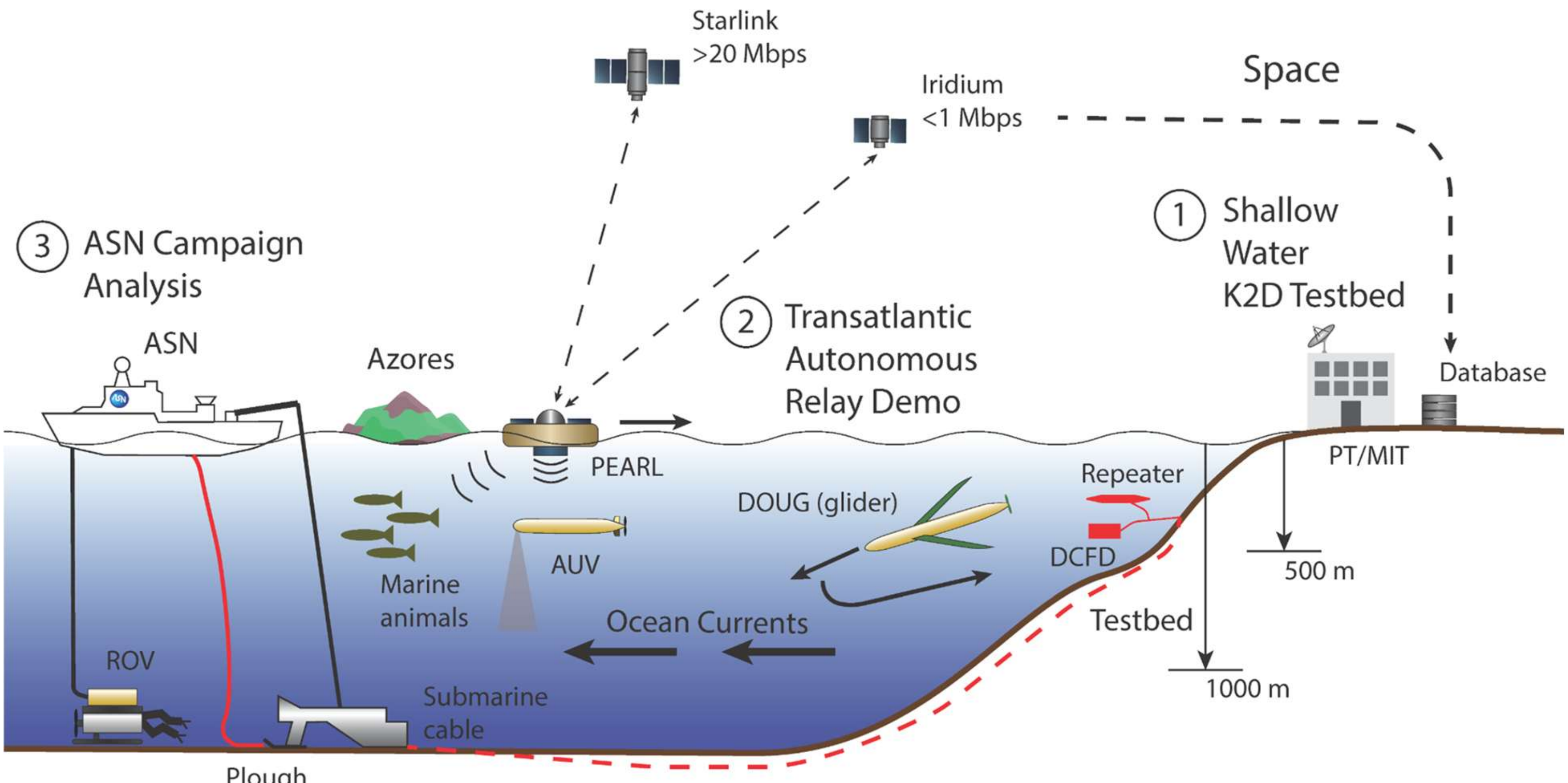
Digital Twin Development of PEARL
Autonomous Surface System Thermal Management

Prof. Olivier L. de Weck

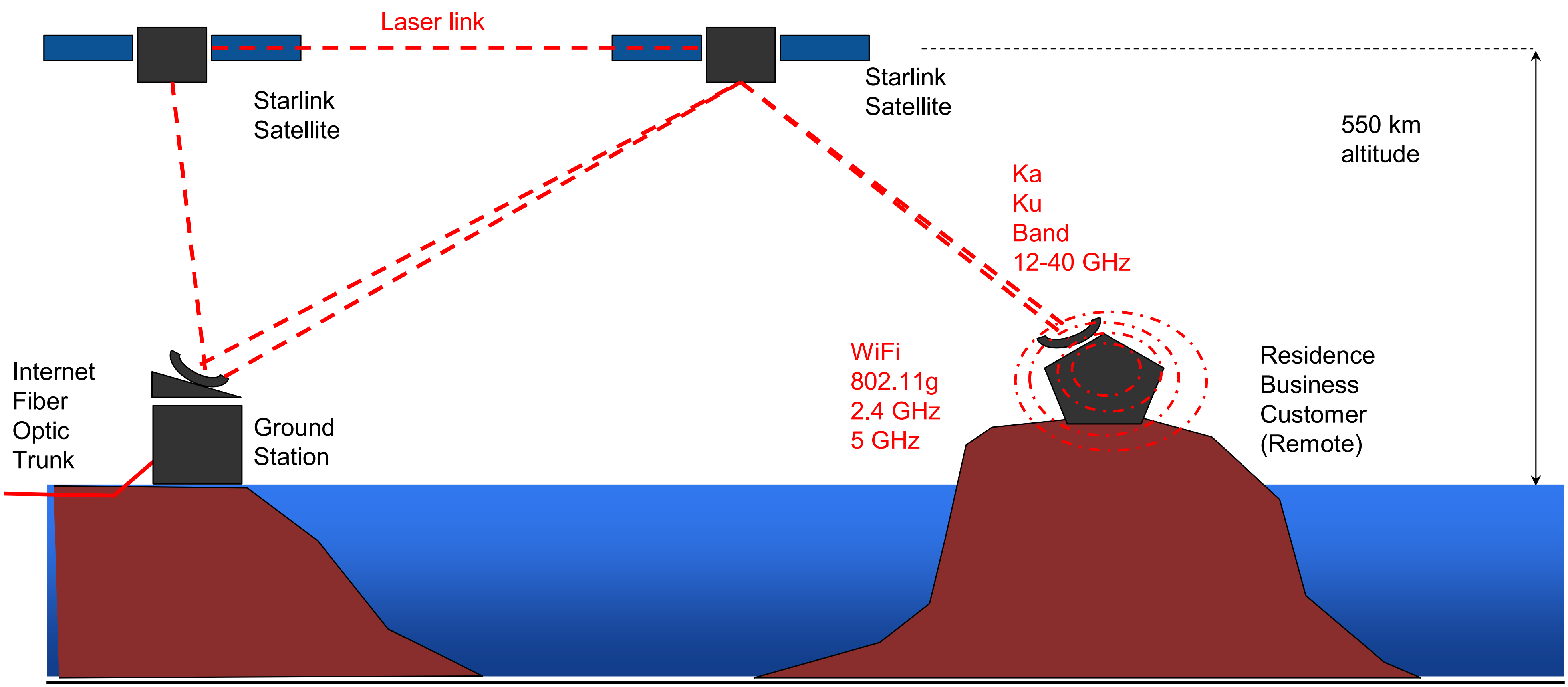
Apollo Program Professor of Astronautics and Engineering Systems
Department of Aeronautics and Astronautics @ MIT
deweck@mit.edu

