CONTROLLING REMOTELY OPERATED VEHICLE MANIPULATORS

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Motivation

Work Class ROVMs:

Human Pilot-1

Master Arm

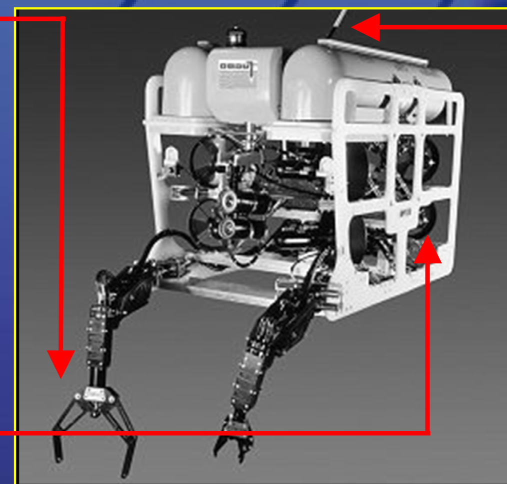
Human Pilot-2

CHU

Slave Arm

Tether

Thrusters



- The motions of the remotely operated vehicle-manipulator **(ROVM)** system are guided by one (two) human pilot(s) on a surface support vessel through a tether that provides power and telemetry.
- In current practice, the desired manipulator joint motions are created using a teleoperated master-slave arm configuration.

Motivation

Logistical Challenges:

- Retrieval of a single point mooring located near Race Rocks.
- ROPOS deployed on Sir Wilfred Laurier.
- Day one:
  - no progress.
- Day two:
  - Technical problems.
  - Unable to stabilize ROPOS.
- Day three:
  - Completed cut.
  - Working time of 7 min.

Operational Challenges:

- The existing systems depends on the ability of the remotely operated vehicle (**ROV**) to hold station and decouples the manipulator and ROVdegrees of freedom. Otherwise, two pilots are assigned for the mission; one for the master arm, the other for the vehicle. This requires coordination between two pilot, which is extremely difficult and not efficient.
- This mode of operation eliminates redundancy inherent in the remotely operated vehicle-manipulator system resulting in a significant loss of system capacity.

Motivation

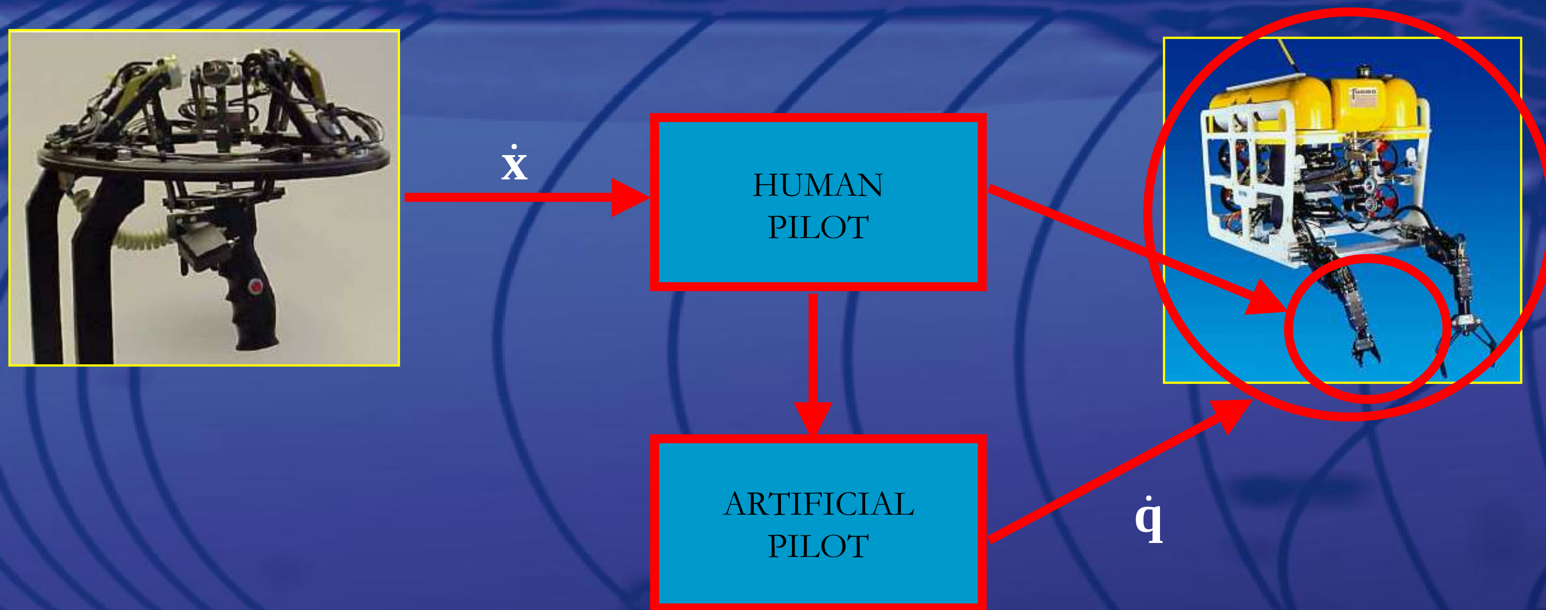
Motivation:

- As interest in ocean resources grows, there is an increasing need for small, low-cost and dextrous ROVM systems.
- Unfortunately, existing small ROV platforms lie within the inspection class and are not equipped to complete complex and interactive submerged tasks.
- Logistical Challenges: At the UVic Subsea Robotics Lab, current research is aimed at adapting a popular small inspection class ROV, a Saab-Seaeye FALCON, into a ROVM capable of low-cost and time-efficient submerged manipulation.
- Operational Challenges: Improve the existing teleoperation scheme for ROVM systems.

- To this end, there are four main research avenues to be visited;
  - ROVM Kinematics (Redundancy Resolution):
  - ROVM Control:
  - Thrust Allocation:
  - Teleoperation Scheme.

Redundancy: Fuzzy Based Approach

High Level Kinematics:



$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{x}_e & \dot{y}_e & \dot{z}_e & \dot{\phi}_e & \dot{\theta}_e & \dot{\psi}_e \end{bmatrix}^T \longrightarrow \dot{\mathbf{q}} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{z} & \dot{\phi} & \dot{\theta} & \dot{\psi} & \dot{q}_1 & \dots & \dot{q}_n \end{bmatrix}^T$$

Redundancy Resolution

End Effector Input

Artificial Pilot Response

Redundancy: Fuzzy Based Approach

High Level Kinematics:

$$\dot{\mathbf{q}} = \underbrace{\mathbf{J}_w^{\dagger}\dot{\mathbf{x}}}_{\text{Primary Objectives}} + \underbrace{\lambda\left(\mathbf{I} - \mathbf{J}_w^{\dagger}\mathbf{J}\right)\mathbf{W}^{-1}\left(\sum_{j=1}^{s} \alpha_j \nabla h_j \Big/ \left\|\nabla h_j\right\|_2\right)}_{\text{Secondary Objectives}},$$

- *Primary task* is following the pilot's end–effector command through the joystick.
- *Secondary tasks* involve the following competing objectives
  - Joint limit avoidance
  - avoiding singularity,
  - keeping the end-effector in sight of the on-board camera,
  - minimizing the vehicle motion,
  - minimizing the drag-force resistance.

Redundancy: Fuzzy Based Approach

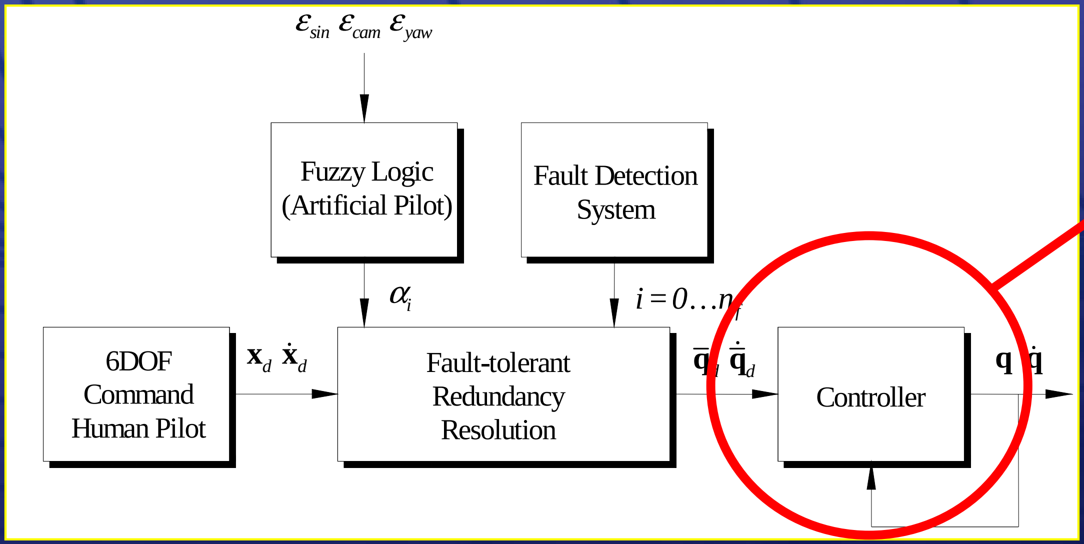
- The order of priority from the highest to the lowest is established to be singularity avoidance > camera angle > yaw angle alignment > minimal vehicle motion.

Set of Linguistic Rules for Fuzzy Logic:

- If the *manipulator* is *singular* then *a*1 is *high*;
- If the *manipulator* is *not singular* then *a*1 is *low*;
- If the *manipulator* is *not singular* and the *camera angle* is *bad* then *a*2 is *high*;
- If the *manipulator* is *singular* or the *camera angle* is *good* then *a*2 is *low*;
- If the *manipulator* is *not singular* and the *camera angle* is *good* and the *yaw angle* is *not aligned* then *a*3 is *high*;
- If the *manipulator* is *singular* or the *camera angle* is *bad* or the *yaw angle* is *aligned* then *a*3 is *low*;
- If the *manipulator* is *not singular* and the *camera angle* is *good* and the *yaw angle* is *aligned* then *av* is *high*;
- If the *manipulator* is *singular* or the *camera angle* is *bad* or the *yaw angle* is *not aligned* then *av* is *low*.

