IAC CONFERENCE'25

PRECISE CONTROL OF SATELLITE RENDEZVOUS AND DOCKING MANEUVER USING PHYSICS INFORMED MODEL PREDICTIVE CONTROLLER

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CONTENTS

PROBLEM STATEMENT

- Satellite dynamics in unknown environments are inherently uncertain—due to factors like varying gravitational fields and atmospheric drag—posing significant challenges for precise and reliable control in mission-critical scenarios like spacecraft rendezvous and docking.
- While Model Predictive Control (MPC) outperforms traditional controllers under dynamic conditions by optimizing trajectories in complex systems like spacecraft docking, its effectiveness heavily depends on the chosen prediction horizon—too short or too long can lead to suboptimal performance or computational inefficiency.
- To overcome this, a PINN-based adaptive MPC framework is proposed, where system dynamics are embedded in the neural network and physical constraints are integrated into its loss function, enabling dynamic horizon adjustment and adaptability to changing environments.

TRADITIONAL NMPC USED FOR SATELLITE RENDEZVOUS AND DOCKING

COUPLED DYNAMICS OF SPACECRAFT RELATIVE MOTION

Problem Setting:

- Chaser Spacecraft must rendezvous with a tumbling uncooperative asteroid.
- Chaser and target feature points (like grasper and rock are not at their centers, leading to kinematic coupling.

Attitude Kinematics:

$$\dot{R}_{c/e} = R_{c/e}\,\omega_c^{c/e\times}, \quad \dot{R}_{t/e} = R_{t/e}\,\omega_t^{t/e\times}$$

Relative Attitude Kinematics:

- Relative Rotation matrix: $R_{c/t} = R_{t/e}^{\top} R_{c/e}$

$$\dot{R}_{c/t} = R_{c/t}\,\omega_{c/t}^{t\times}$$

------(1)

Relative Attitude Dynamics:

- Angular Velocity error: $\omega_{c/t}^{t} = R_{c/t}\,\omega_c^{c/e} - \omega_t^{t/e}$

$$\dot{\omega}_{c/t}^{t} = R_{c/t}J_c^{-1}(J_c\omega_c^{c/e} \times \omega_c^{c/e} + \tau_{cp} + \tau_{cc}) - J_t^{-1}(J_t\omega_t^{t/e} \times \omega_t^{t/e} + \tau_{tp}) + \omega_{c/t}^{t} \times R_{c/t}\omega_c^{c/e}$$

------(2)

COUPLED DYNAMICS OF SPACECRAFT RELATIVE MOTION

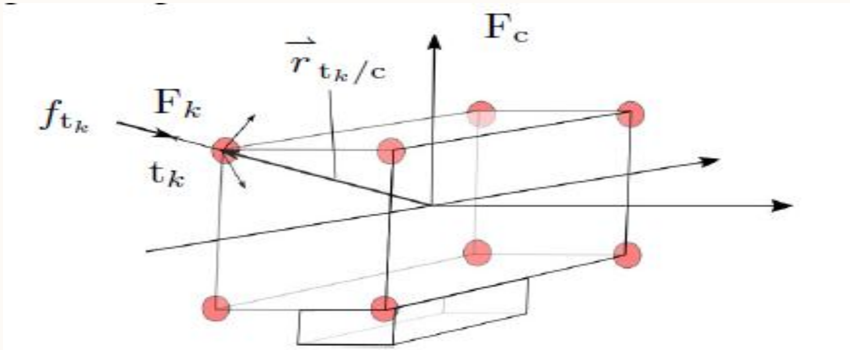
Relative Translational Dynamics:

- Since the feature points on both chaser and target are not located at their respective centers of mass, their relative position is given by:

$$\rho_{c/t} = \vec{r}_{c/t} + \vec{r}_{pc/c} - \vec{r}_{pt/t}$$

$$\ddot{\rho}_{c/t} = \ddot{r}_{c/t} + \dot{\omega}_{c/t} \times R_{c/t} r_{pc/c} + \omega_{c/t} \times \left(\omega_{c/t} \times R_{c/t} r_{pc/c}\right) \qquad \text{------}(3)$$

THRUSTER CONFIGURATION AND NMPC POLICY



Thruster Induced Dynamics Coupling:

- 8 gimballed thrusters produces both forces and torques.
- Total force (in chaser frame):

$$f_c = \sum_{k=1}^{8} R_{k/c} f_{tk}$$

- Total Torque (about COM):

$$\tau_c = \sum_{k=1}^{8} r_{tk/c} \times R_{k/c} f_{tk}$$

Non-Linear Model Predictive Controller:

