Modeling and Predictive Control of an Unmanned Underwater Vehicle

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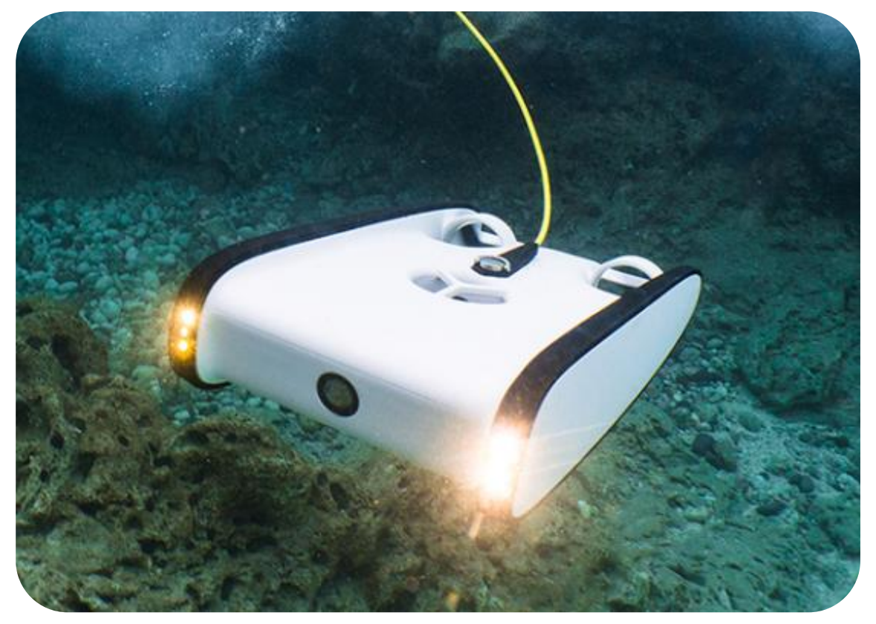
Introduction

This paper presents a model and optimal controller for Unmanned Underwater Vehicles (UUVs). We present a nonlinear six degrees of freedom model of the UUV that includes hydrodynamic and hydrostatic terms. To design the controller, we simplify the model using the geometry of the UUV as well as its operating conditions such as the depth and expected travel speed. Instead of designing a controller for the state space system, we used feedback linearization technique to decouple the motions. Then, a set of controllers were designed for each motion. To incorporate the constraints on the input and the state variables, we designed a fast Model Predictive Controller (MPC) for the UUV and compared its performance with a conventional controller.

Motivation

- High demand for underwater exploration and inspection of offshore infrastructure due to increase in energy demands
  - Require the installation and maintenance of Sub-sea pipelines
  - Energy generation and power transmission cables worldwide
- Inspection of infrastructure is an important part of the preventive maintenance process which aims at eliminating potential breakages that can result in costly equipment and environmental damages.
- The use of UUV for the inspections process address the limitations of current inspection methods
  - Reduce the long-term cost of routine inspections
  - Provide more flexibility in the development of inspection strategies