Redundancy: Fuzzy Based Approach

- The proposed scheme allows putting velocity bounds on the joints;
- It is a fault-tolerant scheme;
- As opposed to other existing methods, it does not require predefined task values, and thus allows completely on-line ROVM operations.



The controller is responsible for realizing the demanded motion from the redundancy resolver.

Control

Basic Challenges:

- However, the control of ROVM systems is very challenging;
  - The operating environment is not entirely characterized.
  - The ROVM dynamics are dominated by estimated hydrodynamic coefficients.
  - The dynamic properties of the ROVM system non-linearly changes due to its interaction with the environment.

Dynamic Modeling:

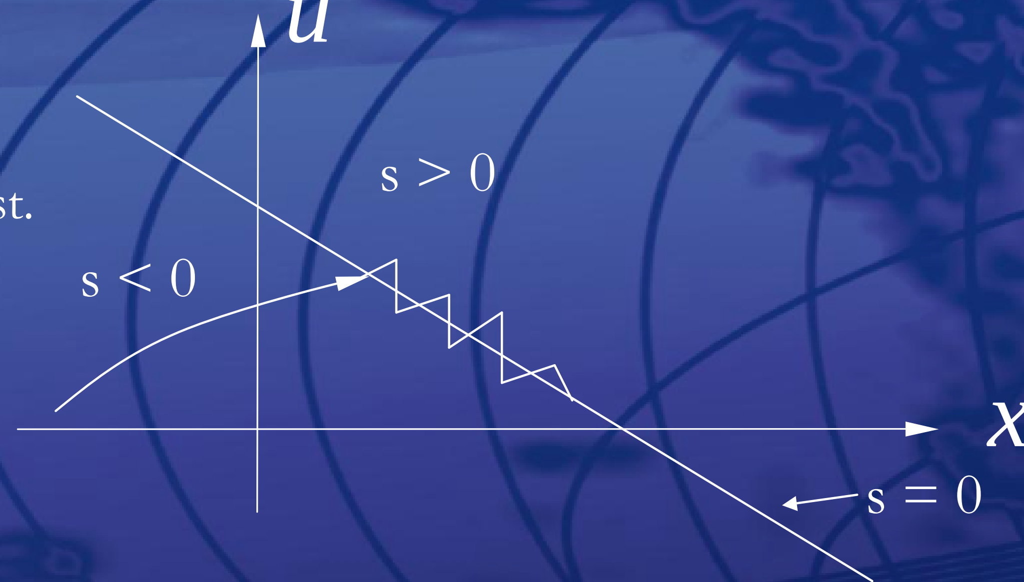
$$\hat{f} = \hat{\mathbf{M}}_q(\boldsymbol{q})\ddot{\boldsymbol{q}} + \hat{\mathbf{C}}_q(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \hat{\mathbf{D}}_q(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \hat{\boldsymbol{g}}_q(\boldsymbol{q}) + \boldsymbol{d} = \mathbf{J}^{-\mathrm{T}}\boldsymbol{\tau}$$

$$\tilde{f} = f - \hat{f}$$

Control: Sliding-Mode Control

Sliding-Mode Control:

- It is a non-linear control technique,
- It is insensitive to inaccuracies in the dynamics and therefore robust.



$$s = u_e + \lambda x_e, \quad x_e = x - x_d$$

$$\tau = \tau_{eq}\left(\hat{f}\right) + \tau_{rb}\left(F\right)$$

- $\tau_{sw}(F)$ is the discontinuous part defined as ... $\dot{s} = 0$, ... dominates the control action. ... when the exact dynamics are known.

$$\tau_{rb}(F) = -\mathbf{K}\,\mathrm{sgn}(\mathbf{s}),$$

- Through the switching term, it is insensitive to inaccuracies in the ROVM dynamics, and is therefore robust.

$$\mathrm{sgn}(s) = +1 \; if \;\; s > 0$$

$$\mathrm{sgn}(s) = -1 \; if \;\; s < 0$$

Control: Adaptive Sliding-Mode Control

Proposed Solution:

- Replacing the discontinuous term with a robust, continuous term.

Proposed Control Law:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{eq} + \boldsymbol{\tau}_{rb}$$

$$\boldsymbol{\tau}_{eq} = \mathbf{J}^T\left(\hat{\mathbf{M}}_\eta \ddot{\mathbf{q}}_r + \hat{\mathbf{C}}_\eta \dot{\mathbf{q}} + \hat{\mathbf{D}}_\eta \dot{\mathbf{q}} + \hat{\mathbf{g}}_\eta\right) = \mathbf{J}^T \hat{\mathbf{f}}_r(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}_r)$$

$$\boldsymbol{\tau}_{rb} = -\mathbf{J}^T\left(\tilde{\mathbf{f}}_{est} + (\mathbf{K} + \hat{\mathbf{C}}_\eta)\mathbf{s}\right), \tilde{\mathbf{f}} = \mathbf{f} - \hat{\mathbf{f}},$$

$$\hat{\mathbf{f}} = \hat{\mathbf{M}}_\eta(\mathbf{q})\ddot{\mathbf{q}} + \hat{\mathbf{C}}_\eta(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \hat{\mathbf{D}}_\eta(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \hat{\mathbf{g}}_\eta(\mathbf{q}) + \tau_p$$

$$\boldsymbol{\tau}_{rb} = -\mathbf{J}^T\left(\tilde{\mathbf{f}}_{est} + (\mathbf{K} + \hat{\mathbf{C}}_\eta)\mathbf{s}\right)$$

Adaptation Law: $\dot{\tilde{\mathbf{f}}}_{est} = \Gamma^{-1}\mathbf{s}$

Continuous Robust Term

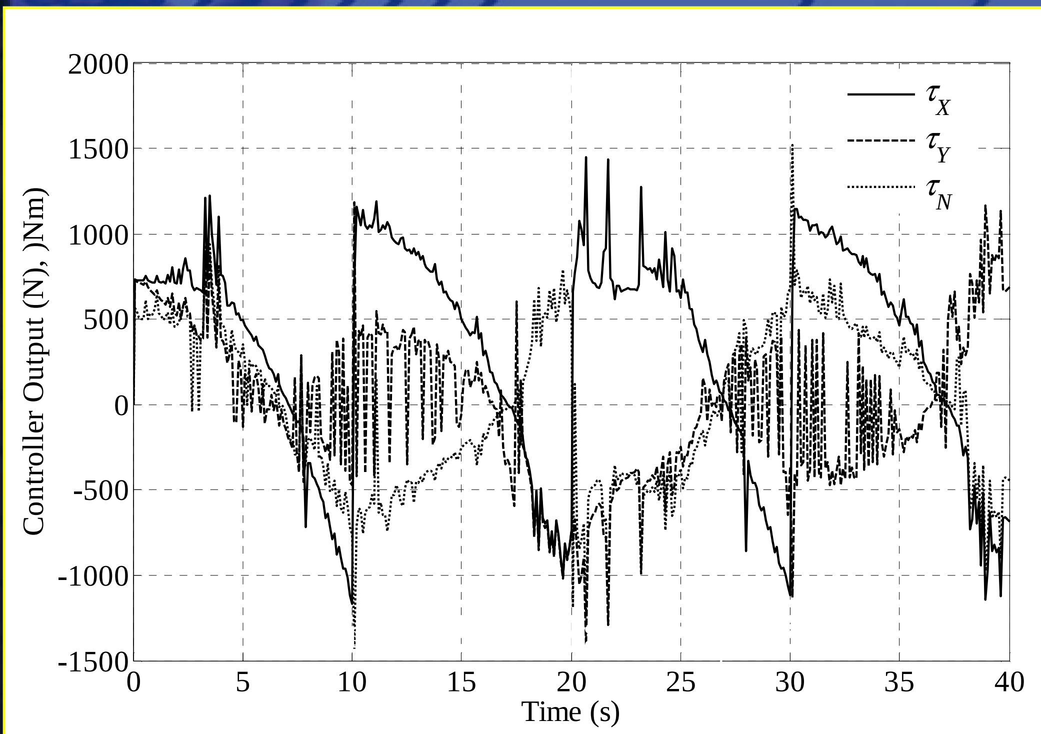
$$\boldsymbol{\tau}_{rb}(F) = -\mathbf{K}\,\mathrm{sgn}(\mathbf{s})$$

