Agile Full-Pose Control of a Slung Load with Multiple Aerial Robots

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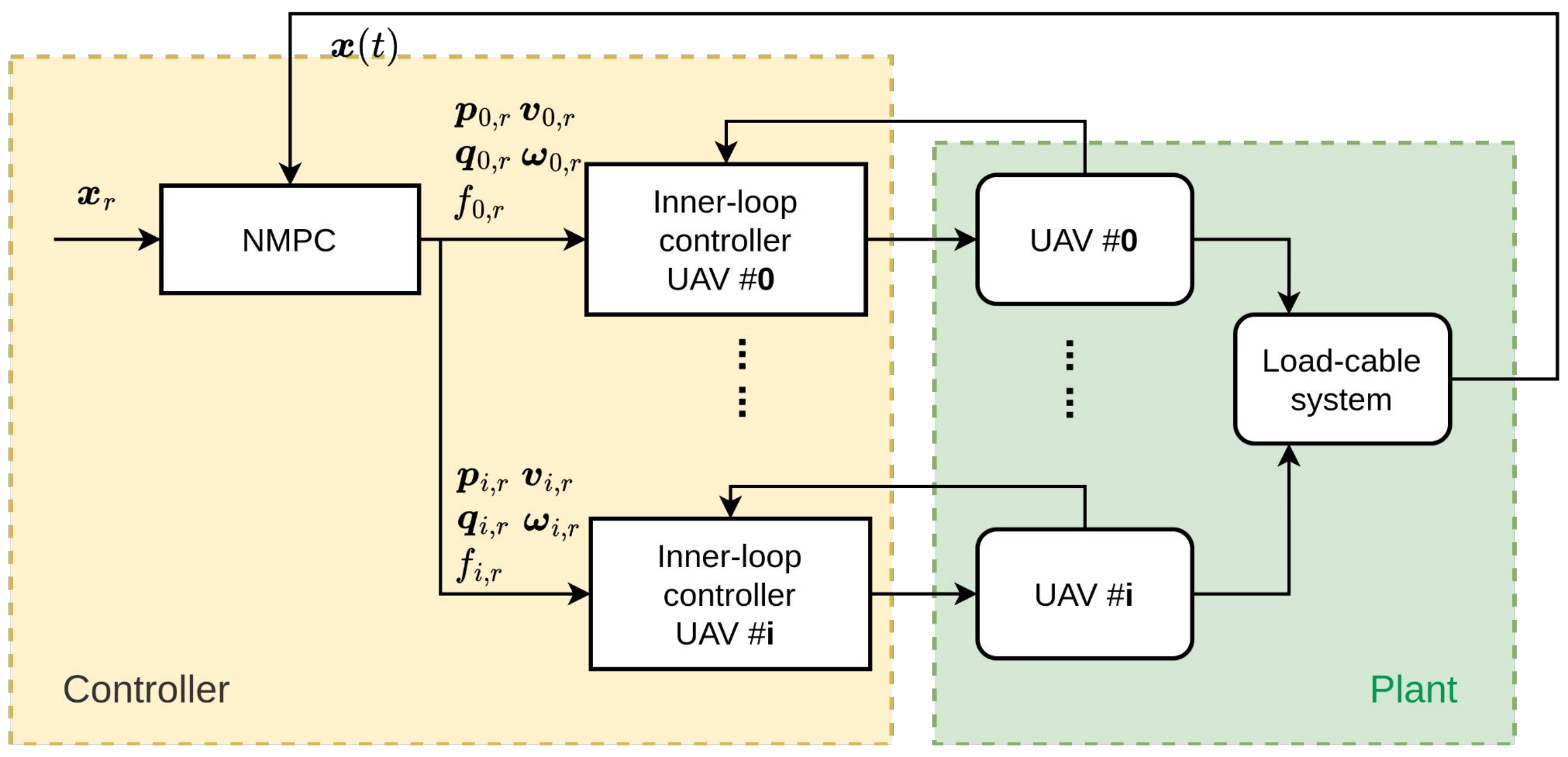
Background

Aerial robots inherently surpass traditional ground-based robots in agility and reachability. They are pivotal for operations where speed and extensive coverage are critical, such as package delivery, search and rescue operations, and even Mars exploration. However, their application has been limited by relatively low payload capacities due to the constraints of aerodynamic lifting, restricting their ability to carry heavy objects.