- Objective: Stabilize relative pose and velocity of chaser w.r.t target.
- State Vector: $x = \begin{bmatrix} R_{c/t}^{\top} & \omega_{c/t}^{t} & \rho_{c/t} & \dot{\rho}_{c/t} & \xi \end{bmatrix}^{\top}$
- Control input: $u = f_{ps} = [f_{t1}^{\top}, \ldots, f_{t8}^{\top}]^{\top}$
- Integral state dynamics for offset free tracking:

$$\dot{\xi} = \rho_{c/t}$$

- Full system dynamics: $\dot{x} = f(x, u)$

NMPC OPTIMIZATION PROBLEM AND CONSTRAINTS

- The cost function, composed of a stage cost integrated along the prediction horizon, and of a terminal cost expressed on the state at the end of the horizon
- The chaser objective is for the feature point to reach and stay at the target, thus attaining zero position and attitude error, with translational and angular velocities matching the target.
- Furthermore, in order to reduce the weight or increase the payload, the use of propellant should be minimized, which we formulate as minimizing the forces and the torques to be produced by the propulsion

$$\min_{u(\cdot|t)} \quad E(x(T|t)) + \int_0^T F(x(\tau|t), u(\tau|t))d\tau$$

Subject to:

$$\dot{x}(\tau|t) = f(x(\tau|t), u(\tau|t)), \quad x(0|t) = x(t), \quad g(x,u) \leq 0$$

$$F(x,u) = QR \cdot \mathrm{tr}(D - DR_{c/t}) + \omega^{t\top}_{c/t} Q_\omega \omega^t_{c/t} + \rho^\top_{c/t} Q_\rho \rho_{c/t} + \xi^\top Q_\xi \xi + \tau_c^\top W_\tau \tau_c + f_{ps}^\top W_f f_{ps}$$

NMPC CONSTRAINTS

1. Thruster Gimbal Constraints(Direction):

Each of the 8 gimbaled thrusters must point within a **polyhedral cone** (due to gimbal limits):

$$A_k f_{tk} \leq b_k$$

2. Thrust magnitude constraints :

Each thruster has a maximum force it can apply: $\|f_{tk}\| \leq f_{\max}$

3. Line of Sight (LOS) Cone Constraint:

The line-of-sight (LOS) constraint imposes that the noncenter-of-mass feature point on the chaser must remain in a line of sight region of the target

$$A\rho_{c/t} \leq b$$

4. Compact Notation for all the constraints:

$$g(x, u) = \begin{bmatrix} A_k f_{tk} - b_k \\ \|f_{tk}\| - f_{\max} \\ A\rho_{c/t} - b \end{bmatrix} \leq 0$$

PHYSICS INFORMED - MPC

Traditional NMPC Challenges:

- Fixed Prediction Horizon -> suboptimal performance
- Complex maneuvers need longer horizons (precision, stability)
- Simple scenarios can use shorter horizons (computational efficiency)
- Manual horizon tuning is scenario specific and non-adaptive.
- Our solution: PINN-based Adaptive MPC that dynamically adjusts prediction horizon based on current system state and physics.

PINN ARCHITECTURE

Input Layer: Current State $[21\times1]$

├──── Position error: $\rho^{t}c/t$ (3)

├──── Velocity error: $\dot{\rho}^{t}c/t$ (3)

├──── Attitude error: Rc/t (9)

├──── Angular velocity: $\omega^{t}c/t$ (3)

└──── Integral states: ξ (3)

Hidden Layers: $[21] \rightarrow [64] \rightarrow [128] \rightarrow [64] \rightarrow [32] \rightarrow [16]$

Output: Optimal Horizon N_{opt}

What makes it "Physics Informed":

- Not just the architecture – standard neural network architecture
- Physics embedded in training process through loss function and MPC Simulation

TRAINING PROCESS – THE PHYSICS LOOP

- Step 1: Horizon Prediction

N_predicted = PINN(current_spacecraft_state)

- Step 2: MPC Simulation with Predicted Horizon

control_sequence, trajectory = solve_MPC(state, N_predicted) # This solves spacecraft dynamics