ESL MIT MIT Portugal MathWorks

PEARL: Extracting Real-Time Knowledge from the Ocean



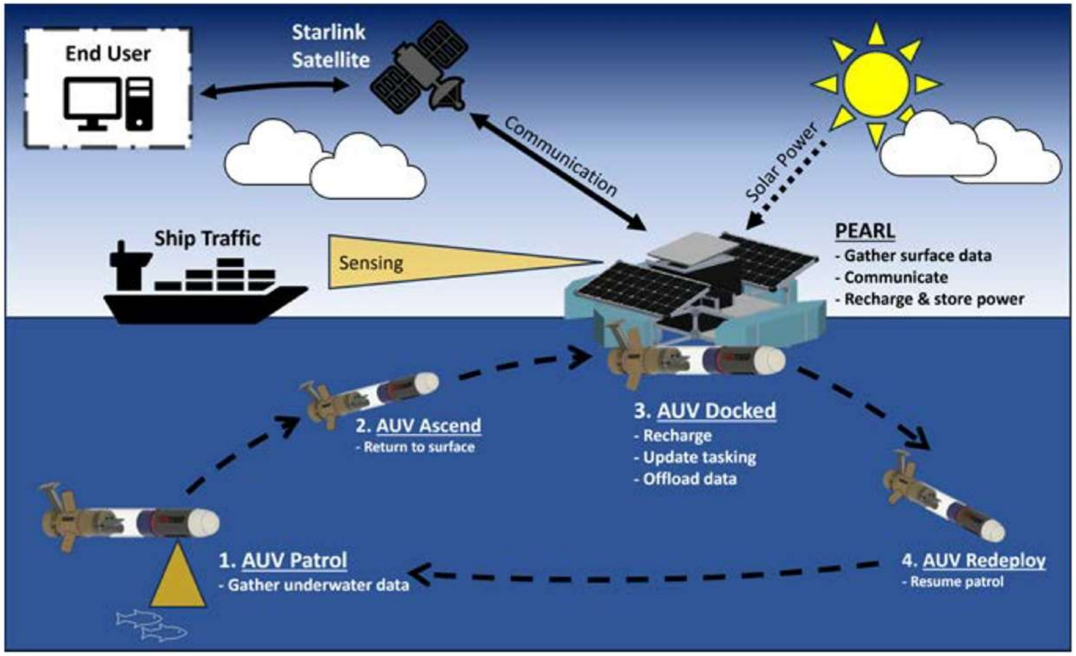
Starlink Concept of Operations



Platform for Expanding AUV exploRation to Longer ranges (PEARL)

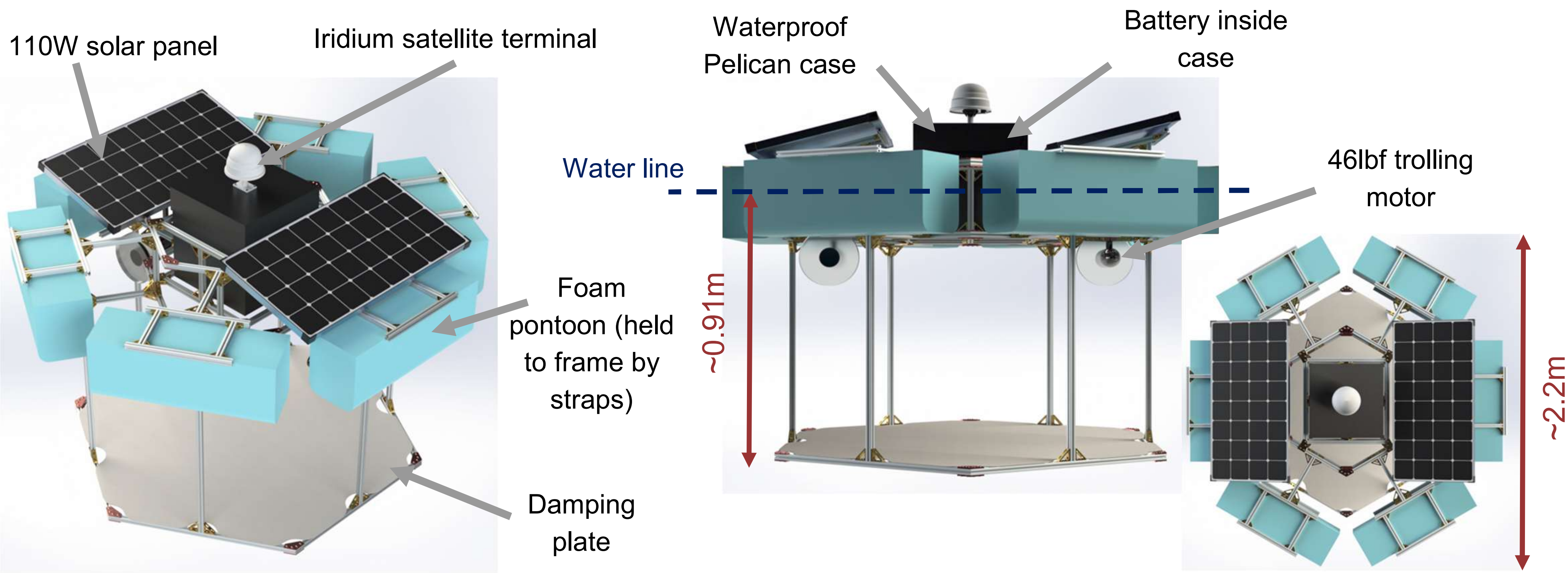
Goal: **Extend the range and endurance of AUVs and allow for near-real-time data transmission by satellite, thereby reducing operating costs via the Platform for Expanding AUV exploRation to Longer ranges (PEARL).**

PEARL provides AUV docking and recharging via renewable energy and data uplink via the new generation of high-bandwidth low Earth orbit (LEO) satellite mega constellations.

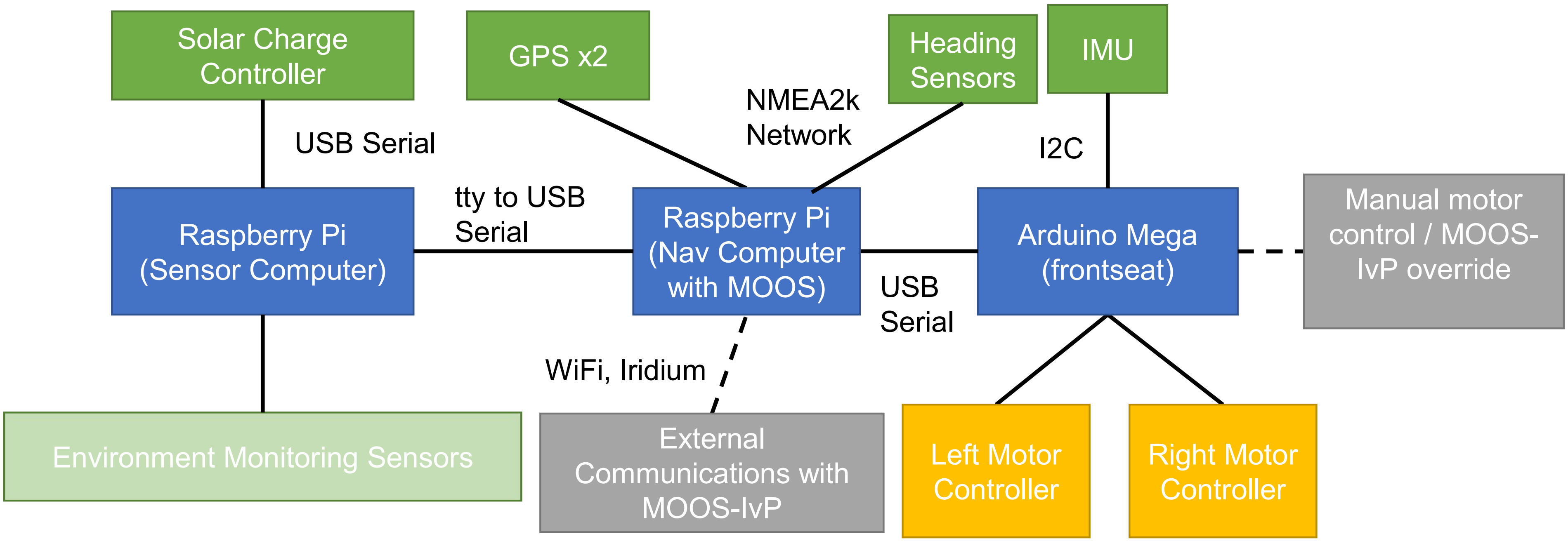


PEARL Prototype (v1) 2020-2022

Goal: Investigate concepts of PEARL energy harvesting, data collection, and data transmission



Autonomy Hardware Architecture (running MOOS-IvP)