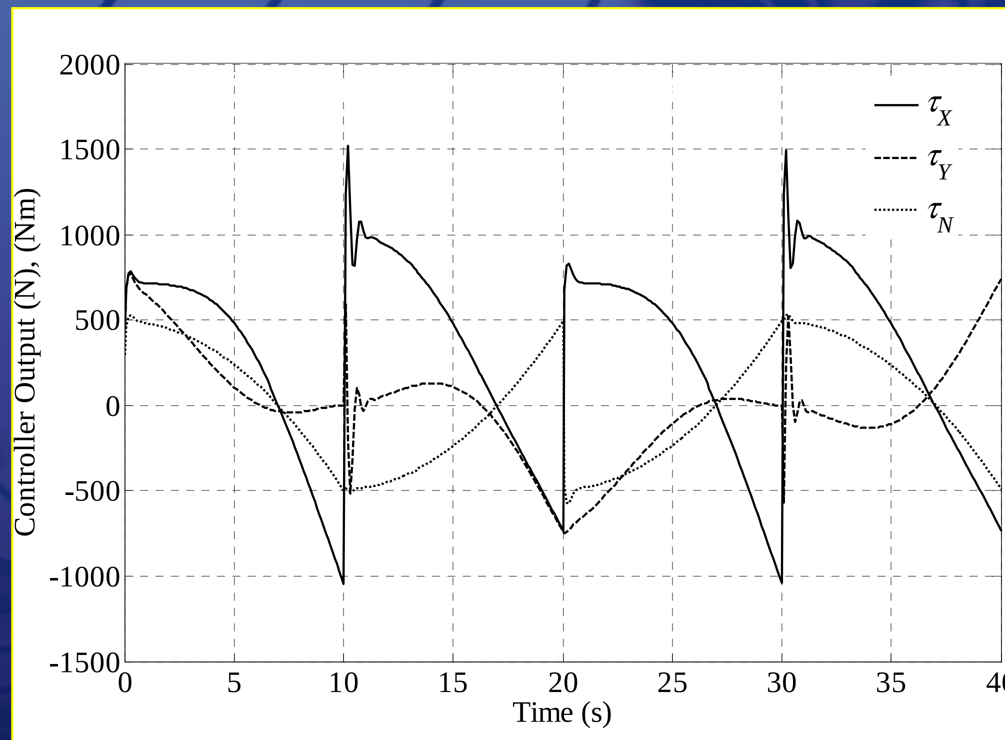
Discontinuous Robust Term

Control: Adaptive Sliding-Mode Control

Control Signal: $\tau = \tau_{eq} + \tau_{dis}$

Control Signal: $\tau = \tau_{eq} + \tau_{ad}$

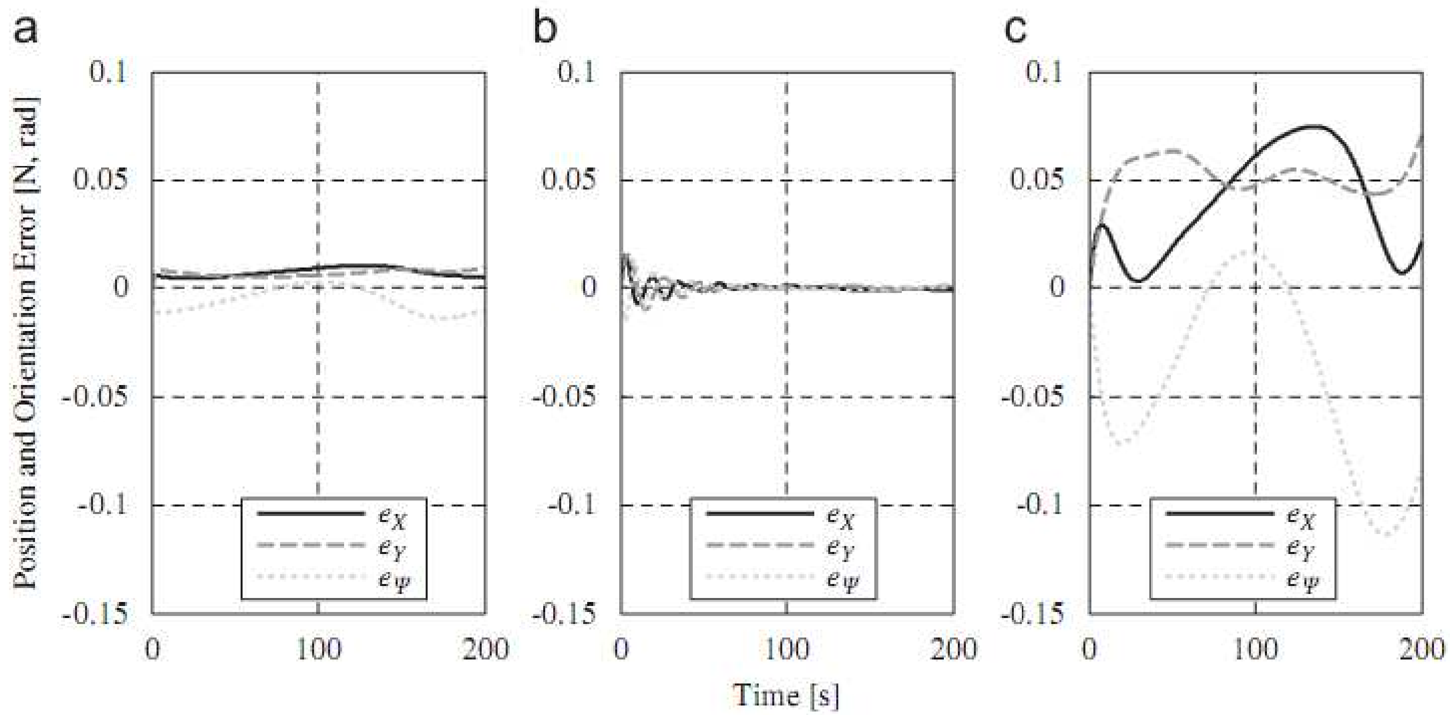




Conventional Sliding Mode Control

Sliding Mode Control with Adaptive Term

Control: Adaptive Sliding-Mode Control



. Position and orientation error with respect to the inertial frame: (a) sliding-mode with boundary layer; (b) adaptive law is ON; (c) adaptive law is OFF.

Control: Upper Bound Adaptive Sliding Mode

Proposed Control Law (Cruise Mode):

$$\tau = \tau_{eq}\left(\hat{f}\right) + \tau_{rb}\left(F\right) + \tau_{PID}\left(s\right)$$

- The adaptive control signal constantly estimates the bound on a lumped uncertainty vector

$$\boldsymbol{\tau}_{rb} = \mathbf{J}^{T}\left(sign(\mathbf{s}) \bullet \hat{\rho}\right), \quad |\tilde{\mathbf{f}}| \leq \hat{\rho}_{r}$$

$$\dot{\hat{\rho}}_i = \gamma_i |s_i|, \quad i = 1 \ldots n$$

$$adaptation\ takes\ place\ when$$

$$\dot{\hat{\rho}}_i = \gamma_i |s_i|, \quad if\ |s_i| \geq s_{o,i}, \quad i = 1 \ldots n$$

$$\dot{\hat{\rho}}_i = 0 \quad , \quad if\ |s_i| < s_{o,i}, \quad i = 1 \ldots n$$

- Finally the PID control layer, with adaptive PID feedback gains, is used to further enhance the controller performance.

$$\boldsymbol{\tau}_{rb} = \mathbf{J}^{\mathrm{T}}\left(\boldsymbol{\Phi}\boldsymbol{r}\right) \qquad \boldsymbol{r} = \begin{bmatrix} \dot{\mathbf{e}}^{T} & \mathbf{e}^{T} & \int \mathbf{e}^{T} \end{bmatrix}$$

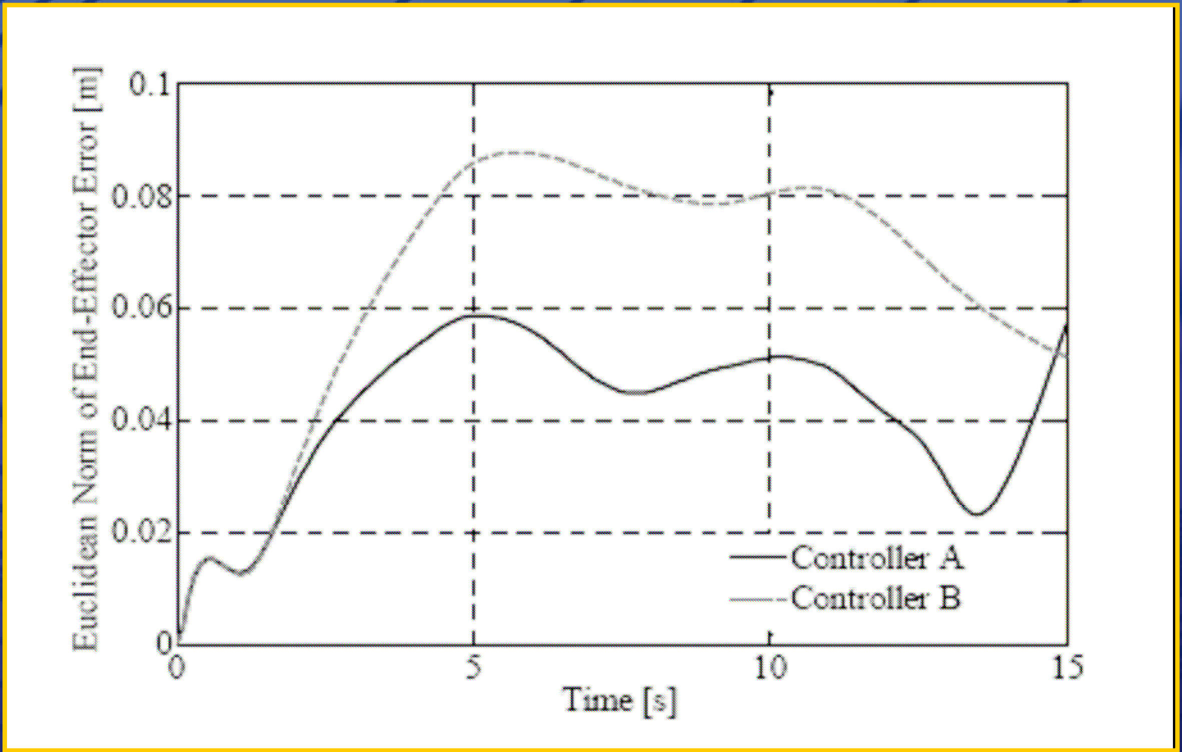
$$\dot{\boldsymbol{\Phi}}^{T} = \boldsymbol{\beta}\boldsymbol{r}\boldsymbol{s}^{T} \qquad \boldsymbol{\Phi} = \begin{bmatrix} \boldsymbol{\Phi}_1 & \boldsymbol{\Phi}_2 & \boldsymbol{\Phi}_3 \end{bmatrix}$$

- The equivalent control signal is the model based component that reflects the knowledge of the system dynamics available to the controller designer.

$$\boldsymbol{\tau}_{eq} = \mathbf{J}^{T}\left(\hat{\mathbf{f}}_{r} - \mathbf{C}_{n}\boldsymbol{s}\right)$$

