A Novel Robust Hexarotor Capable of Static Hovering in Presence of Propeller Failure

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Overview

1. Introduction
2. Theoretical Background
3. Experimental Campaign
4. Conclusion

Motivation

Package Delivery

[theconversation.com]

Human-UAV Interaction

[gpsworld.com]

Motivation

- Platform crash $\rightarrow$ loss of assets & place humans in danger.

Package Delivery

[theconversation.com]

Human-UAV Interaction

[gpsworld.com]

Paper Contributions

- Provide a geometrical tool to analyze platform hoverability.
- Analyze failure robustness of Y-shaped and Star-shaped hexarotors.
- Carry out systematic and extensive real experiments to compare Y-shaped and Star-shaped hexarotors' robustness and efficiency.

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Static Hovering

$$\dot{\boldsymbol{p}}_R \rightarrow 0, \qquad \boldsymbol{\omega}_R \rightarrow 0, \tag{1}$$

As explained in [1] the following conditions are needed for a platform to posses the static hovering ability

$$rank\{\boldsymbol{F}_2\} = 3 \tag{2}$$

$$\exists \boldsymbol{u} \in \text{int}(\mathbb{U}) \; s.t. \begin{cases} \|\boldsymbol{F}_1 \boldsymbol{u}\| \geq m\boldsymbol{g} \\ \boldsymbol{F}_2 \boldsymbol{u} = 0 \end{cases} . \tag{3}$$

Where $\text{int}(\mathbb{U})$ denotes the interior of $\mathbb{U}$, and $\mathbb{U}$ is set of feasible inputs.
$\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ map the platform forces and moments respectively to $\boldsymbol{u}$.

[1] G. Michieletto, M. Ryll, and A. Franchi, “Fundamental actuation properties of multi-rotors: Force-moment decoupling and fail-safe robustness,” IEEE Trans. on Robotics, vol. 34, no. 3, pp. 702–715, 2018.

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Geometrically, conditions (2) and (3) are equivalent to the following:

Proposition

A platform can statically hover iff $0 \in \mathrm{int}(\mathscr{F}_{2+})$

where $\mathscr{F}_{2+}$ is the moment set at hover, *i.e.* while applying a force counteracting gravity.

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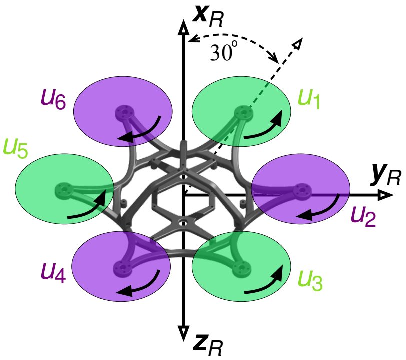
$$\mathscr{F}_{2+} = \{\boldsymbol{\tau} \;\; s.t. \;\; \boldsymbol{\tau} = \boldsymbol{F}_2 \boldsymbol{u} \;\forall\; \boldsymbol{u} \;\in\; \mathbb{U}_+\} \tag{4}$$

where $\mathbb{U}_+$ is the set of feasible inputs s.t. $\|\boldsymbol{F}_1 \boldsymbol{u}\| \geq m\boldsymbol{g}$.

Classical Hexarotor Design



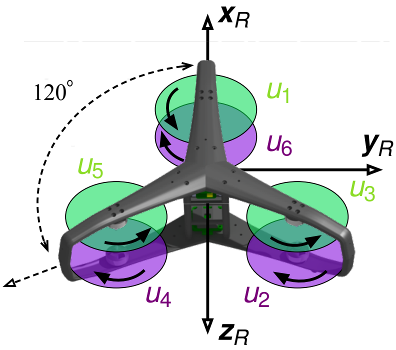
- 6 identical propellers, at equal distance from platform CoM
- force direction along $\boldsymbol{z}_R$

$$\boldsymbol{f}_R = \sum_{i=1}^{n} c_{f_i} u_i \boldsymbol{z}_{p_i}, \tag{5}$$

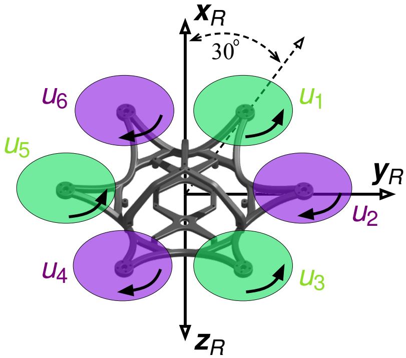
- moment is the sum of torque and drag

$$\tau_R = \sum_{i=1}^{n} (\boldsymbol{\tau}_i^t + \boldsymbol{\tau}_i^d) = \sum_{i=1}^{n} (c_{f_i} \boldsymbol{p}_i \times \boldsymbol{z}_{p_i} + c_{\tau_i} \boldsymbol{z}_{p_i}) u_i \tag{6}$$