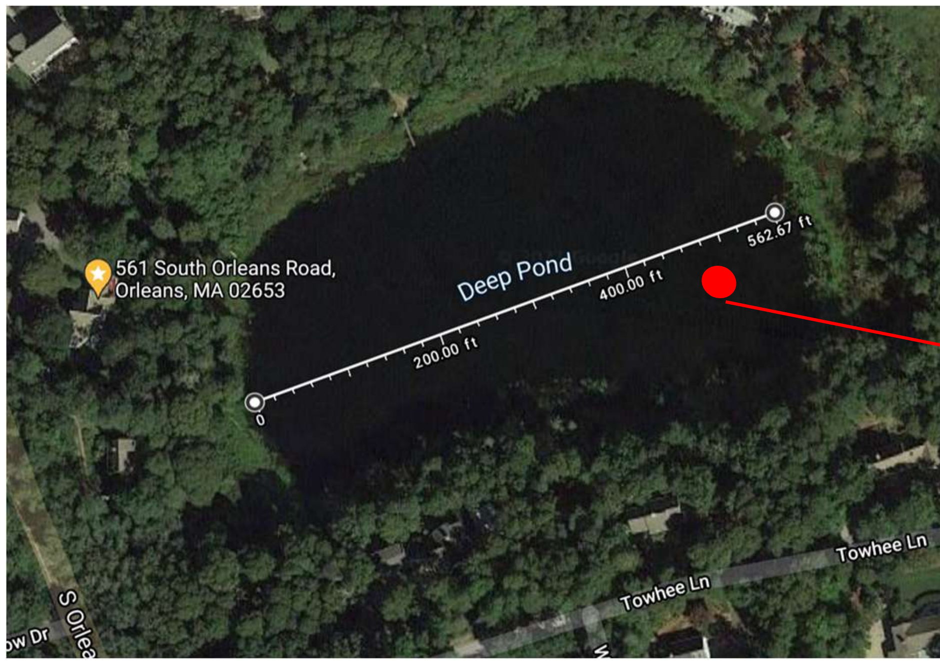


Benjamin, M.R., Schmidt, H., Newman, P.M. and Leonard, J.J. (2010), Nested autonomy for unmanned marine vehicles with MOOS-IvP. *J. Field Robotics*, 27: 834-875. DOI: https://doi.org/10.1002/rob.20370

https://oceanai.mit.edu/moos-ivp/pmwiki/pmwiki.php?n=Main.HomePage

First Stress Test: Six Month Deployment at Deep Pond

- Deep Pond in Orleans, MA: Kettle Pond formed by the last Ice Age, about 30 feet deep
- Overall dimensions: 600 ft by 300 feet (Kidney shaped)



Recent Publication

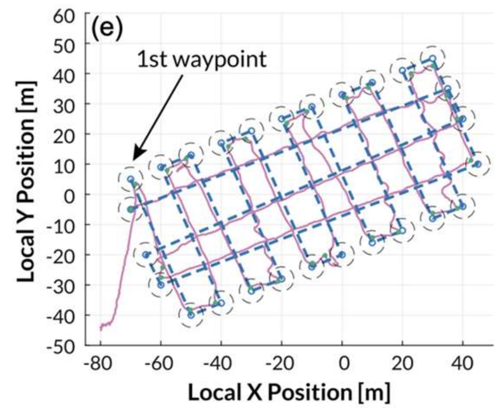
Received: 7 June 2022 | Revised: 8 November 2022 | Accepted: 23 December 2022
DOI: 10.1002/rob.22155

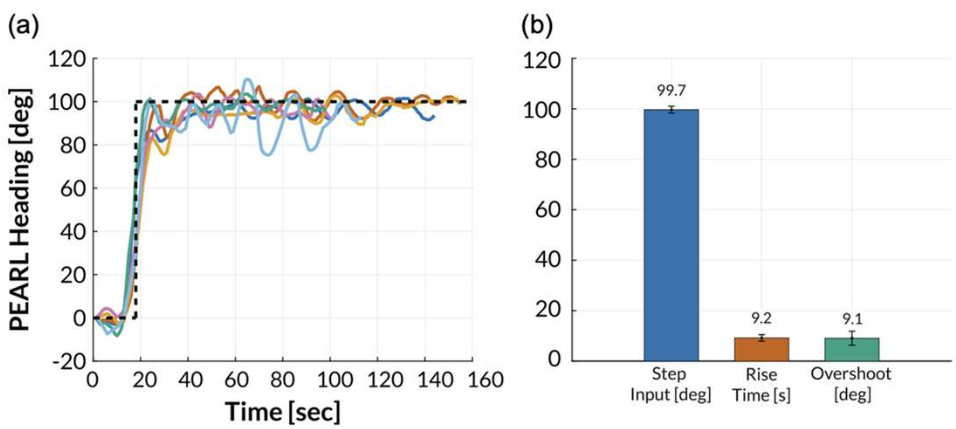
RESEARCH ARTICLE

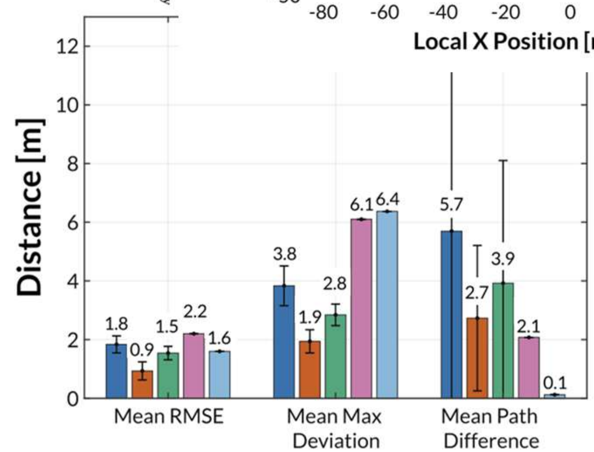
WILEY

Autonomous control of a prototype solar-powered offshore autonomous underwater vehicle servicing platform via a low-cost embedded architecture

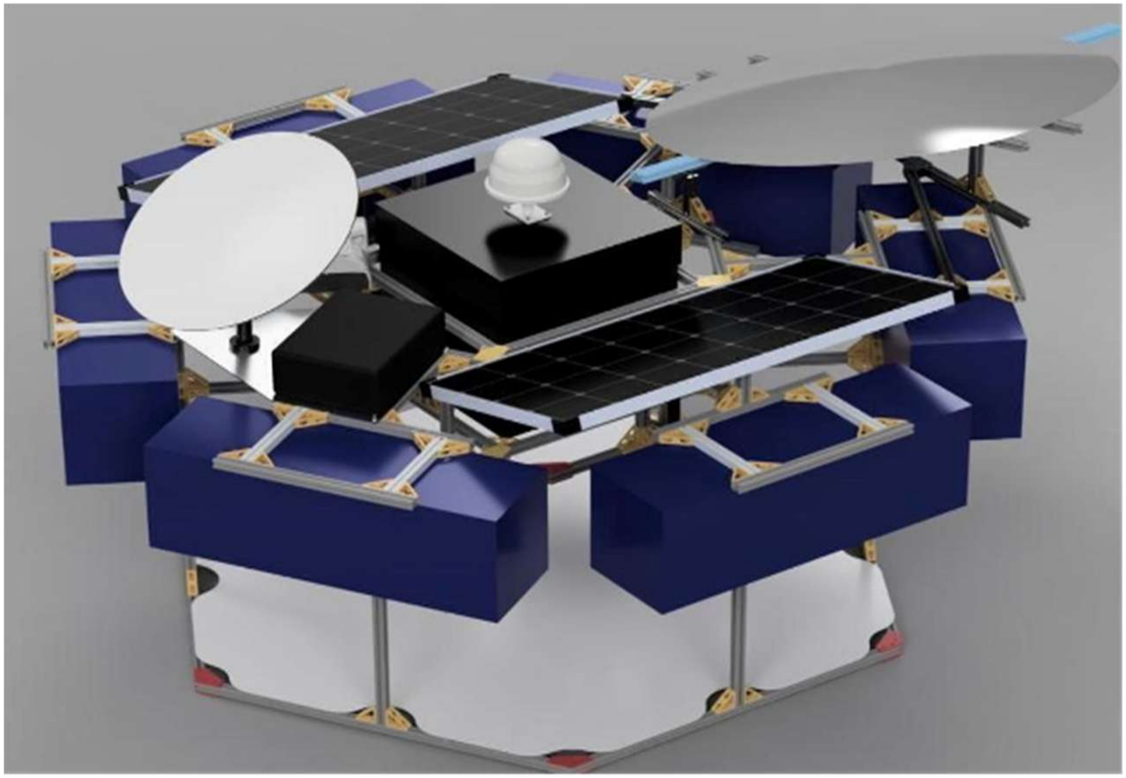
Ethan S. Rolland[1] | Maha N. Haji[2] | Olivier L. de Weck[1]







PEARL v2 (2023-2024)



Date | 9


360 deg rotation

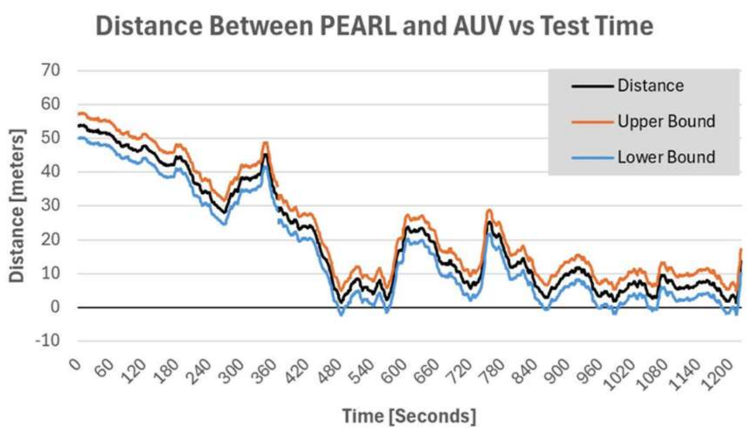
PEARL-AUV Docking Demonstration (2023)

