



Morphology Optimization of a Tilt-Rotor MAV

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Master Thesis

Supervised by Karen Bodie and Zachary Taylor

Motivation



<https://www.duluthnewstribune.com/news/3849087-mndot-test-bridge-inspecting-drones-duluth>



<http://www.constructionmanagermagazine.com/news/uk-construction-use-thousands-drones-2030/>



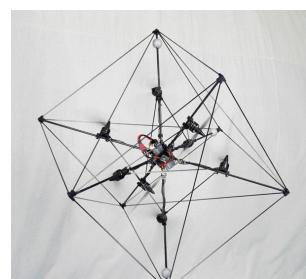
<https://www.duluthnewstribune.com/news/3849087-mndot-test-bridge-inspecting-drones-duluth>

Problem Statement

- Omni-directionality
- Existing omnidirectional MAV have mostly ad hoc designs
- Optimize the design of a MAV with tilting propellers

State of the Art

D. Brescianini and R. D'Andrea, "Design, modeling and control of an omni-directional aerial vehicle," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, May 2016, pp. 3261–3266.



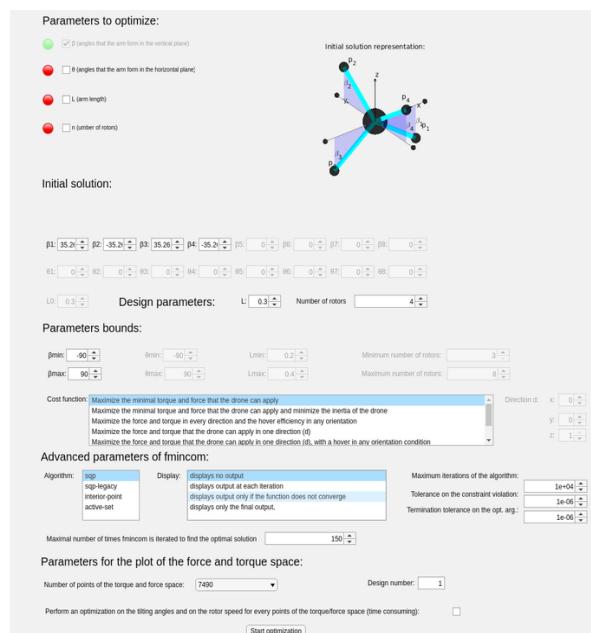
M. Kamel, S. Verling, O. Elkhatib, C. Sprecher, P. Wulkop, Z. Taylor, R. Siegwart, and I. Giliitschenski, "Voliro: An Omnidirectional Hexacopter With Tilttable Rotors," *arXiv:1801.04581 [cs]*, Jan. 2018, arXiv: 1801.04581.

S. Rajappa, M. Ryll, H. H. Bühlhoff, and A. Franchi, "Modeling, control and design optimization for a fully-actuated hexarotor aerial vehicle with tilted propellers," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, May 2015, pp. 4006–4013.



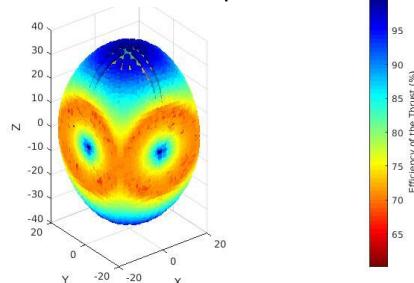
Optimization Tool User Guide

- Choose parameters to optimize
 ↓
 Specify design parameters
 ↓
 Specify an initial solution
 ↓
 Specify a cost function
 ↓
 Launch optimization
 ↓
 Obtain result

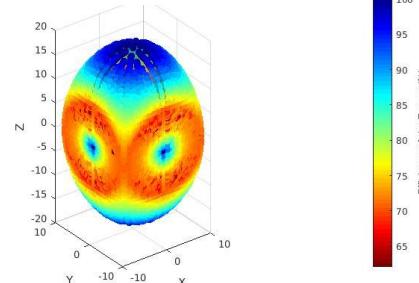


Optimization Tool Output

Reachable Force Space



Reachable Torque Space



Hover Efficiency in every direction

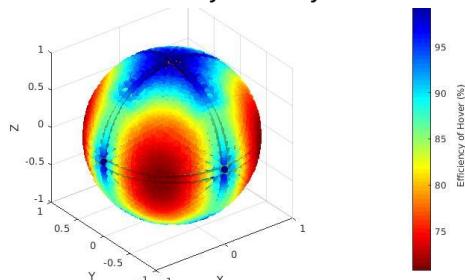
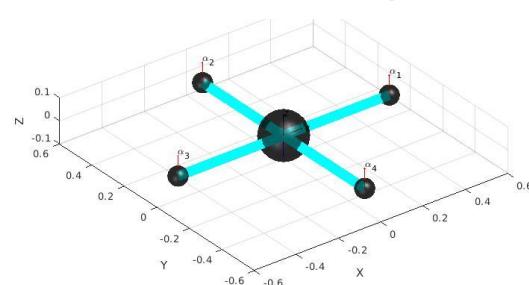


