Developing a Framework for Modeling Underwater Vehicles in Modelica

SHASHANK SWAMINATHAN (CURRENTLY AT F.W. OLIN COLLEGE OF ENGINEERING)
DR. SRIKANTH SARIPALLI
TEXAS A&M UNIVERSITY

Presentation Outline

Introduction

Building and testing the BlueROV2 posed a slew of difficulties:

- Understanding design parameters
- Logistics of testing in bodies of water
- Necessitating multiple tests to create control strategies

These problems are common to all ROVs under construction

An underwater vehicle specific modeling framework would aid the development of ROV designs and controls

Framework Goals

1

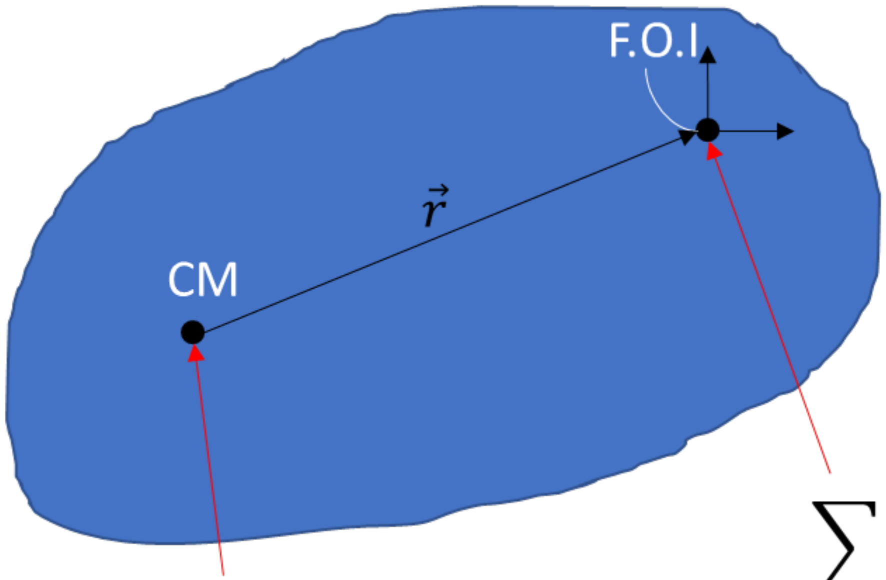
Aid the prototyping and testing of vehicle design and controls.

2

Be readily integrated with common control and feedback mechanisms, specifically ROS.

3

Visualize prototype design and test results via three-dimensional animation.



$$\sum \vec{F}_{FOI} = \sum \vec{F}_{CM}$$

$$\sum \vec{F}_{CM} = \vec{F}_{buoyant} + \vec{F}_{drag}$$

$$\sum \vec{\tau}_{FOI} = \vec{r} \times \sum \vec{F}_{CM}$$

URBL Field Model

DIAGRAM OF FIELD INTERACTIONS WITH RIGID BODY

URBL Field Model

The field interactions are written as dependent on the rigid body's characteristics

The current field implementation only accounts for buoyancy and drag forces.

- It thus has two functions:
  - $\vec{f}_{buoyant} \coloneqq -\frac{\rho_{fluid}}{\rho_{body}} \cdot m \cdot \vec{g}$
  - $\vec{f}_{drag} \coloneqq -v_{viscosity} \cdot A \cdot \vec{v}$
    - To account for angular drag, the following is also added to the drag function: $\vec{\tau}_{drag} \coloneqq -k_{drag} \cdot \vec{\omega}$

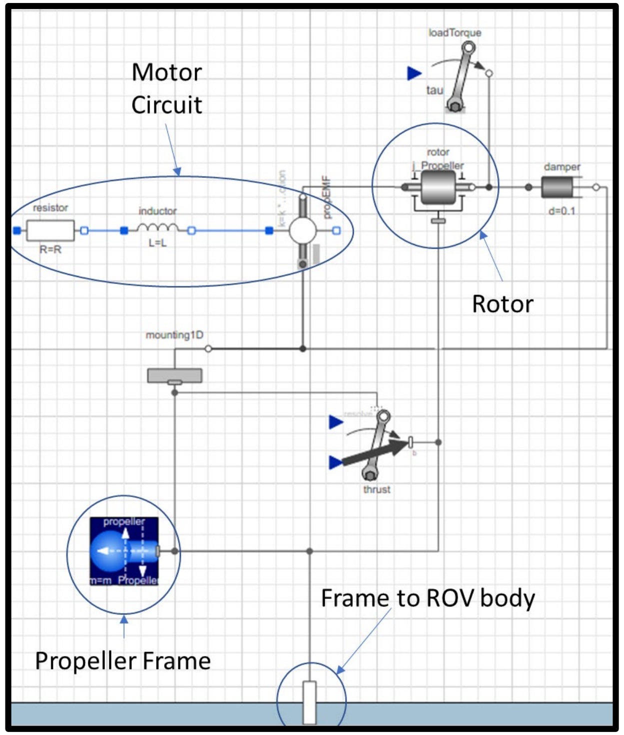
The functions are replaceable, thus allowing a modular approach to upgrading the functions