Research Question:

How to control the **position** and **attitude** of a rigid-body load using multiple aerial robots through tethers, with high agility, while satisfying safety related constraints?

Method



Nonlinear model predictive control

$$\min_{\boldsymbol{u}(\cdot),\boldsymbol{x}(\cdot)} \int_t^{t+h} \left(||\boldsymbol{x}_r(\tau)-\boldsymbol{x}(\tau)||^2_{\boldsymbol{Q}} + ||\boldsymbol{u}_r(\tau)-\boldsymbol{u}(\tau)||^2_{\boldsymbol{R}}\right) d\tau$$
$$+\,||\boldsymbol{x}_r(t+h)-\boldsymbol{x}(t+h)||^2_{\boldsymbol{Q}_e}$$

s.t. *dynamic constraints:*

Load-cable model

inequality path constraints:

UAV thrust constraints
Non-interference constraints
Non-collision constraints

States: load pose / velocities + cable directions / angular rate / angular accelerations

$$\boldsymbol{x} = [\boldsymbol{p},\ \ \boldsymbol{v},\ \ \boldsymbol{q},\ \ \boldsymbol{\omega}^L,\ \ \boldsymbol{s}_1,\ \ \boldsymbol{r}_1,\ \ \dot{\boldsymbol{r}}_1, ...,\ \ \boldsymbol{s}_n,\ \ \boldsymbol{r}_n,\ \ \dot{\boldsymbol{r}}_n]$$

Inputs: cable direction jerks / cable tensions

$$\boldsymbol{u} = [\boldsymbol{c}_1,\ \ t_1, ..., \boldsymbol{c}_n,\ \ t_n]$$

Incremental nonlinear dynamic inversion

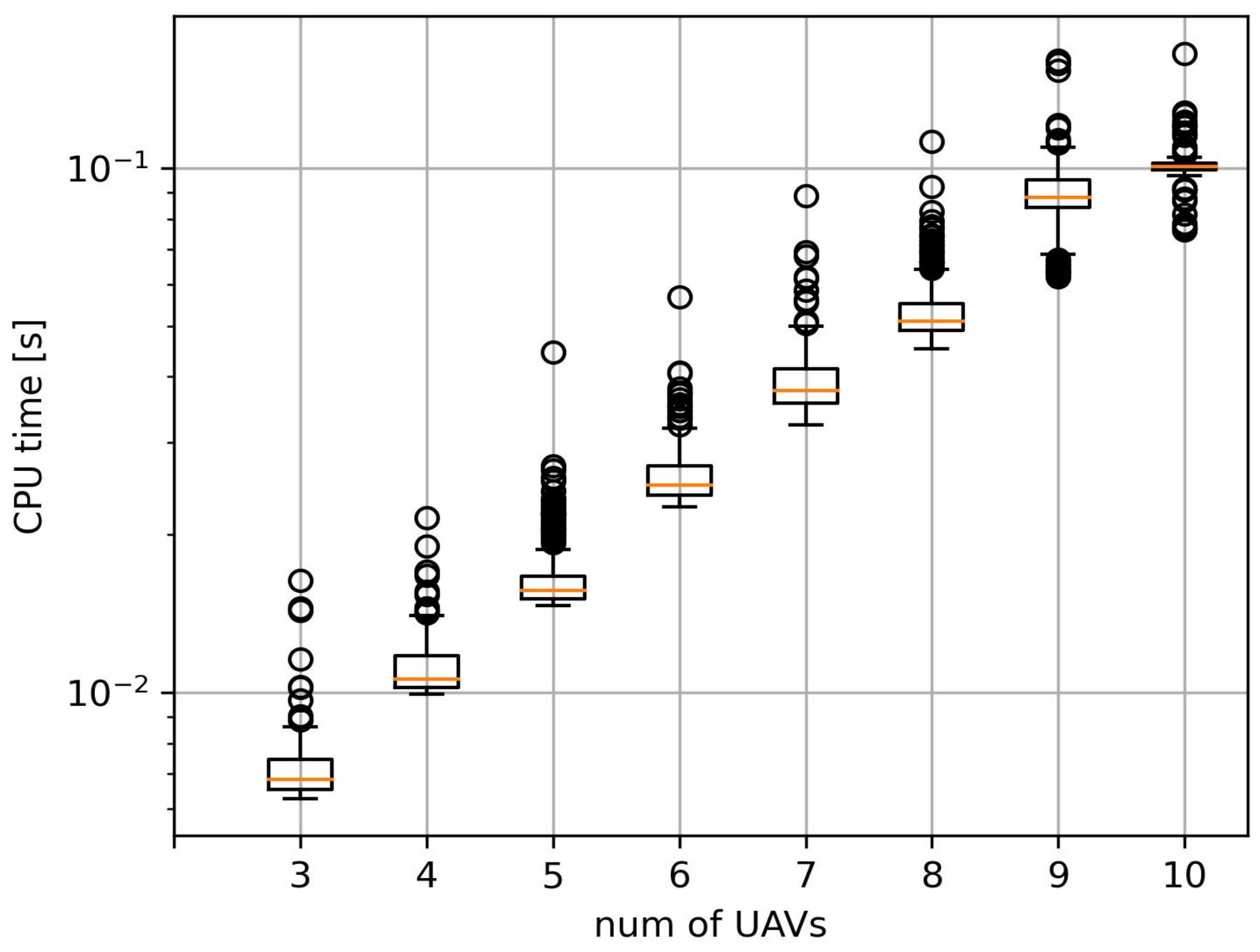
Aerial robotic controller is designed with INDI method for both position and attitude control to compensate for external force and torque from the cables.

