# Controller Design for Thrust-Propelled Underactuated Systems


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## Problem and motivation

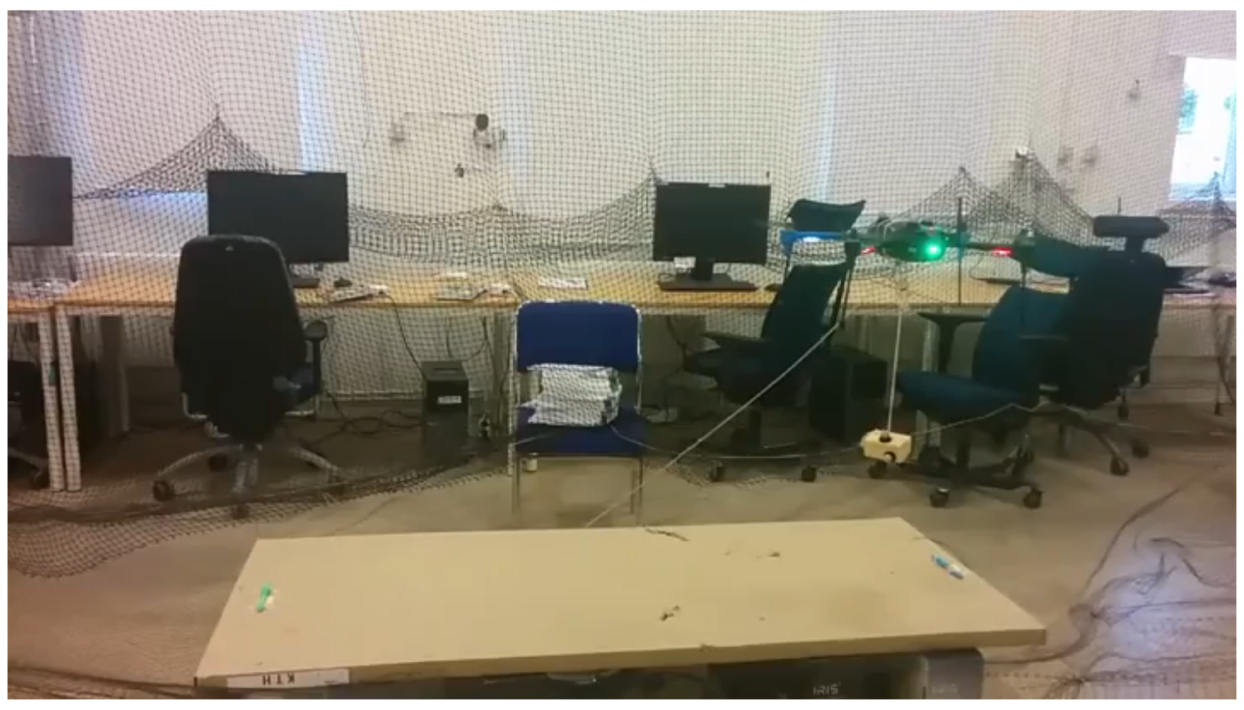

Figure 1: Iris+ and tethered load at the SML.