Control: Comparison Studies

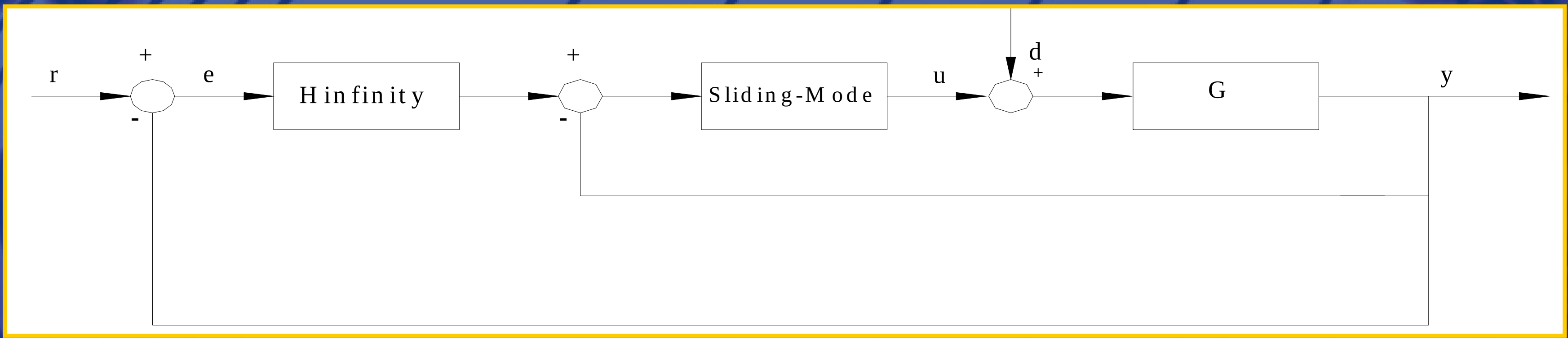
Comparison Studies:

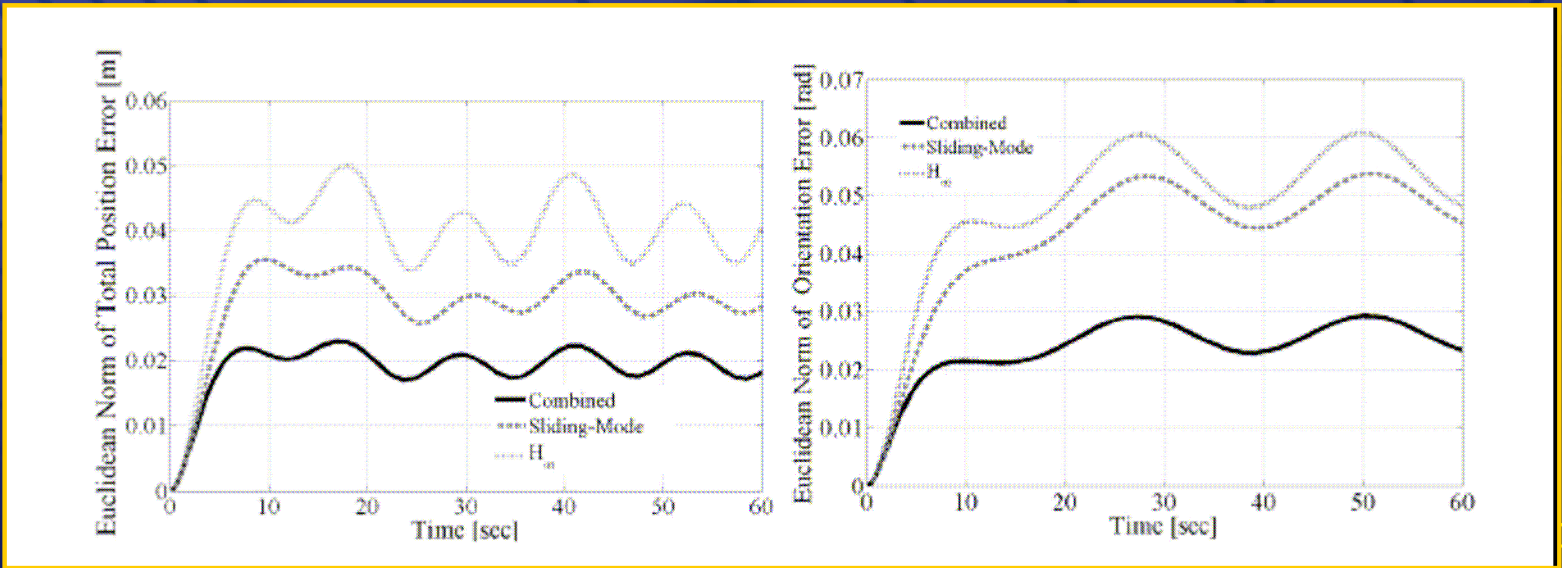


- Controller A (with upper bound dynamics estimation) provides %38 improvement over Controller B (with unknown dynamics estimation).

Control: Sliding Mode- H∞ controller

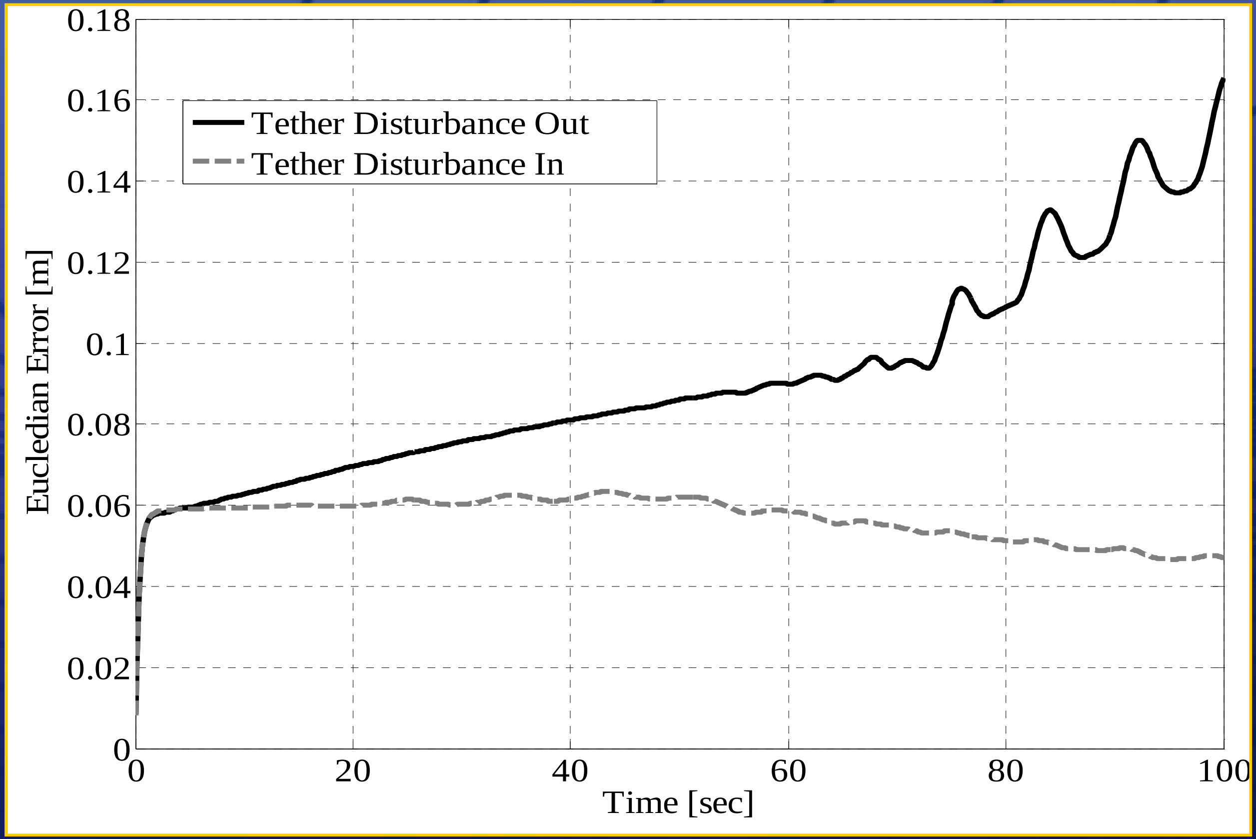
Sliding Mode- H∞ controller (Station Keeping):