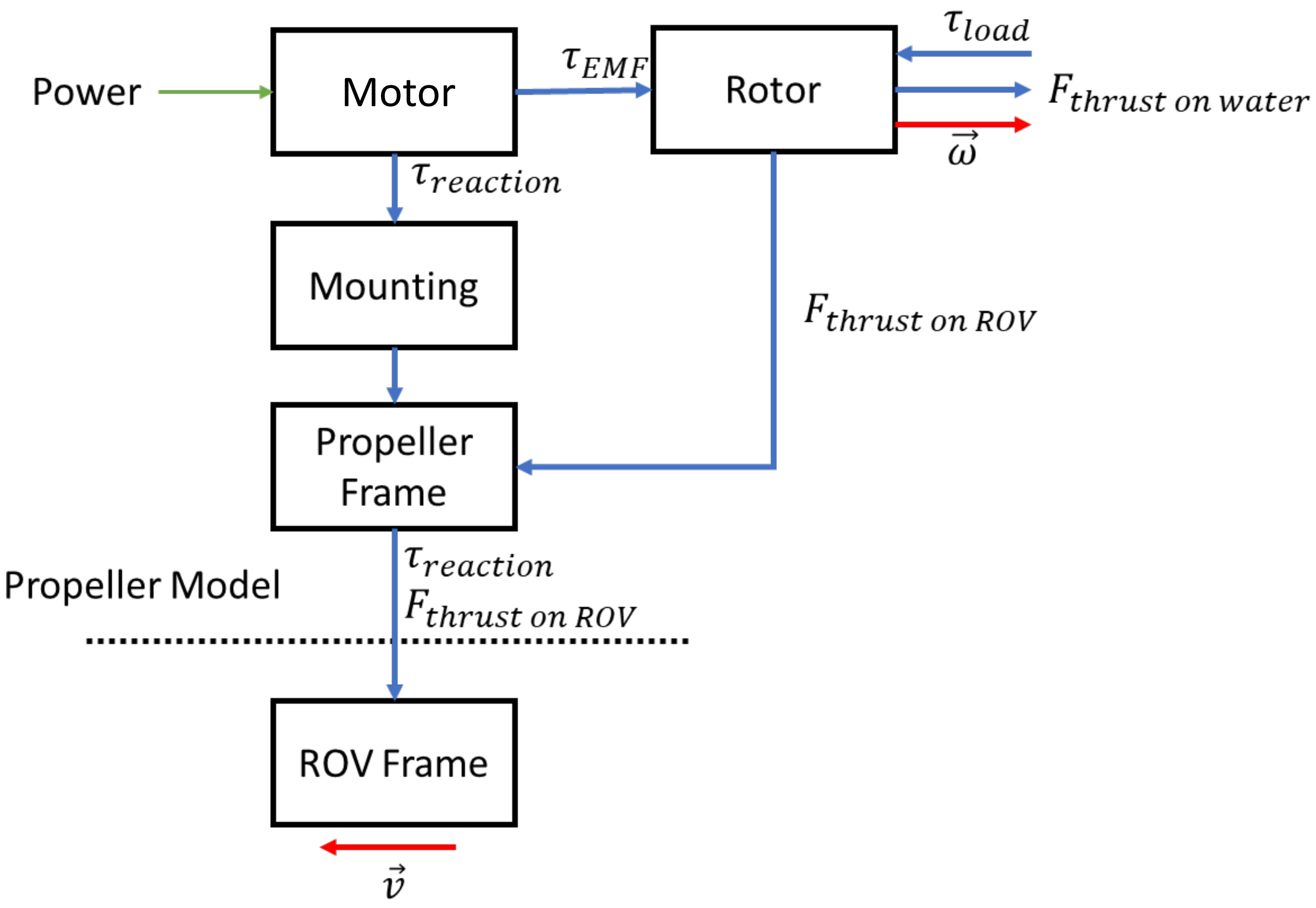
URBL Propeller Template

Motivated from the designs of other underwater vehicles modeled in other papers, as well as that of the BlueROV2

Creates a template for propeller use:

- Has dynamics detailing thrust on body, and load torque from water
- Has inertial mass component for interacting with ROV
- Can be implemented along any axis of motion
- Depends on EMF for actuation – source of voltage to the propeller is not provided





Propeller Component Schematic

HIGH LEVEL DIAGRAM OF FORCE INTERACTIONS IN PROPELLER

Propeller Dynamics - Thrust

Thrust can be written as follows:

- $F_{thrust} \propto \omega^2 K_T(J^*)$
- Where ω is the rotor's angular velocity, and $K_T(J^*) = \beta_1 - \beta_2 J^*$
  - $J^* = \frac{v}{\omega}$
- This means that F_{thrust} can be rewritten as $F_{thrust} \propto \omega^2 \left(\beta_1 - \beta_2 \frac{v}{\omega}\right)$

Expanding and regrouping constants gives

- $\vec{F}_{thrust} = -k_m|\omega|(k_r\vec{\omega} - \widehat{\omega} \cdot \vec{v})\, b_{dir}$
  - $\vec{v}$ is the relative velocity between the ROV and the water
  - k_m, k_r are appropriate constants of proportionality derived from β_1 and β_2
  - b_{dir} indicates the direction of the propeller's mounting

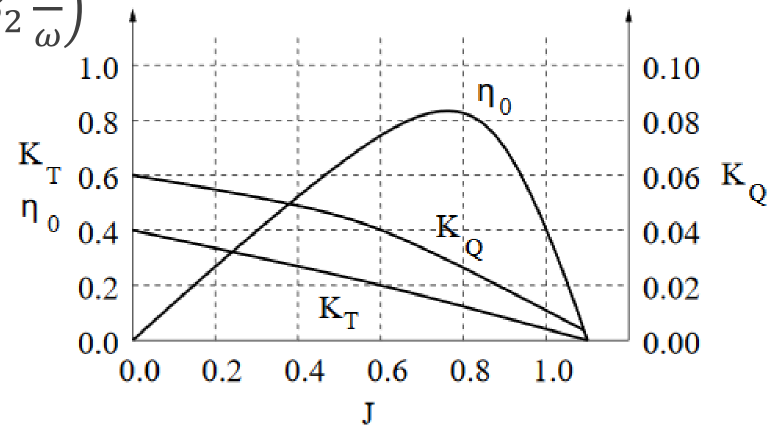


Figure 4: Typical thrust and torque coefficients.

Source: M. Triantafyllou. *2.154 Maneuvering and Control of Surface and Underwater Vehicles (13.49).* Fall 2004. Massachusetts Institute of Technology: MIT OpenCourseWare, https://ocw.mit.edu. License: Creative Commons BY-NC-SA