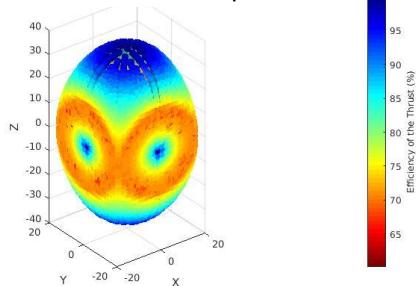
Illustration of the design



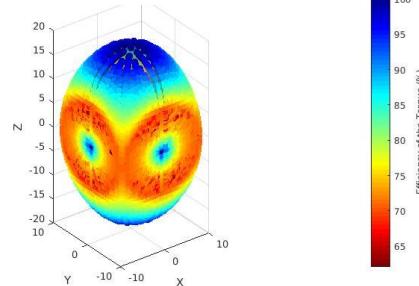
Optimization Tool Output

- Information on the design:
 - Volume of the reachable force and torque space

Reachable Force Space



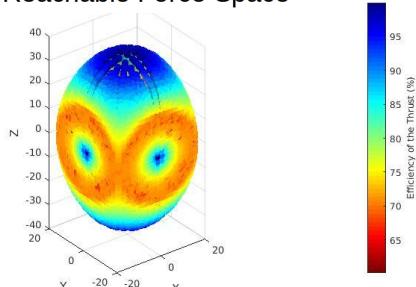
Reachable Torque Space



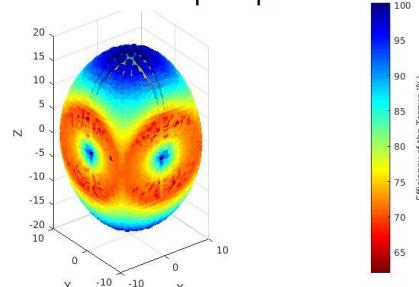
Optimization Tool Output

- Information on the design:
 - Surface of the reachable force and torque space

Reachable Force Space



Reachable Torque Space



Optimization Tool Output

- Information on the design:
 - Maximal and minimal forces and torques
 - Mean of the force, torque and hover efficiency
 - Absolute mean deviation of the force, torque and hover efficiency

MAV Morphology Optimization Tool

- The MAV's design is the result of an optimization problem

$$\min_x f(x) \text{ such that} \begin{cases} c(x) \leq 0 \\ ceq(x) = 0 \\ A \cdot x \leq b \\ Aeq \cdot x = beq \\ lb \leq x \leq ub \end{cases}$$

- The optimisation solved by matlab and an Sequential quadratic programming (sqp) algorithm

Cost functions

- Maximize the minimal force and the minimal torque
- Maximize the force and torque in x, y and z directions
- Maximize the volume of the reachable force and torque space
- Maximize the force, the torque and the hover efficiency in every direction
- Maximize the force and the torque in one defined direction d

Limitations

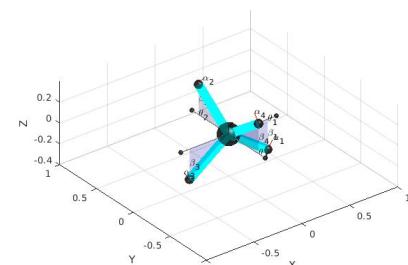
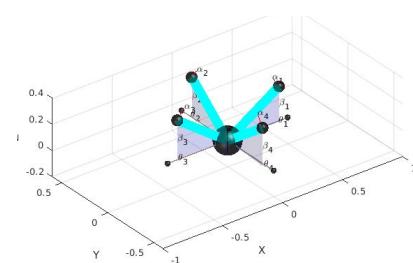
- Non-linear cost functions
- Algorithm provide local minima
- Solution strongly dependent on the initial solution
- The more parameter to optimize the more it get stuck in local optima