Y-Shaped
Coaxial propeller pairs

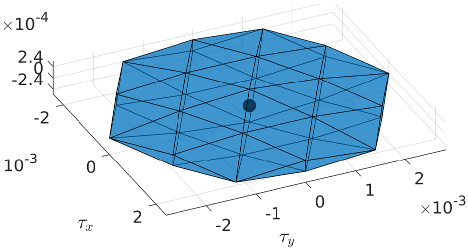


Star-Shaped
Equally spaced propellers

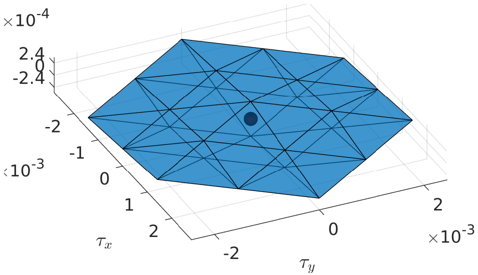


- Healthy platform cases

Y-Shaped



Star-Shaped



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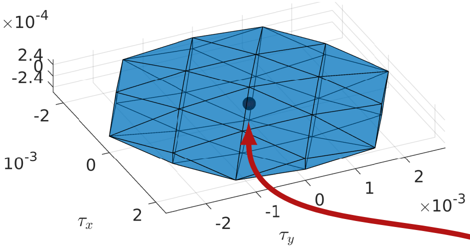
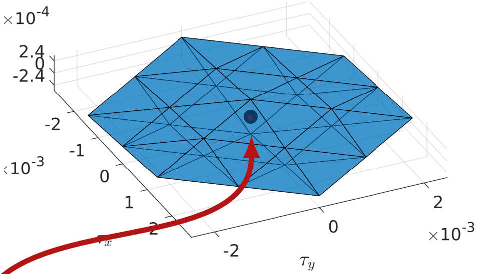


Star-Shaped



The origin is an interior point of both sets

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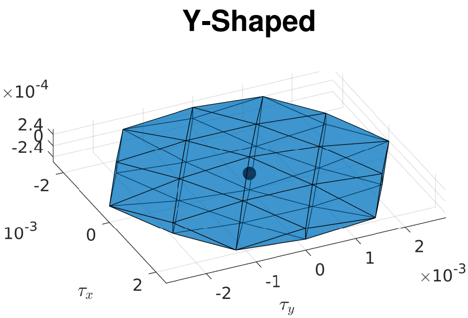

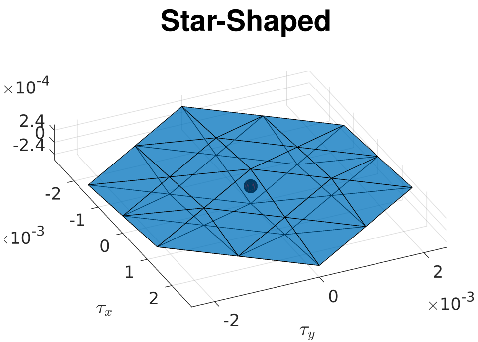

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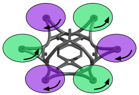
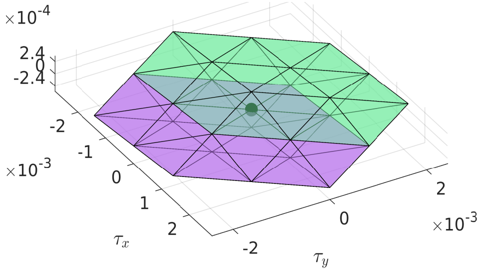
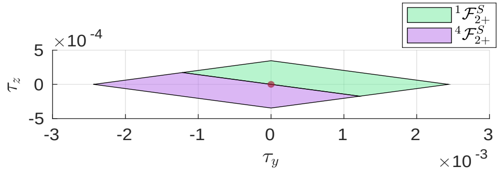
Robustness after Propeller Failure