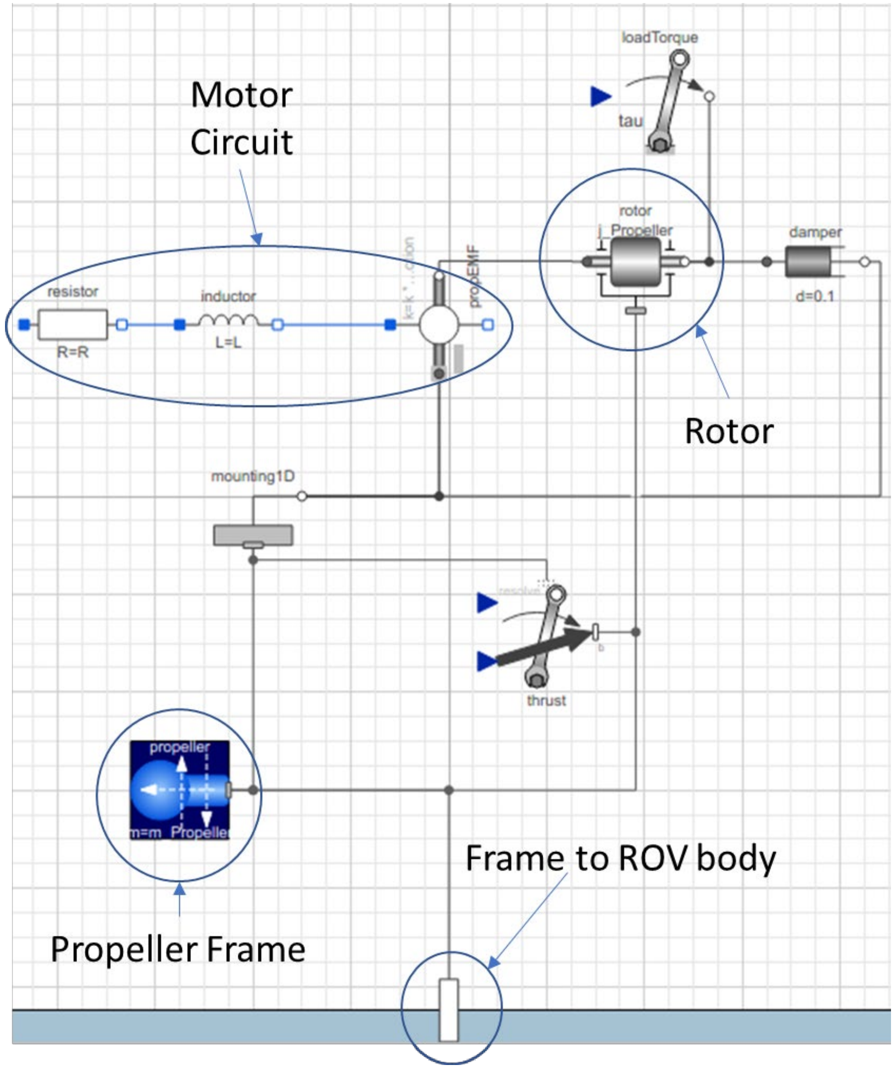
Propeller Dynamics – Load Torque

The load torque on the propeller due to moving water is found via power balance:

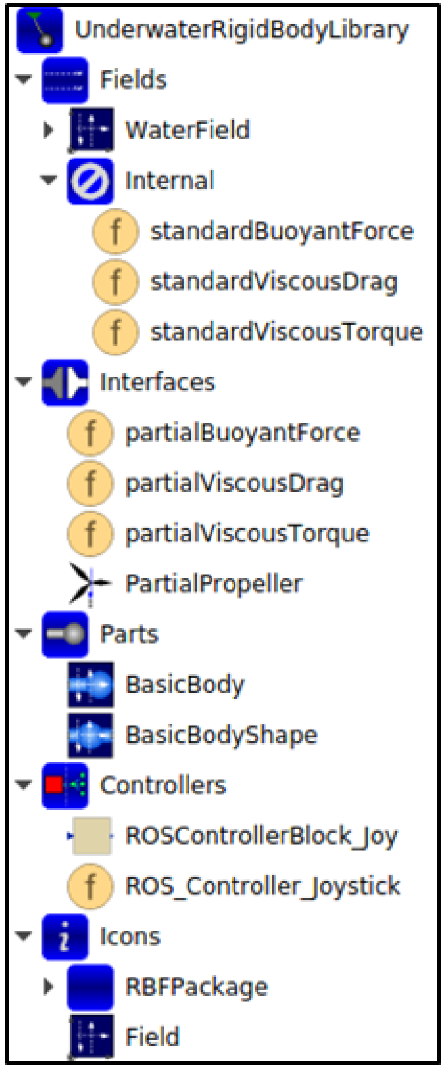
- $\vec{\tau}_{load} = -\frac{\vec{F}_{thrust}\,\widehat{\omega}\cdot\vec{v}}{|\vec{\omega}|\eta}$
  - $\vec{F}_{thrust}$ is thrust
  - $\vec{v}$ is the relative velocity between the ROV and the water
  - $\vec{\omega}$ is the rotor's angular velocity
  - η is the efficiency of the power balance

To better handle when $\vec{\omega}$ goes to zero, this equation is rewritten by expanding the thrust term:

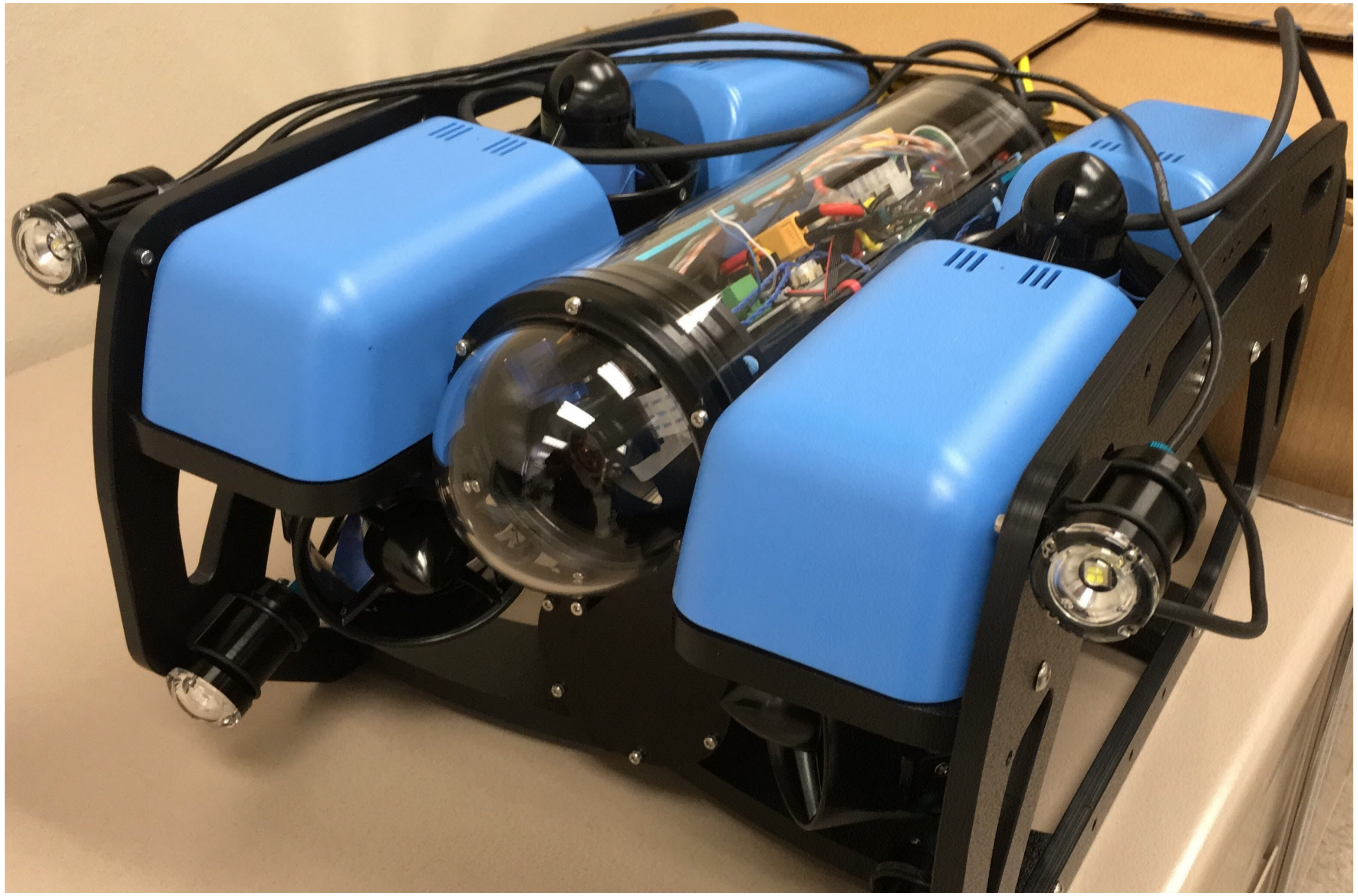
- $\vec{\tau}_{load} = -k_m\vec{v}(k_r\vec{\omega} - \widehat{\omega}\cdot\vec{v})\, b_{dir} - k_{loss}\vec{\omega}$
- $k_{loss}\vec{\omega}$ is added to represent loss purely due to the rotor's motion.