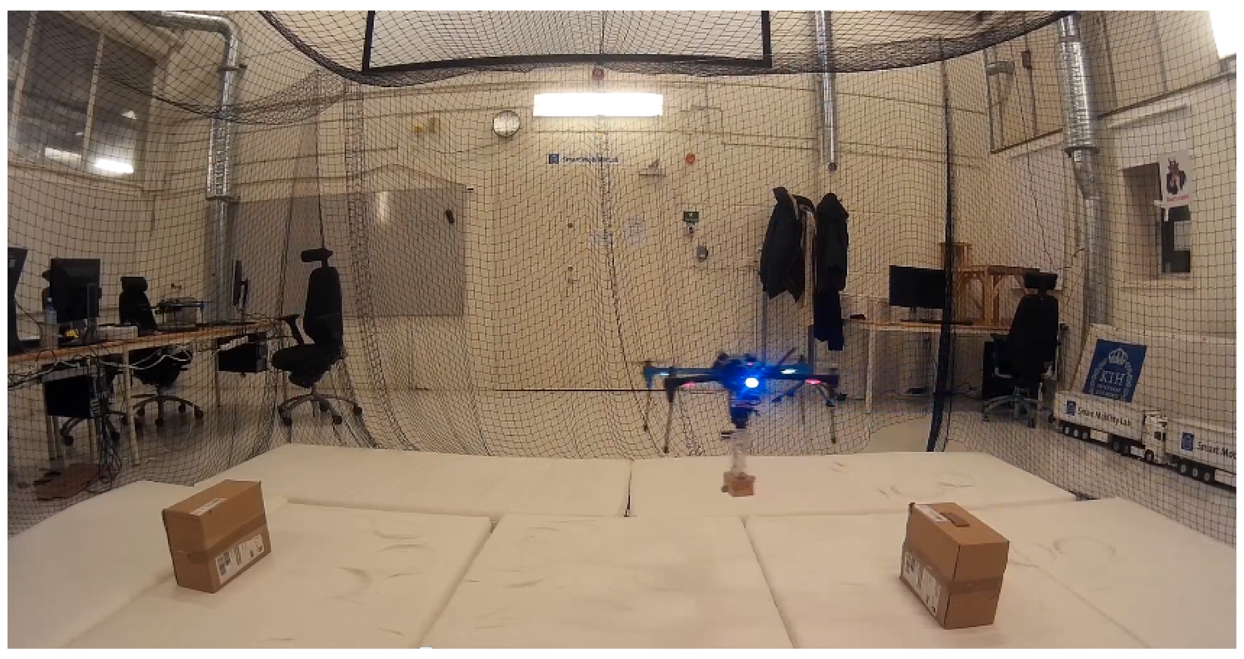

Figure 2: Iris+ and rigid manipulator at the SML.

- Controller for thrust vectored systems: suitable for different systems
- Contribution to the AEROWORKS project [1]: inspection of aging infrastructures by ARWs (Aerial Robotic Workers); trajectory tracking with tethered loads or rigid manipulators

## Thrust vectored system

$\mathbf{p} =$ position
$\mathbf{g} =$ time varying gravity
$T\mathbf{n} =$ Thrust acceleration
$\boldsymbol{\tau} =$ Angular acceleration

$$\mathbf{f}(t, \mathbf{x}, \mathbf{u}) = \begin{bmatrix} \mathbf{v} \\ T\mathbf{n} - \mathbf{g}(t) \\ \mathcal{S}(\boldsymbol{\omega})\mathbf{n} \\ \Pi(\mathbf{n})\boldsymbol{\tau} \end{bmatrix}$$

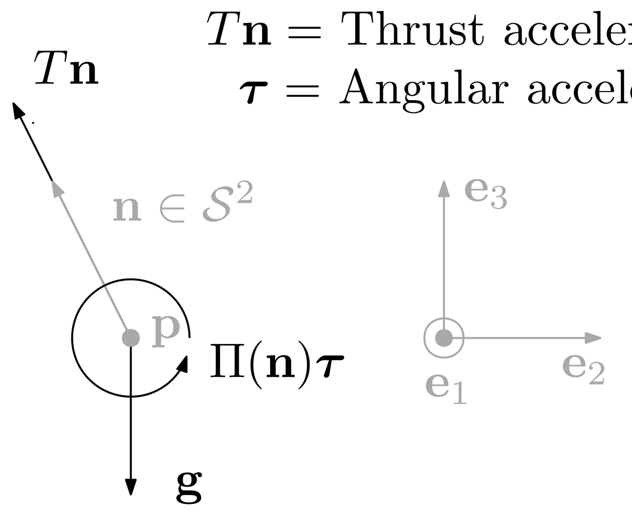


Figure 3: System description and vector field

- State $\mathbf{x} = [\mathbf{p}^T\, \mathbf{v}^T\, \mathbf{n}^T\, \boldsymbol{\omega}^T]^T \in \mathbb{R}^3 \times \mathbb{R}^3 \times \mathcal{S}^2 \times \mathbb{R}^3 =: \Omega$
- Control inputs $\mathbf{u} = [T\, \boldsymbol{\tau}^T]^T \in \mathbb{R}^4$: thrust force and torque
- Control goal: $\lim_{t\to\infty} \mathbf{p}(t) = \mathbf{0}$
- Proposed control law: $\mathbf{u}^{cl} : \mathbb{R}_{\geq 0} \times \Omega \mapsto \mathbb{R}^4$ [2]
- $\mathbf{u}^{cl}(t, \mathbf{x}) = \tilde{\mathbf{u}}^{cl}(t, \mathbf{x}, \mathbf{u}_{di})$ where $\tilde{\mathbf{u}}^{cl} : \mathbb{R}_{\geq 0} \times \Omega \times \mathcal{C}^2(\mathbb{R}^6, \mathbb{R}^3) \mapsto \mathbb{R}^4$
  – dependence on a stabilizing controller $\mathbf{u}_{di}(\cdot)$ for a double integrator
- Controller is suitable for all systems whose vector field $\mathbf{f}_z(\cdot)$ may be converted to the standard vector field $\mathbf{f}(\cdot)$