Results

- Drone design found for differ

Results

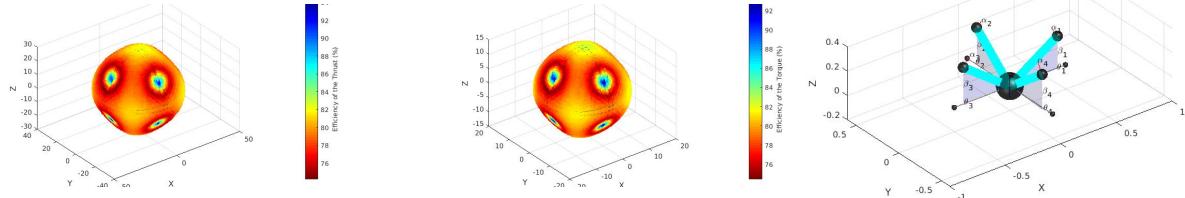
- Quad-copter
 - Starting as with $\beta_0 = [0, 0, 0, 0]$
 - Solution $\beta = [-32.42, -35.49, -35.44, -35.49]$
 - Starting with $\beta_0 = [35.26, -35.26, 35.26, -35.26]$
 - Solution $\beta = [35.26, -35.26, 35.26, -35.26]$



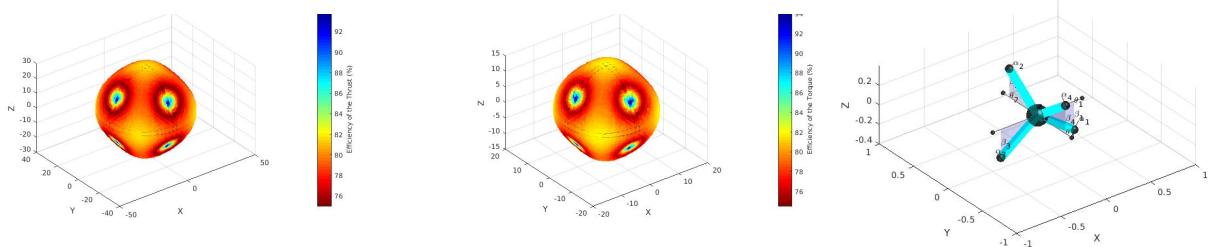
Results

- Quad-copter

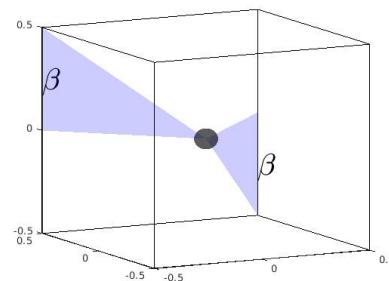
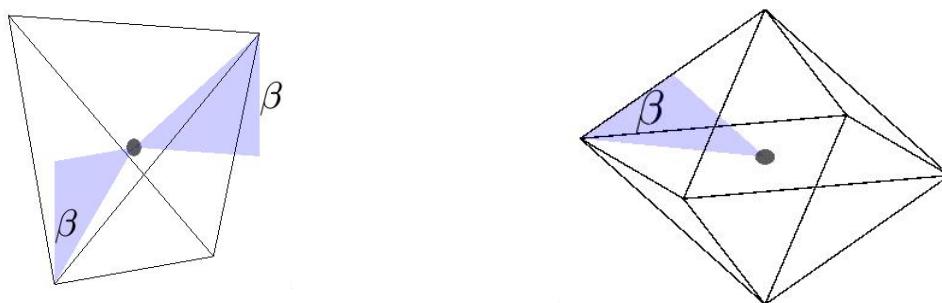
Design 1: $F_{min} = 23.18, F_{max} = 28.56, M_{min} = 11.61, M_{max} = 14.3, H_{eff,min} = 81.11\%, H_{eff,max} = 95.2\%$



Design 2: $F_{min} = 23.22, F_{max} = 28.37, M_{min} = 11.65, M_{max} = 14.23, H_{eff,min} = 81.65\%, H_{eff,max} = 94.73\%$



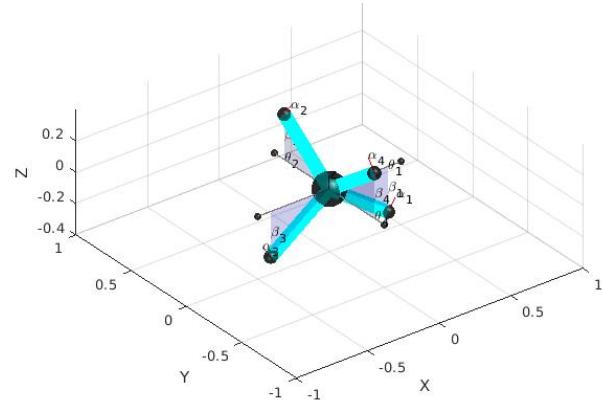
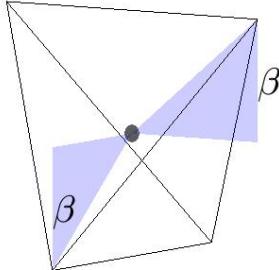
Platonic solids and Tetrahedron angle



$$\cos(\beta) = \sqrt{\left(\frac{2}{3}\right)} \Rightarrow \beta = 35.26^\circ$$