Propeller Dynamics – Modelica Implementation



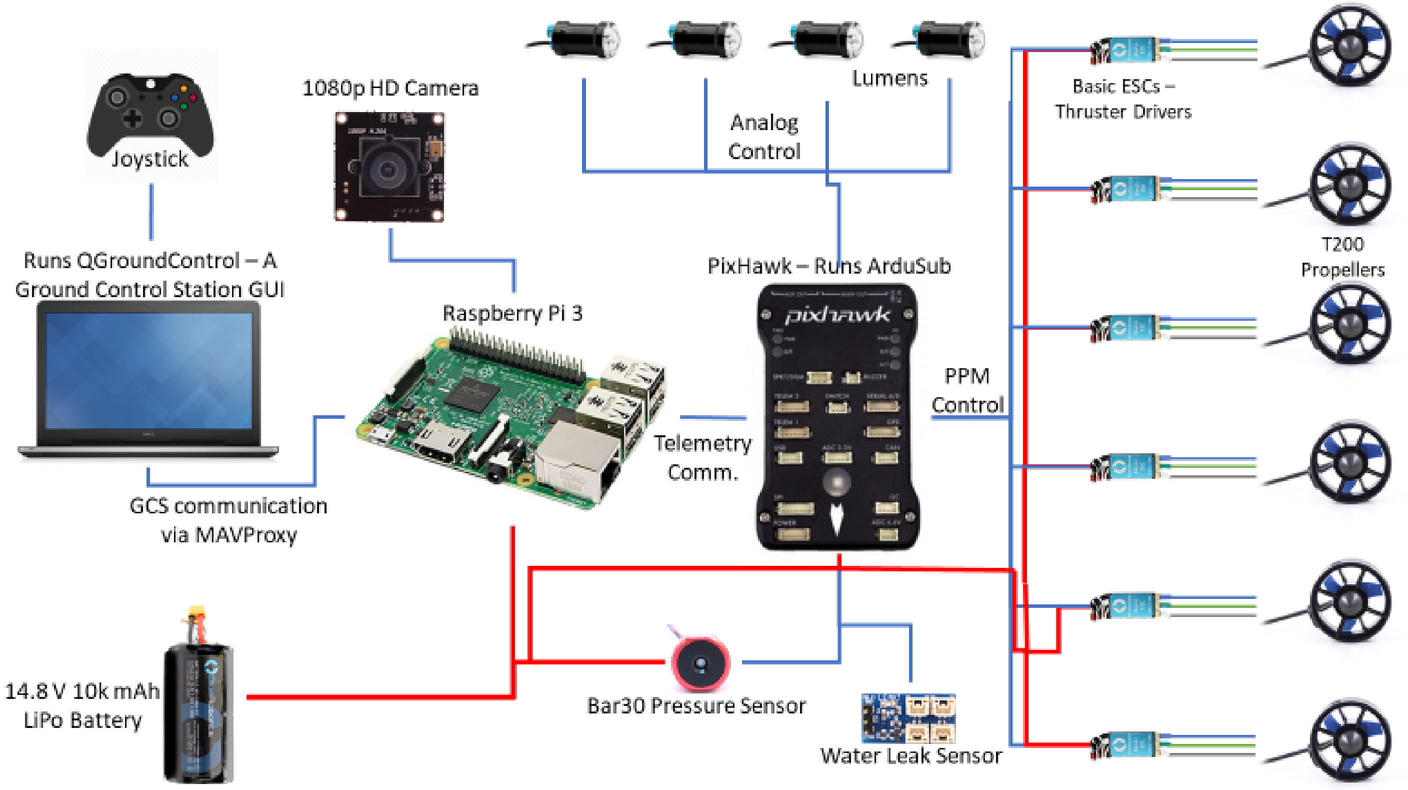
URBL Package Structure

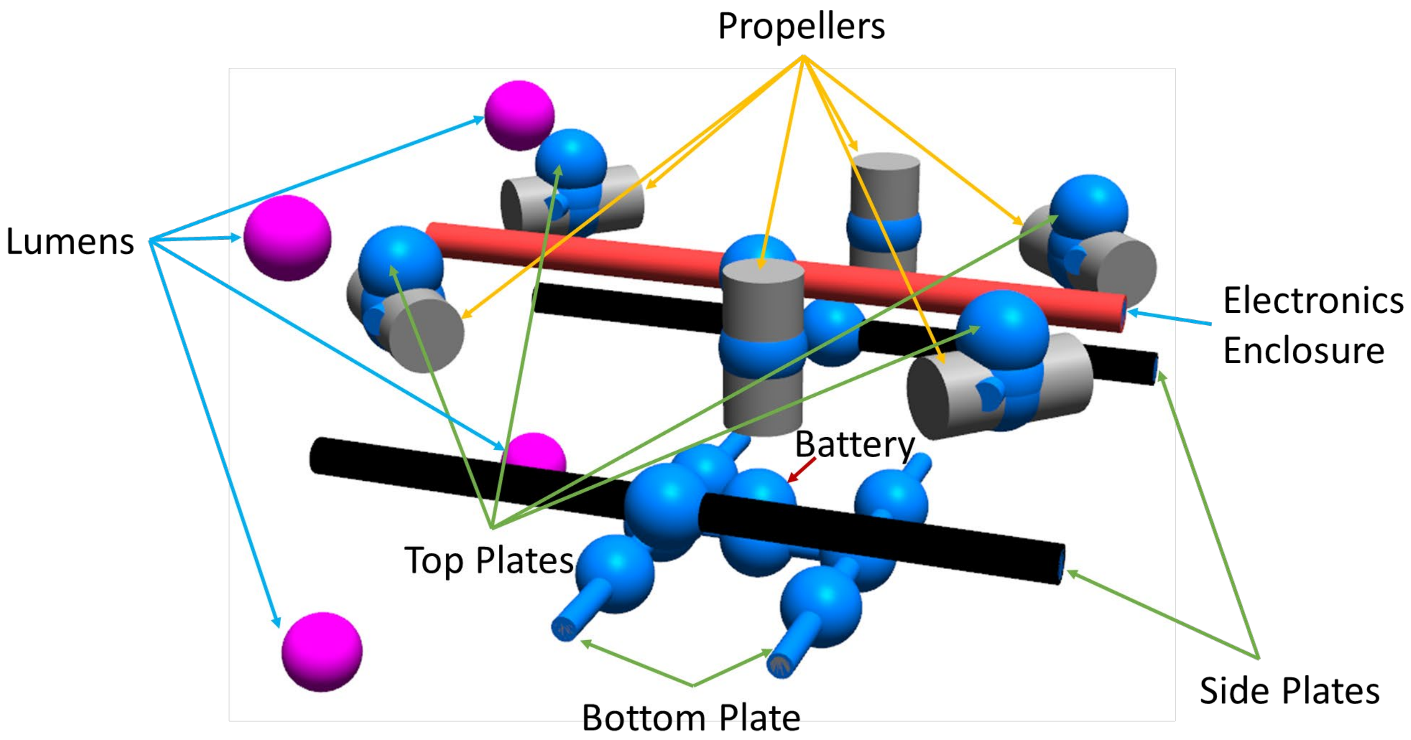


Application of the URBL

The framework is used to model a commercially available ROV, the BlueROV2 from Blue Robotics

Hardware Schematic

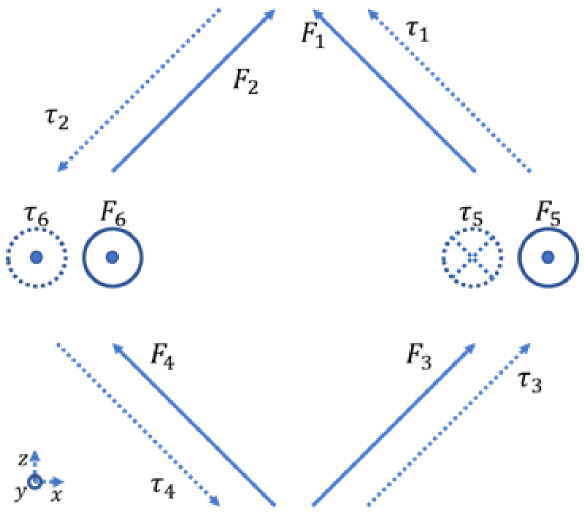




Animation of BlueROV2

GENERATED VIA SYSTEMMODELER

Controller Derivation



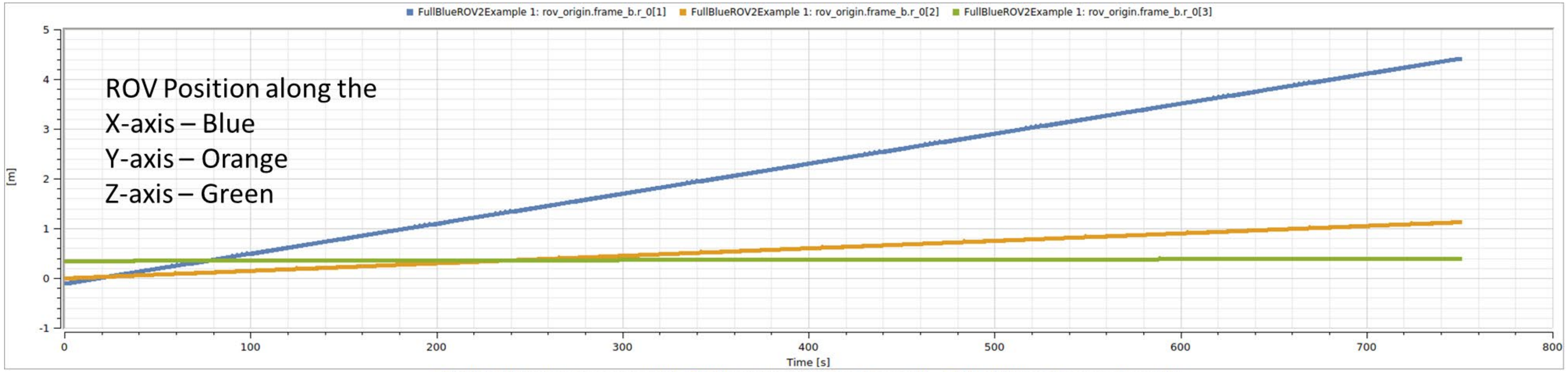
$$\begin{pmatrix} \frac{n}{\sqrt{2}} & \frac{n}{\sqrt{2}} & \frac{n}{\sqrt{2}} & \frac{n}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & n & n \\ -\frac{n}{\sqrt{2}} & \frac{n}{\sqrt{2}} & \frac{n}{\sqrt{2}} & -\frac{n}{\sqrt{2}} & 0 & 0 \\ \frac{1-nh_{1,y}}{\sqrt{2}} & \frac{nh_{2,y}-1}{\sqrt{2}} & \frac{nh_{3,y}+1}{\sqrt{2}} & \frac{-nh_{4,y}-1}{\sqrt{2}} & -nh_{5,z} & -nh_{6,z} \\ \frac{n(h_{1,x}+h_{1,z})}{\sqrt{2}} & -\frac{n(h_{2,x}-h_{2,z})}{\sqrt{2}} & -\frac{n(h_{3,x}-h_{3,z})}{\sqrt{2}} & \frac{n(h_{4,x}+h_{4,z})}{\sqrt{2}} & -1 & 1 \\ \frac{-nh_{1,y}-1}{\sqrt{2}} & \frac{-nh_{2,y}-1}{\sqrt{2}} & \frac{1-nh_{3,y}}{\sqrt{2}} & \frac{1-nh_{4,y}}{\sqrt{2}} & nh_{5,x} & nh_{6,x} \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{pmatrix} = \begin{pmatrix} F_i \\ F_j \\ F_k \\ \tau_i \\ \tau_j \\ \tau_k \end{pmatrix}$$