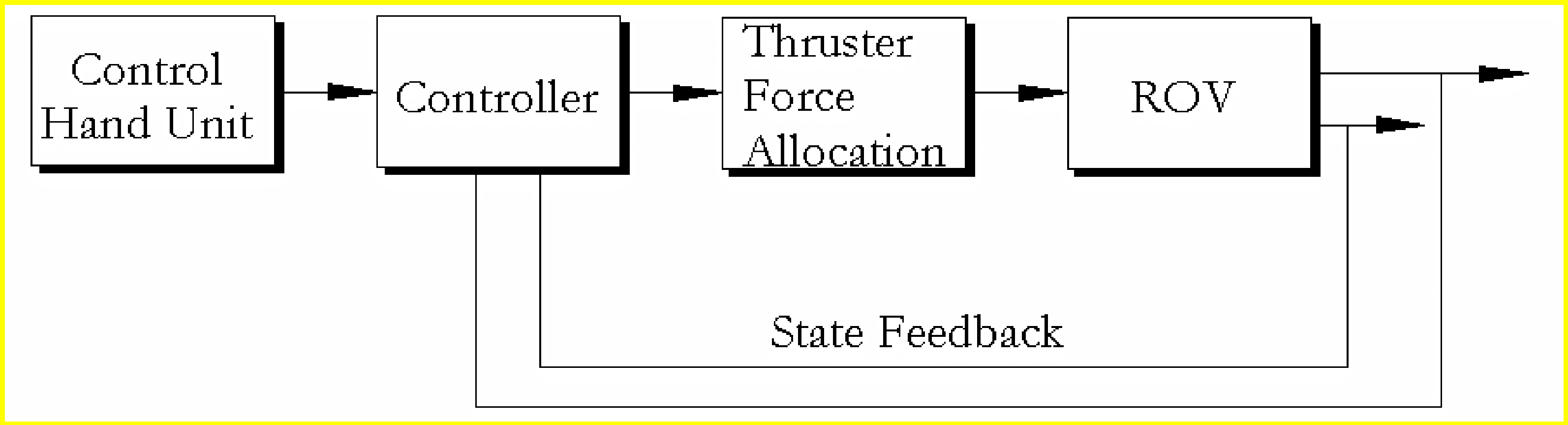
Control: Tether Inclusion

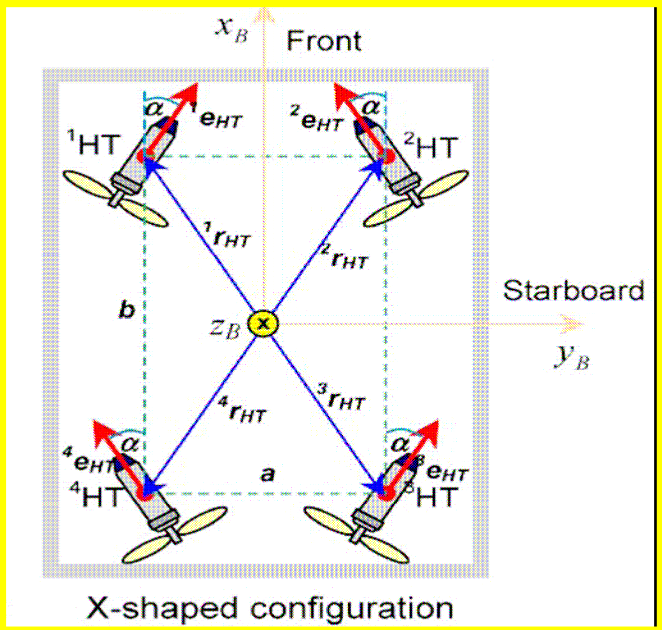
- A tether dynamic model is coupled with the vehicle dynamics.
- It is concluded that the controller performance can be increased significantly by introducing the tether disturbance knowledge into the controller.



Euclidean norm of the position error with tether force in and out.

Thrust Allocation





X-shaped configuration

- The generated control signal is with respect to the center of mass of the vehicle. This signal must be mapped into a set of desired thrust values.
- Typical ROVM systems has redundant thruster arrangement.
- Due to the excess number of thrusters, there is an infinite number of ways to allocate the pilot's commanded thrust over the existing thrusters.

Thrust Allocation

Existing Solutions:

- A prominent approach to thrust allocation is pseudo-inverse solutions that correspond to the least-squares, or 2-norm, solution in which the sum of the squares of the individual thruster forces is minimized.

Disadvantages:

- The Pseudo-inverse solution does not necessarily minimize the magnitudes of the individual thrusts, and hence could generate thrust demands that exceed a thruster's saturation point.
- The Pseudo-inverse method does not afford direct implementation of thruster saturation limits.
- The satisfaction of additional constraints is not guaranteed.

Thrust Allocation: Infinity-Norm

Proposed Solution:

- Instead of minimizing the sum of the squares of the individual thruster forces, it is proposed that the largest single thrust be minimized. This corresponds to the infinity-norm solution.

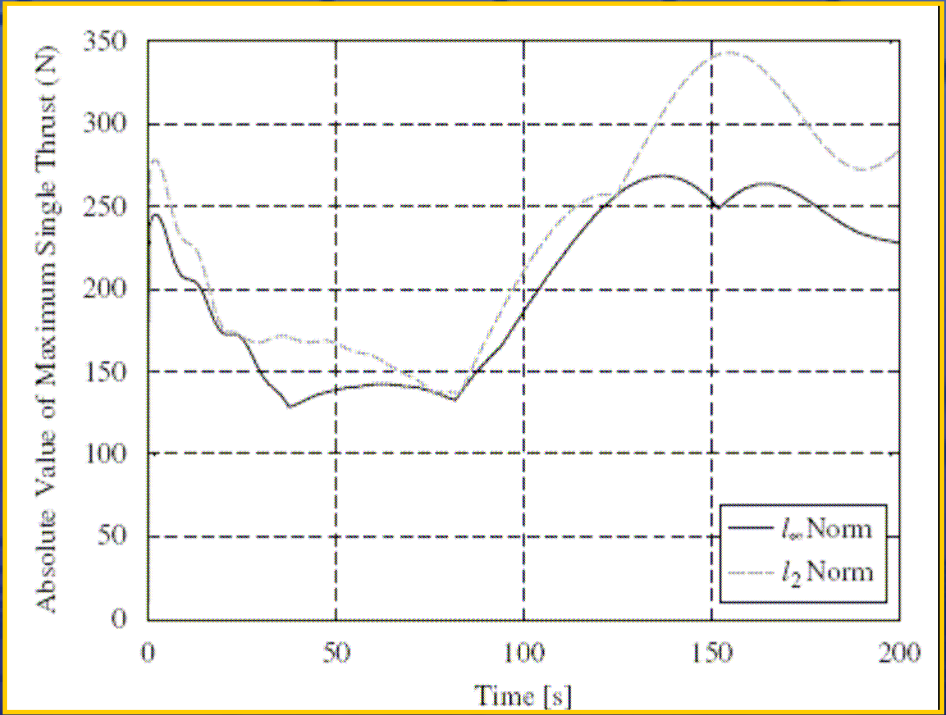
Thruster Force Vector: $\mathbf{f}_t = [\, f_1 \quad f_2 \quad \cdots \quad f_n \,]^T$

$$\underbrace{\|\mathbf{f}_t\|_2 = \sqrt{|f_1|^2 + |f_2|^2 + \ldots |f_n|^2}}_{\text{2-norm solution}}$$

$$\|\mathbf{f}_t\|_\infty = \underbrace{\max\{|f_1| \quad |f_2| \quad \cdots \quad |f_n|\} = \max_{1\le i\le n} \left|\mathbf{I}_i^T \mathbf{f}_t\right|}_{\text{Infinity-norm solution}}$$

Thrust Allocation: Infinity Norm

Infinity-Norm Thrust Allocation:

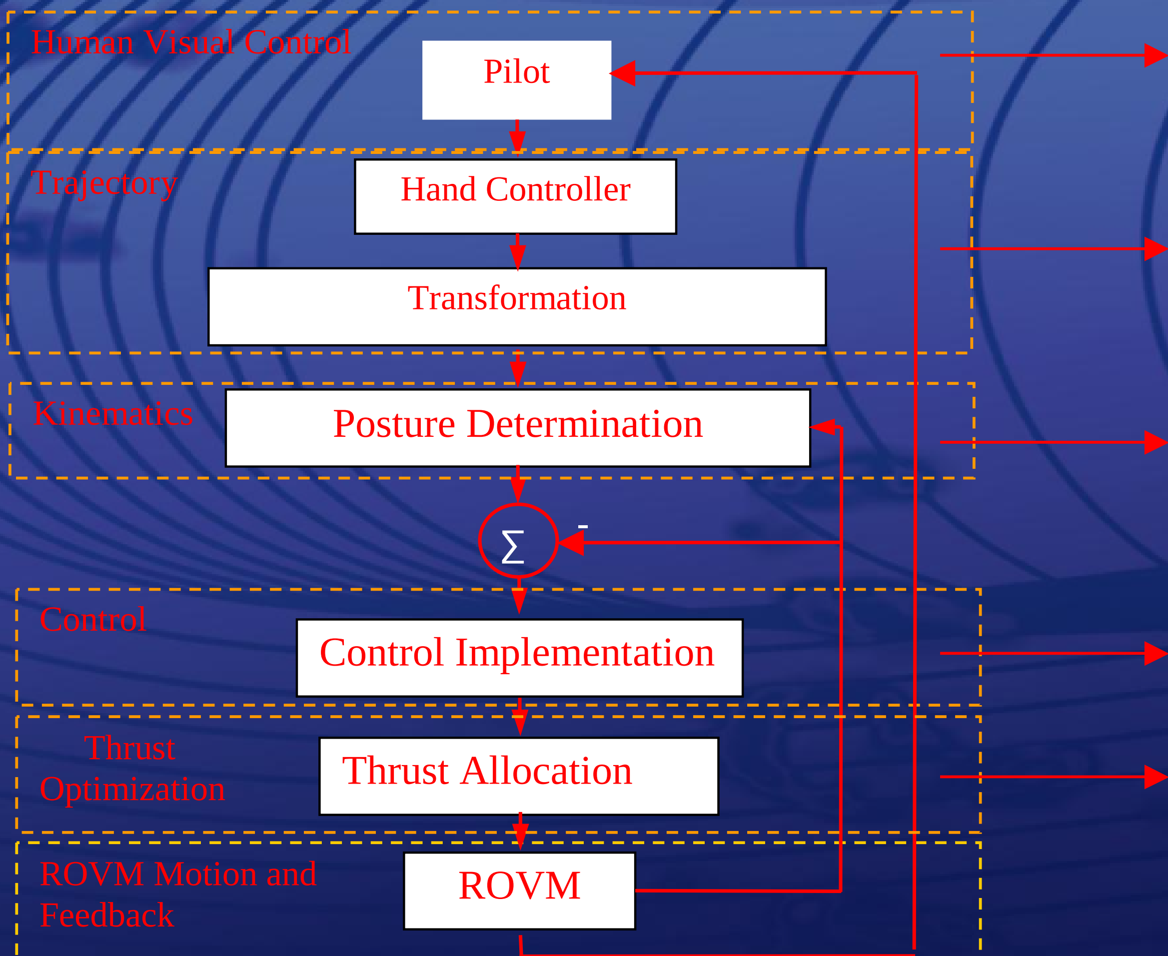


Comparison of the norms

Max l_2 norm thrust (N)	Max l_∞ norm thrust (N)	Reduction (%)	Average reduction (%)
342.6	268.4	21.6	11.9

