Energy Harvesting and Autonomous Underwater Vehicle docking for a Persistent Presence of Oceanographic Instrumentation

Andrew Hamilton

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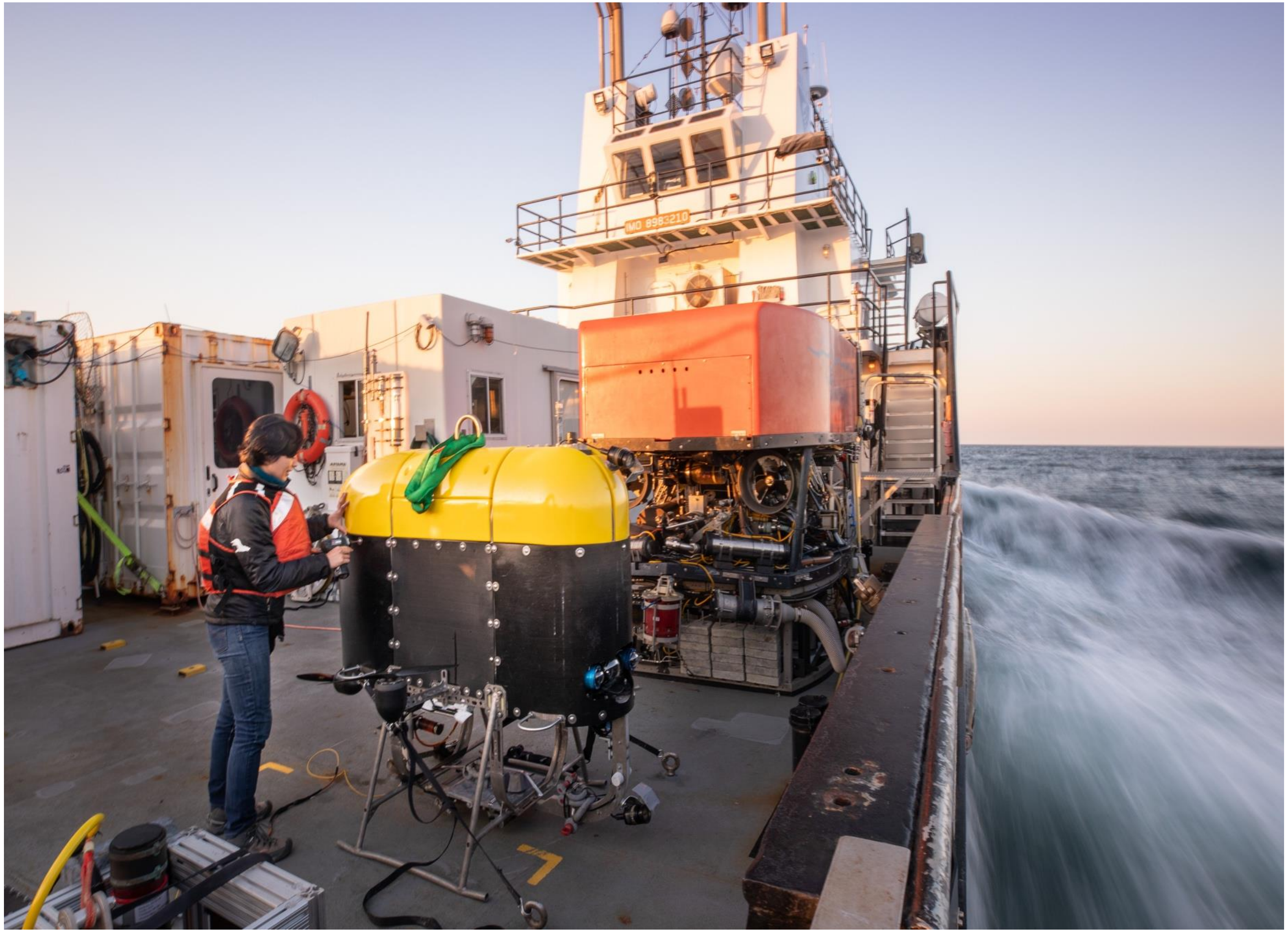

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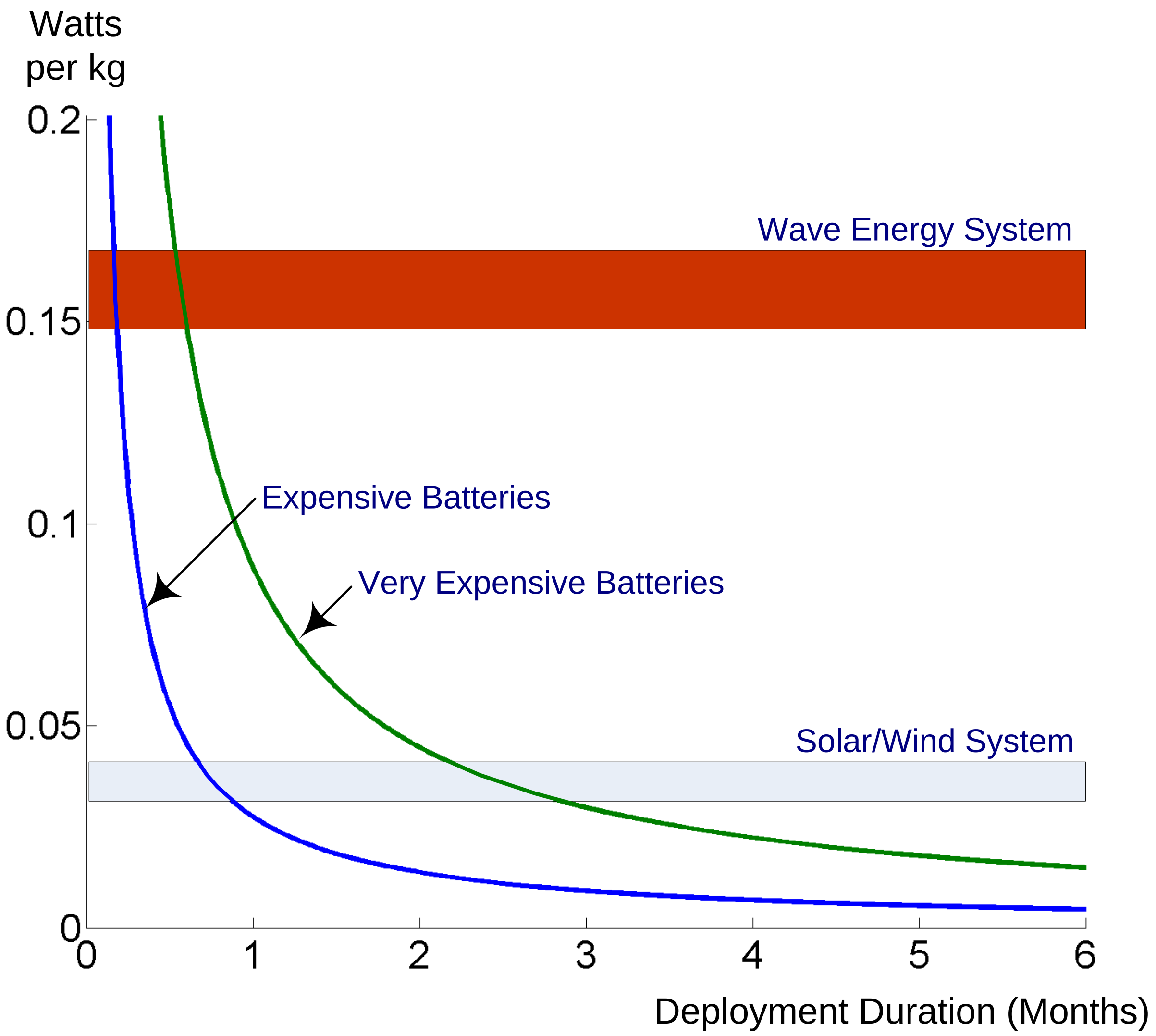
Persistent Presence

Technology needed:

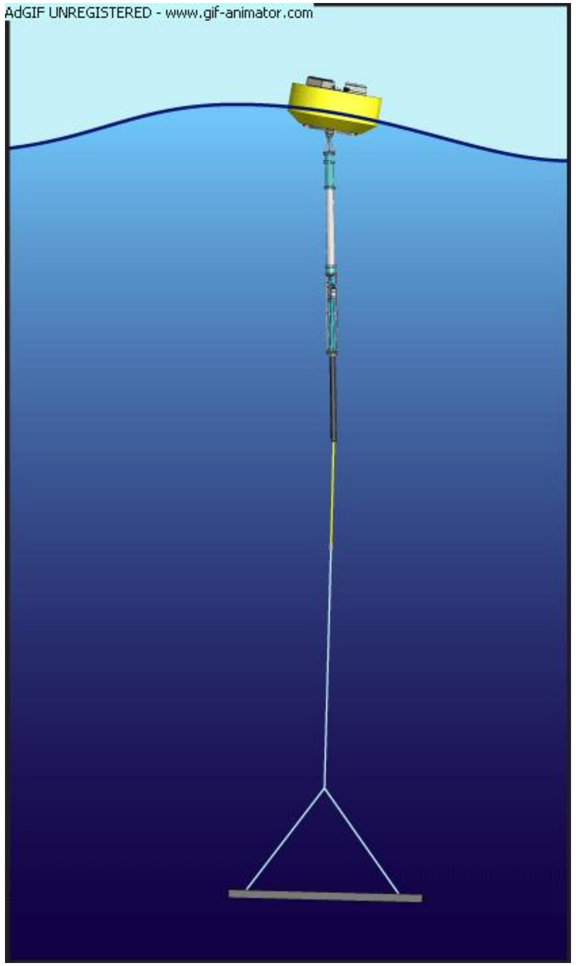
- Vehicles (Capability, Reliability)
- Autonomy
- Instrumentation
- **Energy**
- Communications

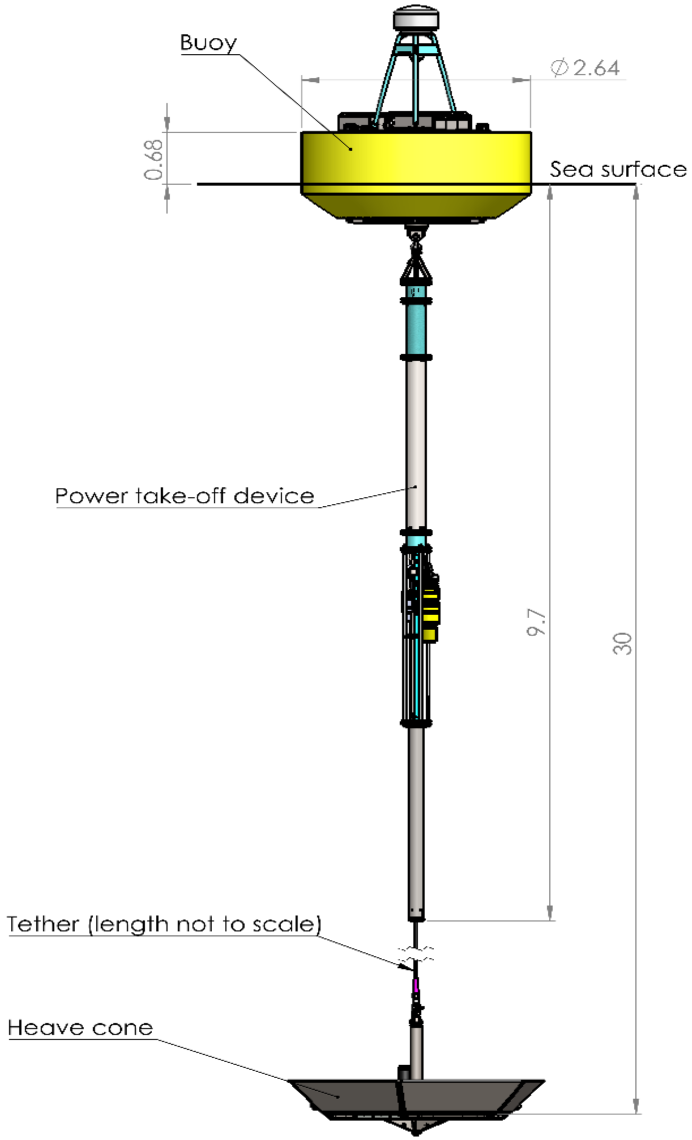


Energy Options:

- Bring energy along (in batteries).
- Collect energy from the environment.

MBARI Wave-Energy Converter



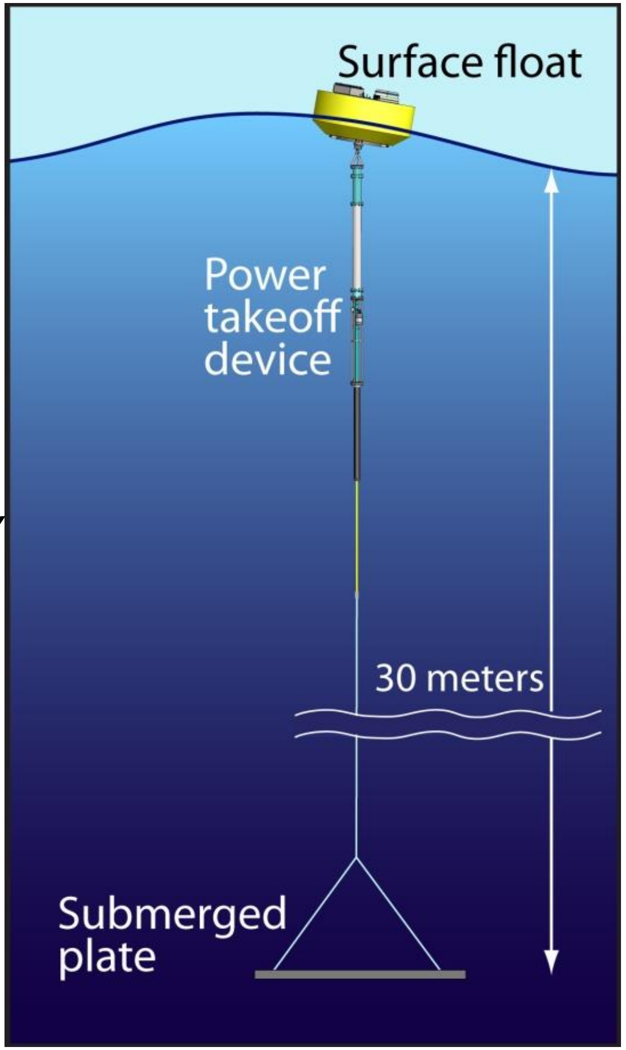


MBARI Mooring with
Wind and Solar Collection:

Weight	Avg. Power
5000lbs	50W

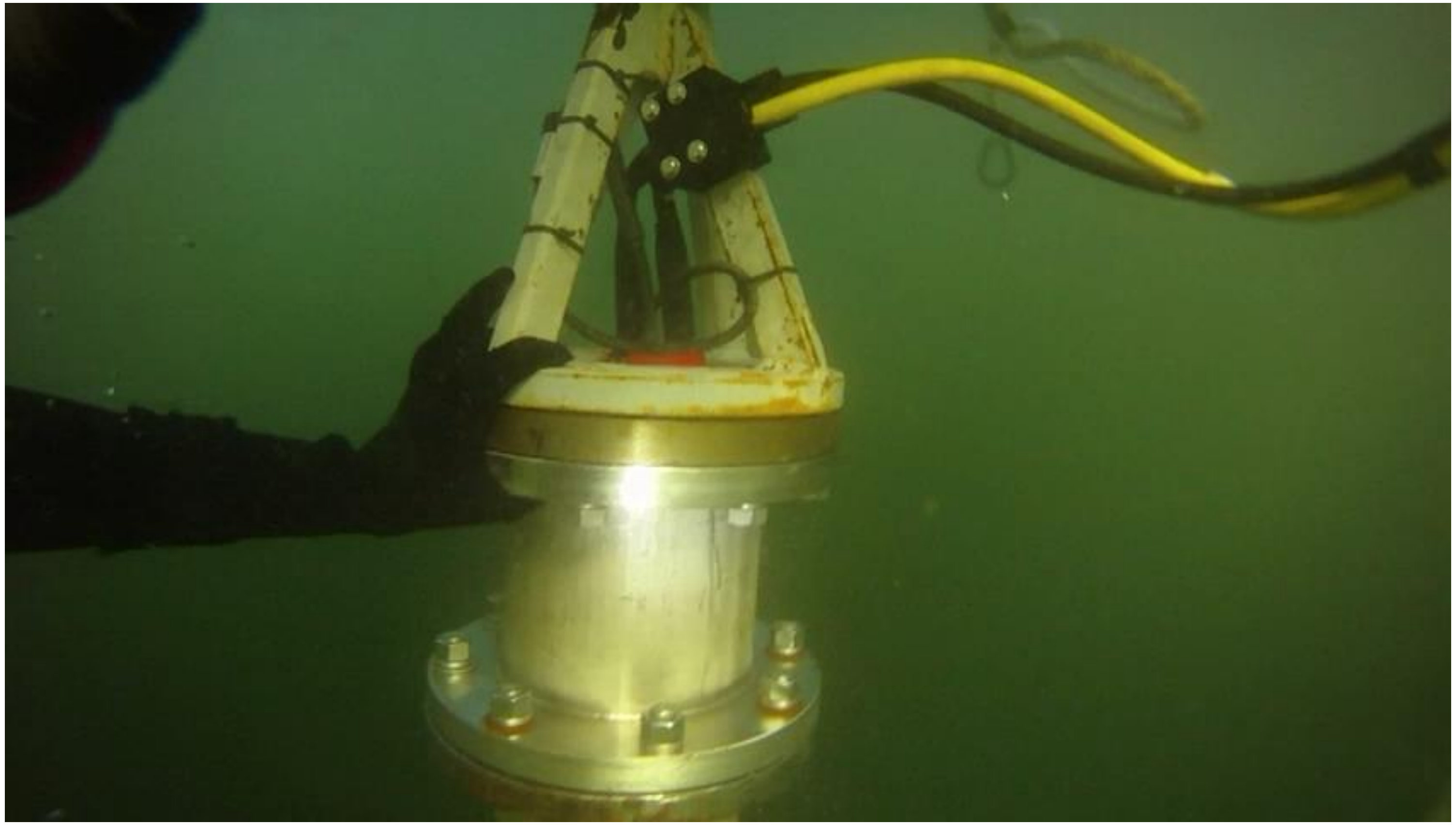
Wave Power Buoy Prototype

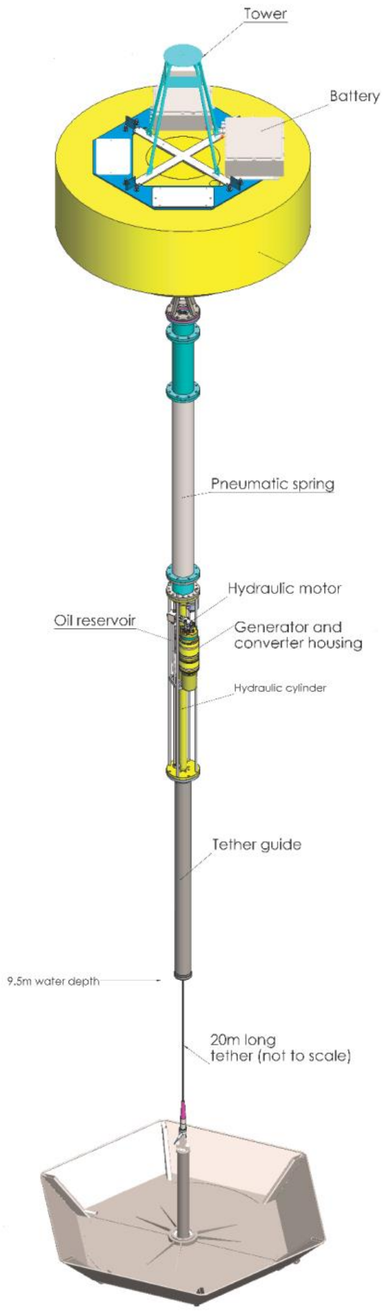
Weight	Avg. Power
5000lbs	200W-300W



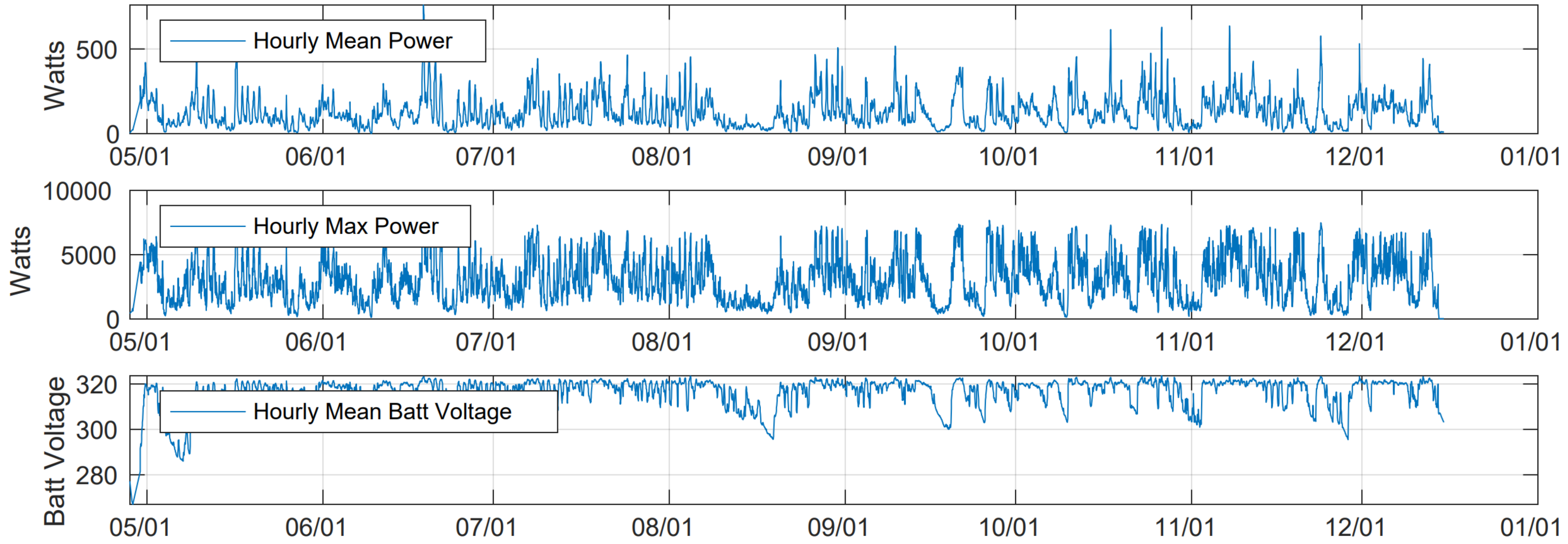
Oceanographic WEC

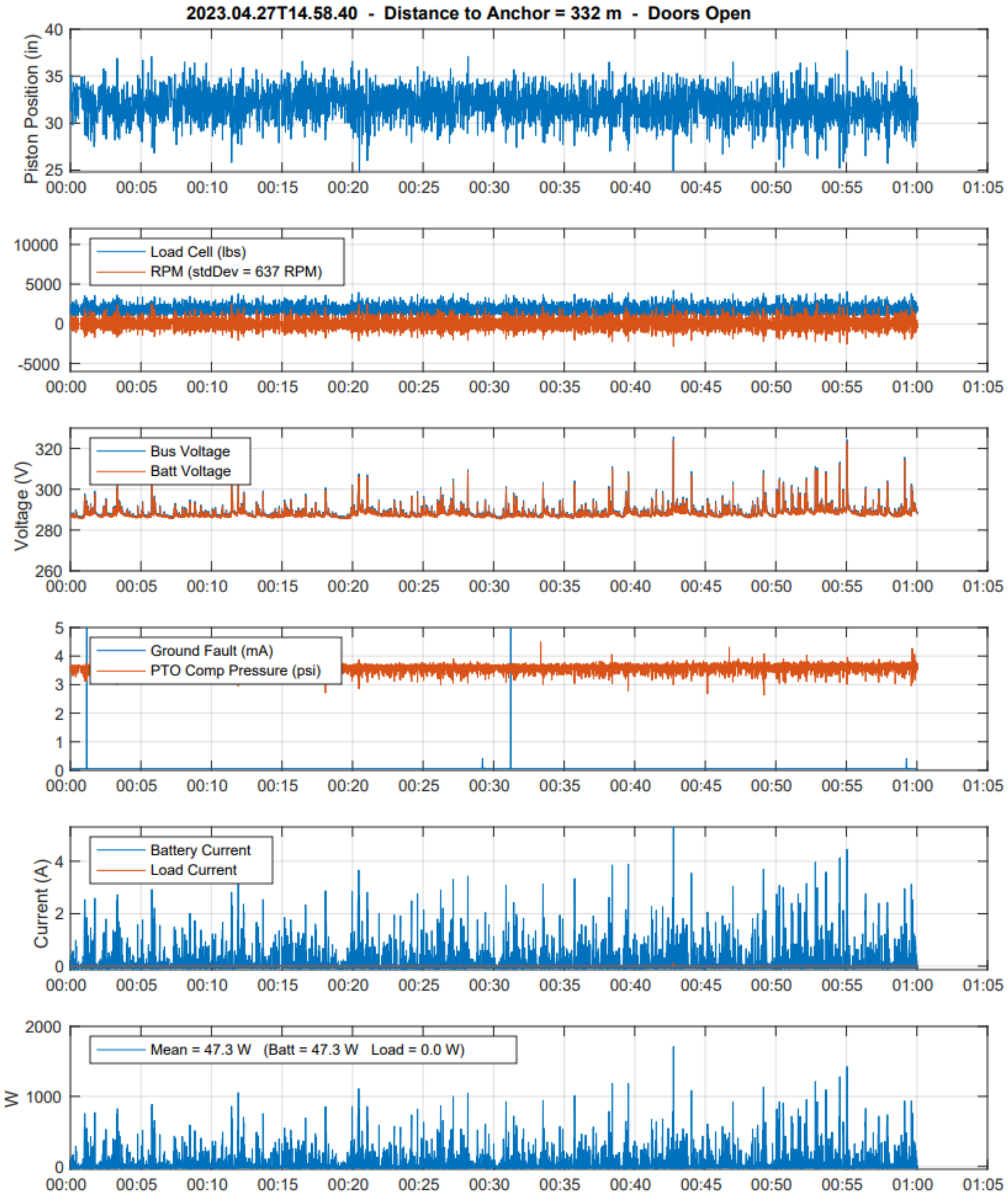
- 10’ diameter Buoy
- 200W Average
- Regular Deployments





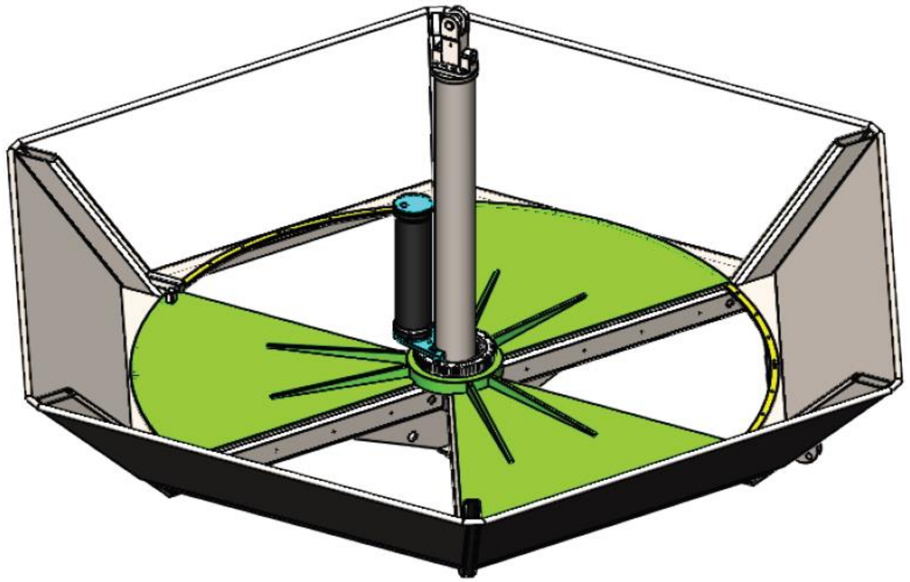
2023 Deployment - 232 Days

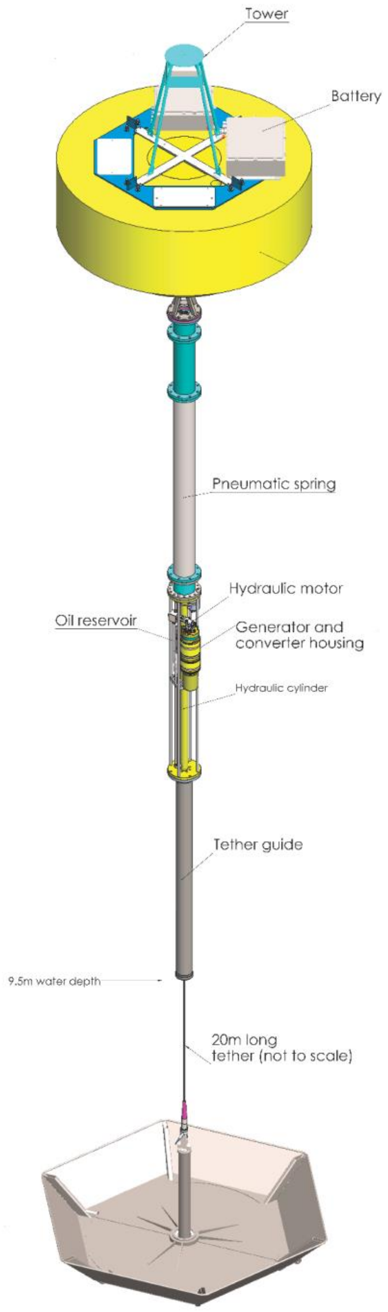



2023.04.27T14.58.40 - Distance to Anchor = 332 m - Doors Open
Piston Position (in)
Load Cell (lbs)
RPM (stdDev = 637 RPM)
Voltage (V)
Bus Voltage
Batt Voltage
Ground Fault (mA)
PTO Comp Pressure (psi)
Current (A)
Battery Current
Load Current
W
Mean = 47.3 W (Batt = 47.3 W Load = 0.0 W)