Jack Hamel
SM SDM ‘24
USCG Officer

Figure 6.3: PEARL with dummy AUV docked

5.2.1 MOOS-Ivp Code

pAUVdock Application



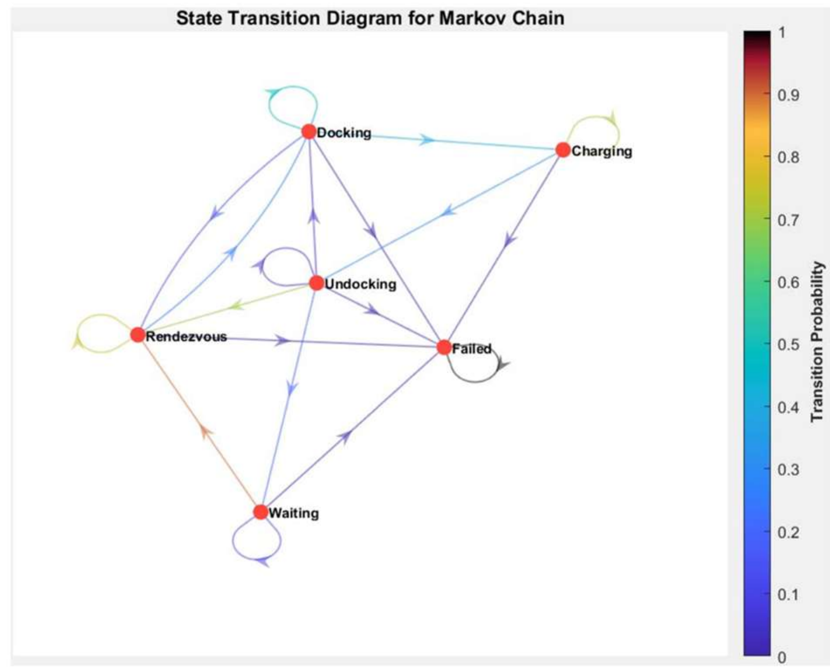
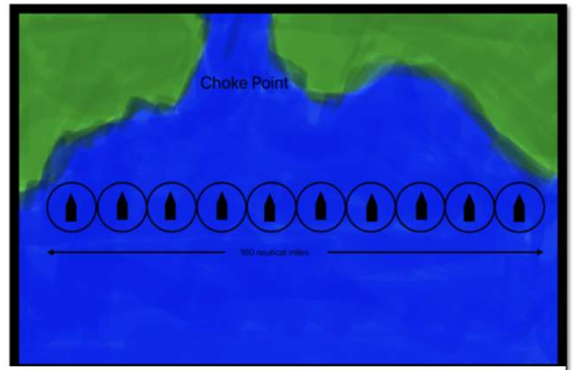


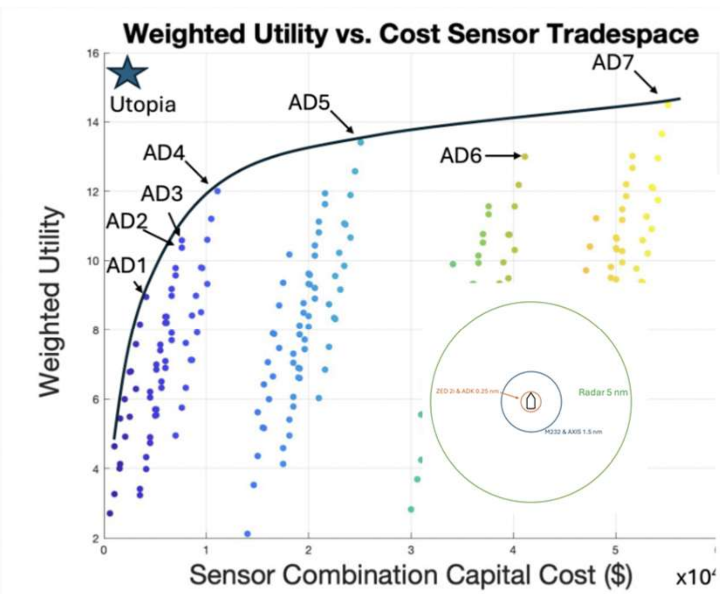
Figure 5.1: Markov State Diagram of PEARL

Hamel, John M. "A Systems Approach to Low-Cost, Modular Autonomous Surface Vehicle and Autonomous Underwater Vehicle Integration." SM Thesis., MIT, 2024.

PEARL Fleet: Coastal Monitoring (2024)

Maritime Domain Awareness Using Low-Cost, Long-Range Autonomous Surface Vehicles





John Nothacker
SM SDM ‘24
USN Officer

$$U_T = 0.35U_R + 0.35U_P + 0.05U_V + 0.05U_{Re} + 0.05U_D + 0.05U_W + 0.05U_M$$

Where:

- U_T is the total weighted utility
- U_R is the range utility
- U_P is the power consumption utility
- U_V is the field of view utility
- U_{Re} is the resolution utility
- U_D is the darkness utility
- U_W is the weather utility
- U_M is the marinized utility

Sensor Combination	AIS	RADAR	Visual Camera	Stereo Camera	IR - Low Performance	IR - Medium Performance	IR - High Performance	LIDAR	Power Consumption (W)	Cost (USD)	Utility
AD1	x	x	x	x					39	$4,100	8.95
AD2	x	x	x	x	x				43	$7,600	10.37
AD3	x	x	x	x		x			57	$7,600	10.58
AD4	x	x	x	x	x	x			61	$11,100	12.01
AD5	x	x	x	x	x		x		117	$25,100	13.40
AD6	x	x	x	x	x	x		x	73	$41,100	13.00
AD7	x	x	x	x	x	x	x	x	129	$55,100	14.48

TABLE III
LEADING SENSOR COMBINATIONS

Deployment at MIT Sailing - Charles River - 2024

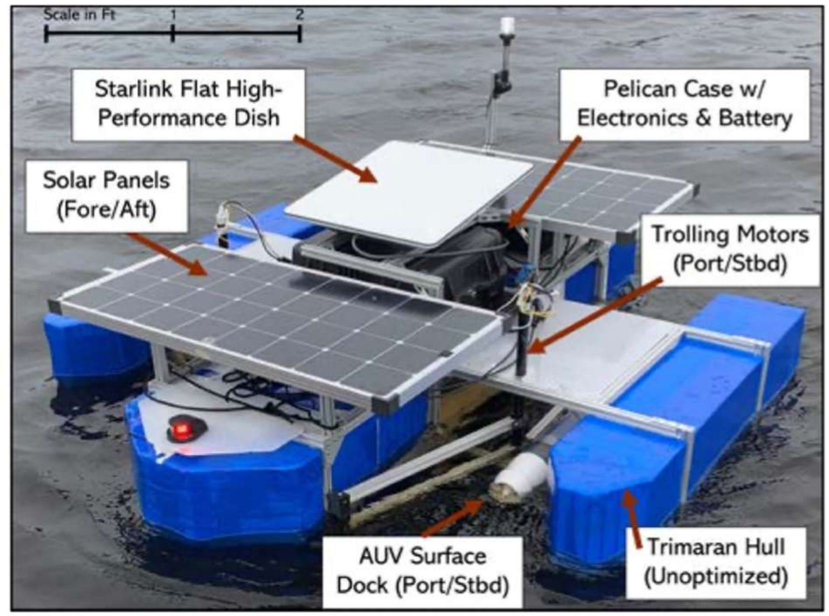
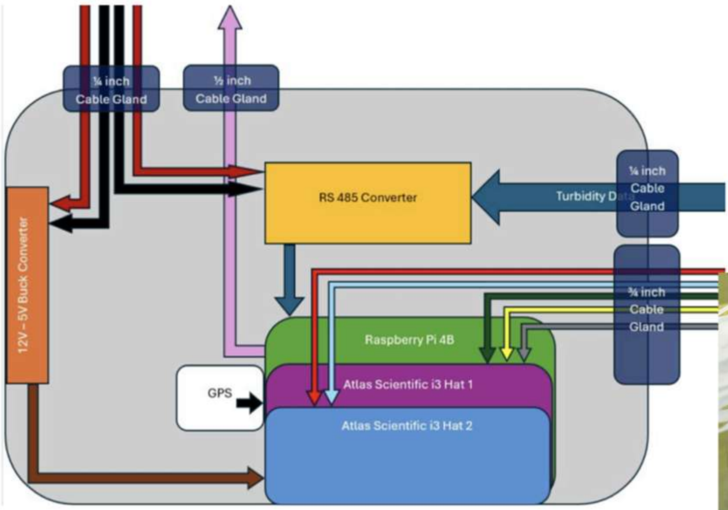