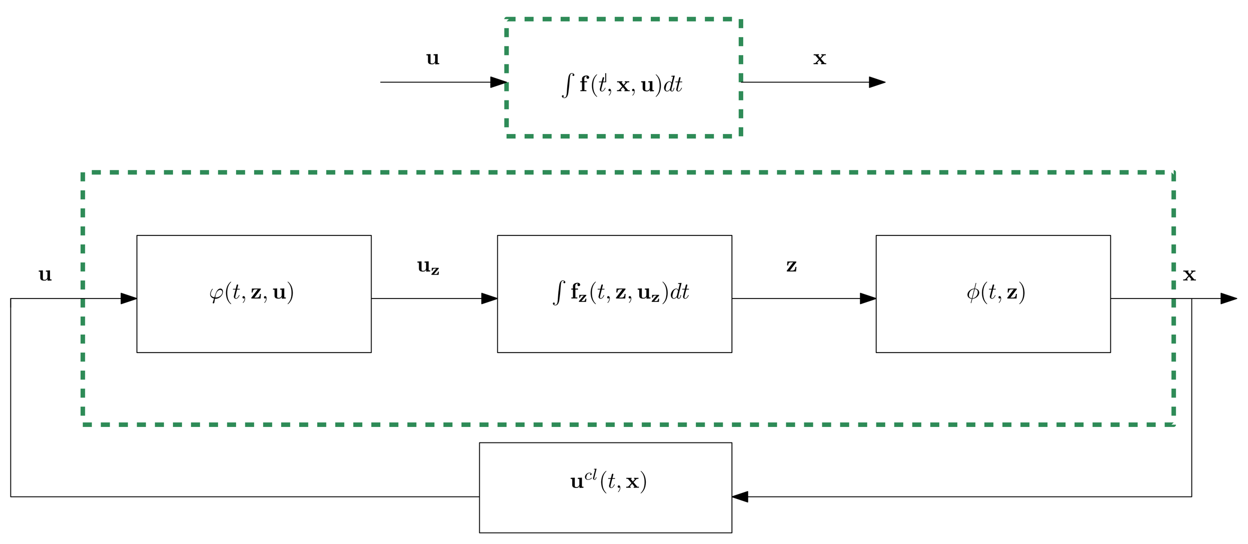


Figure 4: Controller framework for different systems: find mappings $\varphi(\cdot)$ and $\phi(\cdot)$ that make $\mathbf{f}_z(\cdot)$ similar to $\mathbf{f}(\cdot)$