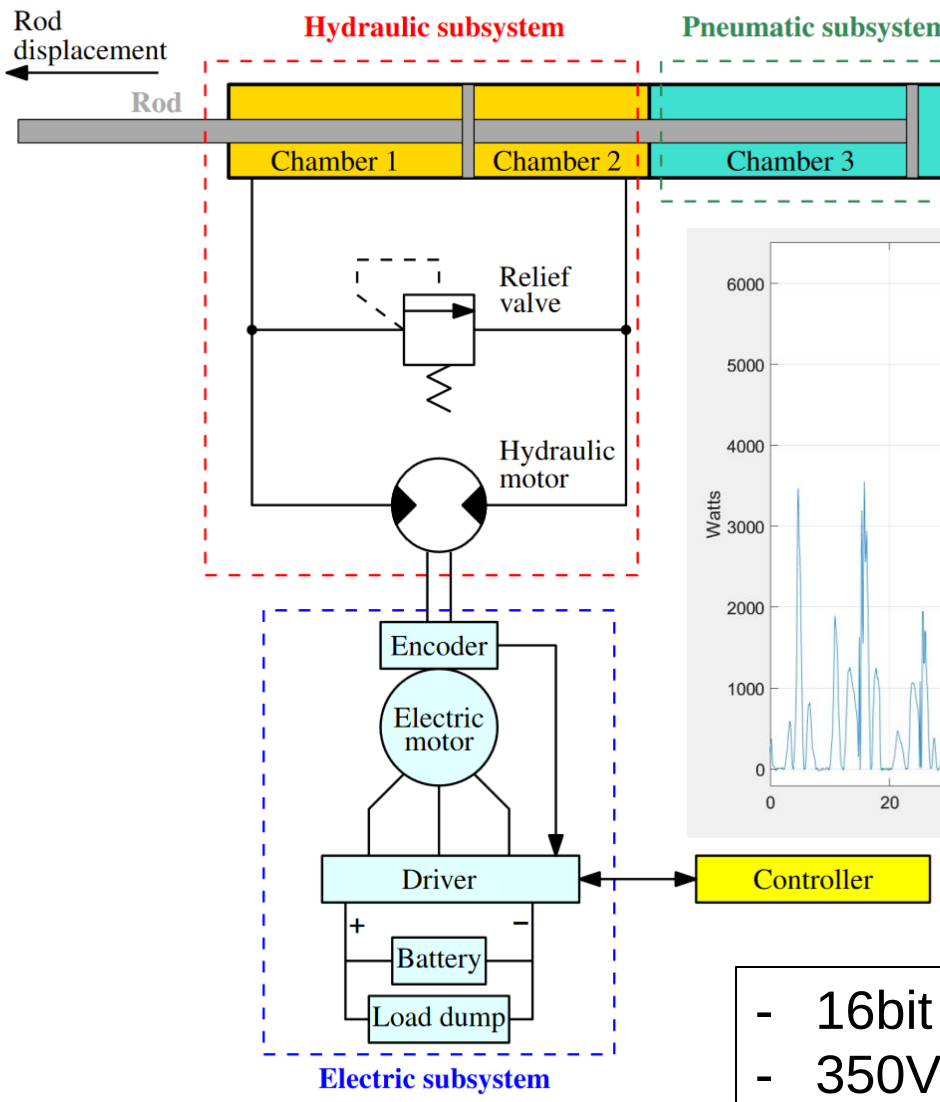
Some design features

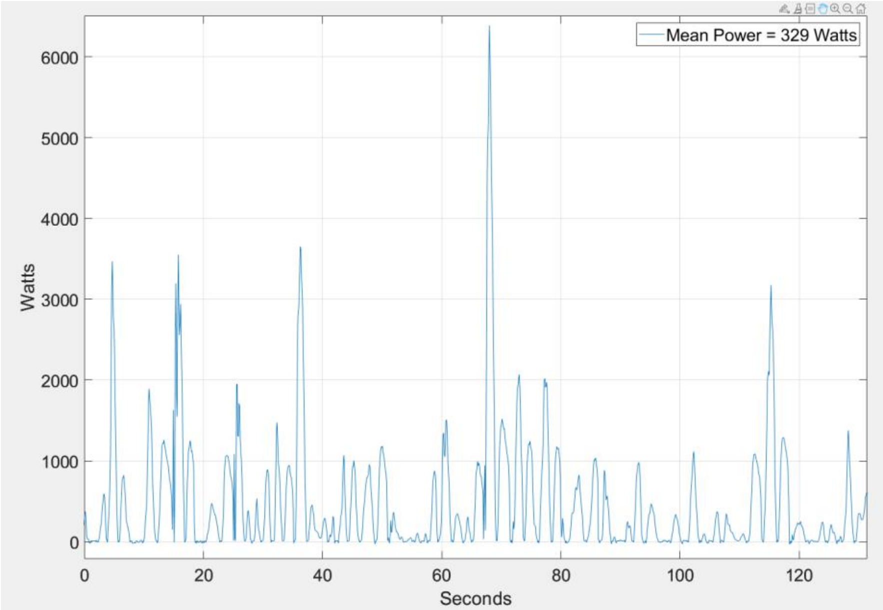
- Electro-Hydraulic PTO and Pneumatic Spring
- Heave-Cone w/ Trefoil doors
- 4-Quadrant Power Electronics, 10kW motor/drive.
- 6kW-Hr On-board Battery
- 24V Power Supplies and Ethernet Network (instruments)
- Linux Control Computer and Cell Connection





Custom Power Electronics





- 16bit DSP based controller
- 350V Bus, 35A Winding Current
- 10 kW Device

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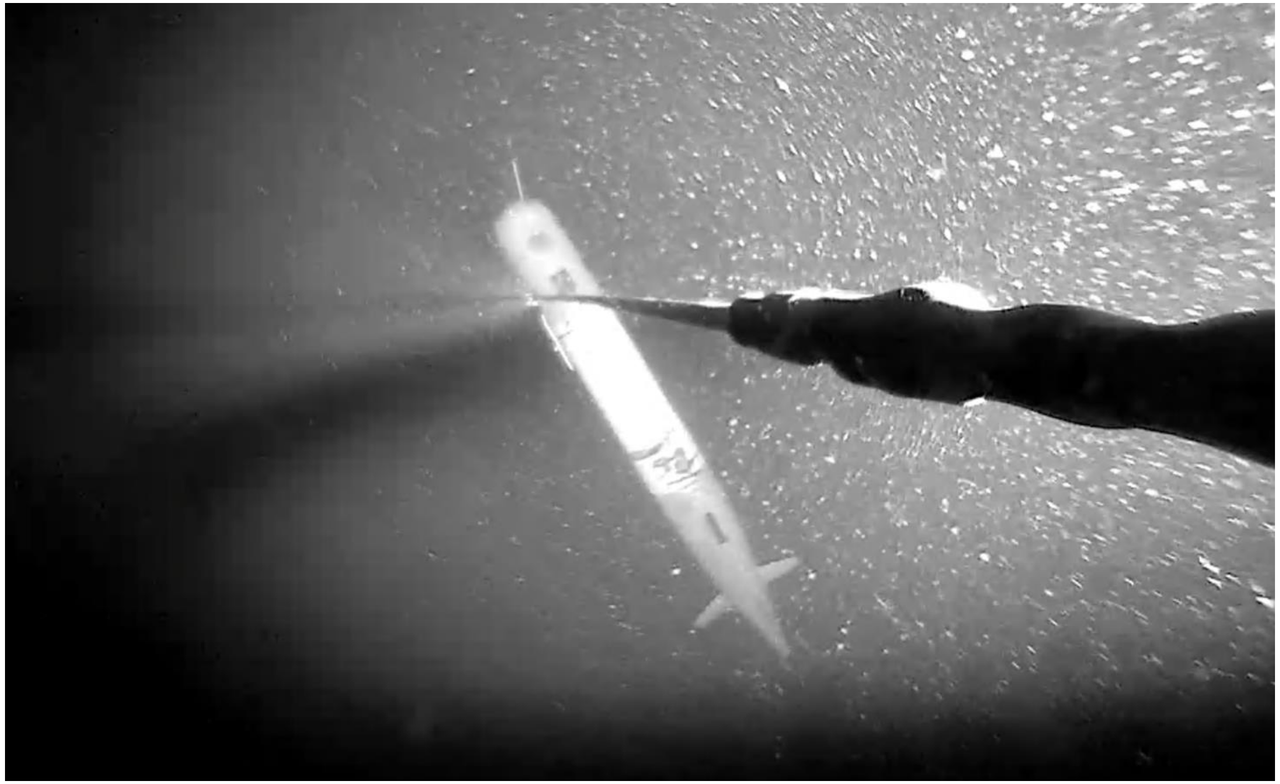
What is 200 Watts Continuous Used For?

On buoy instrumentation

- Unusual that typical instrumentation requires hundreds of watts
- Some exceptions: Imaging Flow CytoBot

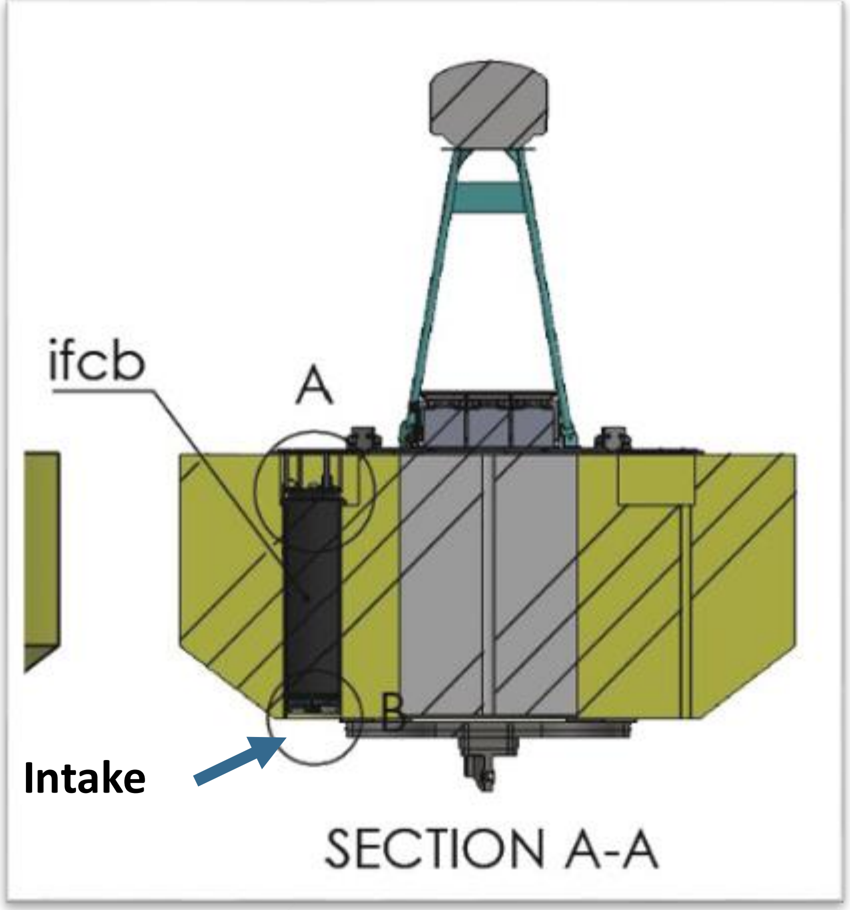
Autonomous vehicle re-charge

- Requires docking capabilities
- Fleets of vehicles



Imaging Flow Cytobot On Wave-Energy Buoy (2022, 2023, 2024)