Star-Shaped Design



Robustness derived analyzing the feasible moment sets after propeller failure

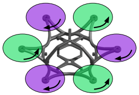




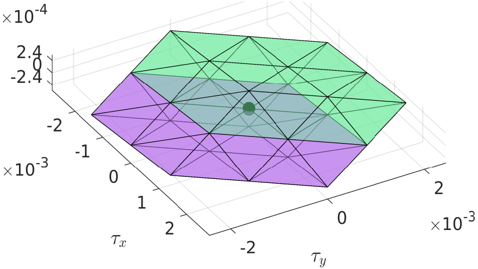
- Feasible moment sets when opposite propellers fail intersect only at boundary

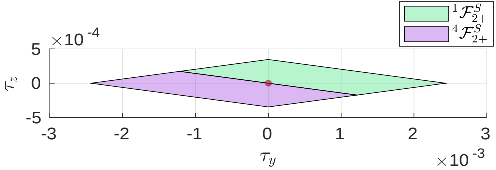
Robustness after Propeller Failure

Star-Shaped Design



Robustness derived analyzing the feasible moment sets after propeller failure

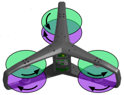




- Origin belongs to the boundary ⇒ **impossible** to compensate for disturbance moments in some directions ⇒ static hovering no longer possible for all propellers

Robustness after Propeller Failure

Y-Shaped Design



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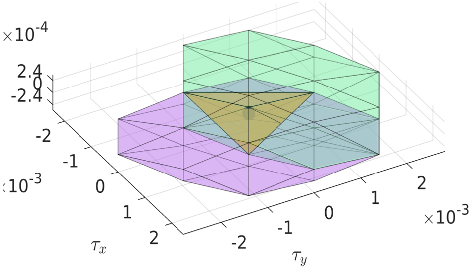
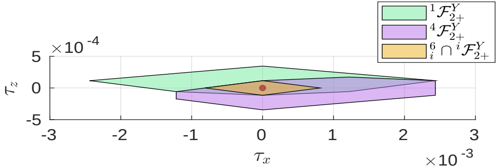
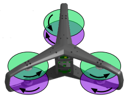




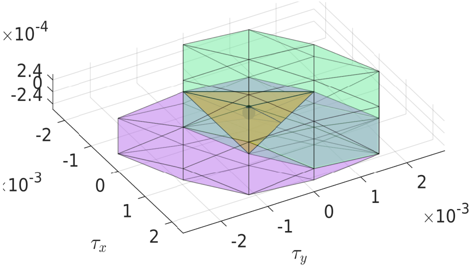
- Interior of Feasible moment sets in case of any propeller loss intersect

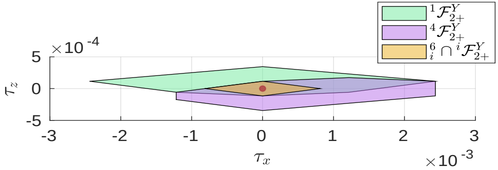
Robustness after Propeller Failure

Y-Shaped Design



Robustness derived analyzing the feasible moment sets after propeller failure





- Origin contained in intersection $\Rightarrow$ **possible** to compensate for disturbance moments in all directions $\Rightarrow$ static hovering still possible for any propeller failure

Effect of Model Uncertainties

Can a Star-shape hexarotor fly?

A platform that cannot hover after a propeller loss, can still hover if an external moment is applied such as:

$$\tau_R^c = -\tau_R^{dist} \in \text{int}({}^k\mathscr{F}_{2+}) \tag{7}$$

However, in the case of a Star-shaped hexarotor, no single moment could render the platform fully robust to propeller failures:

$$\text{int}(\bigcap_k {}^k\mathscr{F}_{2+}^S) = \emptyset \tag{8}$$

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- Nominal Star-shaped hexarotor fully vulnerable to propeller failure
- Real Star-shaped hexarotor partially robust to propeller failure

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Design & Building of Two Prototypes

- Two platforms with similar components and size
- Same actuators and mass (745 [g])
- Cascaded Incremental Nonlinear Dynamic Inversion Controller flies the platforms despite propeller failure