## Examples

### Load lifting with an aerial vehicle

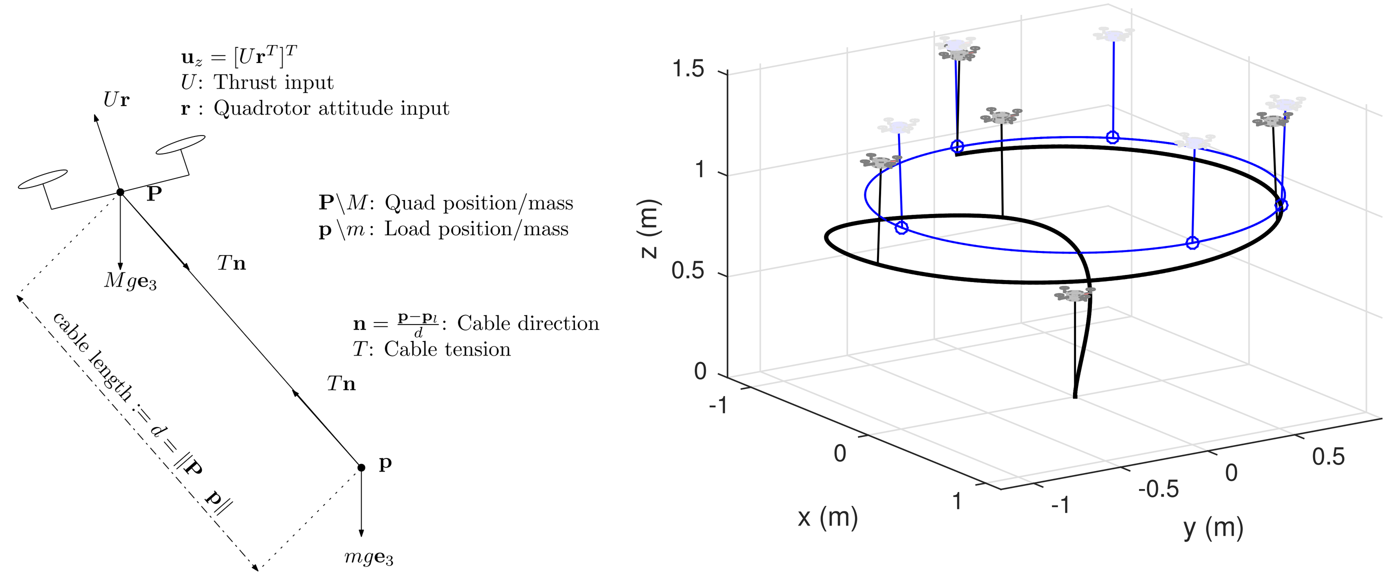


Figure 5: Mappings $\varphi(\cdot)$ and $\phi(\cdot)$ are found in [3]