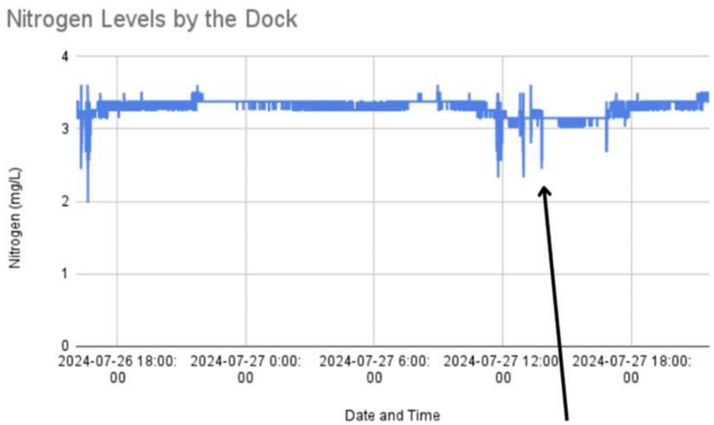
Figure 2.2: 2023 Version of PEARL

PEARL Prototype (v3)

PANTHER Module: Environmental Water Quality Monitoring



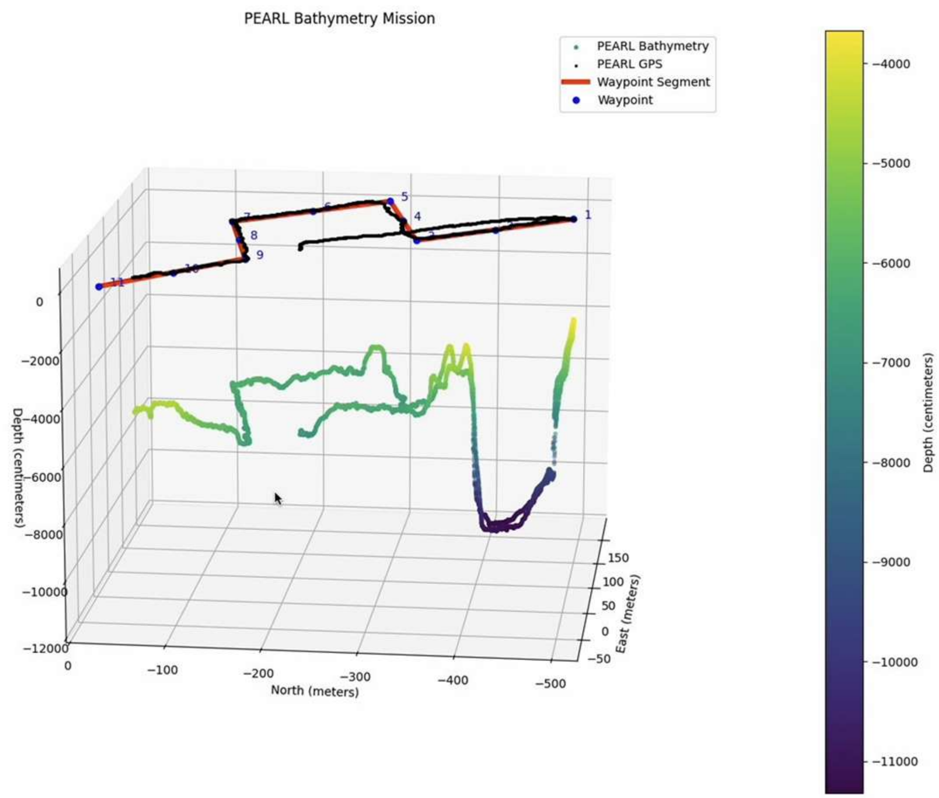
CONOPS: Real-time remote and autonomous water quality monitoring



Capstone Project
UMASS Dartmouth

- Atlas Scientific Water Probes
- Sensor requirements:
  - Probe - sample data
  - Circuit - process data
  - Tentacle T3 Hat

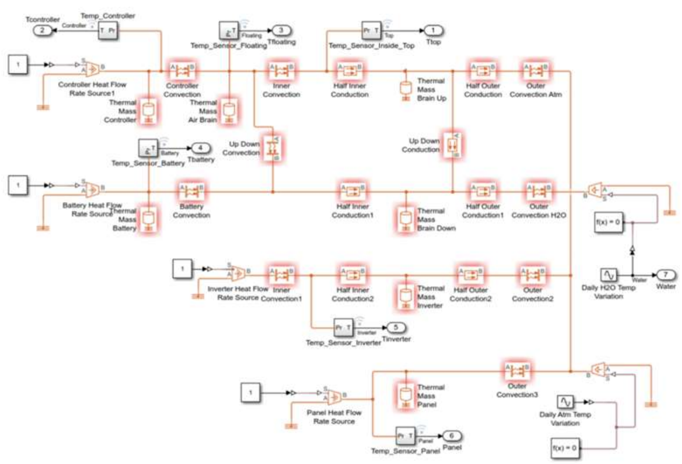
Precision Autonomous Bathymetry

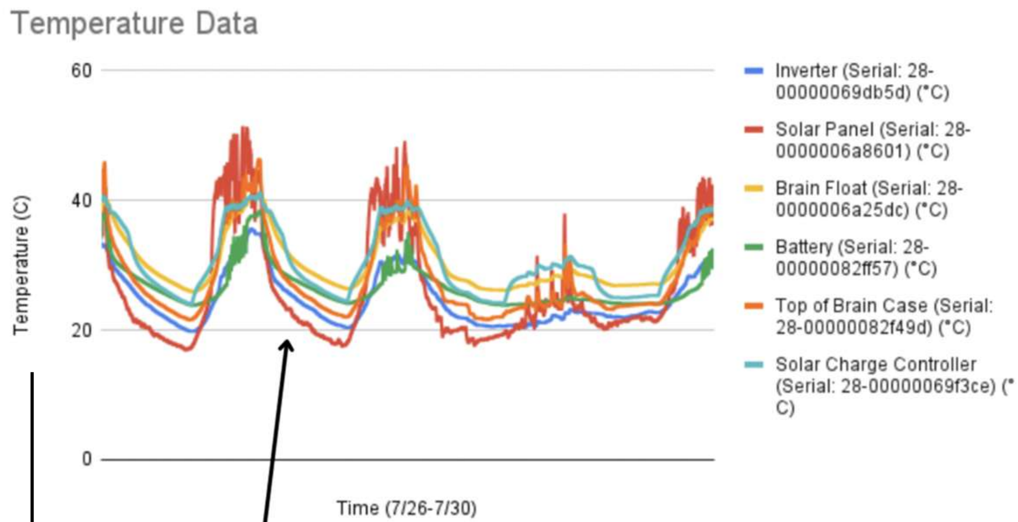


Digital Twin Development (Thermal System)

MathWorks

- Testing Plan and Data Analysis
- Power Generation
- Electronics Connections
- Sensors
- Data Transmission
- Thermal Modeling



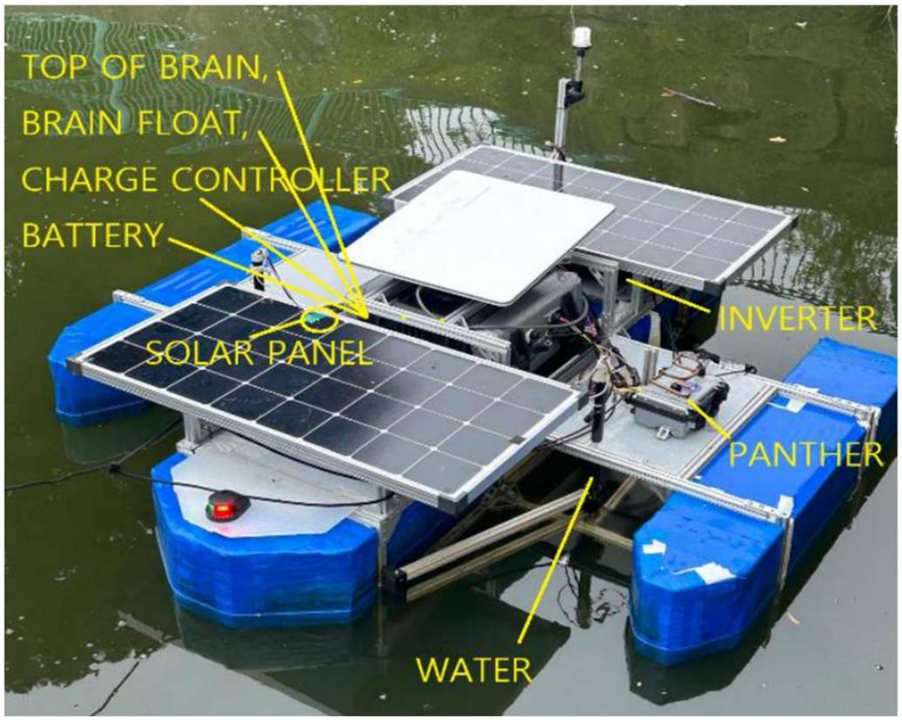


Temperature fluctuations can be observed based on the day/night cycle.

