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Interaction control of under-actuated UAV capable of exerting downward force

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ABSTRACT

The interaction control scheme is a key ingredient in realizing complex manipulation tasks of quadrotors. In particular, Interconnection and Damping Assignment Passivity Based Control (IDA-PBC) is noteworthy because it provides a means to modulate the system's energy which plays an important role in physical interaction problems. However, since conventional quadrotors cannot exert downward forces, there is a limitation that the maximum downward acceleration is limited by the gravitational constant. In this paper, we propose to use two additional downward-facing motors enabling quadrotors to exert downward forces greater than gravity. Consequently, it will be shown that the interaction control can be realized more realistically compared to the existing method. Simulation results confirm the validity of our approach.

CONTENTS

1. Introduction

- In order to realize complex manipulation tasks of UAVs, the interaction control has been studied.
- Interconnection and Damping Assignment Passivity Based Control (IDA-PBC) is powerful because the desired interaction can be obtained by shaping the total energy of the system.
- Since the conventional quadrotors cannot exact downward forces, IDA-PBC may not work when the system interacts with the ground.
- The motivation of this study is to use two additional downward-facing motors enabling quadrotors to exert a negative thrust and interact with the ground better.

2. Background

- IDA-PBC

$$\begin{cases} \dot{\mathbf{x}} = [\mathcal{J}(\mathbf{x}) - \mathcal{R}(\mathbf{x})]\frac{\partial H}{\partial \mathbf{x}} + \mathbf{G}(\mathbf{x})\mathbf{u} \\ \mathbf{y} = \mathbf{G}(\mathbf{x})^{\mathrm{T}}\frac{\partial H}{\partial \mathbf{x}}, \end{cases} \Rightarrow \quad \begin{aligned} \dot{\bar{\mathbf{x}}} &= [\mathcal{J}_d(\bar{\mathbf{x}}) - \mathcal{R}_d(\bar{\mathbf{x}})]\frac{\partial H_d}{\partial \bar{\mathbf{x}}} \\ \mathbf{x} &= \mathbf{\Phi}(\bar{\mathbf{x}}, t) \end{aligned}$$

$$\mathbf{u} = \mathbf{G}^{+}(\mathbf{x})\left[\frac{\partial \mathbf{\Phi}}{\partial \bar{\mathbf{x}}}(\mathcal{J}_d(\bar{\mathbf{x}}) - \mathcal{R}_d(\bar{\mathbf{x}}))\frac{\partial H_d}{\partial \bar{\mathbf{x}}} - (\mathcal{J}(\mathbf{x}) - \mathcal{R}(\mathbf{x}))\frac{\partial H}{\partial \mathbf{x}} + \frac{\partial \mathbf{\Phi}}{\partial t}\right]$$

$$\mathbf{G}^{\perp}(\mathbf{x})\left[\frac{\partial \mathbf{\Phi}}{\partial \bar{\mathbf{x}}}(\mathcal{J}_d(\bar{\mathbf{x}}) - \mathcal{R}_d(\bar{\mathbf{x}}))\frac{\partial H_d}{\partial \bar{\mathbf{x}}} + \frac{\partial \mathbf{\Phi}}{\partial t} - (\mathcal{J}(\mathbf{x}) - \mathcal{R}(\mathbf{x}))\frac{\partial H}{\partial \mathbf{x}}\right] = \mathbf{0}$$

3. Port-Hamiltonian Modeling & Control Design

- Dynamics of quadrotor

$$m\ddot{\mathbf{p}}_q = u_t\mathbf{R}(\boldsymbol{\eta})\mathbf{e}_3 - mg\mathbf{e}_3 + \mathbf{f}_{ext}, \quad \mathbf{p}_q = [x_q \; y_q \; z_q]^{\mathrm{T}}$$

$$\mathbf{M}_{qr}\dot{\omega} = [\boldsymbol{\omega}]_{\wedge}\mathbf{M}_{qr}\boldsymbol{\omega} + \mathbf{u}_r + \boldsymbol{\tau}_{ext}, \quad \dot{\boldsymbol{\eta}} = \mathbf{T}(\boldsymbol{\eta})\boldsymbol{\omega}$$

$$\mathbf{u}_r = \mathbf{M}_{qr}\mathbf{T}^{-1}\left[(-k_d\mathbf{I} + \mathbf{Q})\dot{\boldsymbol{\eta}} + \bar{\mathbf{u}}_r + (\mathbf{I} - \mathbf{M}_{qr}^{-1})\boldsymbol{\tau}_{ext}\right]$$

$$\mathbf{Q} = \mathbf{T}\dot{\mathbf{T}}^{-1} + \mathbf{T}\mathbf{M}_{qr}^{-1}[\boldsymbol{\omega}]_{\wedge}\mathbf{M}_{qr}\mathbf{T}^{-1} : \text{Pre} - \text{Compenating Control}$$

$$\ddot{\boldsymbol{\eta}} = -k_d\dot{\boldsymbol{\eta}} + \bar{\mathbf{u}}_r + \boldsymbol{\tau}_{ext}$$