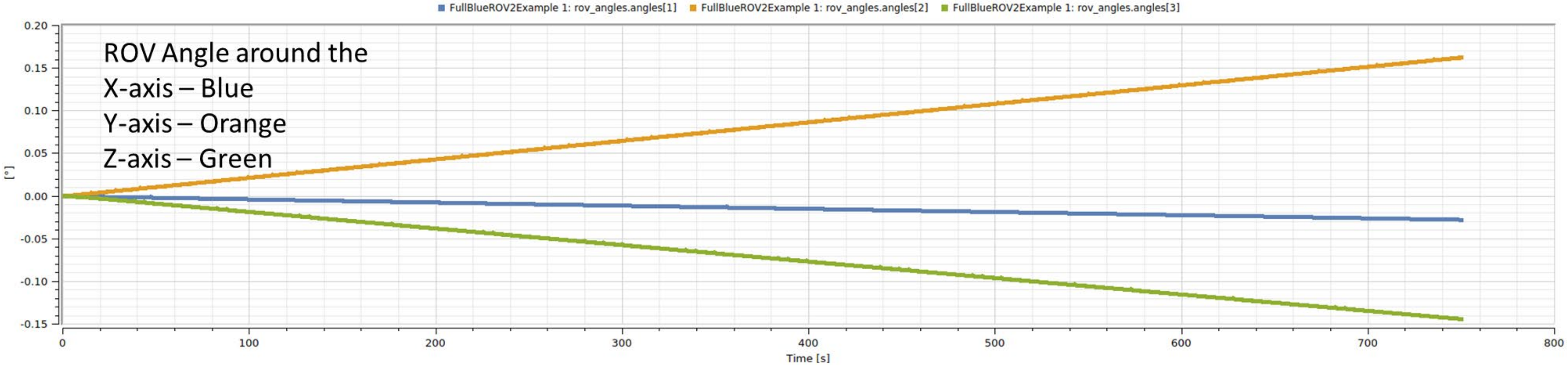
The diagram shows the propeller torque and associated thrust force orientations for all six propellers

What follows is a simple relation between propeller torque, thrust, and reaction torque:

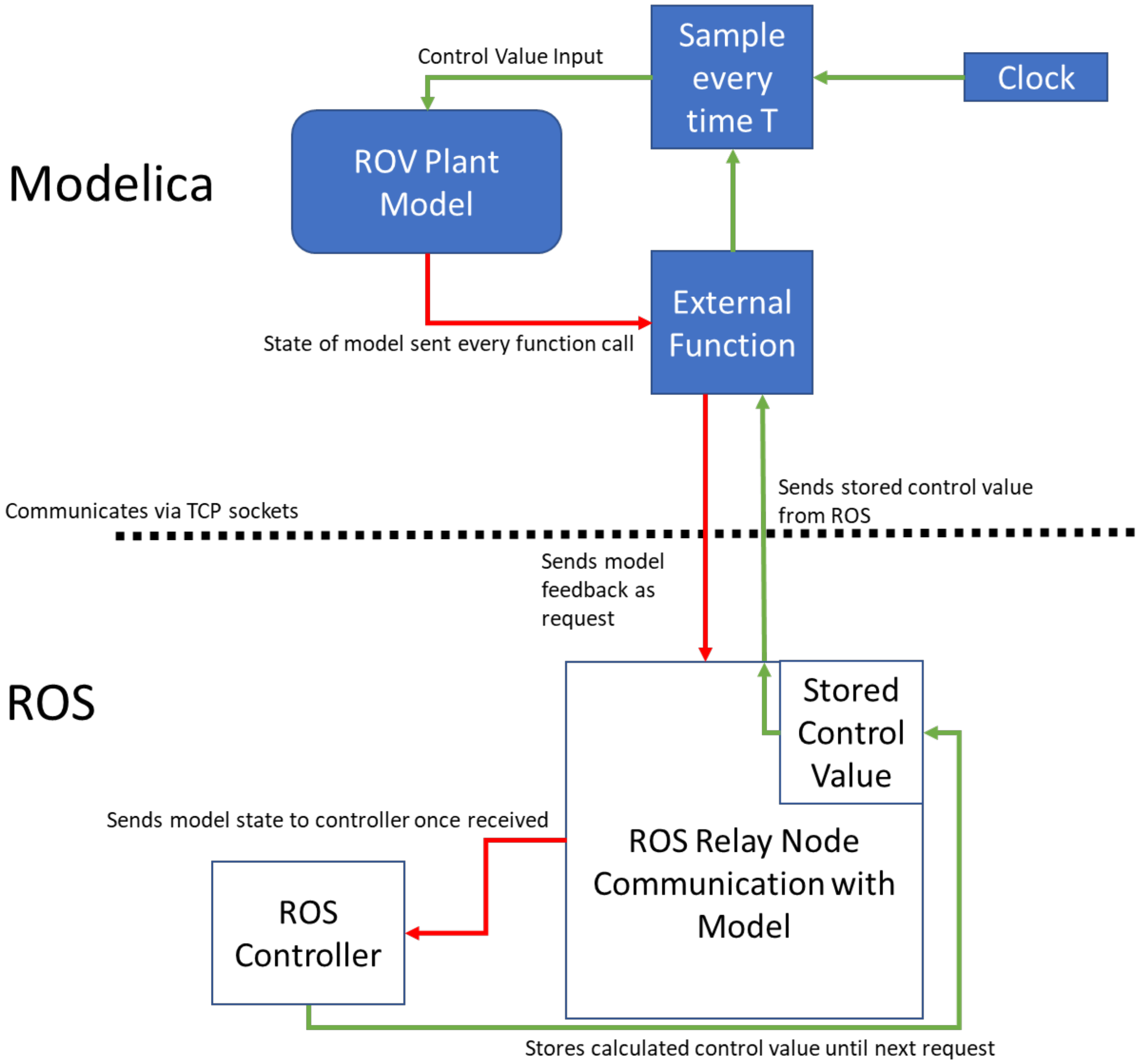
- $\vec{\tau}_1 = \tau_1 \sin 45\, \hat{\imath} - \tau_1 \cos 45\, \hat{k}$
- $\vec{F}_1 = n\tau_1 \sin 45\, \hat{\imath} - n\tau_1 \cos 45\, \hat{k}$
- $\vec{\tau}_{F_1} = \left(h_{1x}\hat{\imath} + h_{1y}\hat{\jmath} + h_{1z}\hat{k}\right) \times \vec{F}_1$
- The equations for the other propellers differ in orientation