CONOPS: Predict and prevent unexpected thermal shutdown experienced in 2023/2024

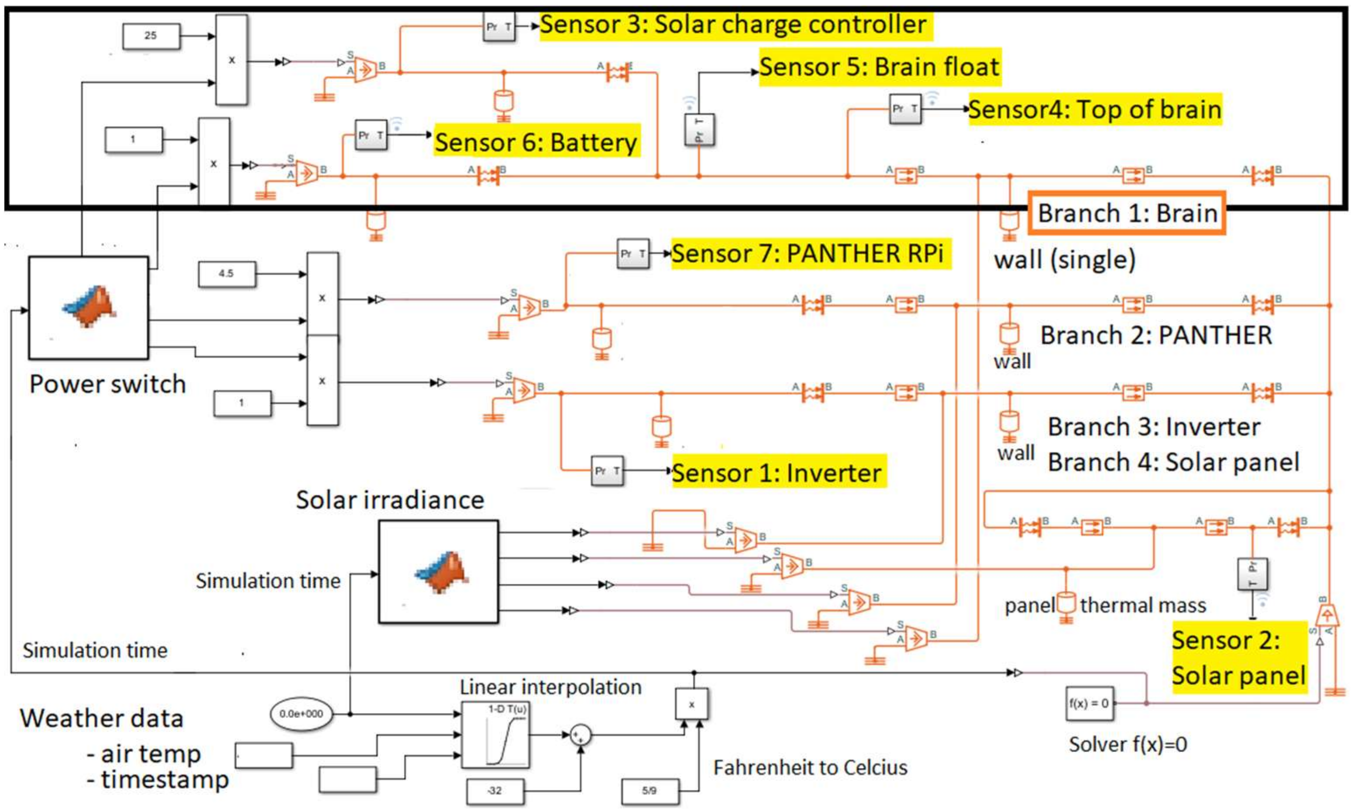
https://followpearl.mit.edu
https://www.notion.so/PEARL-Prototype-af8b72173f7346619b3b7bcdec3cf2f8

The Digital Twin Development



- → 8 Thermal nodes

Single Zone Brain Model



KEY:

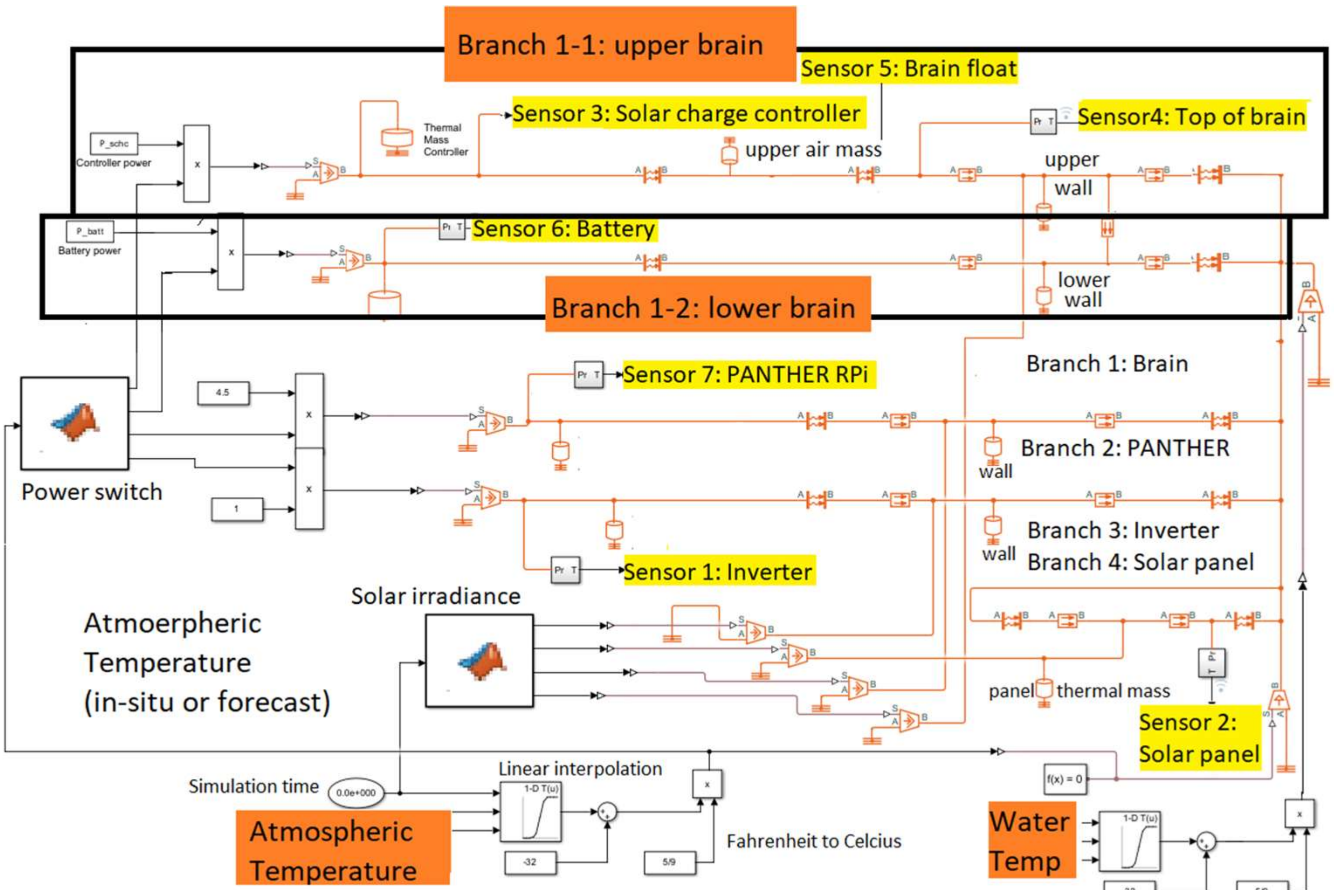
Black Lines represent simulink signal connections