Teleoperation

High-Level Teleoperation Scheme:



3-D Visualization

6-DOF Joystick

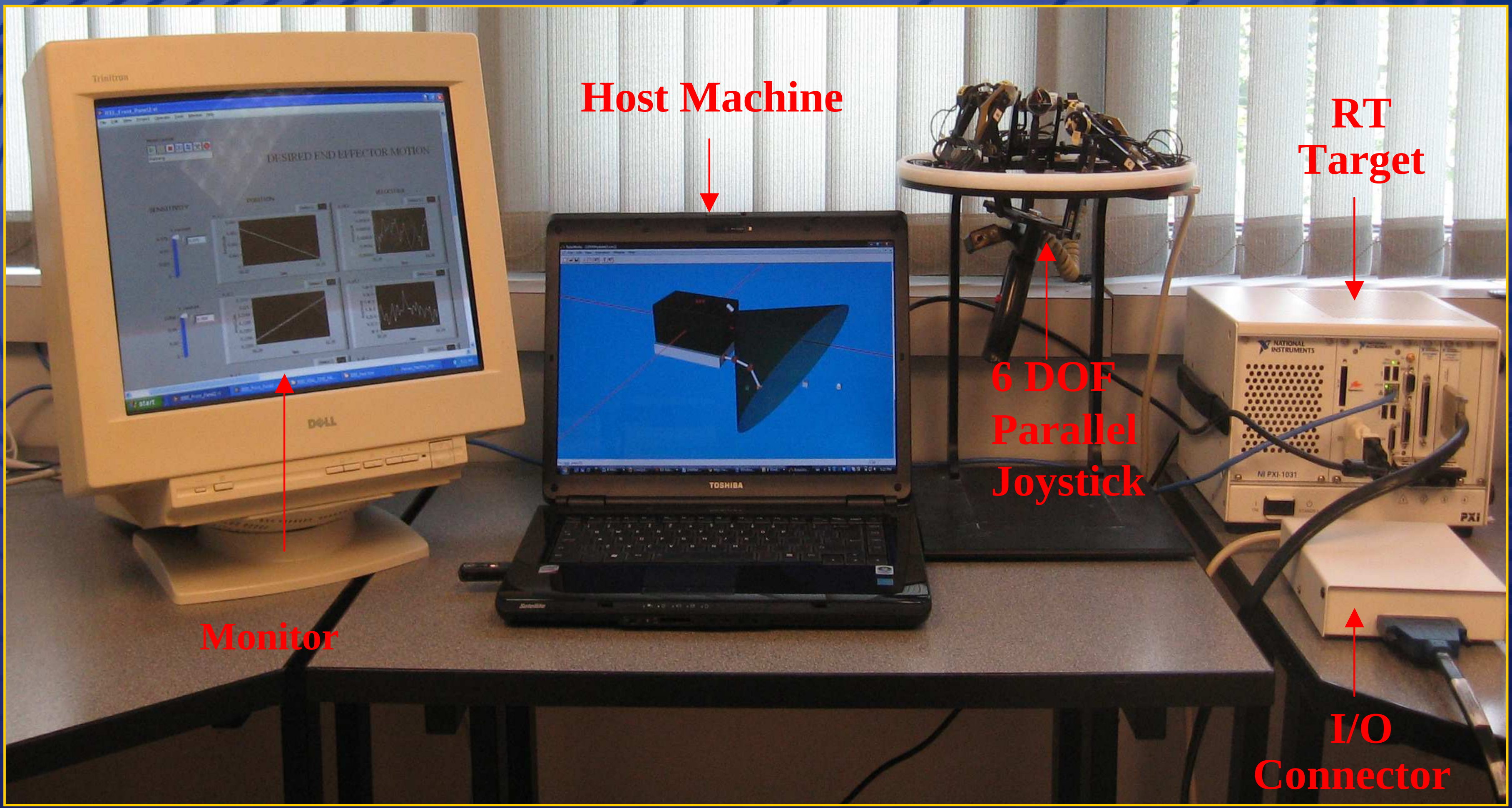
Fuzzy Redundancy Resolution

Upper Bound Adaptive SMC

Infinity-Norm Thrust Allocation

Teleoperation: Operating Console

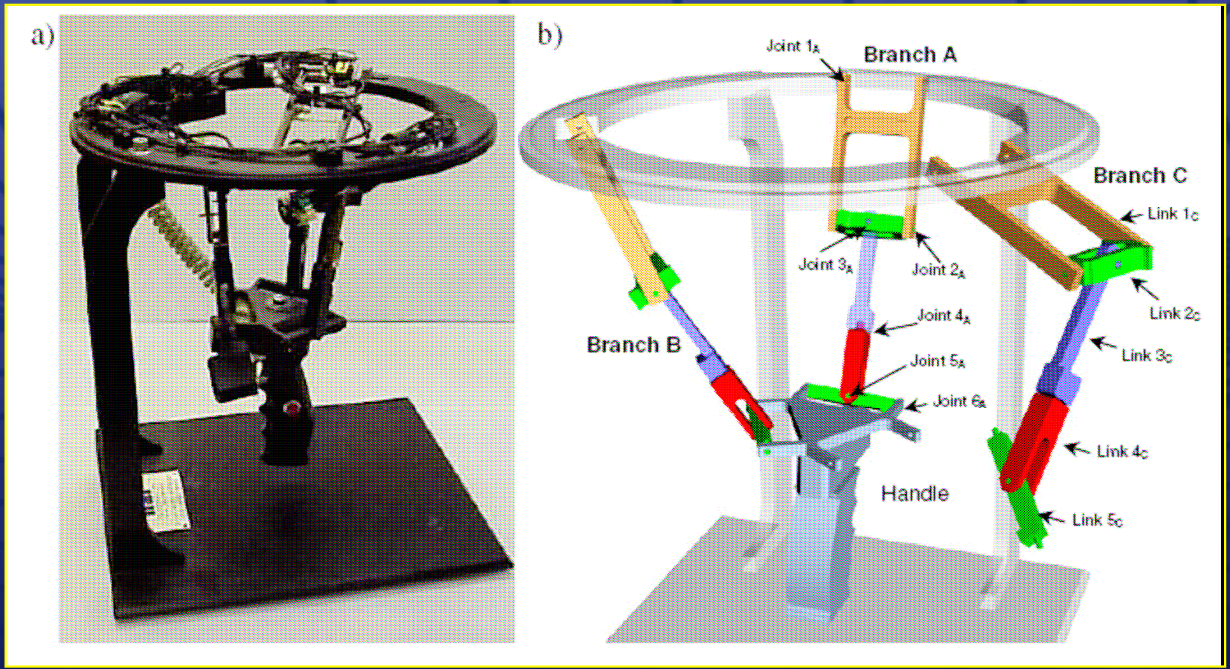
Real-time teleoperating console:



Teleoperation: Hand Controller

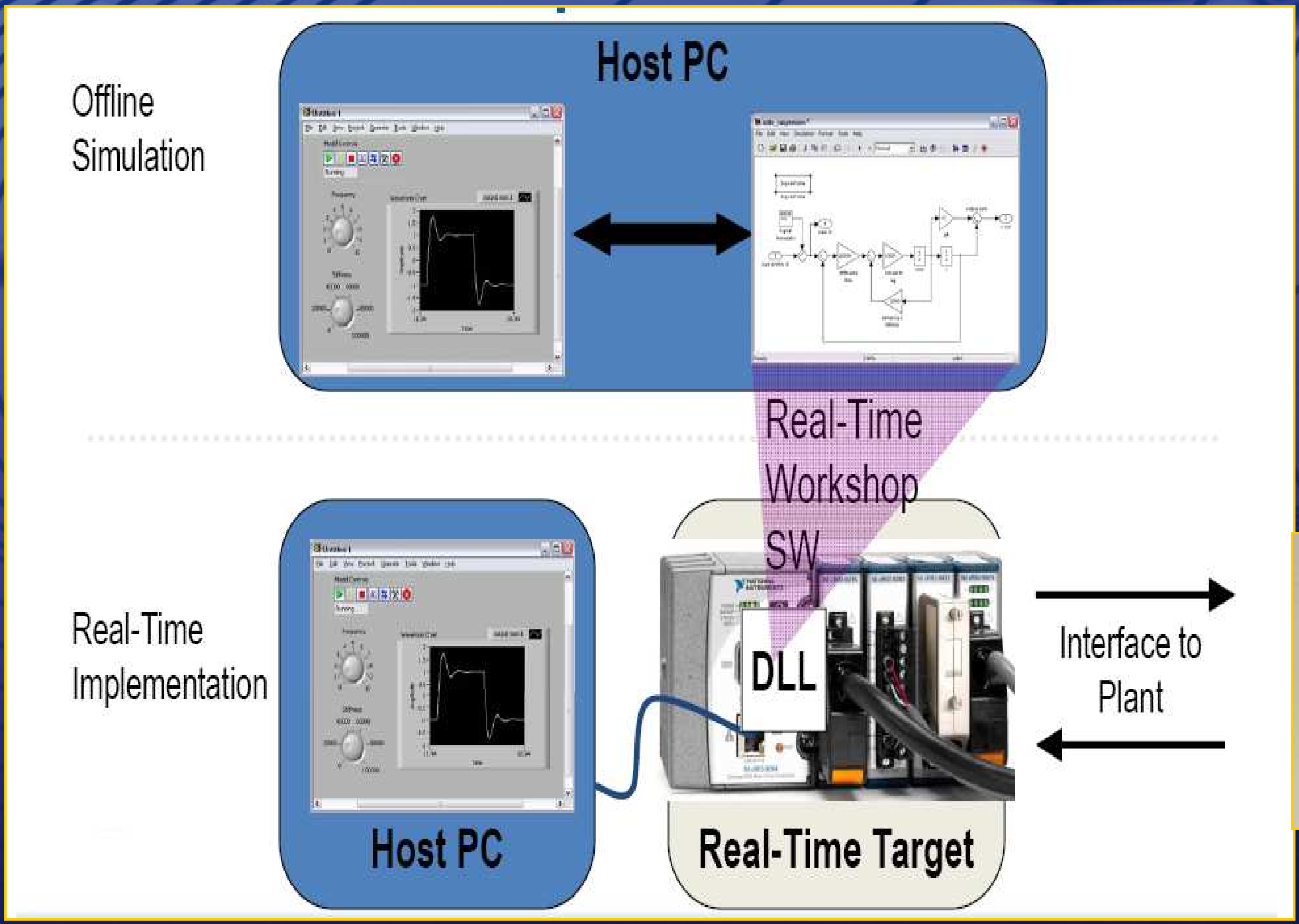
Interfacing with a 6DOF Joystick:

- It has nine transducers, in particular rotary Midori® CP-2FB potentiometers.
- To digitize the output voltages of the potentiometers, National Instrument® M Series multifunction data acquisition (DAQ) card for Universal Serial Bus (USB), in particular the NI USB-6251 DAQ is being used.