This results in the invertible matrix relating the six propeller torques to composite forces and torques, used to control the ROV's propellers





Simulation Results – Constant Motor Input

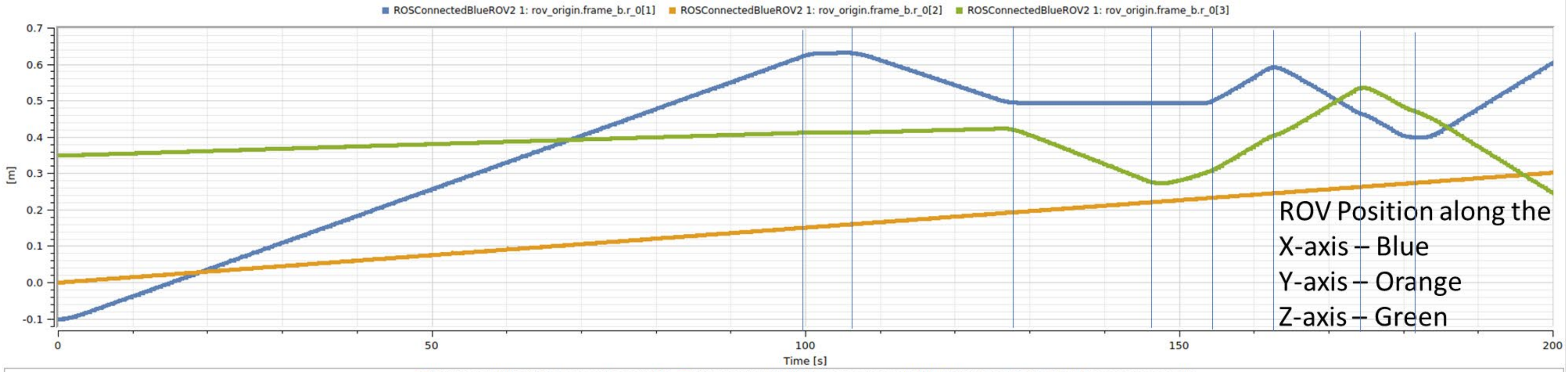


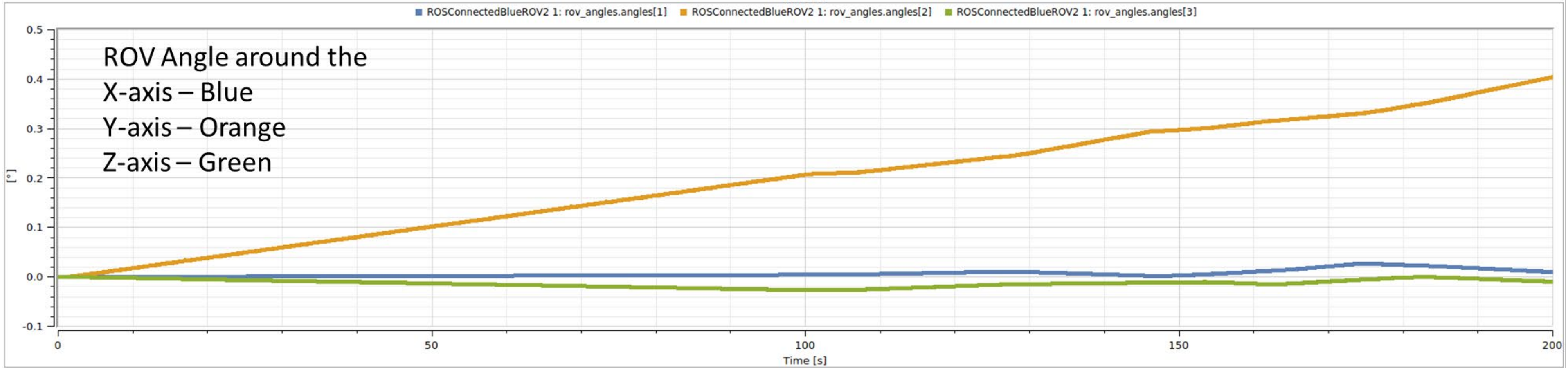
Bridge to ROS

Diagram detailing the connection between Modelica and ROS

Communicates via TCP/IP sockets

Developed separately beyond paper's scope as *modelica_bridge*





Simulation Results – Motor Inputs via ROS

Conclusions

The URBL was stably constructed to provide basic ROV modeling components, as well as ready-to-use integration with ROS

The URBL was successfully used to model an existing commercially available ROV design, the BlueROV2.

Future Work:

Library Improvements

- Viscous drag representation
- Hydrodynamic function replaceability

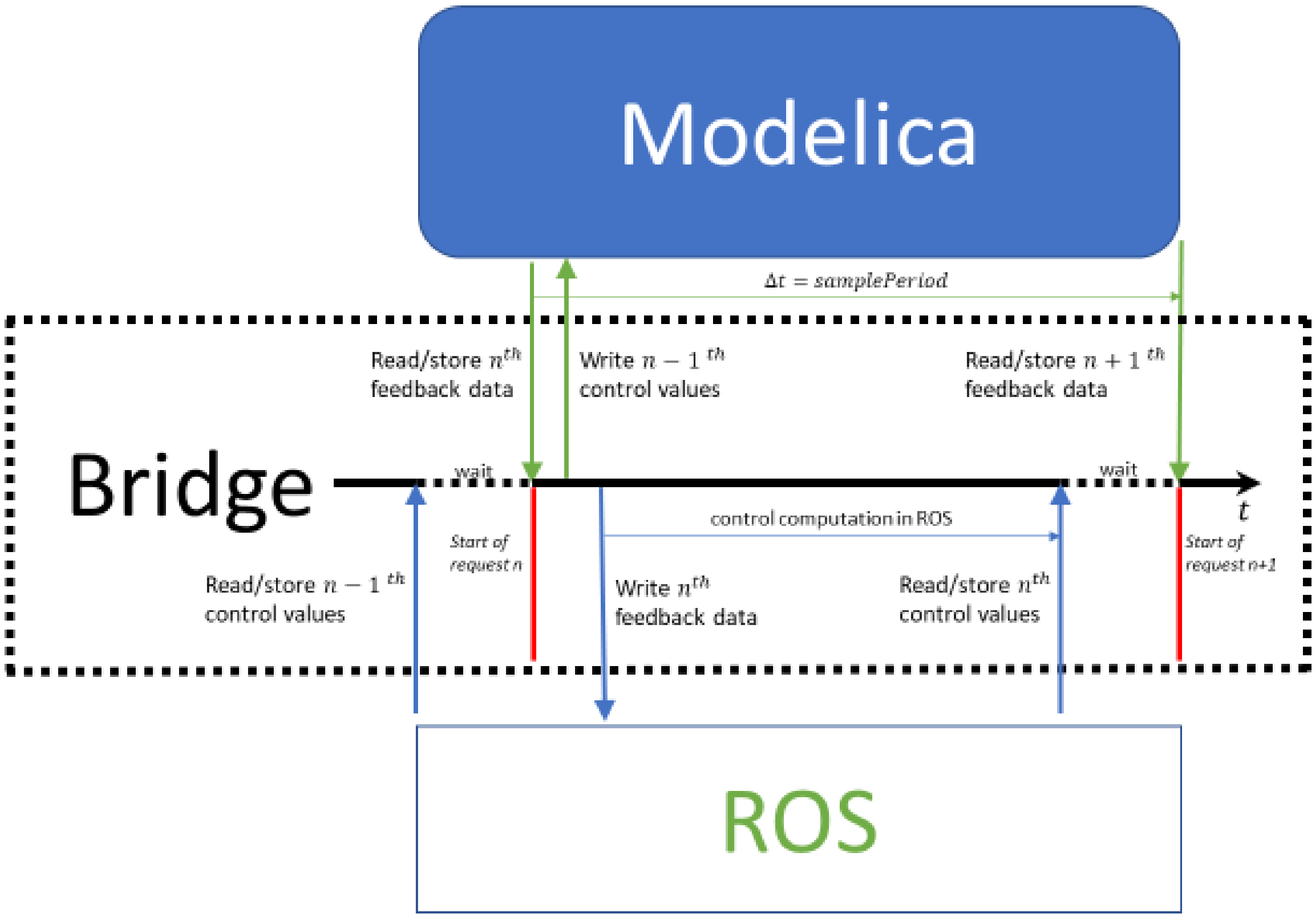
Model Improvements

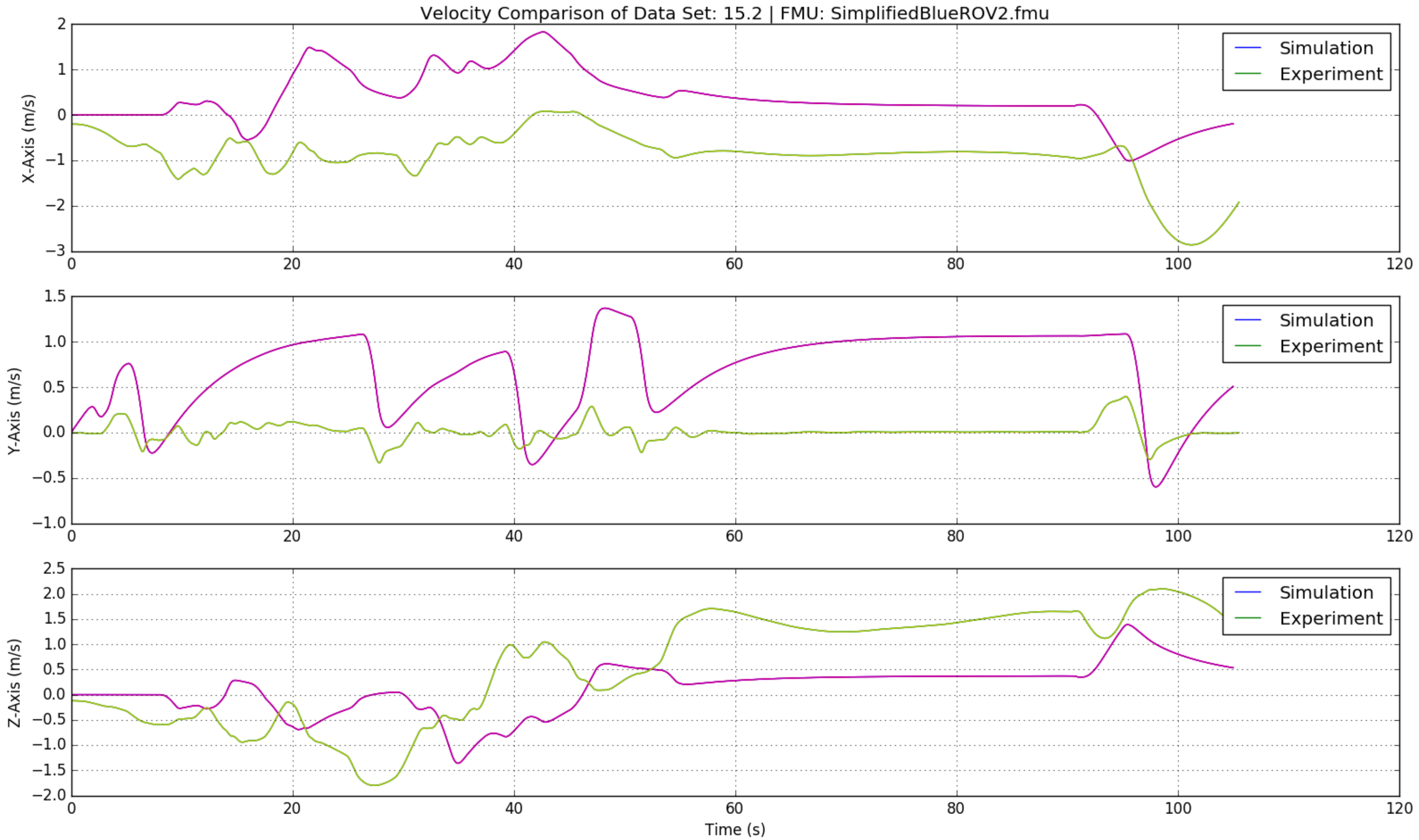
- Redraw model as consolidated rigid body

Validation Improvements

- Increase motion test complexity
- Compare against experimental data

Discrete Data Flow in Bridge





Comparing the Simulation against Data