Orange Lines represent Simscape thermal connections

Single Zone Complexity Limitation

Atmospheric Vs **Water**

Dual Zone Brain Model

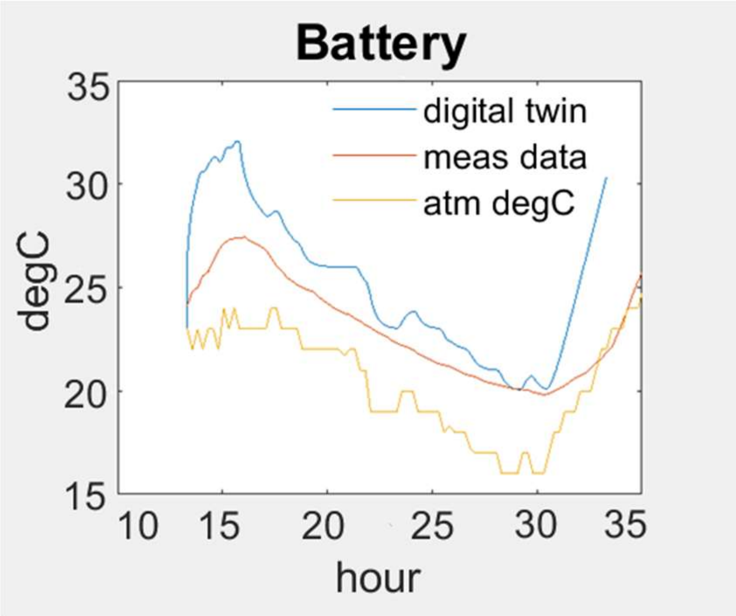


KEY:

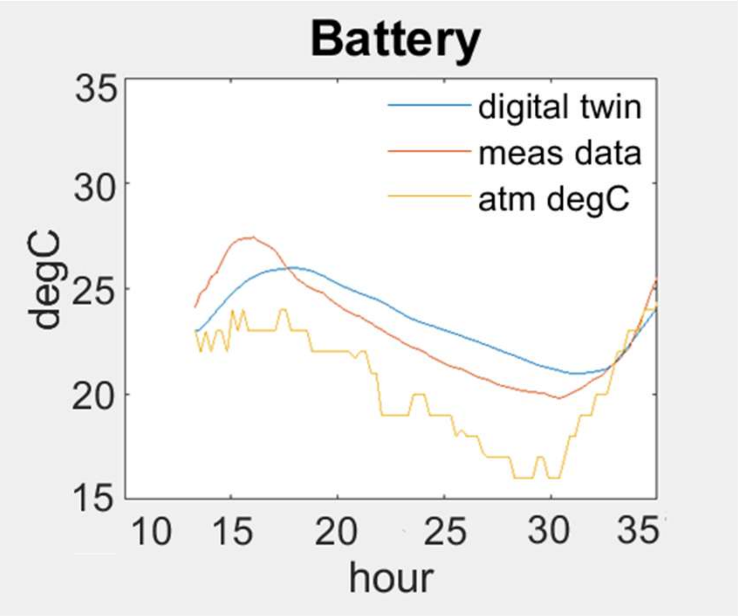
Black Lines represent Simulink signal connections

Orange Lines represent Simscape thermal connections

Data and Analysis- Aug 22, 2024

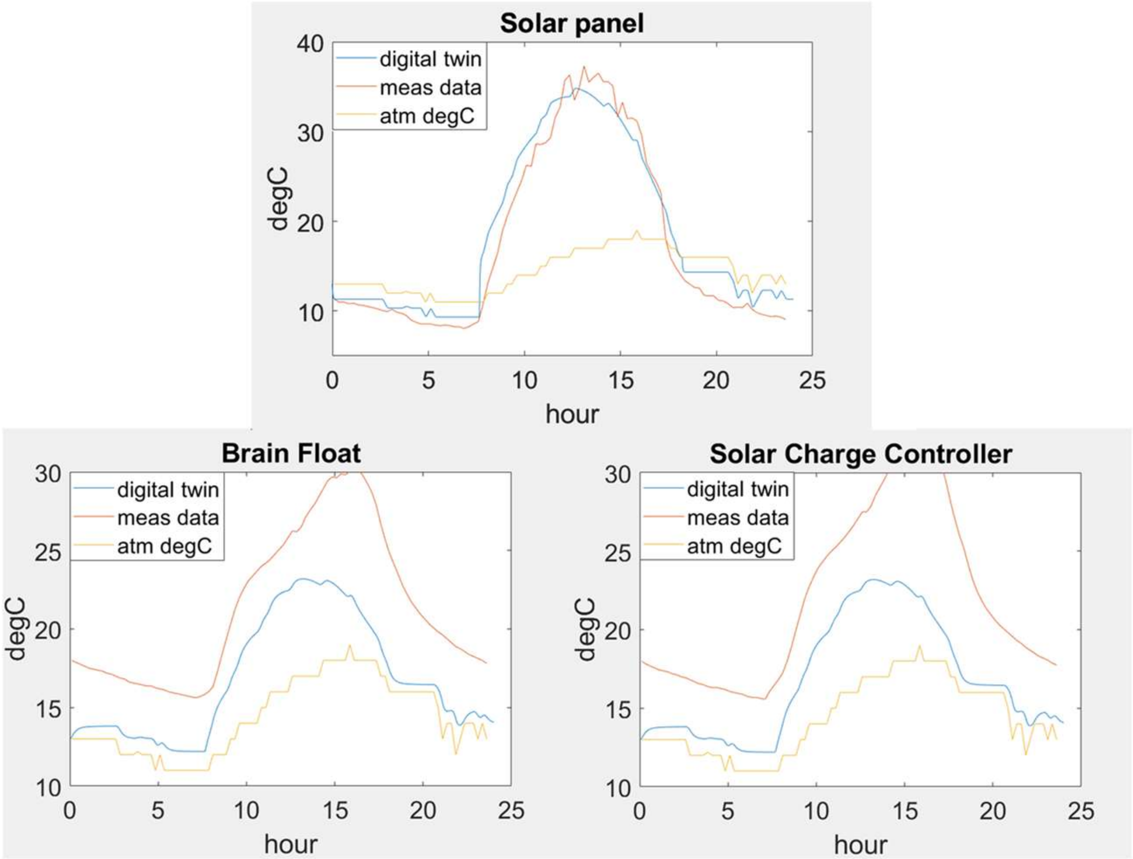


Single zone Model



Dual zone Model

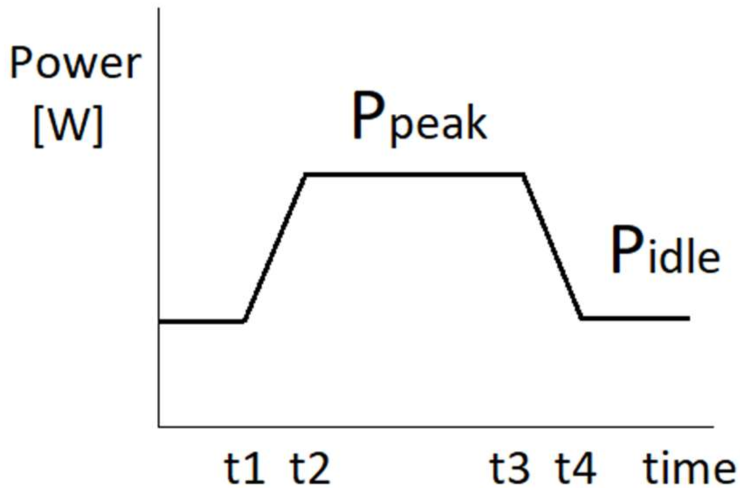
Data and Analysis- Oct 8, 2024



Iterations/Parameter Variations (Aug -> Oct)

Internal heat generation

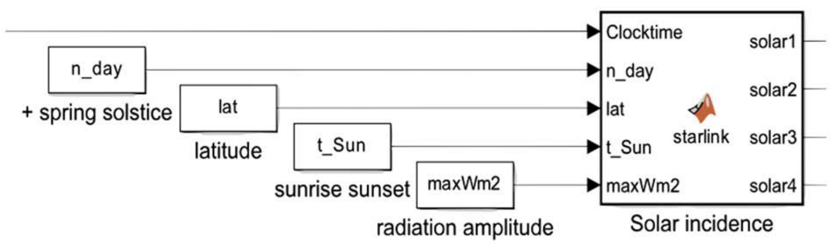
- ➔ Charge controller produces heat from charging during sunny days
- ➔ Affects "brain float" and "top of brain"