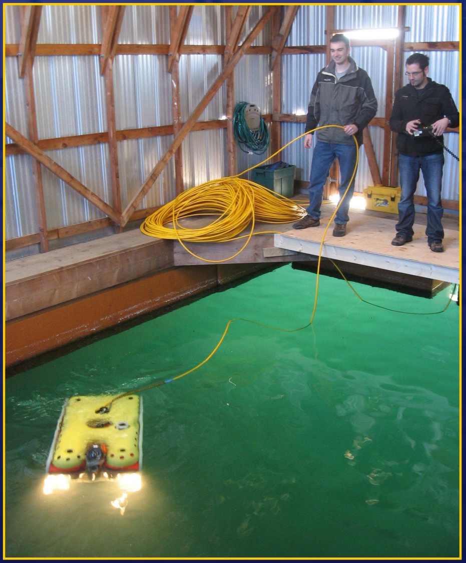
RSI 6-DOF Hand Controller

Real-Time Prototyping:



Simulation: System Overview

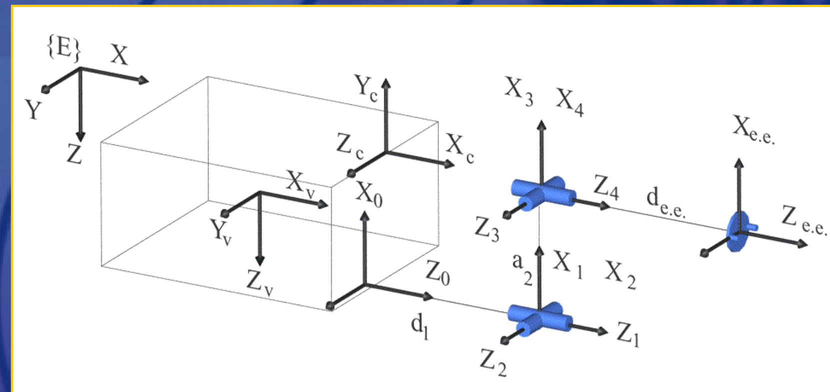
- Inspection Class ROV
  - Partnered with Suboceanic Sciences Canada Ltd.
- Subsurface Vehicle
  - 300m depth rating
  - 50kg dry weight
  - 5 electric thrusters each 130N
- Tether
  - 350m length, 14mm diameter
  - Neutrally buoyant
  - Delivers power and communication
- Surface Station
  - Video display with navigation overlay
  - Sonar display
  - Power conditioning and telemetry processing



Real-Time Simulation

- Hydro-Lek HLK 43000
  5 function manipulator

Zero-displacement configuration

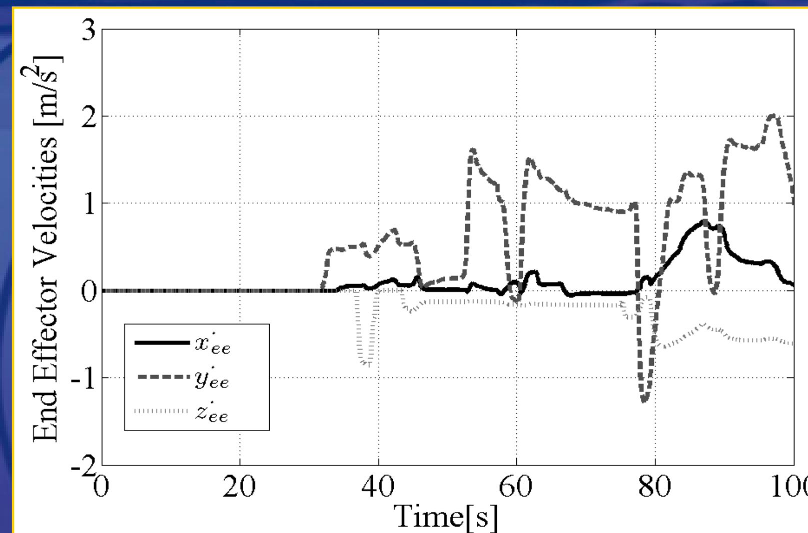


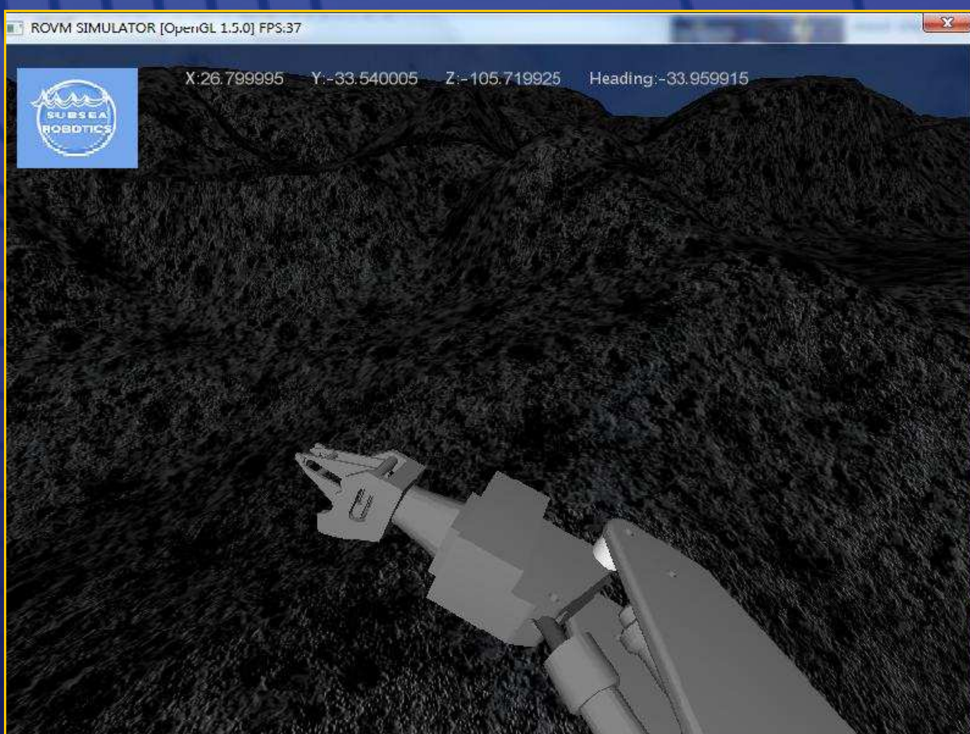
D&H Parameters

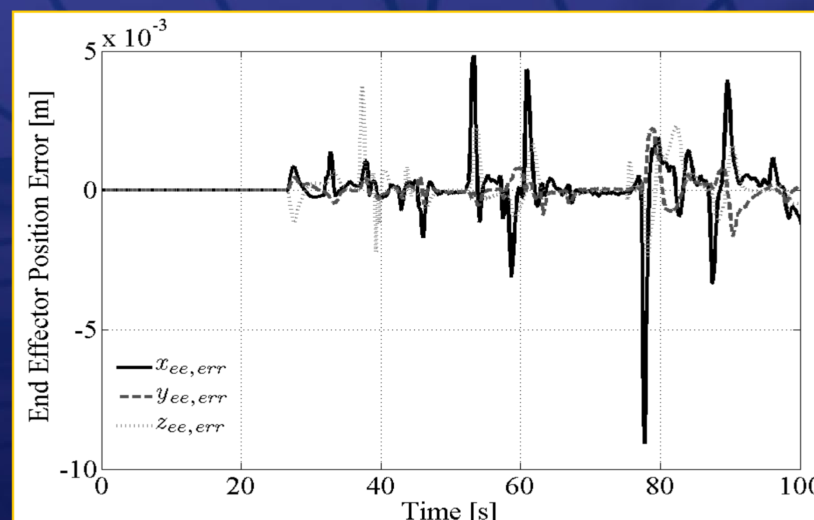
i-1	α-1	a_{i-1}	d_i	θ_j	i
0	0	0	0	q_1	1
1	$-\pi/2$	0	d_1	q_2	2
2	0	a_2	0	q_3	3
3	$\pi/2$	0	d_3	q_4	ee