UUV

Environmental Effects

Offshore Infrastructure

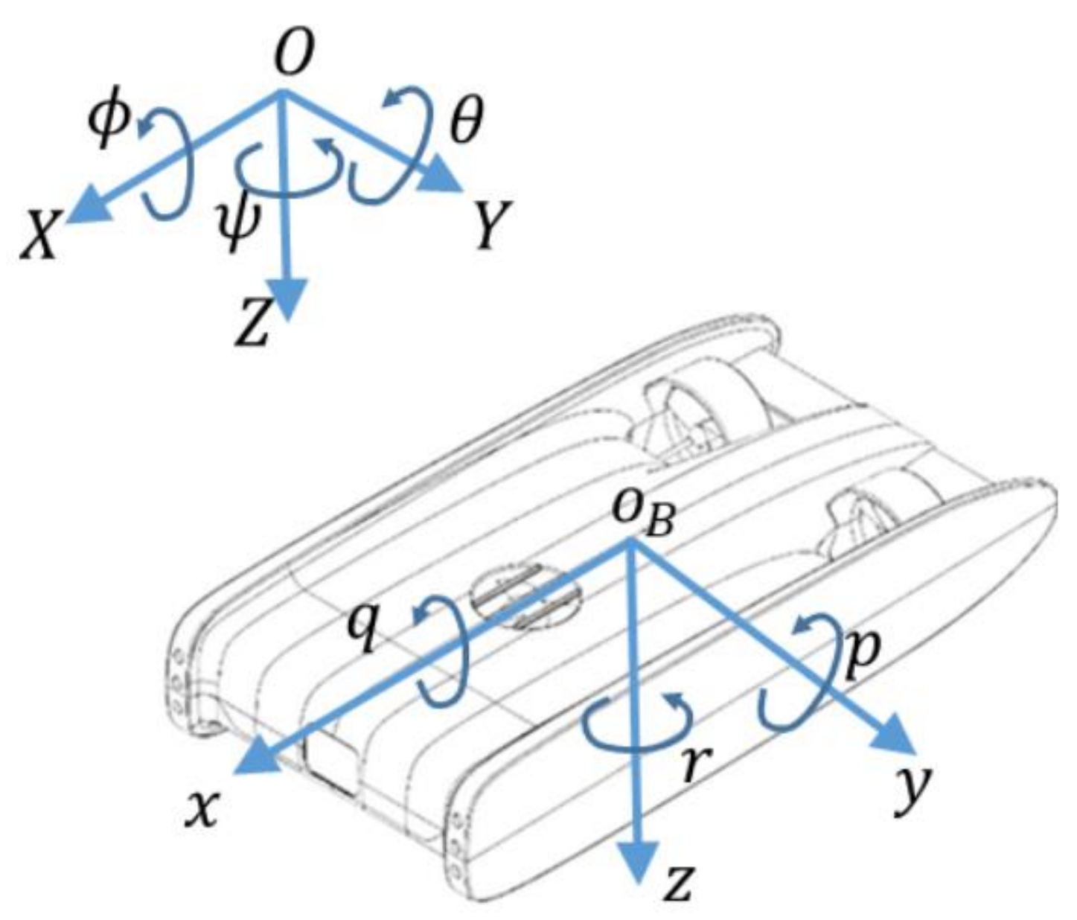
Methods

Modeling

Nonlinear 6-DOF model of the UUV:

- Surge, Sway, Heave, Roll, Pitch and Yaw
- Hydrostatic, hydrodynamic, rigid-body forces
- Actuator generated thrust

6-DOF UUV



Equation of motion is composed of matrix terms

- i.e. Hydrodynamic Mass and Inertia term (M_A)

$$M_A = -\begin{bmatrix} X_{\dot u} & X_{\dot v} & X_{\dot w} & X_{\dot p} & X_{\dot q} & X_{\dot r} \\ Y_{\dot u} & Y_{\dot v} & Y_{\dot w} & Y_{\dot p} & Y_{\dot q} & Y_{\dot r} \\ Z_{\dot u} & Z_{\dot v} & Z_{\dot w} & Z_{\dot p} & Z_{\dot q} & Z_{\dot r} \\ K_{\dot u} & K_{\dot v} & K_{\dot w} & K_{\dot p} & K_{\dot q} & K_{\dot r} \\ M_{\dot u} & M_{\dot v} & M_{\dot w} & M_{\dot p} & M_{\dot q} & M_{\dot r} \\ N_{\dot u} & N_{\dot v} & N_{\dot w} & N_{\dot p} & N_{\dot q} & N_{\dot r} \end{bmatrix} \qquad X_{\dot u} = \frac{\partial X}{\partial \dot u}$$

$$\underbrace{M_{RB}\dot v + C_{RB}(v)v}_{rigid-body\ forces} + \underbrace{M_A \dot v + C_A(v)v + D(v)v}_{hydrodynamic\ forces} + \underbrace{g(\eta)}_{hydrostatic\ forces} = \underbrace{\tau}_{force/torque}$$

