CFD estimates (drag only)
  - Canonical values
- **Canonical Values:**
  - 11% (0.08 m/s) increased limit
  - Under predicted yaw control and variation
- **Worst Case:**
  - CFD for drag and canonical values for added mass
  - 25% (0.19 m/s) increased limit
  - Under predicted yaw control and variation



Simulation thrust allocation

Dynamic Analysis Conclusions

- **Deployment limit of 0.7 m/s**
- **"Inspection"-class ROV operations at marine energy sites**
- **Turbulence effects are non-negligible in these environments**
- **Hydrodynamic coefficients measurements through free-decay pendulum motion**
- **2 pending publications**

Joslin, J., B. Polagye, and A. Stewart(in review) Hydrodynamic coefficient determination for an open-framed underwater vehicle, *J. Ocean Eng.*

Joslin, J., B. Polagye, A. Stewart, and B. Fabien (in prep) Dynamic Simulation of a Remotely-operated Underwater Vehicle in Turbulent Currents for Marine Energy Applications.

Summary

- **AMP and Millennium Falcon development**
- **Optical monitoring capabilities for marine energy converters**
- **Hydrodynamic coefficient measurements**
- **Dynamic stability and operational limits in turbulent currents**

System Deployment from the R/V Jack Robertson

What's Next?

- **AMP and Millennium Falcon field testing**
- **Instrument integration and algorithm development**
- **Autonomous deployment capabilities**
- **Benchmarking simulated performance against field performance**
- **MarineSitu spin off to provide marine monitoring services to industry developers**

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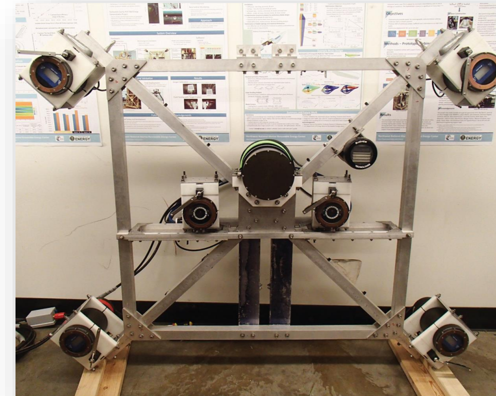
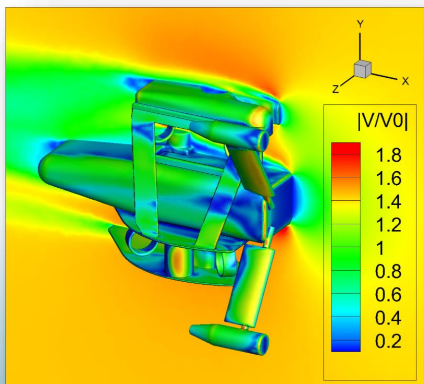


Thank You



Questions?

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