Photo: McLane



Sampling freq: 20-30 mins

Sampling Vol: ~5 ml

Size Range: <10 µm to 150 µm

Image Resolution: ~ 3.4 pixels/micron

1000s of images generated every hour

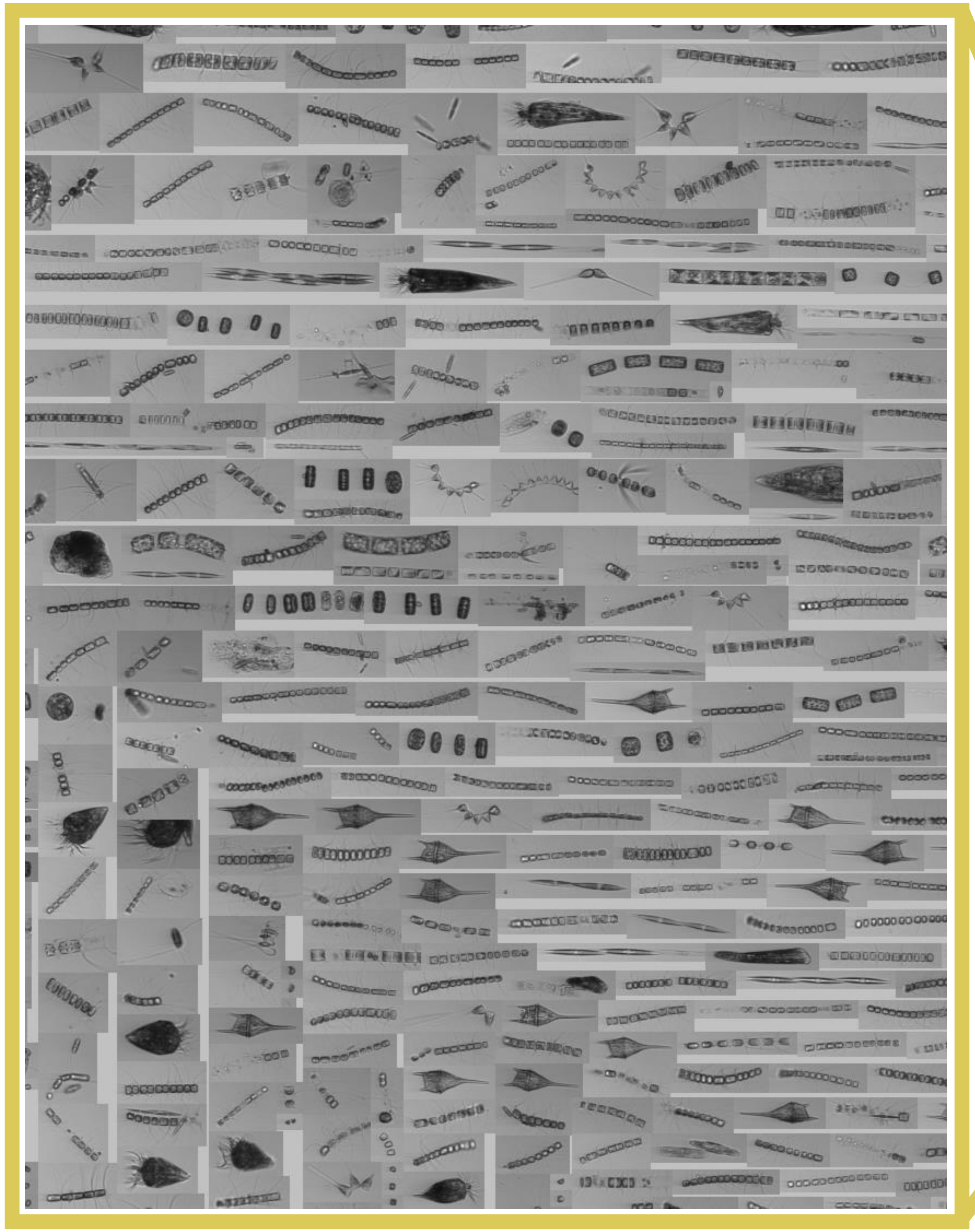
Over 190 days of Operation

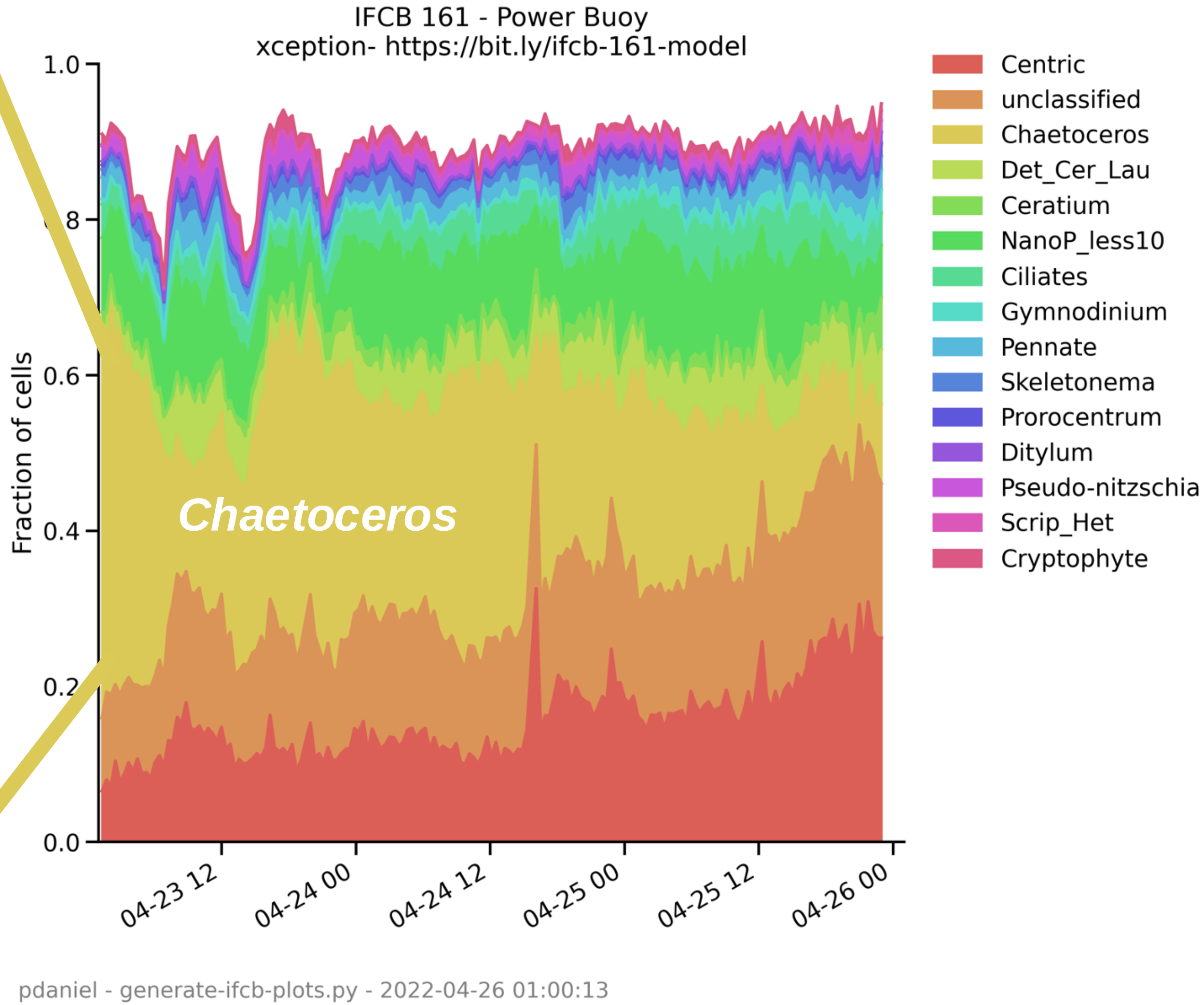
~ 190 Gb of images

~ 45 Watts

Patrick Daniel (Kudela Lab / UCSC)

Chaetoceros Bloom





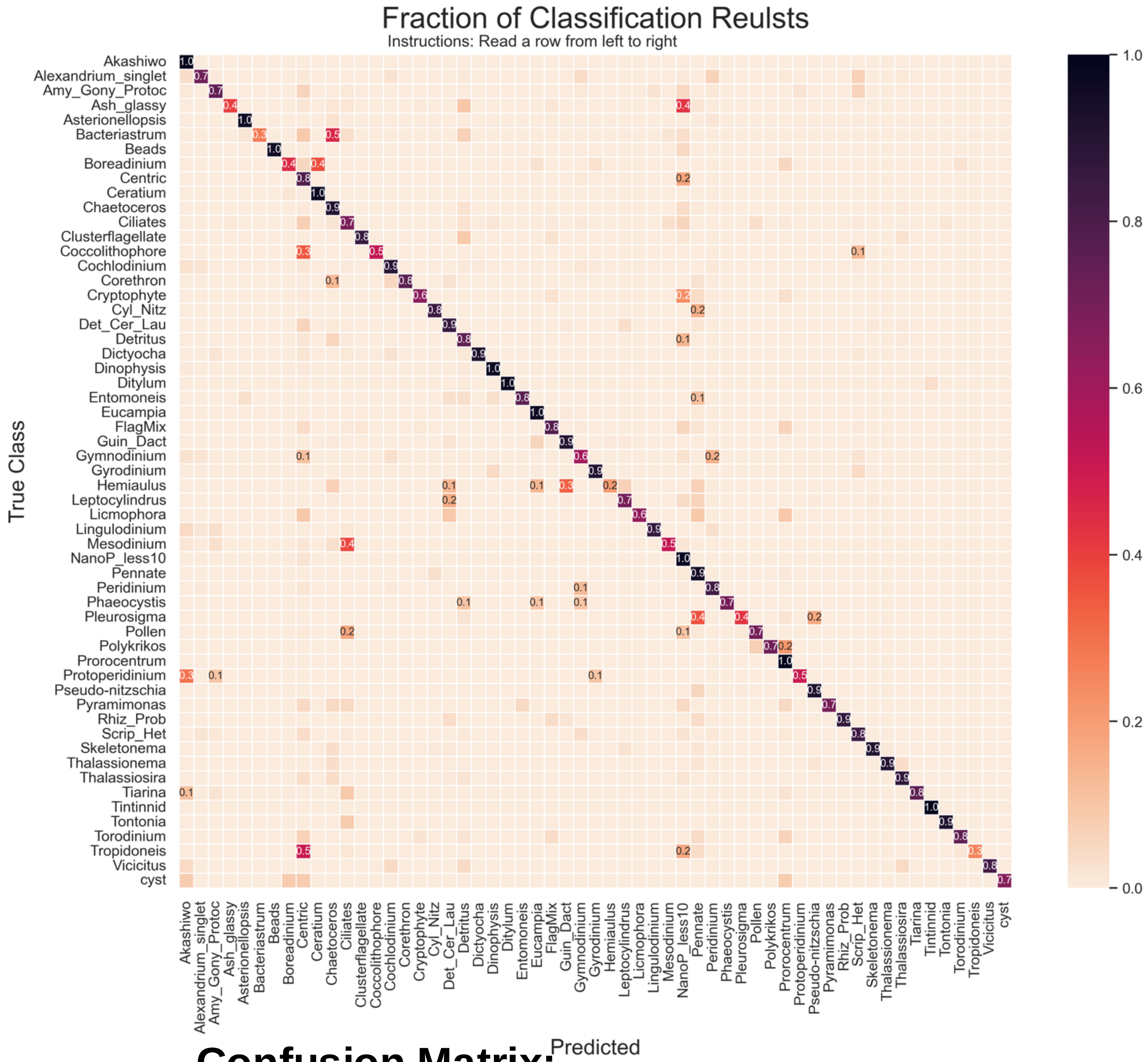
Machine Classifier

51 class CNN (Xception)

100k + manually classified images

Work in progress…

Accuracy (f-1 score) = .93



Confusion Matrix:

True images vs Class Prediction

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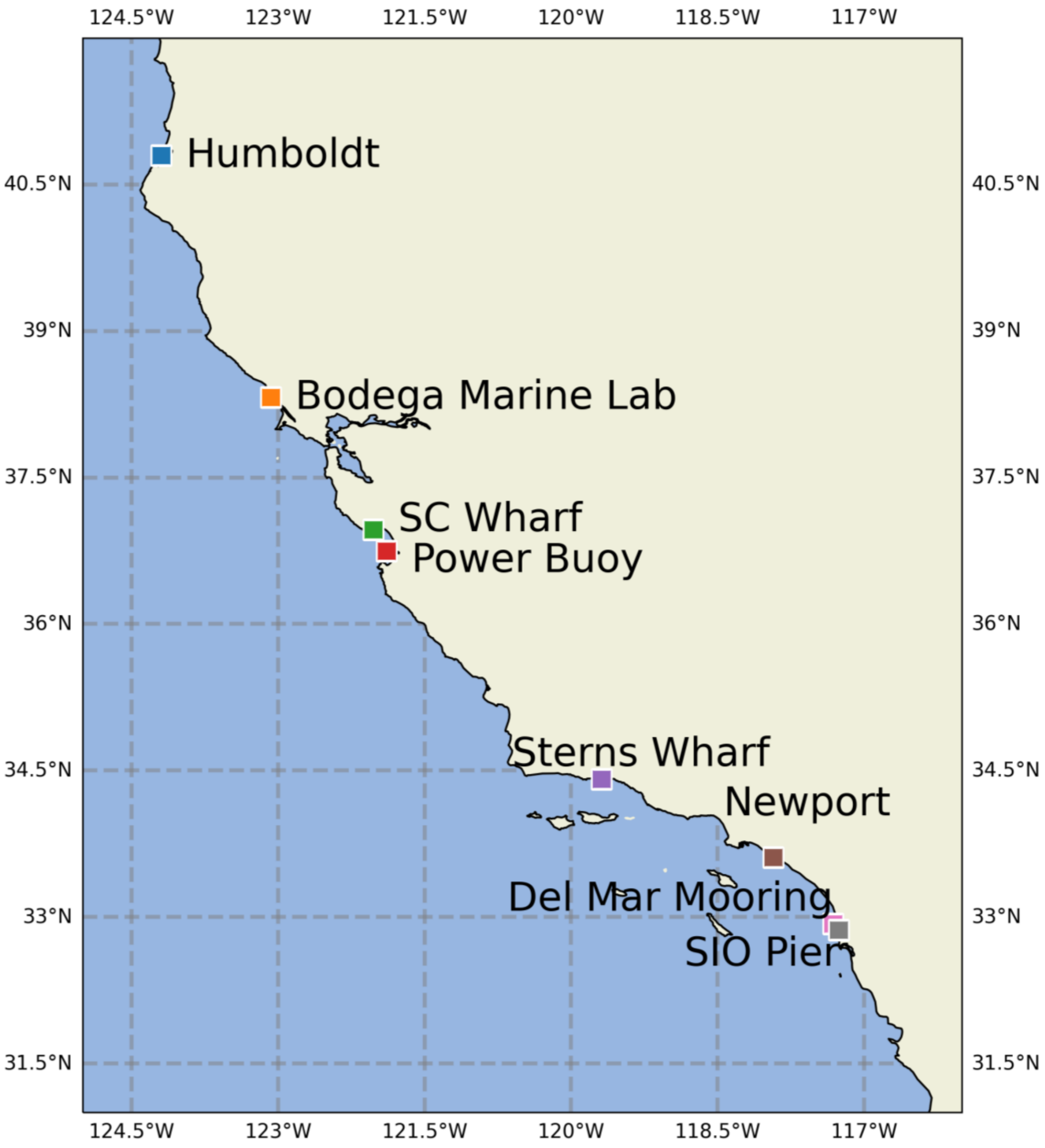
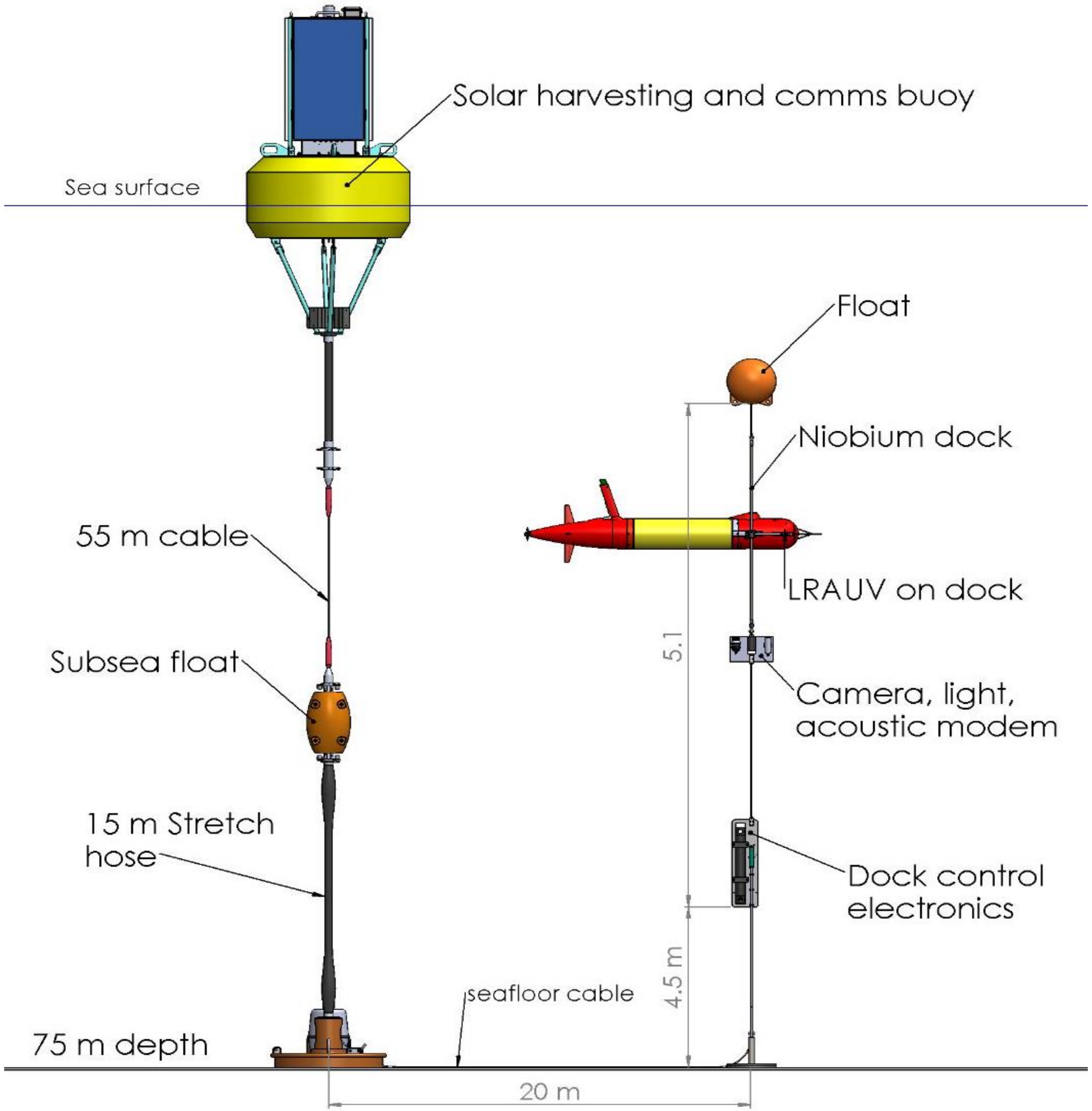
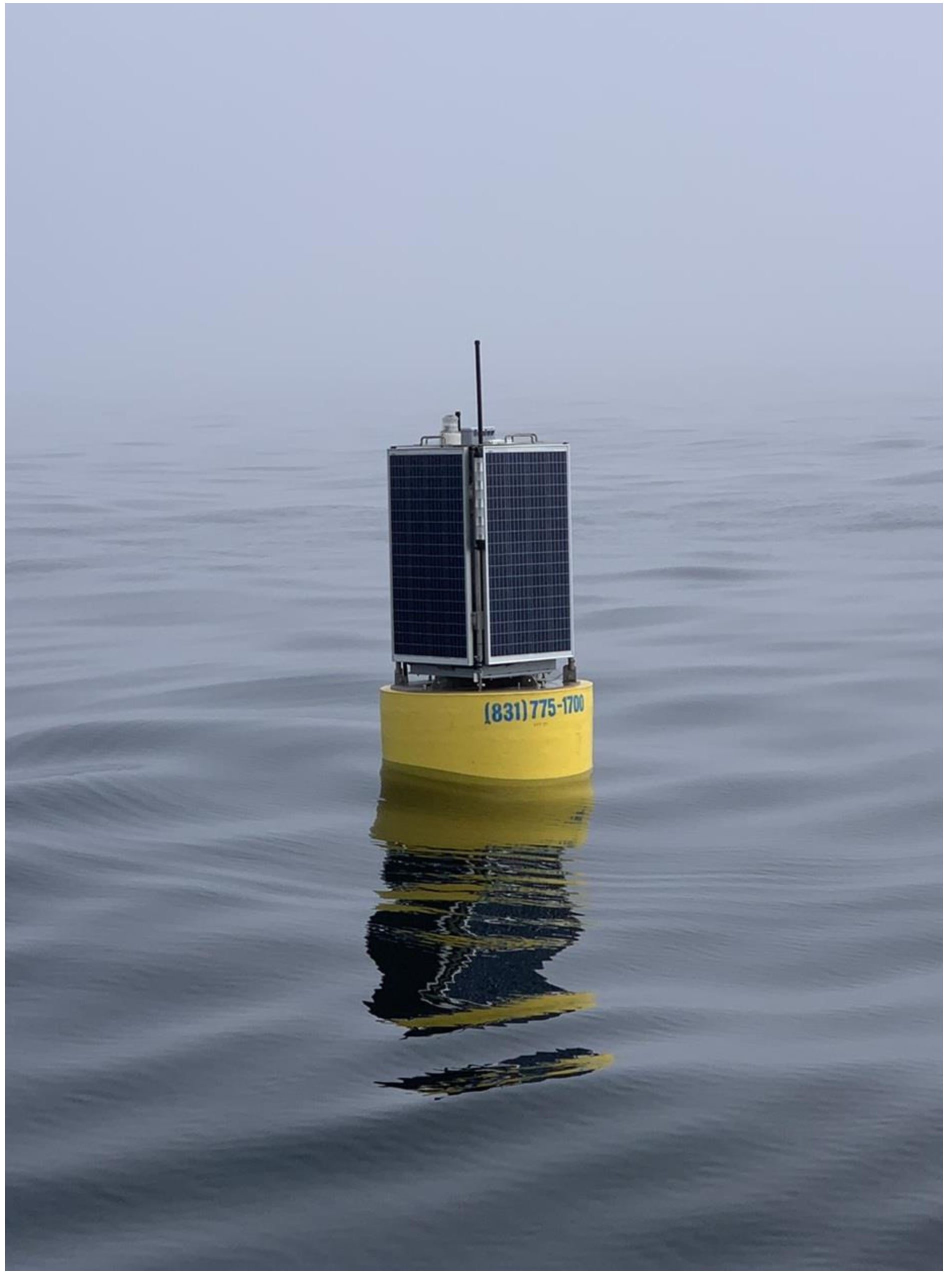