- PH Form

$$\begin{bmatrix} \dot{\mathbf{q}} \\ \dot{\mathbf{p}} \end{bmatrix} = \left[\begin{pmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{I} & \mathbf{0} \end{pmatrix} - \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathcal{R} \end{pmatrix}\right]\begin{bmatrix} \frac{\partial H}{\partial \mathbf{q}} \\ \frac{\partial H}{\partial \mathbf{p}} \end{bmatrix} + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{G} & \mathbf{I} \end{bmatrix}\begin{bmatrix} \mathbf{u}_i \\ \mathbf{w}_{ext} \end{bmatrix}$$

$$\mathbf{q} = [\mathbf{p}_q^{\mathrm{T}} \; \boldsymbol{\eta}^{\mathrm{T}}]^{\mathrm{T}}, \quad \mathbf{p} = \mathbf{M}\dot{\mathbf{q}} \in \mathbb{R}^6, \quad \mathbf{M} = \mathrm{diag}([m\mathbf{I}, \mathbf{I}]) \in \mathbb{R}^{6\times 6}$$

$$\mathbf{G} = \begin{bmatrix} \mathbf{R}\mathbf{e}_3 & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \in \mathbb{R}^{6\times 4}, \quad H(\mathbf{q}, \mathbf{p}) = \frac{1}{2}\mathbf{p}^{\mathrm{T}}\mathbf{M}^{-1}\mathbf{p} + V(\mathbf{q})$$

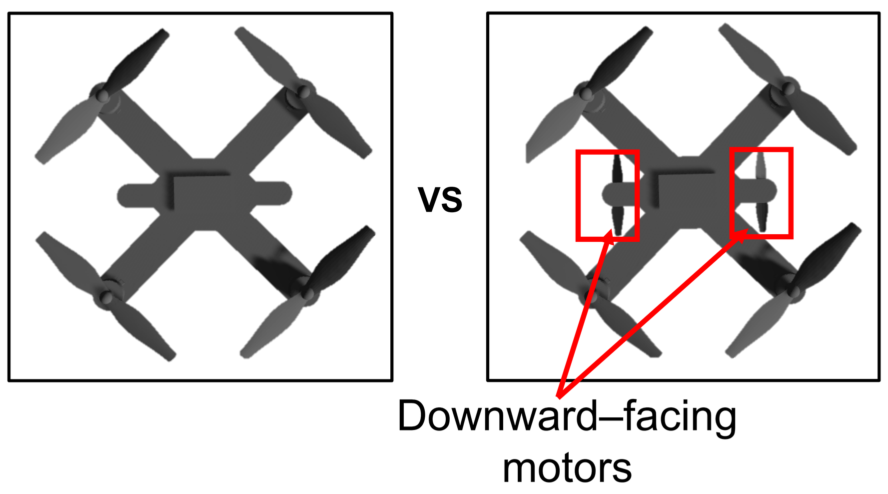
- Control Design
  - Energy Shaping
  - Damping Injection
  - External Wrench Compensation
  - High Level Control (u_0)

$$\begin{bmatrix} \dot{\mathbf{q}} \\ \dot{\mathbf{p}} \end{bmatrix} = \left[\begin{pmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{I} & \mathbf{0} \end{pmatrix} - \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathcal{R}_d \end{pmatrix}\right]\begin{bmatrix} \frac{\partial H_d}{\partial \mathbf{q}} \\ \frac{\partial H_d}{\partial \mathbf{p}} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix}\bar{\mathbf{w}}_{ext} + \begin{bmatrix} \mathbf{0} \\ \mathbf{M}_d\mathbf{M}^{-1}\mathbf{G} \end{bmatrix}\mathbf{u}_o$$

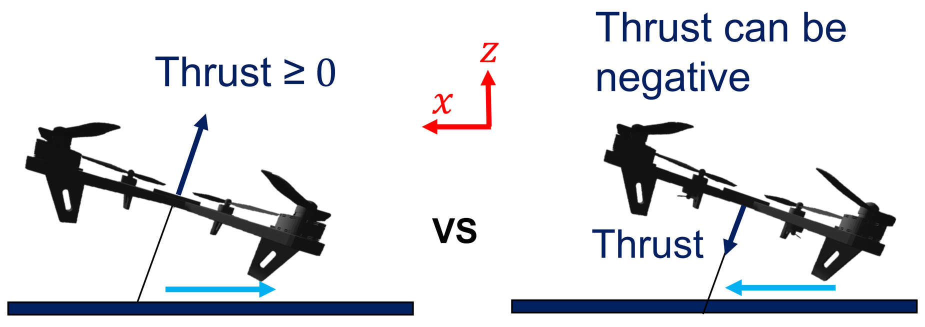
4. Simulation

- Quadrotor modeling

[Conventional quadrotor][Proposed quadrotor]