Controller

Used Feedback linearization

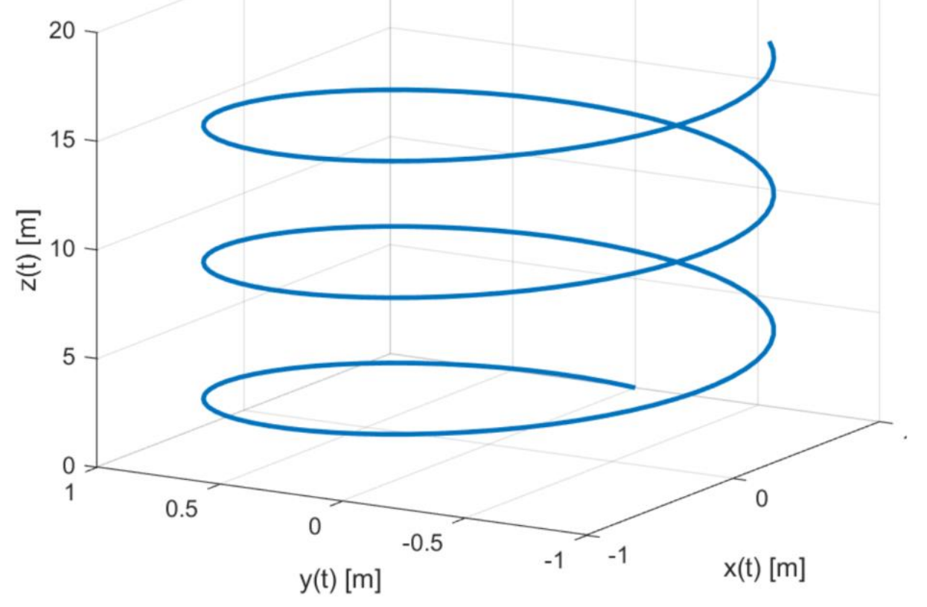
$$\ddot x_B = \frac{1}{m_{\dot x_B}}\left(-d_{\dot x_B}\dot x_B - d_{\dot x_B|\dot x_B|}\dot x_B\,|\dot x_B| - g_{\dot x_B} + \tau_{\dot x_B}\right)$$

$$u_c = \frac{1}{d}(a\dot x_B + b\dot x_B|\dot x_B| + v_c)$$

Decoupled linear dynamics

$$\dot x = Ax + Bv_c$$

Sub-sea Pipeline Inspection Trajectory



MPC for fast scanning of the pipeline

- Terminal Cost
- Tracking Error Cost
- Input cost
- Input rate cost

MPC is computationally expensive

- Solution: Parallelized MPC
- Designed and simulated Parallelized MPC for real-time implementation

MPC and Cost Function Parameters

$Parameters$	$Definition$
k	Time Step
N	Prediction Horizon
$N_d = N - d$	Control Horizon
Q_t	Terminal Cost
$e_{k+i} \overset{\text{def}}{=} \boldsymbol{x}_{k+i} - \boldsymbol{x}_{ref_{k+i}}$	Tracking Error
$v_{r_{k+i}} \overset{\text{def}}{=} v_{k+i} - v_{ref_{k+i}}$	Input Error
$\Delta v_{k+i} \overset{\text{def}}{=} v_{k+i} - v_{k+i-1}$	Input variations

$$\underset{u,\boldsymbol{x}}{min.}\ J = \sum_{i=1}^{N-1} \tfrac{1}{2} e[k+i]^T Q e[k+i] + \sum_{i=0}^{N-1} \frac{1}{2}\{v_{ref}[k+i]^T R_1 v_c[k+i] + \Delta v_c[k+i]^T R \Delta v_c[k+i]\} + \frac{1}{2} e[k+N]^T Q_{1t} e[k+N]$$