124.5°W
123°W
121.5°W
120°W
118.5°W
117°W
40.5°N
39°N
37.5°N
36°N
34.5°N
33°N
31.5°N
Humboldt
Bodega Marine Lab
SC Wharf
Power Buoy
Sterns Wharf
Newport
Del Mar Mooring
SIO Pier


Solar harvesting and comms buoy
Sea surface
Float
Niobium dock
55 m cable
LRAUV on dock
5.1
Subsea float
Camera, light,
acoustic modem
15 m Stretch
hose
Dock control
electronics
4.5 m
seafloor cable
75 m depth
20 m

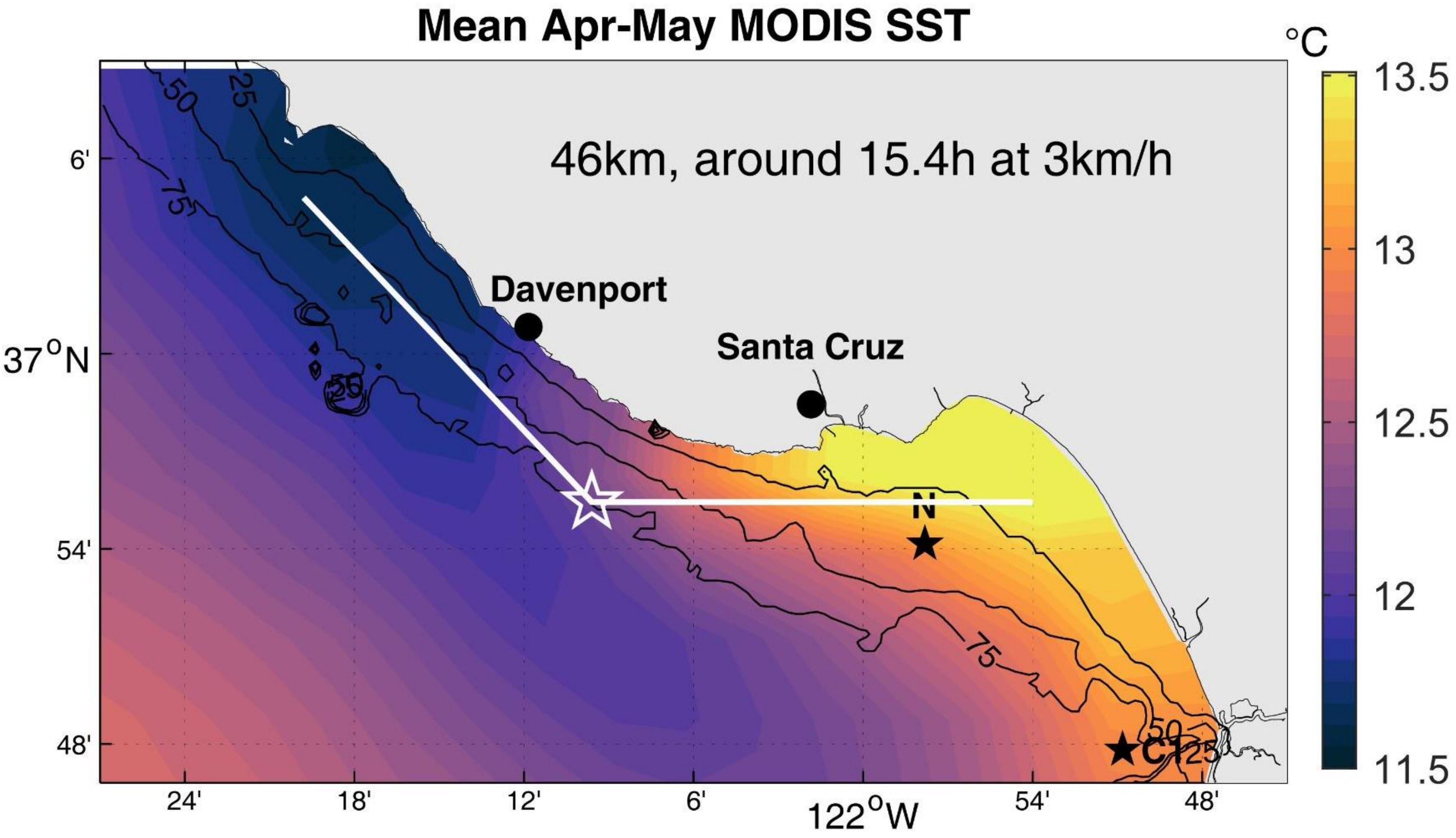

(831) 775-1700


MBARI

Niobicon technology

- Patented and developed by Northrop-Grumman
- Uses pure niobium
- Thin film isolates niobium in water
- Can allow axial and rotary motion
- Limited to 60 V and moderate power

2024 Dock Deployment and Use - May 2024



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Wave-Energy Conversion Technical Challenges

- Reliability and Storm Survivability
  - 3-5 Million wave cycles per year
  - 1-2 Million meters of linear travel
  - Designed to maximize forces - extreme events

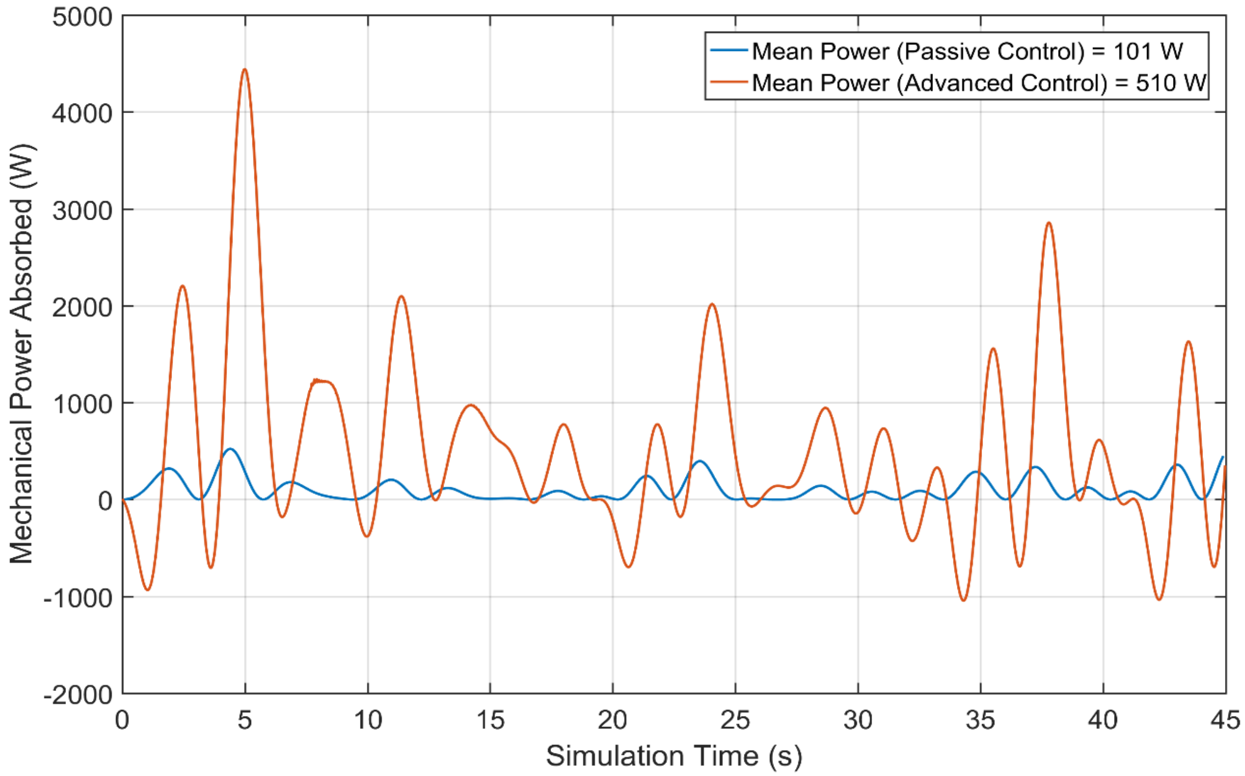
Control-System Approaches

- System natural period = 2-3 seconds

- Simplest approach, PTO force proportional to velocity

Control Opportunity

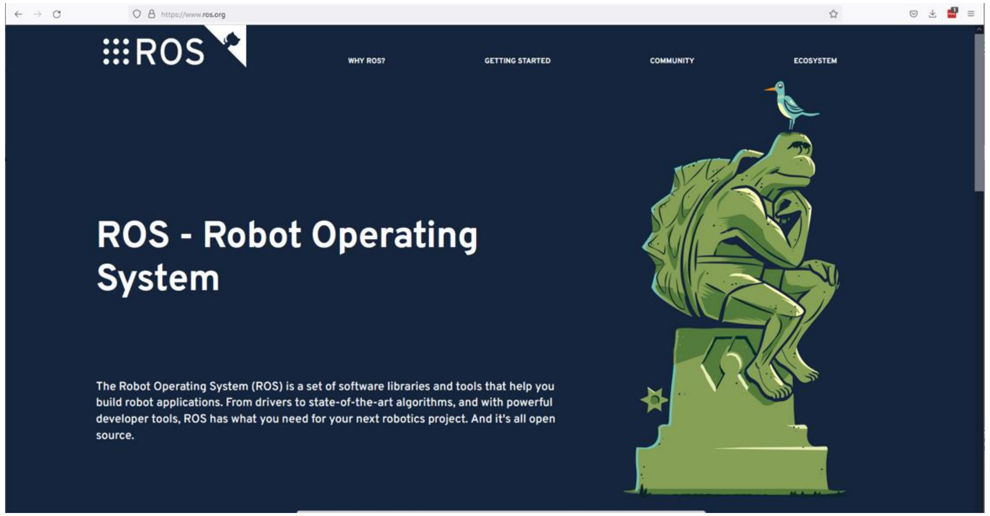
- Make device smaller
- Stroke constraint
- Increase robustness
- Increased energy capture