### Load lifting with two aerial vehicles

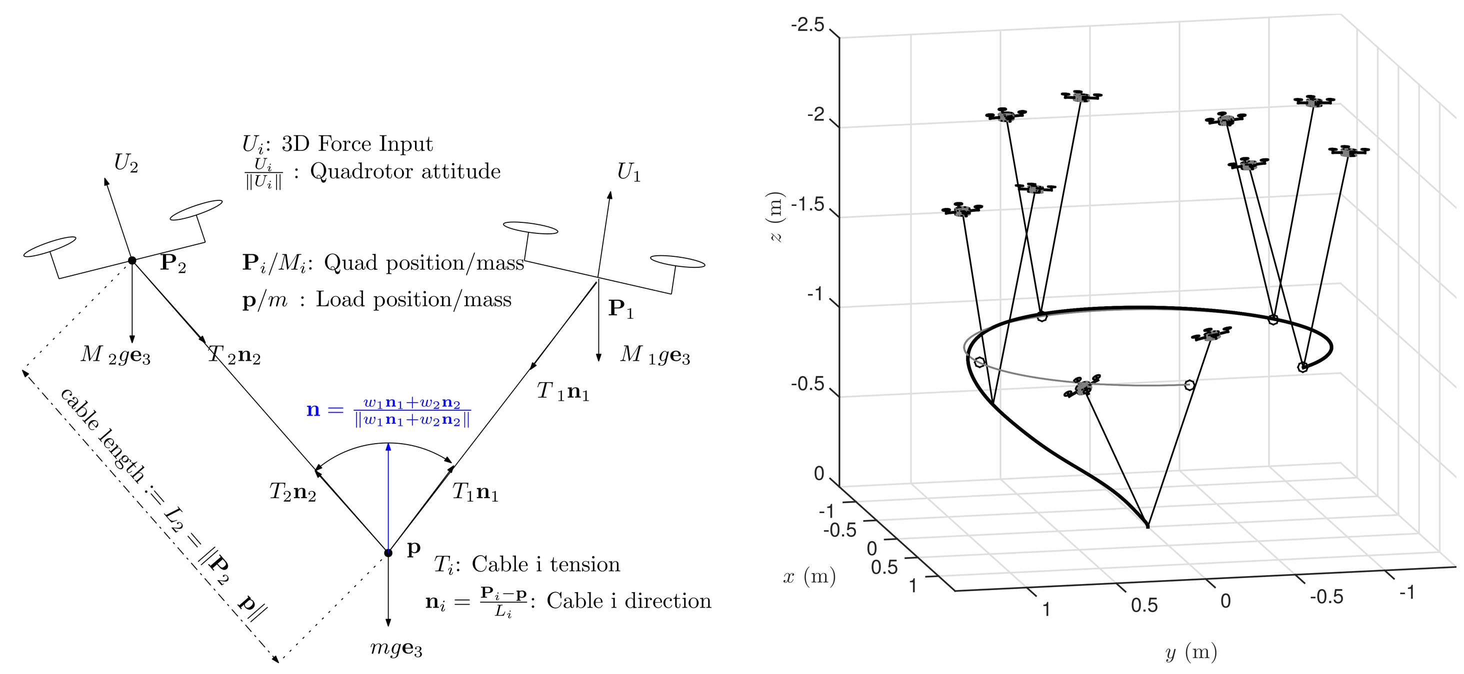


Figure 6: Tethered load lifting by two aerial vehicles

### Aerial vehicle and rigid manipulator

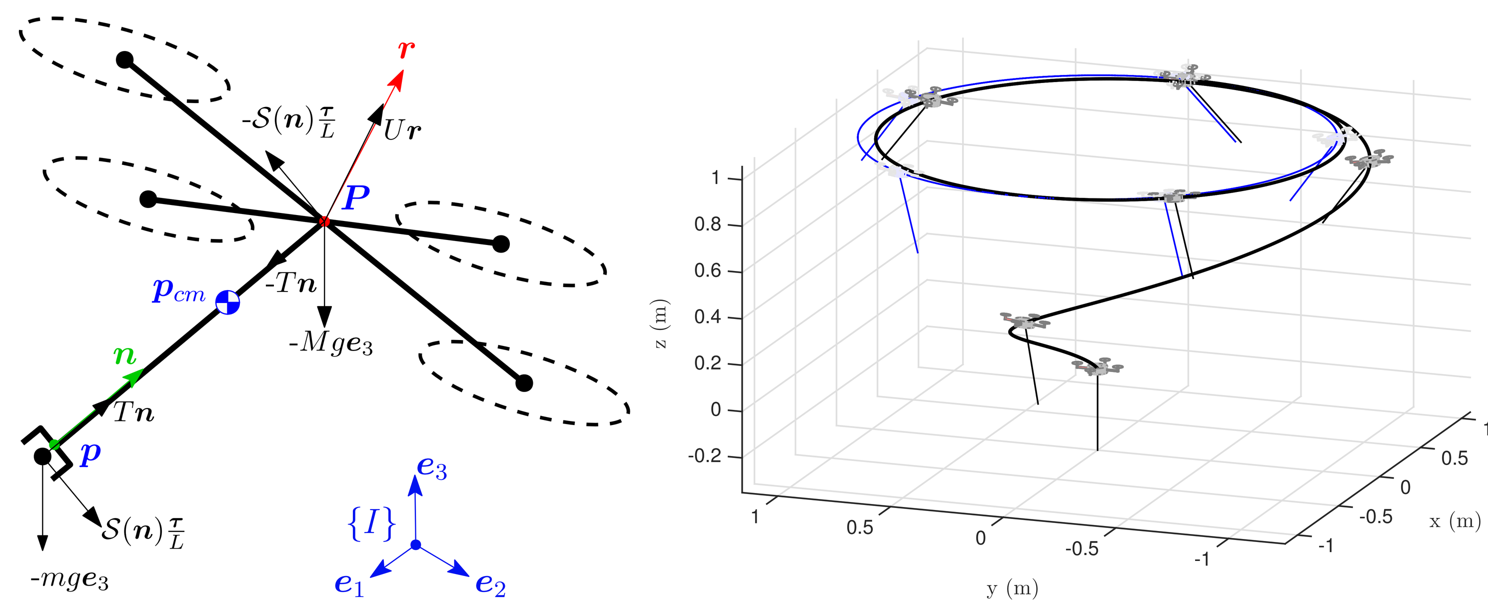

Figure 7: Mappings $\varphi(\cdot)$ and $\phi(\cdot)$ are found in [4]

## Future/Current Work

- Experimental validation
- Robustness to model mismatch
- Disturbance removal, for specific types of disturbances
- High level planning: automatically select motion primitives according to environmental/user input
- Detection and adaption to failures (e.g. broken propeller, or motor failure)

## References


[1] AEROWORKS aim. http://www.aeroworks2020.eu/

[2] Pereira, P. O. and Dimarogonas, D. V. *Lyapunov-based Generic Controller Design for Thrust-Propelled Underactuated Systems*. ECC 2016 (to appear).

[3] Pereira, P. and Herzog, M. and Dimarogonas, D. V. *Slung Load Transportation with Single Aerial Vehicle and Disturbance Removal*. MED 2016 (to appear).

[4] Pereira, P. and Zanella, R. and Dimarogonas, D. V. *Decoupled Design of Controllers for Aerial Manipulation with Quadrotors*. IROS 2016 (submitted).