PAPARAZZI
The Free Autopilot

Y-Shaped Hexarotor

Star-Shaped Hexarotor

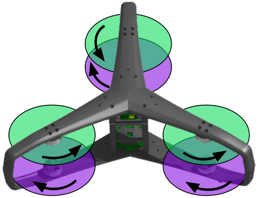
Open source design: https://mrtbrnz.github.io/RoBust/

Static hovering of the two platforms with all propellers functional

Experimental Campaign

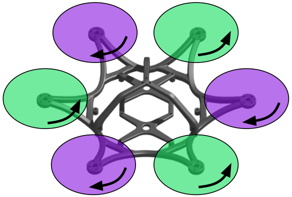
Goal: demonstrate

- Robustness of Y-shaped hexarotor design



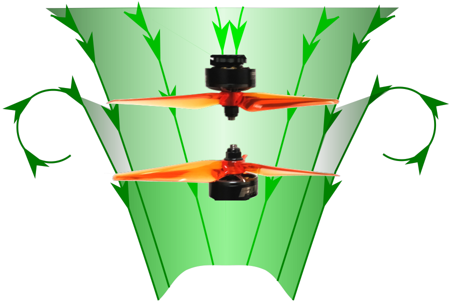
- Possibility of static hovering after the failure of any propeller

- Vulnerability of Star-shaped hexarotor design



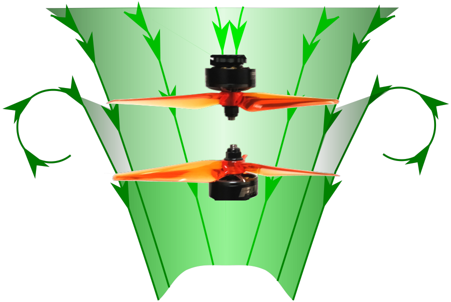
- Impossibility of static hovering after the failure of some propellers

Interaction between coaxial propellers $\Rightarrow$ reduced combined efficiency

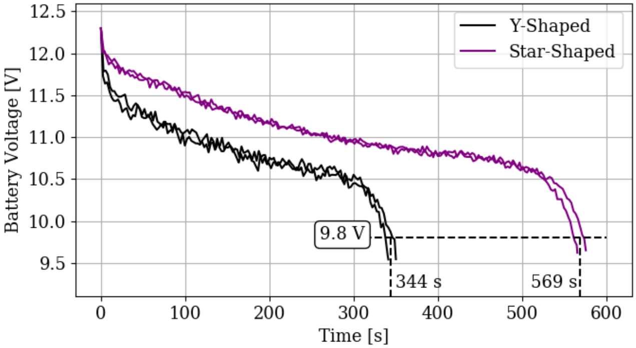


Efficiency Comparison

Interaction between coaxial propellers ⇒ reduced combined efficiency



Voltage decreases faster ⇒ higher demanded current ⇒ less efficient platform



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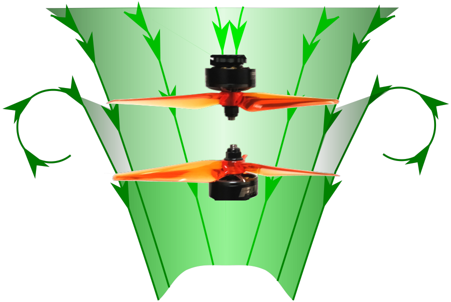

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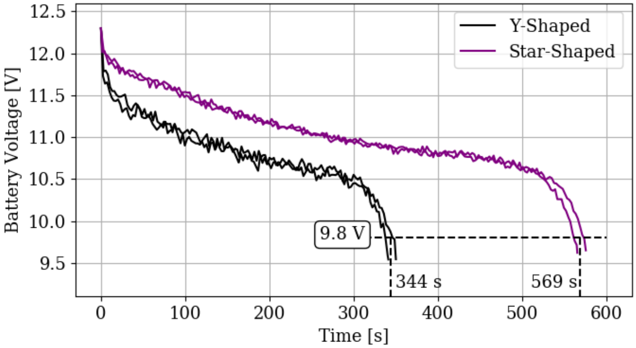

Y-shaped flight time is 60% of Star-shaped flight time

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Conclusion

Summary:

- Analysis of hexarotor robustness to propeller failure
- Extensive experimentation to study Y-shaped and Star-shaped robustness and efficiency

Future Work:

- Novel design with varying configuration between Y-shaped and Star-shaped
- The new design balances robustness of Y-shaped and efficiency of Star-shaped

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⋆ authors contributed equally