Open Software Interface – Dept of Energy/Open Robotics

Goal: Make the MBARI WEC available to outside researchers

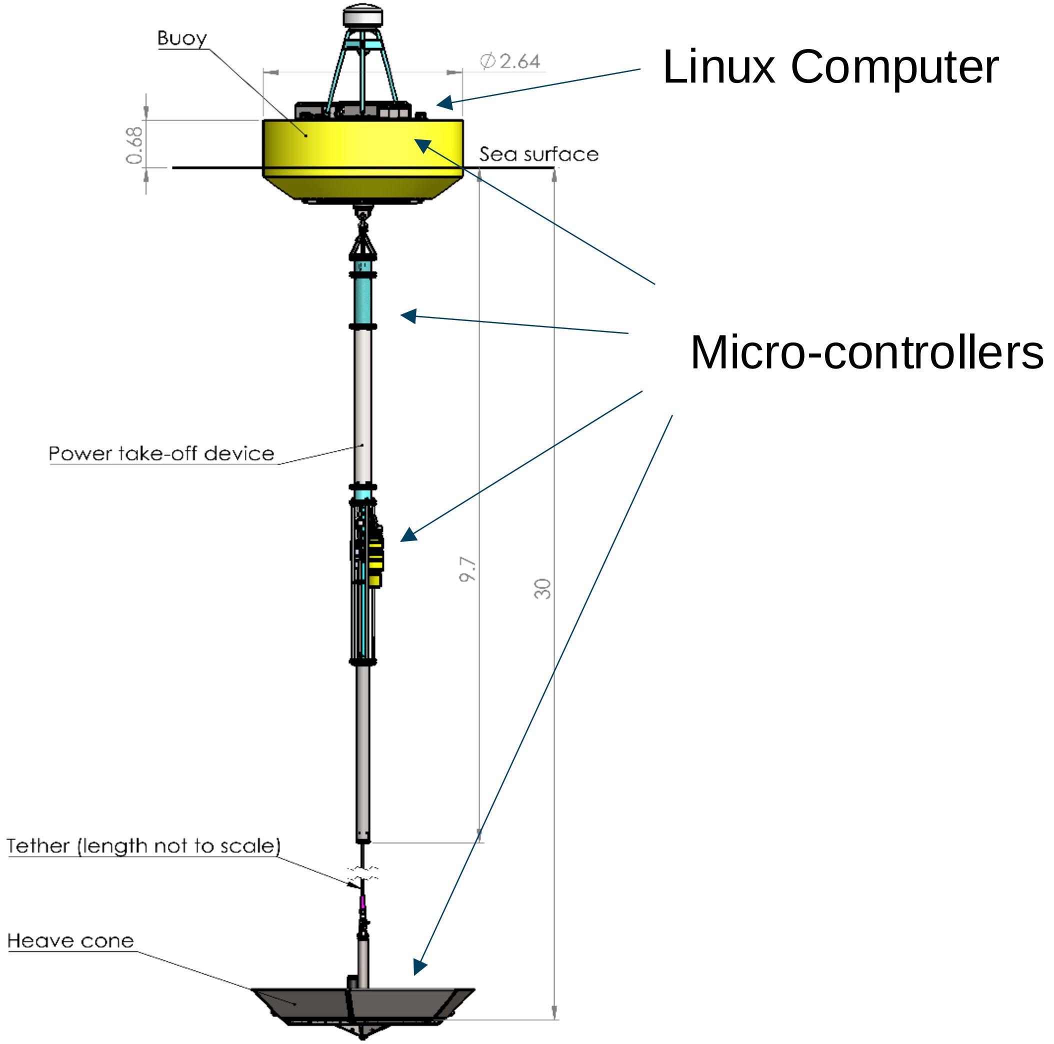
Approach: ROS 2 software on buoy Linux computer provides all telemetry data to user process and allows control of WEC

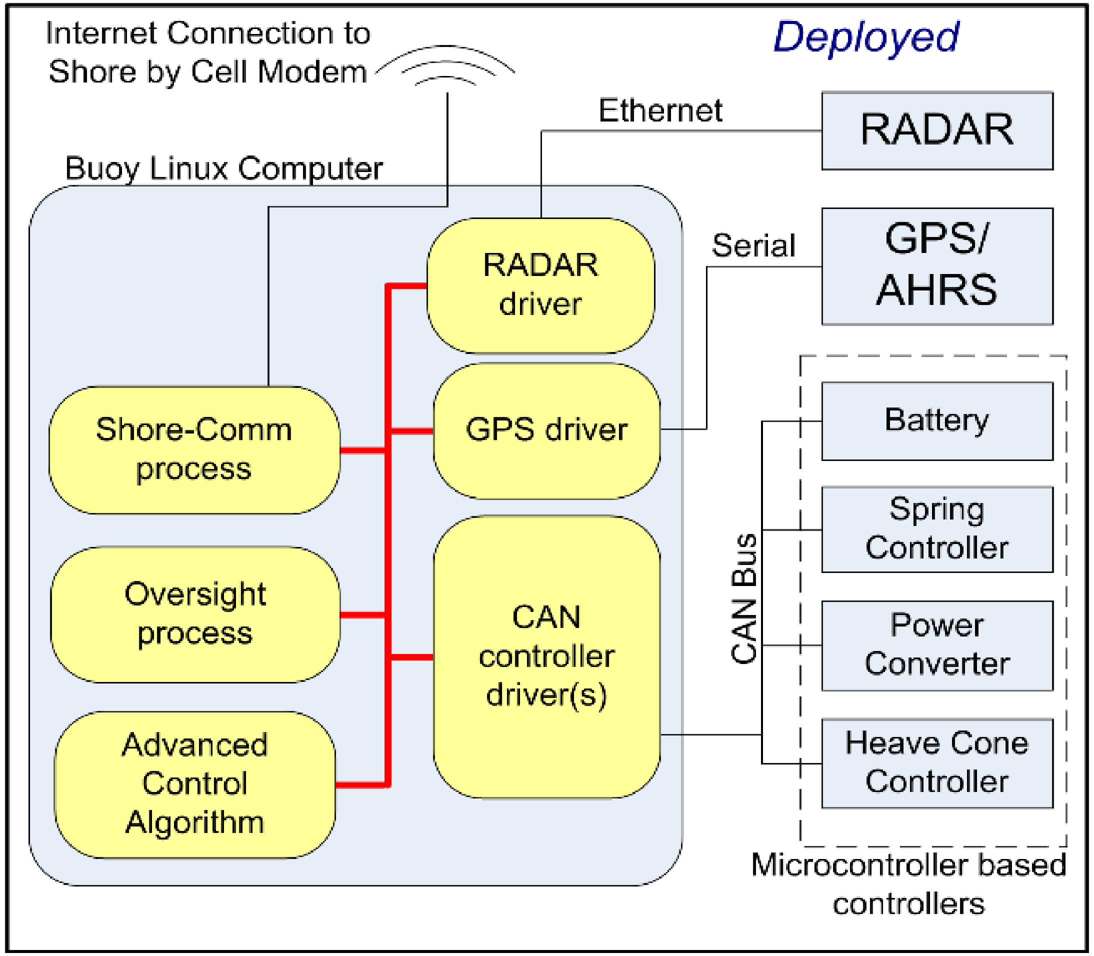


ROS 2

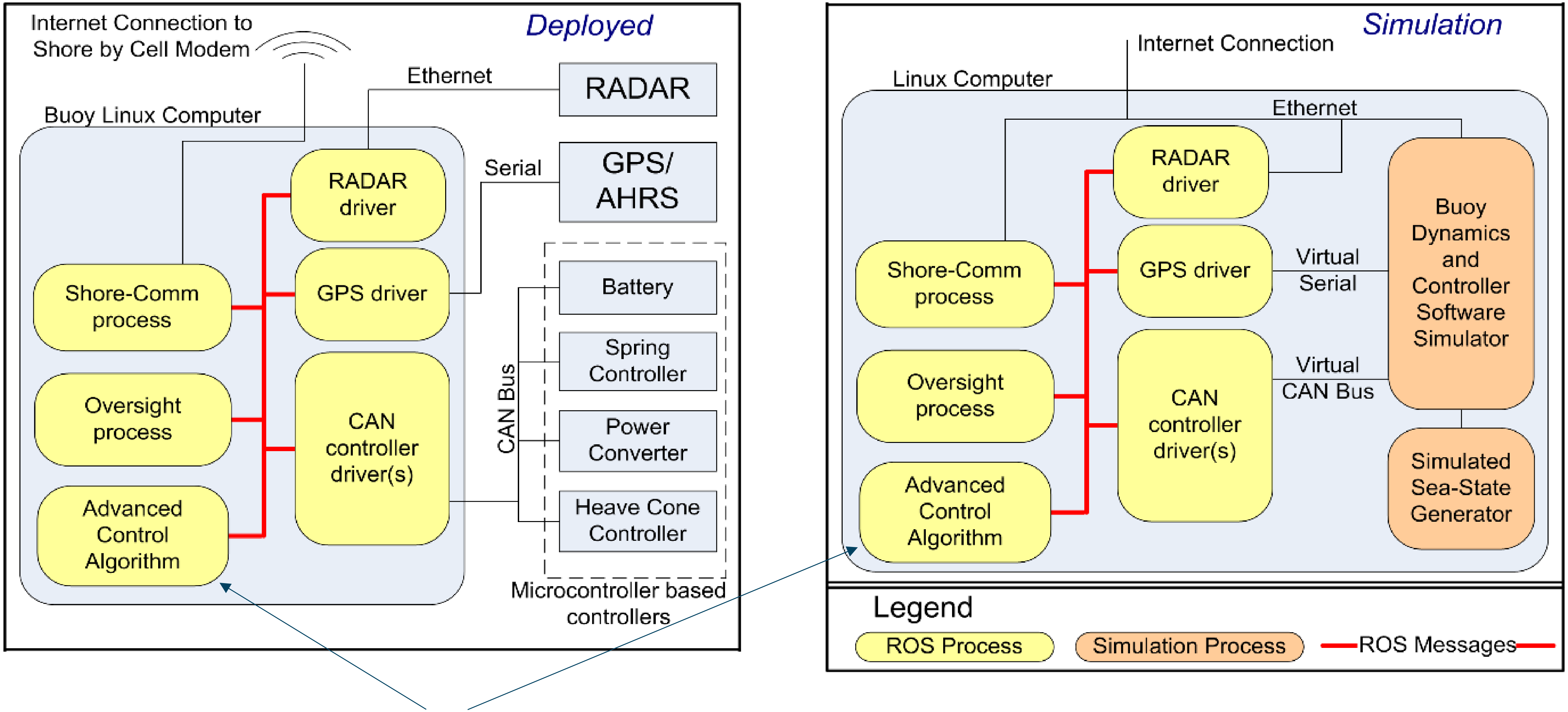
- Publish/Subscribe message infrastructure.
- Very popular in robotics
- Python/C++ Bindings
- One user process on Linux controls buoy

Compute and Control Architecture





Simulation Environment



Goal: Control software can not tell if its running on the real buoy or on the simulator

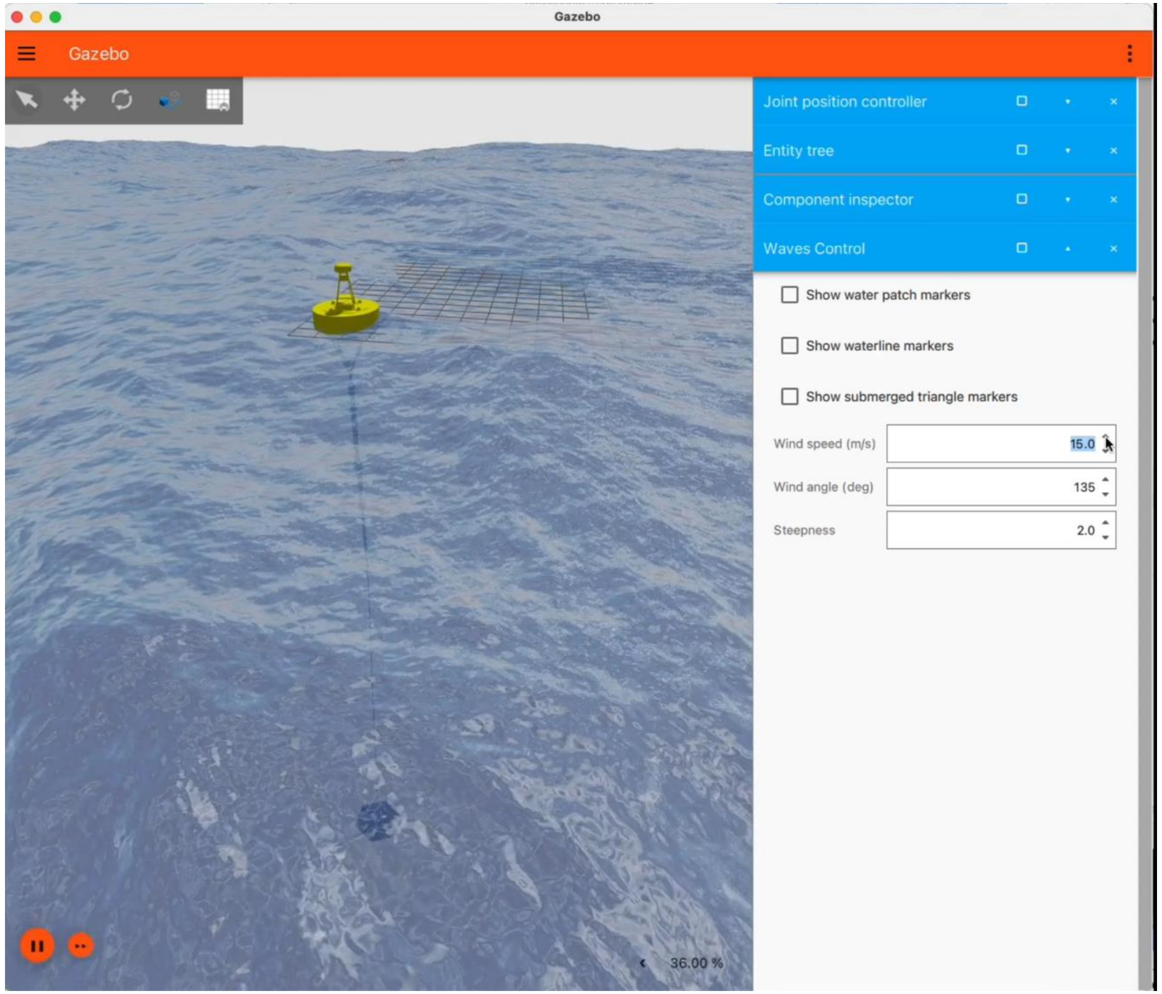
Simulation

Gazebo: Open Robotics supported simulation environment.

- Provides physics simulation (rigid body dynamics of joined bodies)
- Plugin based, designed for new forcings to be added.
  - Pneumatic Spring
  - Electro-Hydraulic PTO
  - Free-surface hydrodynamics
  - Flexible tether
- Lacked support for added-mass terms!

- While running, the ROS interface provided to user software is exactly the same as the real buoy.
- Plus, addition information only available in simulation…

Simulation


Gazebo
Gazebo
Joint position controller
Entity tree
Component inspector
Waves Control
Show water patch markers
Show waterline markers
Show submerged triangle markers
Wind speed (m/s)
15.0
Wind angle (deg)
135
Steepness
2.0
36.00 %


PlotJuggler
tab1
/power_data/rpm
/spring_data/range_finder
/spring_data/upper_psi
/spring_data/lower_psi
/power_data/wcurrent
/spring_data/load_cell
/power_data/bcurrent
/power_data/voltage
/power_data/loaddc
337.034
Speed:
1.0
Step size:
0.000

Analysis on Evaluations of MBARI-WEC Field Data using WEC-Sim and Gazebo: A Simulation Tool Comparison

Chris Dizon, Ryan G. Coe, Andrew Hamilton, Dominic Forbush, Michael Anderson,
Ted Brekken, *Senior Member, IEEE*, Giorgio Bacelli

***Abstract*—This paper compares two numerical models of Monterey Bay Aquarium Research Institute's Wave Energy Converter (MBARI-WEC), a two-body point absorber with an electro-hydraulic power take-off system (PTO). The models are implemented in *WEC-Sim/Simscape* and *Gazebo Simulator*. Statistical analysis of the models and field results was performed to compare the models' accuracy in predicting the RMS piston velocity, RMS motor speed, and mean electric power compared to field data for 56 observations across varying sea states. The *Gazebo* model demonstrated a closer agreement across all three parameters for a majority of the observations. When compared to the field data, the *Gazebo* and *WEC-Sim* models exhibited average mean electric power overestimations of 13% and 22%, respectively.**

***Index Terms*—software packages, statistical analysis, time-domain analysis, wave energy converters**

I. Introduction

Accurate numerical models of physical systems are vital resources for the design and optimization of complex systems. They aid in understanding the effects on the system before undergoing physical design changes or implementing ideas such as new control strategies. Two numerical models have been developed that represent Monterey Bay Aquarium Research Institute's Wave Energy Converter - the *MBARI-WEC*.