- Step 3: Physics Informed Loss Evaluation

L_total = λ_1L_physics + λ_2L_performance + λ_3L_computational + λ_4L_safety

Where

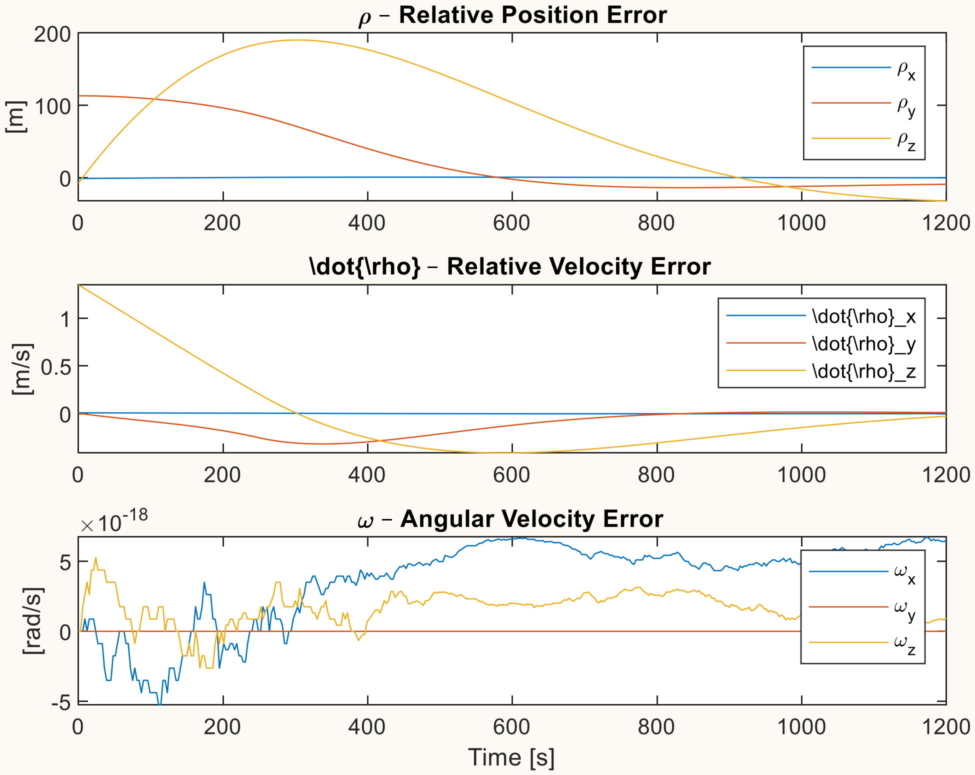
L_physics : Dynamic Consistency= $||\dot{x}$_predicted - f(x, u)$||^2$

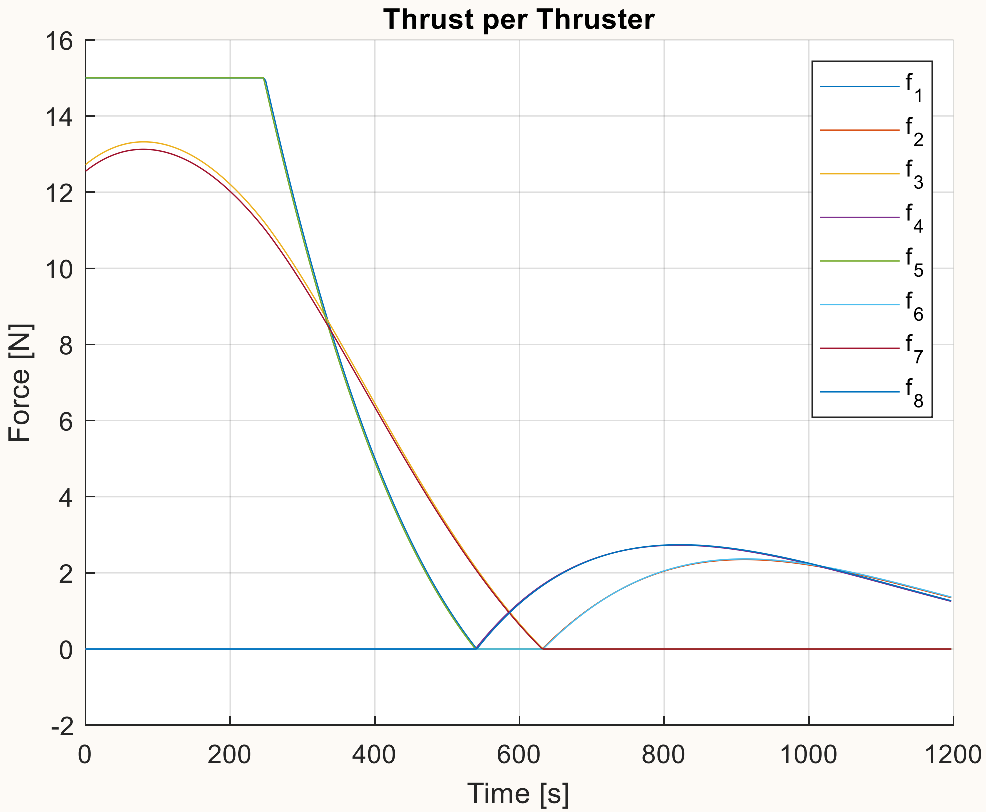
L_performance : Penalizes poor tracking performance = $||$position_error$||^2$ + $||$attitude_error$||^2$

L_computational: Prevents unnecessary long horizons = $\alpha \times$ N_predicted^2

L_safety: Constraint satisfaction = Line-of-sight cone constraints + thruster limits

SIMULATION RESULTS





THANK YOU