Real-Time Simulation

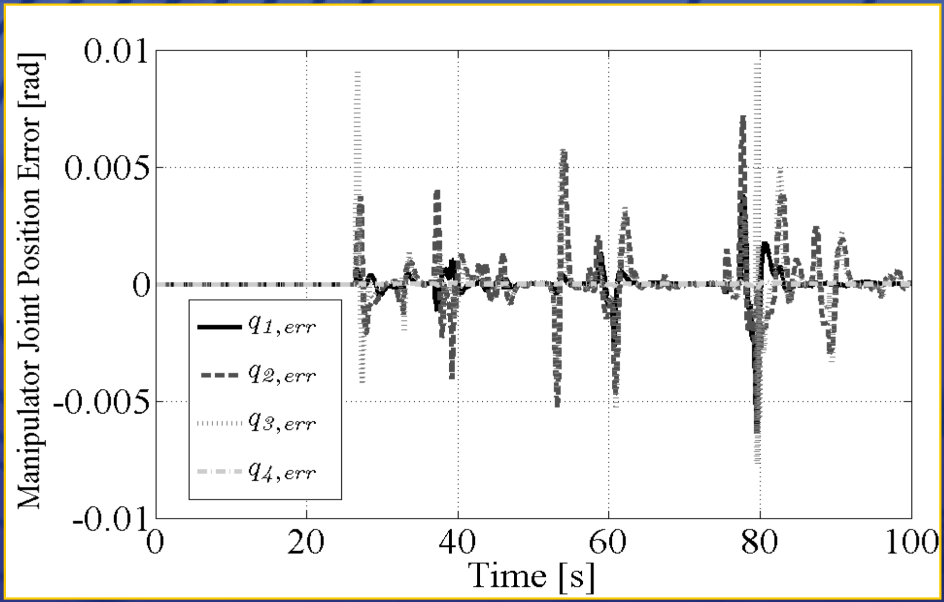
$$\dot{\boldsymbol{x}}_{\boldsymbol{p},i} = k_i \, {}^{b}\boldsymbol{p}_i$$

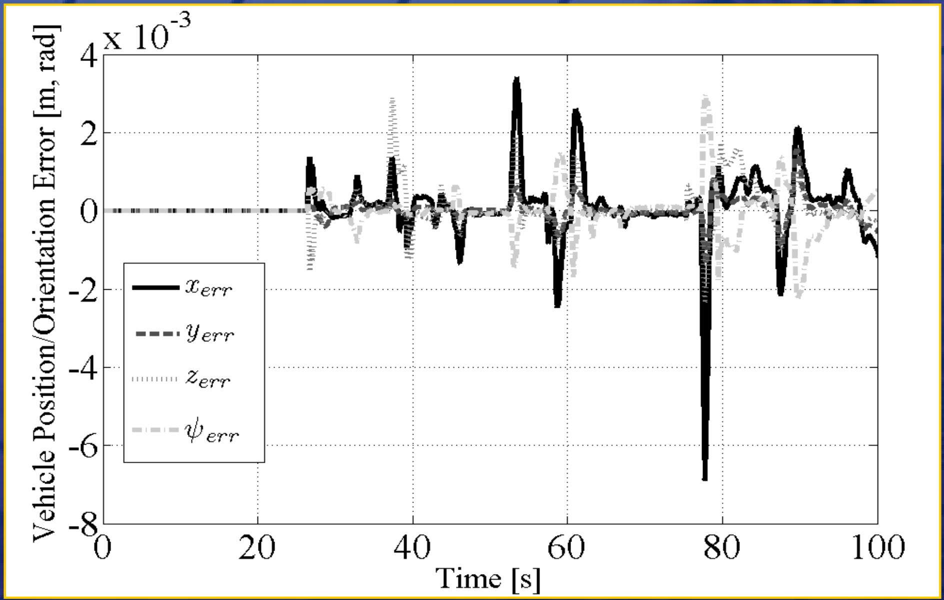




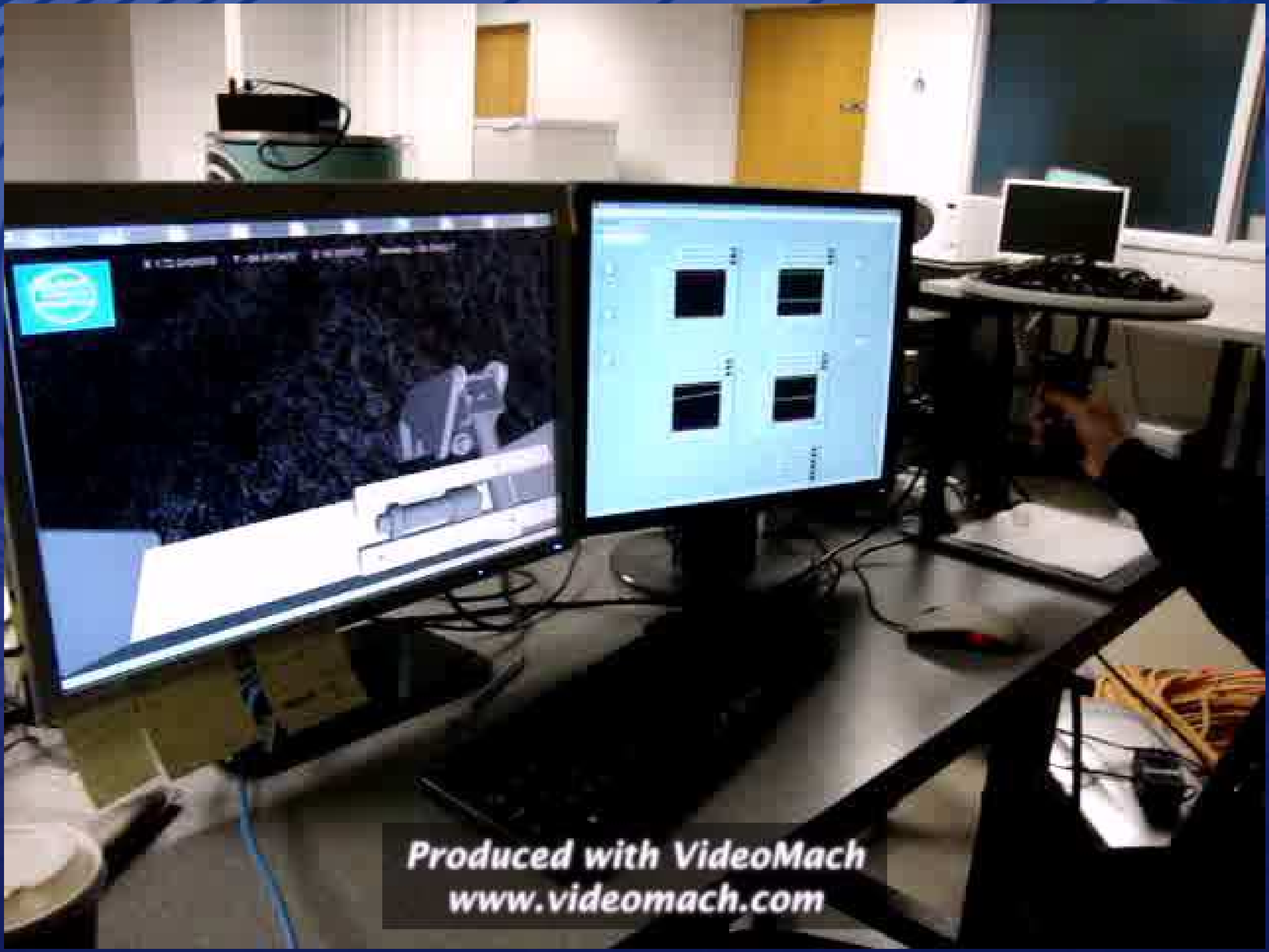


Real-Time Simulation



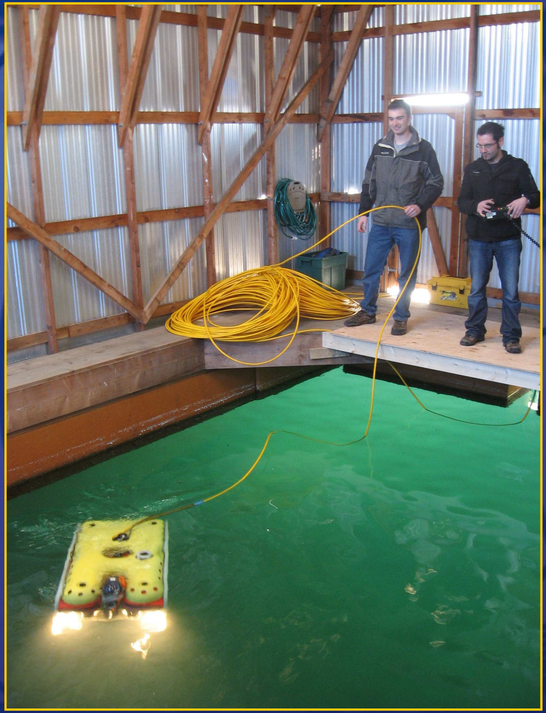


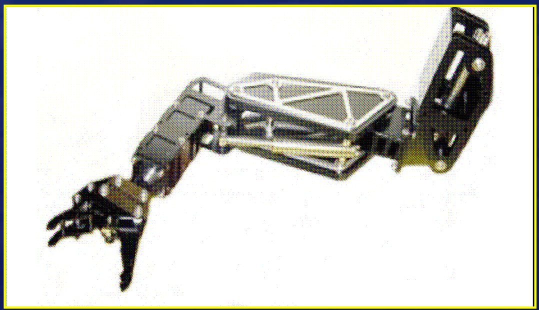
Real-Time Simulation



Implementation Progress

- Falcon ROV
  - Partnered with Suboceanic Sciences Canada Ltd.
- Manipulator
  - 5 Function HLK 43000 Hydrolek Hydraulic Powered Hydrolek Manipulator
  - Retrofitting of the arm for the coordinated control scheme is being done in collaboration with Hydro-LEK.
- Tether
  - Fiber Optic, 350m length, 14mm diameter
- Input Device
  - the commercial RSI 6-DOF Joystick produced by RSI Research Ltd
- ENGAGE Project:
  - The implementation phase of the project is underway.
  - This project is funded by NSERC's Engage Grant.





Conclusions:

- A new teleoperation scheme is proposed for ROVM systems.
- New redundancy resolution and control strategy has been developed.
- Real-time hardware-in-the-loop simulations have been performed.
- The hardware-in-the-loop simulation studies illustrate that detailed subsea tasks can be completed with a small, low-cost ROVM system using the proposed ROVM operation scheme.