The MBARI-WEC is a two-body point absorber consisting of a surface buoy and a submerged heave cone connected together by an electro-hydraulic power take-off (PTO) system as shown in Fig. 1. The relative heave motion between

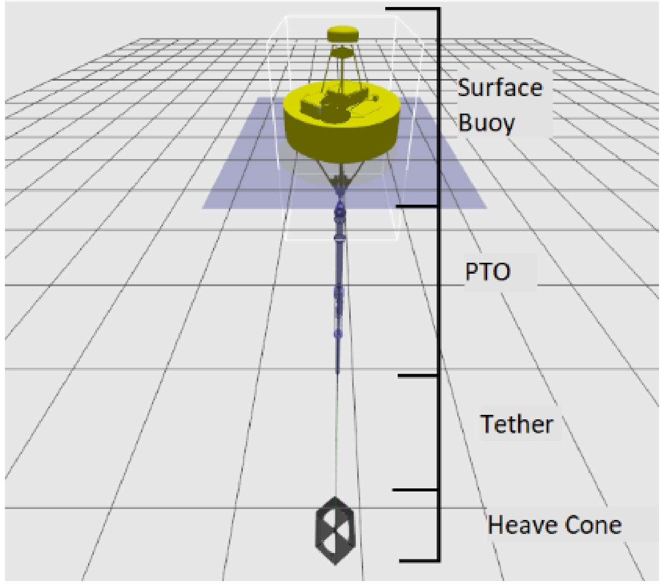


Fig. 1: The MBARI-WEC portrayed in *Gazebo*. Labeled from top to bottom are the surface buoy, PTO, tether, and heave cone. Relative motion between the surface buoy and heave cone actuate the PTO piston which drives a hydraulic/electric motor. An air spring driven by the piston provides the necessary restoring force.

data acquisition, data logging, data transmission, and auxiliary

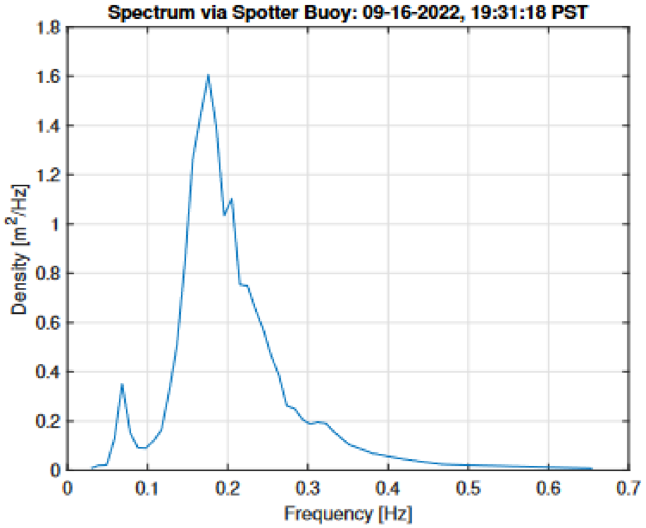


Fig. 4: Example spectrum used for simulation depicting the ocean spectra for the date September 16, 2022 at 19:31:18 PST; obtained via Sofar Spotter Buoy data.

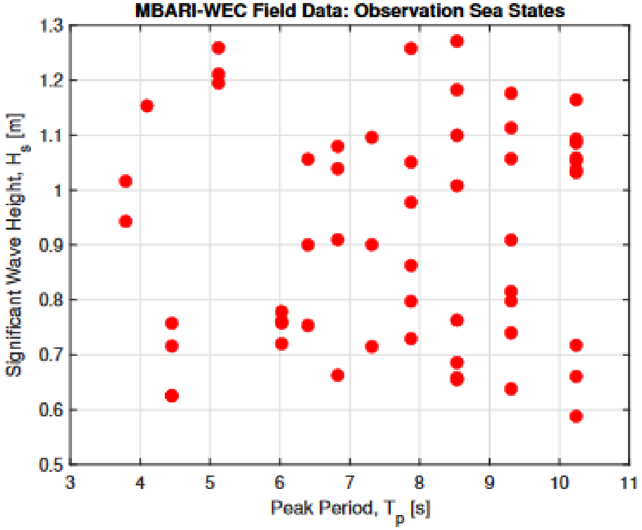
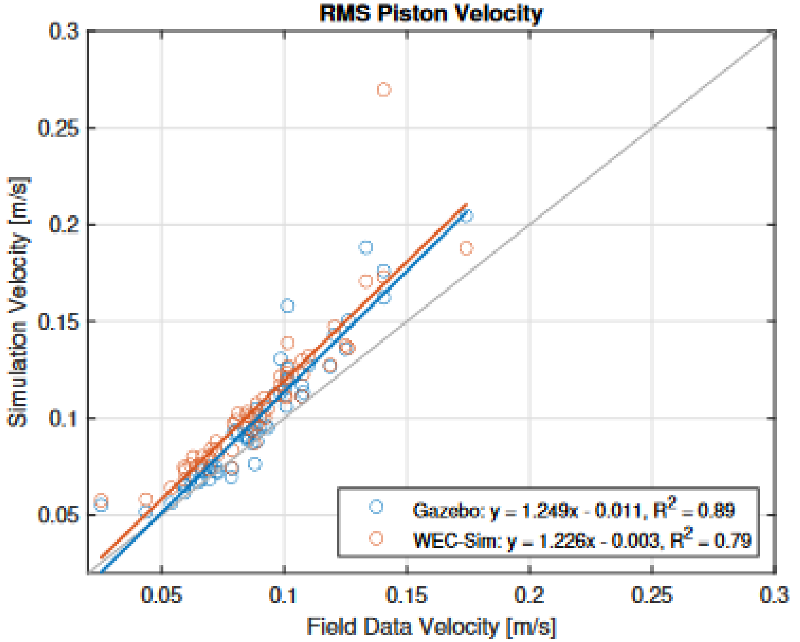
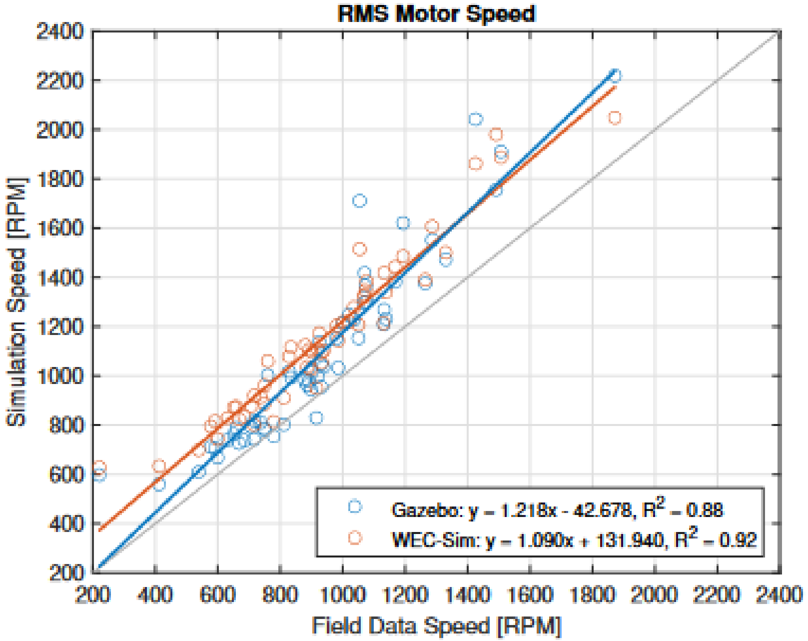
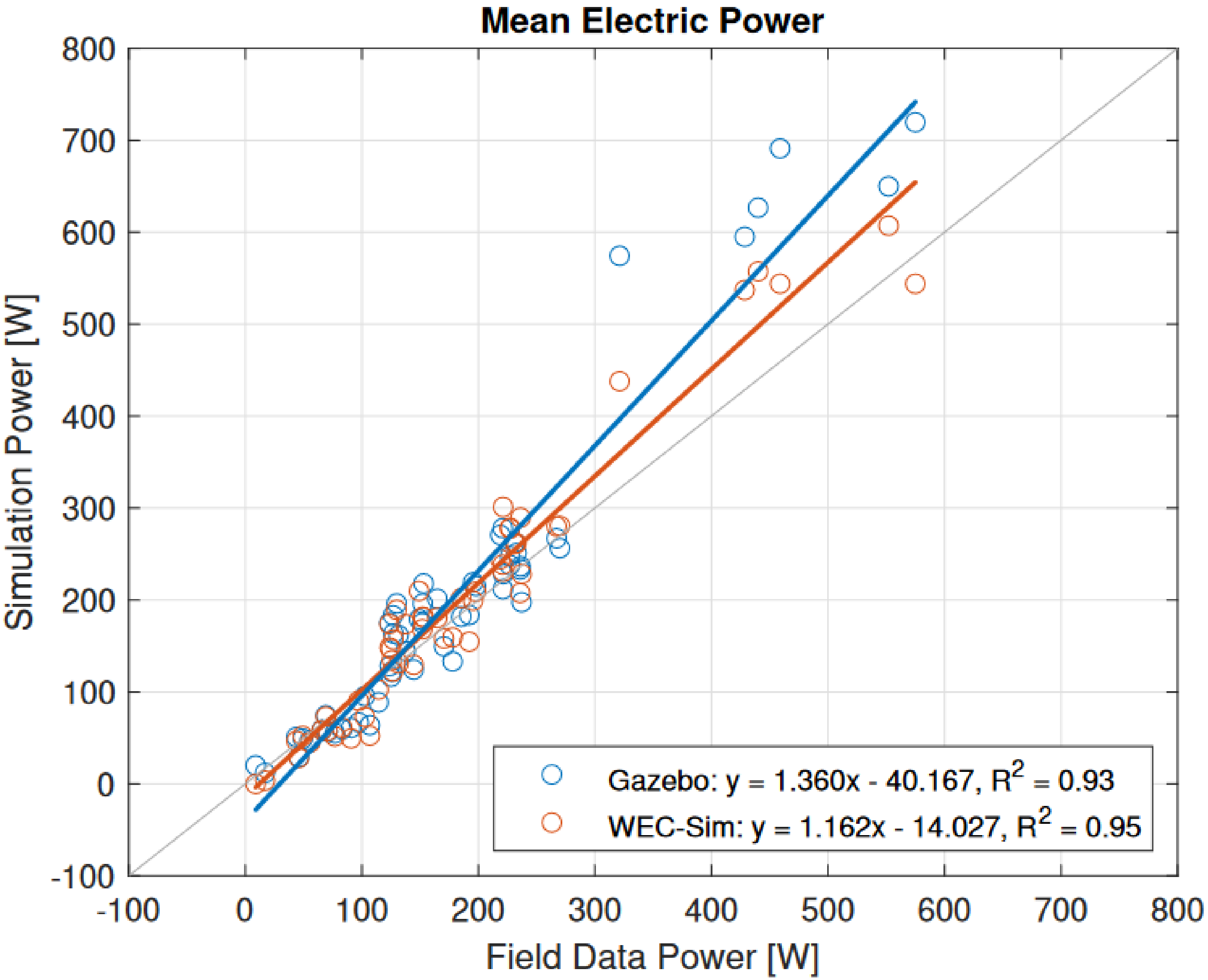


Fig. 5: Sea states for each MBARI-WEC observations considered in the study.


RMS Piston Velocity
Simulation Velocity [m/s]
Field Data Velocity [m/s]
Gazebo: y = 1.249x - 0.011, R2 = 0.89
WEC-Sim: y = 1.226x - 0.003, R2 = 0.79

(a)


RMS Motor Speed
Simulation Speed [RPM]
Field Data Speed [RPM]
Gazebo: y = 1.218x - 42.678, R2 = 0.88
WEC-Sim: y = 1.090x + 131.940, R2 = 0.92


Mean Electric Power
Simulation Power [W]
Field Data Power [W]
Gazebo: y = 1.360x - 40.167, R2 = 0.93
WEC-Sim: y = 1.162x - 14.027, R2 = 0.95

Outside Researchers

- Simulation first, then on-buoy operations.

- Researchers may be ROS2 beginners, so we’ve tried to make the system approachable. Simplest solutions possible.

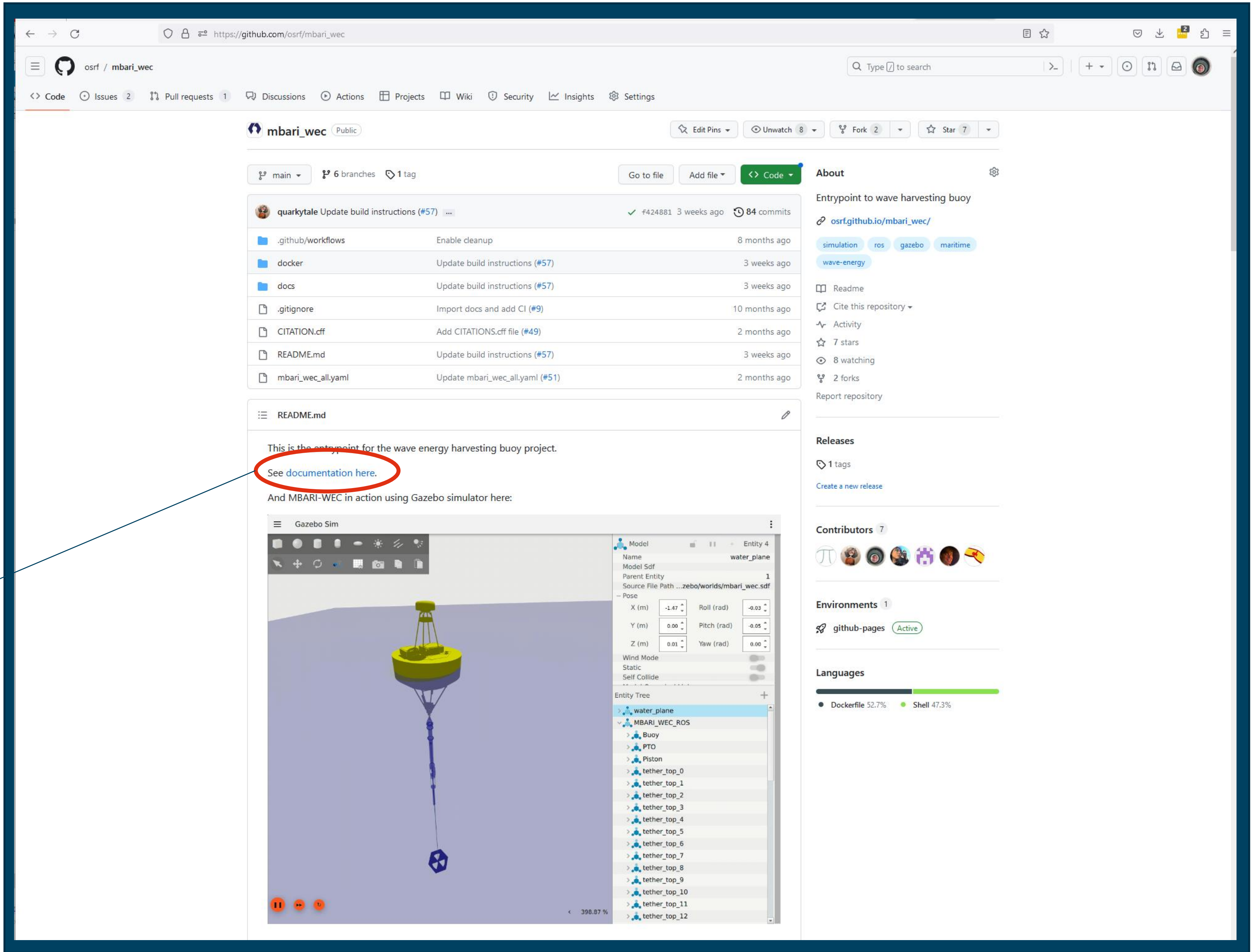
- Tutorials and examples

- Easy access. GitHub Templates, Docker.