Seasonal thermal change

- ➔ Solar incidence angle (ψ) can be derived using spherical geometry

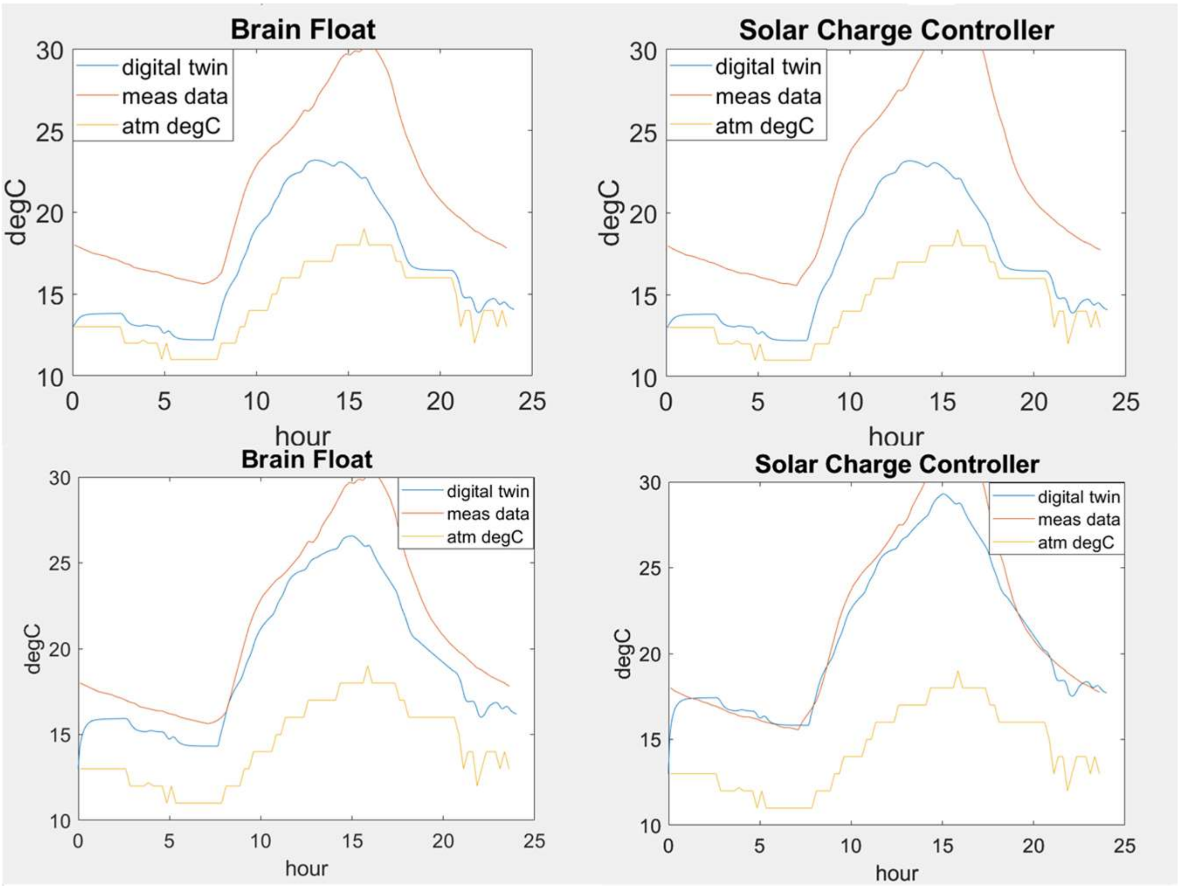
$$\cos\psi = \cos\theta\ \cos a\ \cos\varphi + \sin\theta\ \sin\alpha$$



Data and Analysis- Oct 8, 2024

Without heat profile

With heat profile



Model Complexity trade off

Model Free:
15% (air only)
13% (air only)

7% (air + water)
6% (air + water)

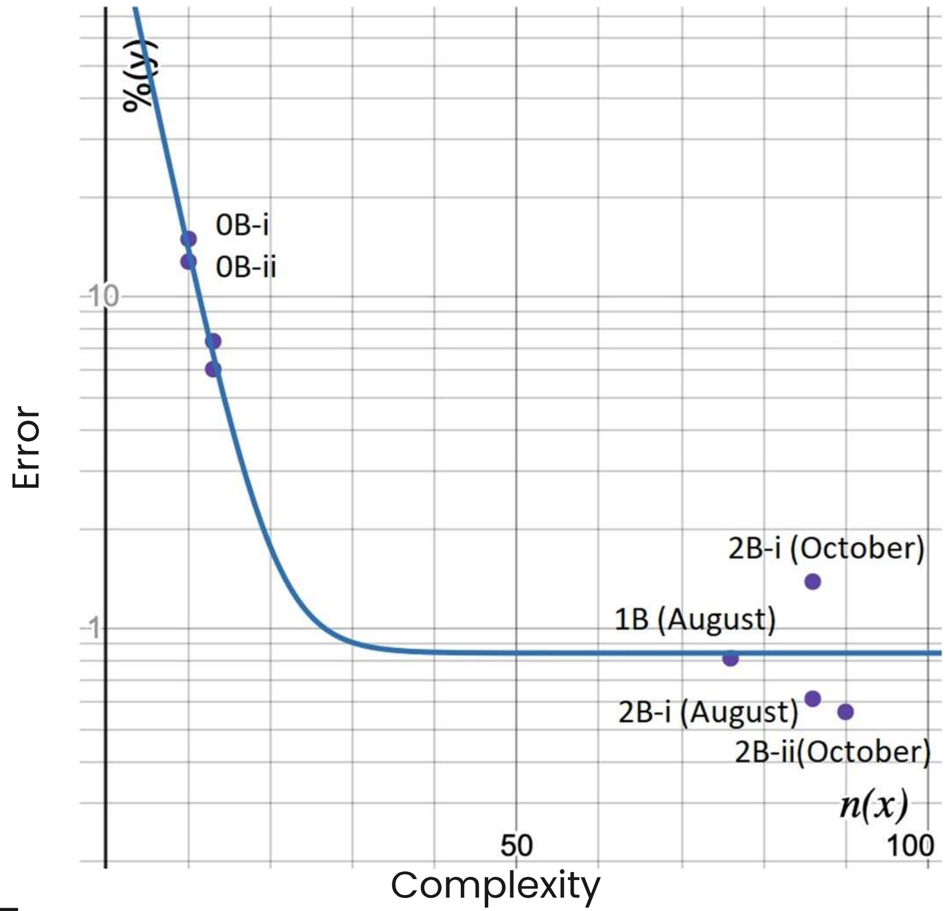
Single Zone Brain:

1%
1.5%

Double Zone Brain:
0.6%
0.6%

KEY: August-22, October-9

n(conn)
10
13
76
94



Conclusions

Digital twin has been developed to emulate and predict the **thermal behavior** of **PEARL within 10** ℃ **to 57** ℃

Digital twins **cannot** capture **all aspects** of a system bur rather need to be **tailored** to **specific aspects**

In order to **half** the **error** of the predictive model, the **complexity** has to be roughly **doubled**

Development of digital twin must be proceeding in an **iterative fashion** to achieve a low **RMSE digital twin in our case 0.6% error**

Future Work

➔ Overcast or Rainy weather conditions calibration
➔ Introducing larger heatsinks to increase thermal mass of RPis
➔ Thermal monitoring during motor powdered navigation for calibration
➔ Measuring Electrical Subsystems to combine thermal management with power monitoring
➔ Expand PEARL to Multi-Platform Coordination

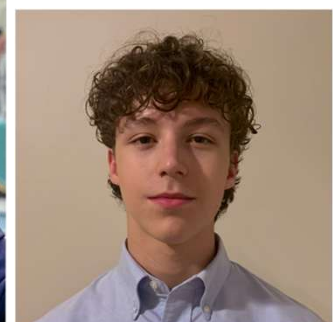
Meet the MIT PEARL Team

Olivier de Weck
Professor MIT
Aero Astro

Nik
Tapanainen
SB Candidate
UMASS
Dartmouth

Christina Nguyen
SB 16 MIT 24’

Abhishek
Bhattiprolu
UMASS
Dartmouth
SB ‘24



Ayden
Soderblom
Boston Latin
School Rising
Senior

Sung Wook Paek
Sr Lecturer
City U London

Acknowledgements

- ➔ All PEARL team member’s and their contributions to the development and deployment of PEARL Gen3 with PANTHER.
- ➔ The staff at MIT Sailing Pavilion and MIT Marine Autonomy Lab (Pavlab) for their assistance.
- ➔ Funding for this research was provided by The MathWorks under DCRG Project No. 259 under the title "Digital Twin Development for PEARL Autonomous Surface Vehicle.”
- ➔ Special thanks go to Dr. Neha Sardesai and Dr. Andy Grace from the MathWorks.

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