Results

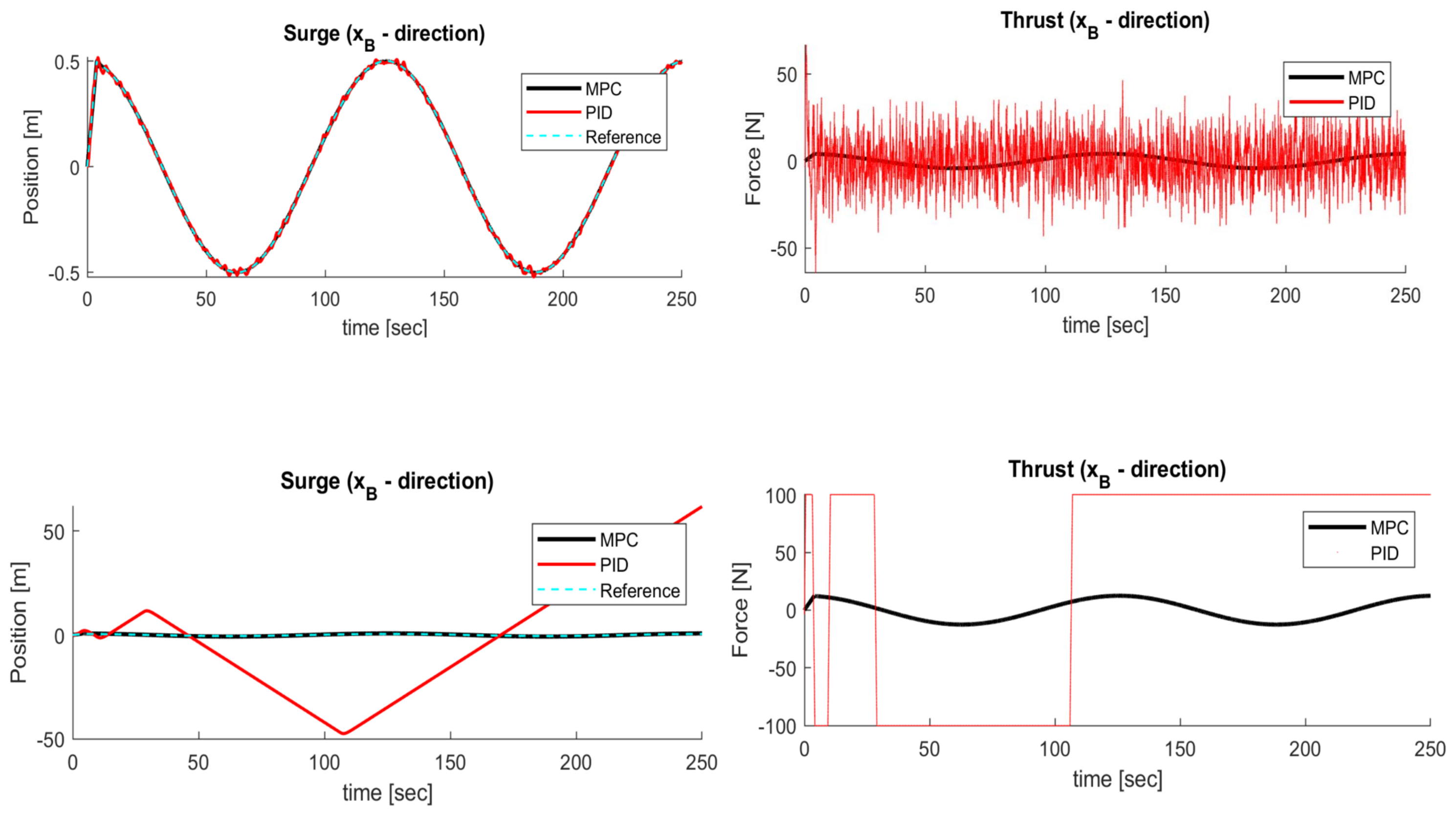
Results

Operating Conditions

- Variation on diameter of trajectory
- Variation on travel speed

Compared results for different control strategies

- Tracking Performance
- Efficiency



Future Work

- Design and simulation other control strategies
- Designed and simulated: PID, LQR, Backstepping
- Implementation of the controllers on real hardware

Conclusion

Modeling and predictive control of a 6-DOF unmanned underwater vehicle was presented

- *Kinematic model covers the geometric aspect of the UUV's motions, and relates its motions from the body to the world frame of reference*
- *The dynamic model includes both hydro-static and hydrodynamic, and rigid body terms*

Feedback linearization control technique was used to decouple the dynamics

MATLAB/Simulink was used to create the model, the controllers, and noisy sensor data

Parallelized MPC was designed and tested for various operational maneuvers

Performance compared to PID and LQR controllers

Next steps include hardware implementation

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