- Discussion forum.

Resources – Open Source

https://github.com/osrf/mbari_wec



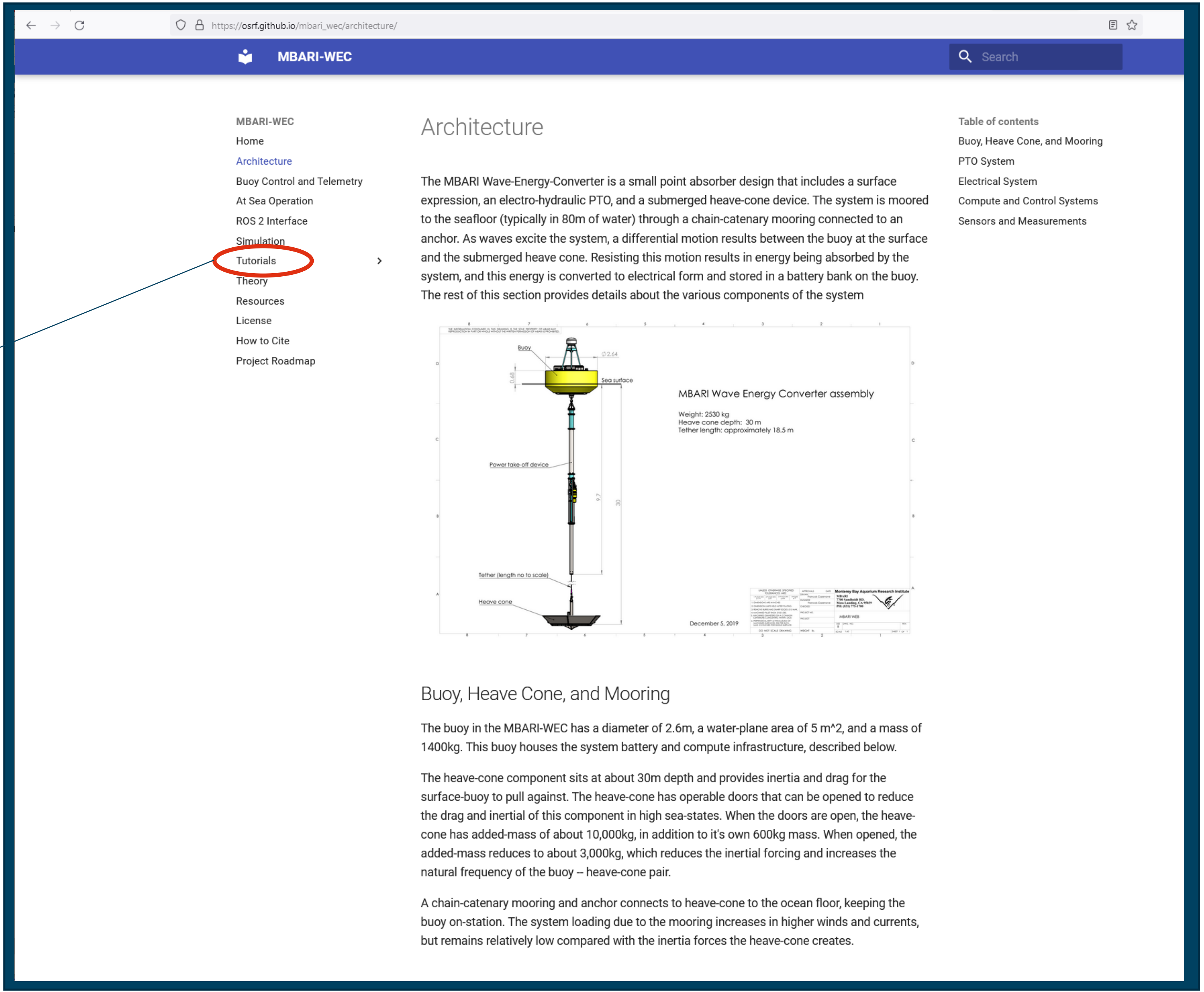
Documentation

MBARI Monterey Bay Aquarium Research Institute

Resources – Documentation Site

https://osrf.github.io/mbari_wec/

Tutorials



https://osrf.github.io/mbari_wec/architecture/

MBARI-WEC

Search

MBARI-WEC
- Home
- Architecture
- Buoy Control and Telemetry
- At Sea Operation
- ROS 2 Interface
- Simulation
- Tutorials
- Theory
- Resources
- License
- How to Cite
- Project Roadmap

Architecture

The MBARI Wave-Energy-Converter is a small point absorber design that includes a surface expression, an electro-hydraulic PTO, and a submerged heave-cone device. The system is moored to the seafloor (typically in 80m of water) through a chain-catenary mooring connected to an anchor. As waves excite the system, a differential motion results between the buoy at the surface and the submerged heave cone. Resisting this motion results in energy being absorbed by the system, and this energy is converted to electrical form and stored in a battery bank on the buoy. The rest of this section provides details about the various components of the system

Buoy, Heave Cone, and Mooring

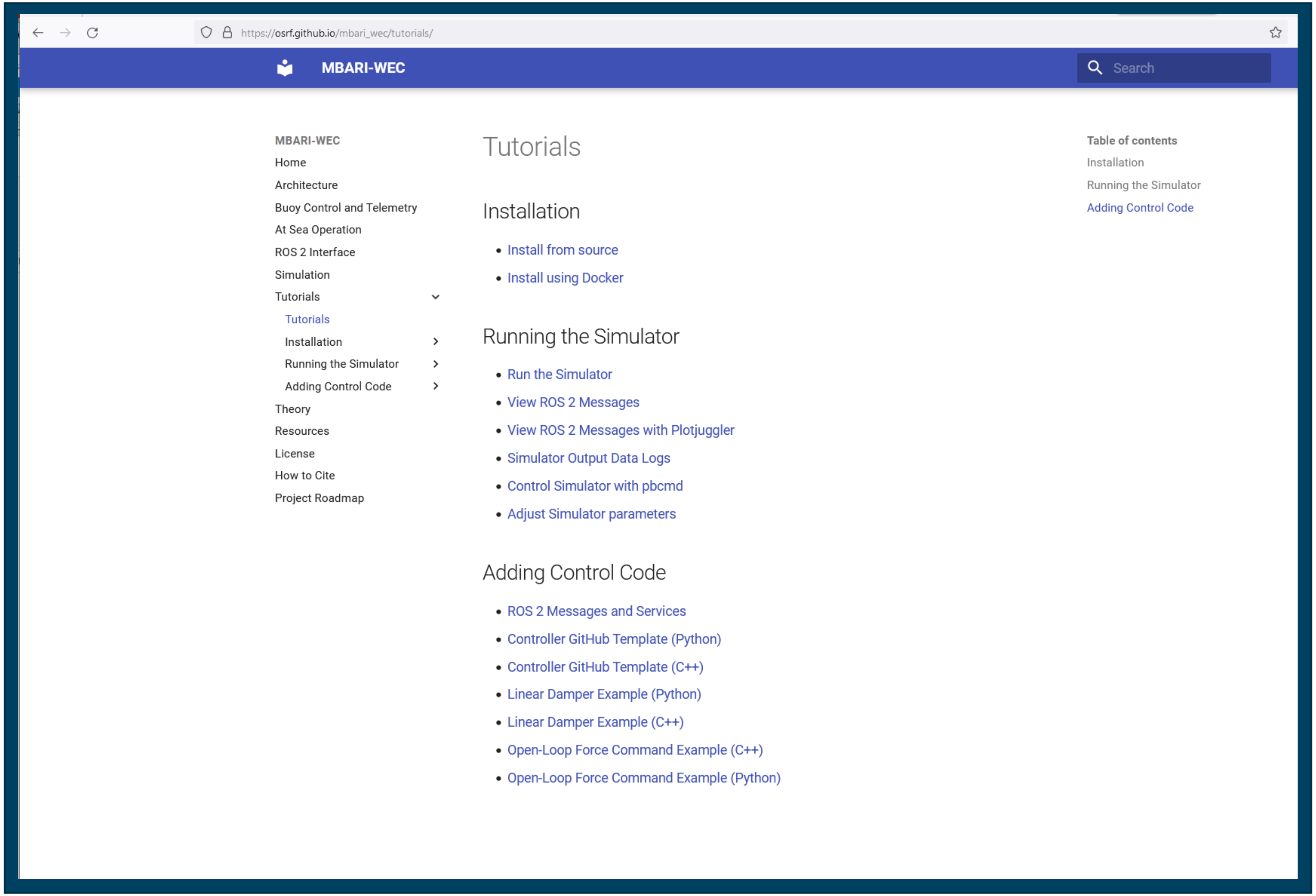
The buoy in the MBARI-WEC has a diameter of 2.6m, a water-plane area of 5 m^2, and a mass of 1400kg. This buoy houses the system battery and compute infrastructure, described below.

The heave-cone component sits at about 30m depth and provides inertia and drag for the surface-buoy to pull against. The heave-cone has operable doors that can be opened to reduce the drag and inertial of this component in high sea-states. When the doors are open, the heave-cone has added-mass of about 10,000kg, in addition to it's own 600kg mass. When opened, the added-mass reduces to about 3,000kg, which reduces the inertial forcing and increases the natural frequency of the buoy -- heave-cone pair.

A chain-catenary mooring and anchor connects to heave-cone to the ocean floor, keeping the buoy on-station. The system loading due to the mooring increases in higher winds and currents, but remains relatively low compared with the inertia forces the heave-cone creates.

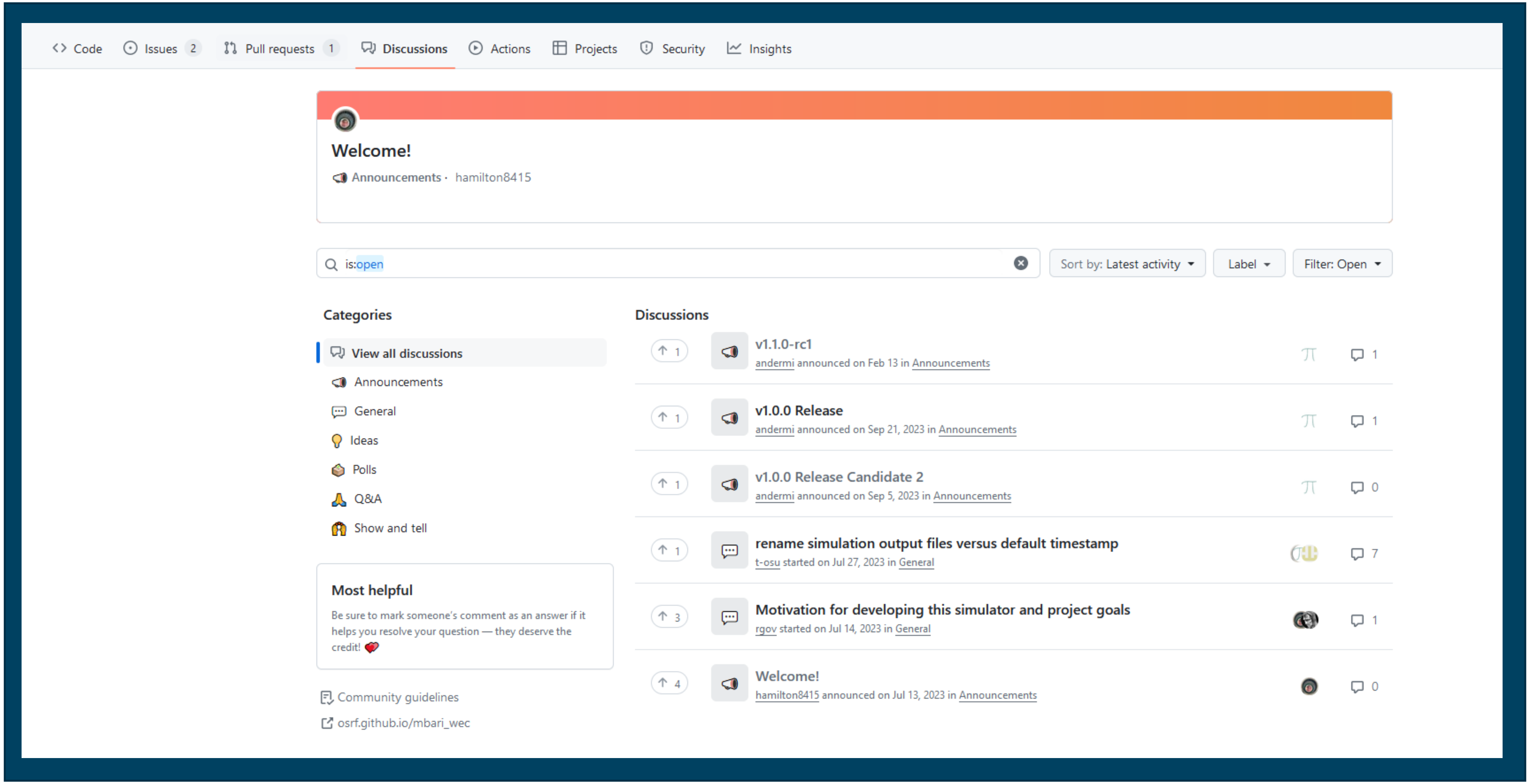
Resources – Tutorials

hamilton@mbari.org



Resources – Forum

https://github.com/osrf/mbari_wec/discussions



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People:

- François Cazenave
- Scott Jensen
- Michael Anderson
- Jon Erickson
- Rich Henthorn
- Eric Martin
- Denis Klimov
- Rob McEwen
- Jose Rosal
- John Ferrierra