$$\dot{\boldsymbol{v}}_{i,ref} = \dot{\boldsymbol{v}}_i = \boldsymbol{g} + \frac{t_i}{m_i}\boldsymbol{s}_i + \frac{1}{m_i}\boldsymbol{T}_i$$
$$\approx\ \dot{\boldsymbol{v}}_{i,f} + \frac{1}{m}(\boldsymbol{T}_i - \boldsymbol{T}_{i,f})$$

$$\Rightarrow\ \boldsymbol{T}_i = m_i\left[\dot{\boldsymbol{v}}_{i,ref} - (\boldsymbol{g} + \boldsymbol{R}_f\boldsymbol{a}_{i,f})\right] + \boldsymbol{T}_{i,f}$$

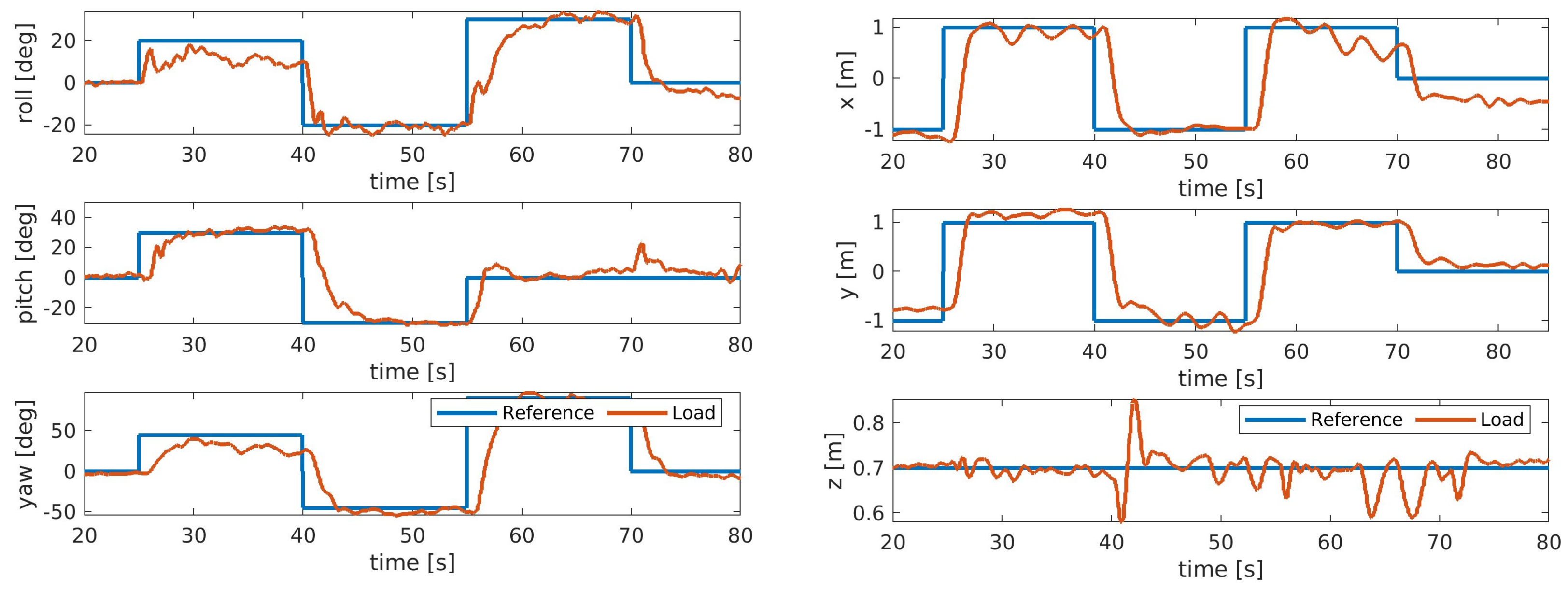
Video of Flights

Computational load

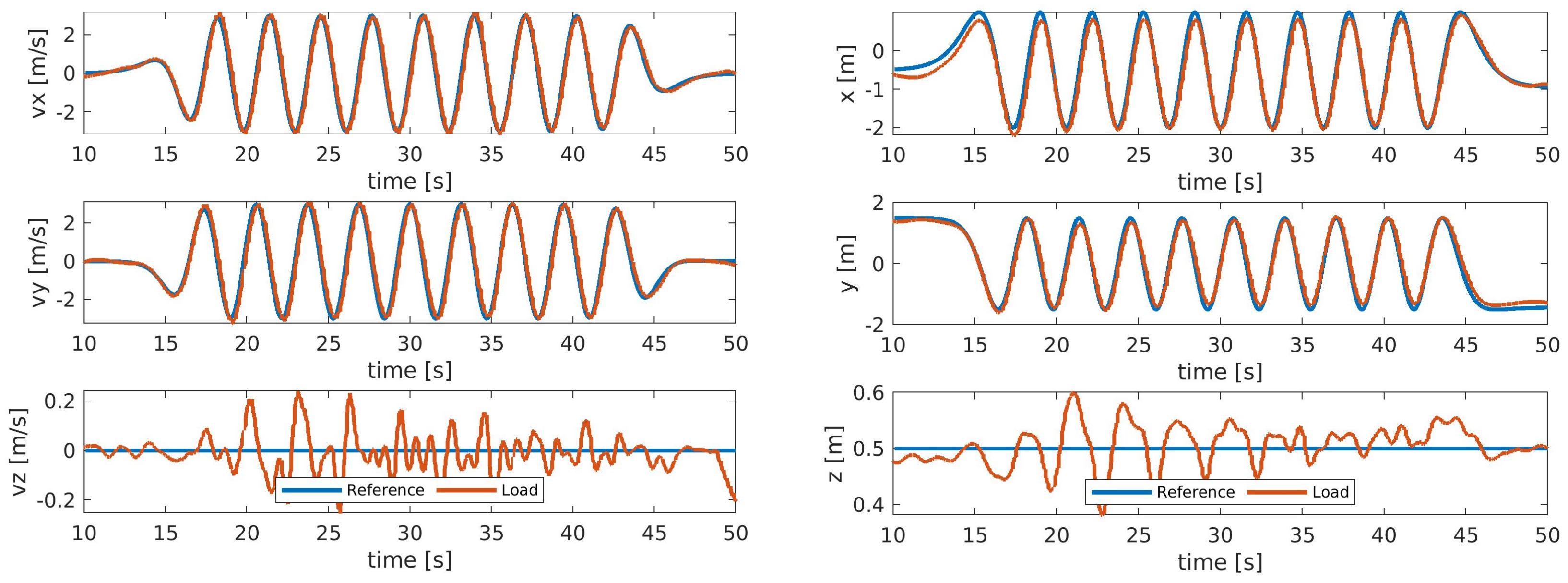


- Acados toolkit[1]
- Real-time iteration (RTI) scheme
- HPIPM as SQP solver
- Horizon: 1 seconds, 20 segments
- Online applicability
    - Intel i7 10750H 2.6Hz
    ~10 ms for 4 units
    ~100ms for 10 units