- Task : Tooltip is in contact with the ground and sliding along x axis



$$f_{ext,x} = -\mu\dot{q}_1$$

$$f_{ext,z} = -k_{\mathrm{wall}}z_t$$

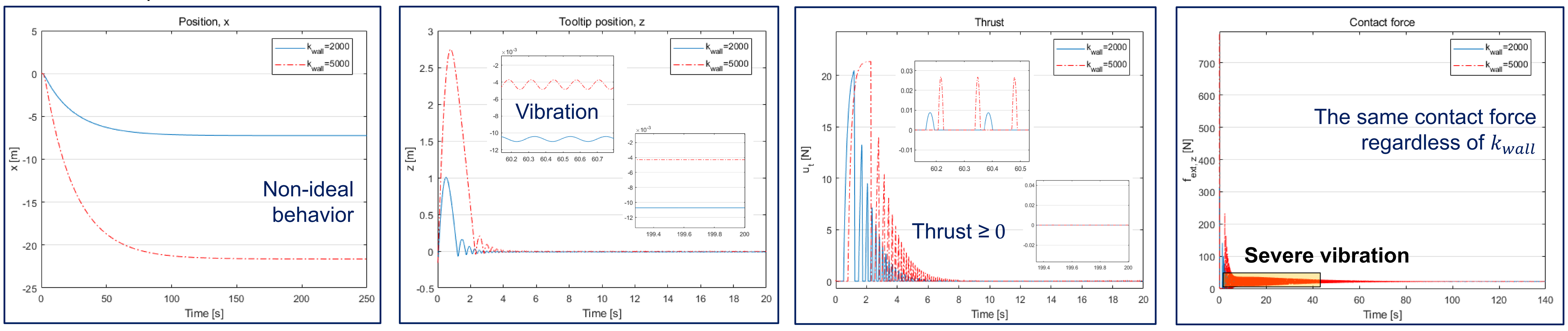
$$f_{ext} = 0 \in \Re^3, \text{ if } z_t > 0$$

$$f_{ext} = [f_{ext,x} \; 0 \; f_{ext,z}]^T, \text{ if } z_t \le 0$$

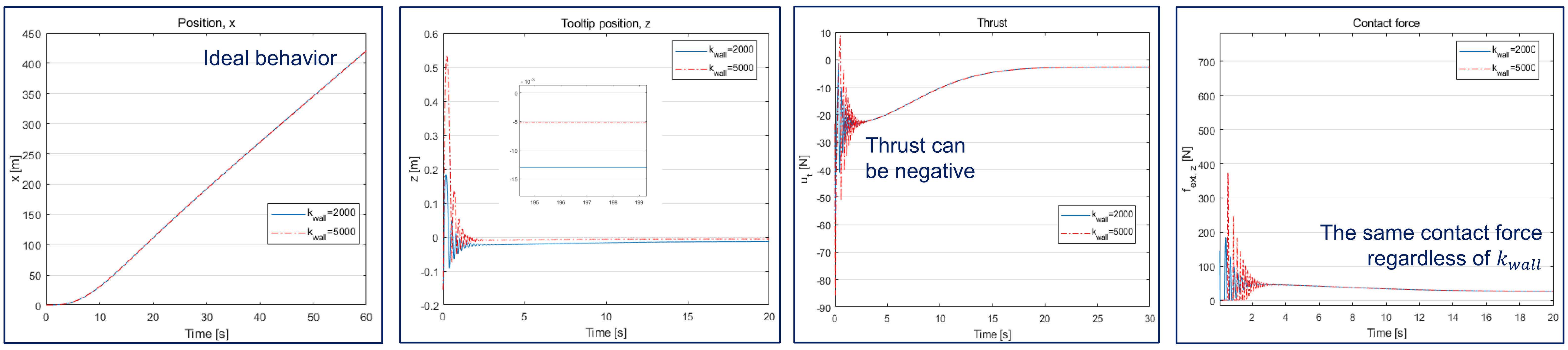
A thrust of -mg is applied using high level control to maintain contact and slid along the x - axis

5. Result

- Conventional quadrotor



- Proposed quadrotor



CONCLUSION

- In this study, two additional downward-facing motors are proposed to realize aerial physical interaction realistically.
- The proposed quadrotor maintains contact with the ground and slides, while the conventional quadrotor vibrates and eventually stops.
- The thrust would be negative when the system is controlled based on passivity and interacts with the ground.
- Since the conventional quadrotors cannot exact a negative thrust, it may cause undesirable behavior.
- The system motion does not change when the k_{wall} changes because the desired interaction behavior is obtained.

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