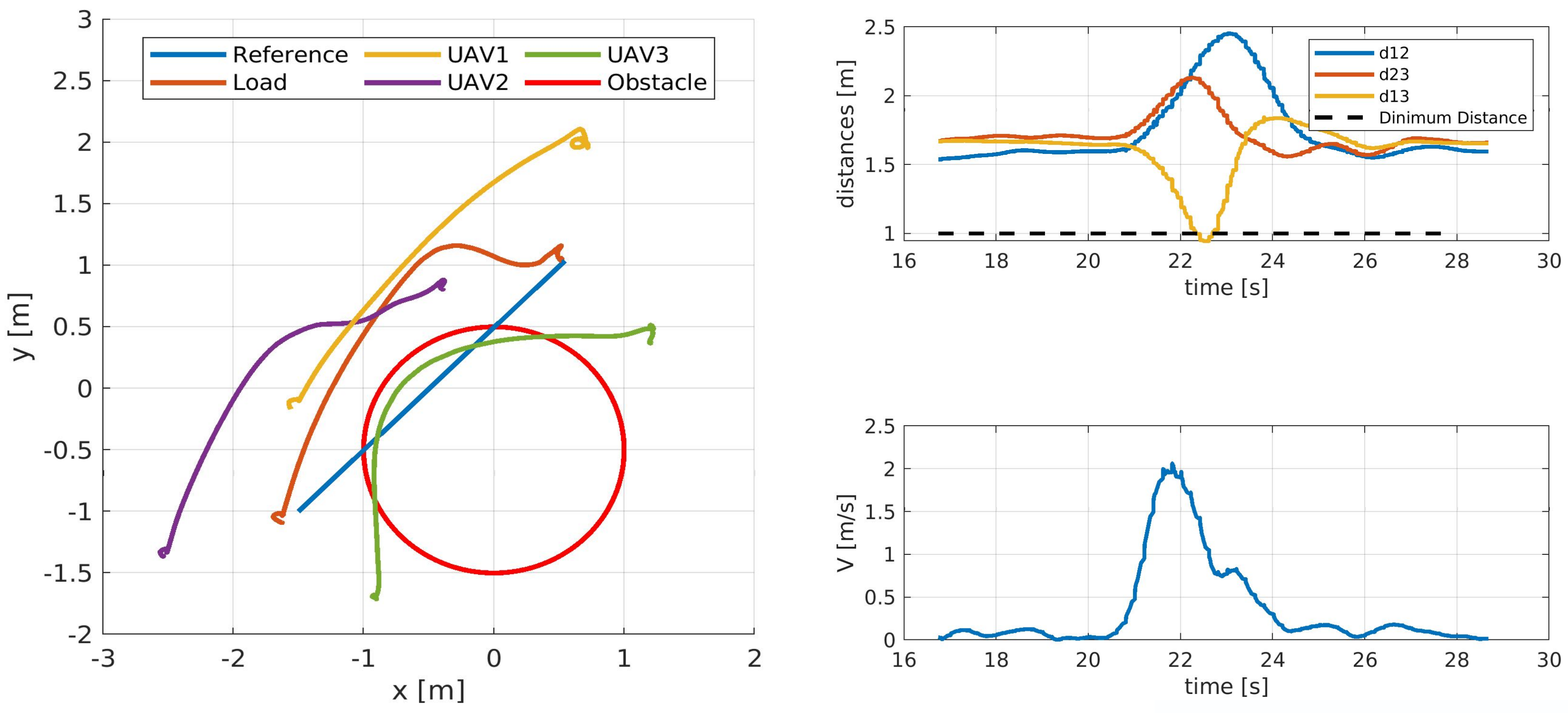
Pose Control



Trajectory Tracking



Obstacle Avoidance



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