Results

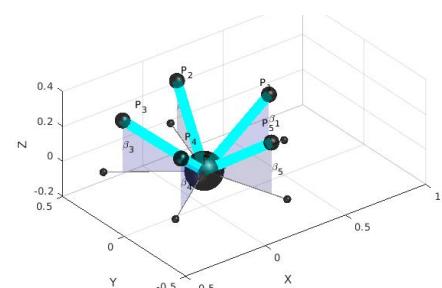
- Quad-copter



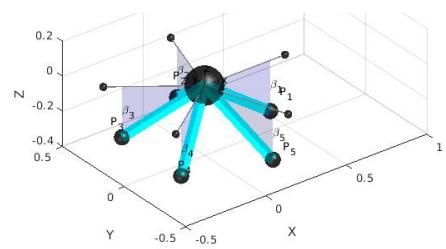
Results

- Penta-copter

- Starting with $\beta_0 = [0, 0, 0, 0, 0]$
 - Solution $\beta = [-36, -36, -36, -36, -36]$



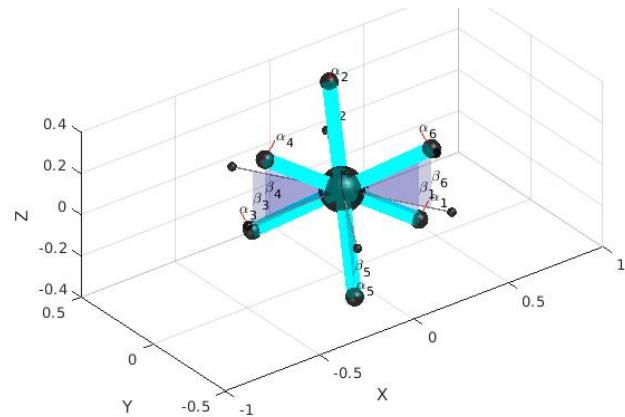
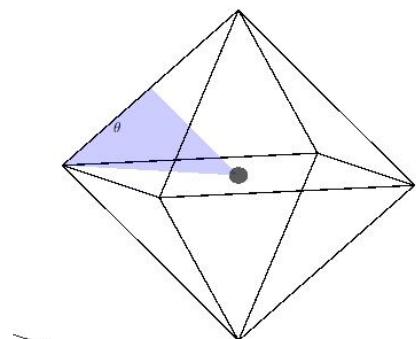
- Starting with $\beta_0 = [35.26, 35.26, 35.26, 35.26, 35.26]$
 - Solution $\beta = [35.26, 35.26, 35.26, 35.26]$



Results

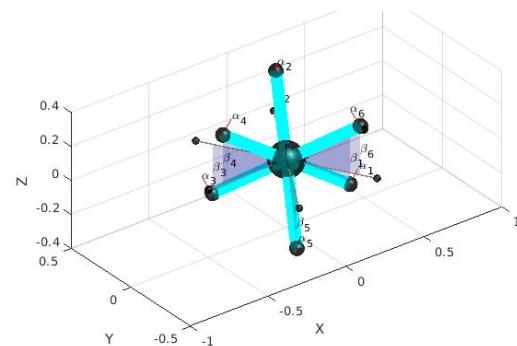
- Hexa-copter

- Solution $\beta = [35.26, -35.26, -35.26, 35.26, -35.26, 35.26]$



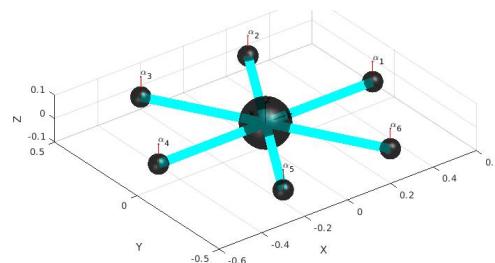
Results

- Hexa-copter



$F_{min} = 34.74, F_{max} = 42.55, M_{min} = 17.42, M_{max} = 21.34, H_{eff,min} = 81.65\%, H_{eff,max} = 100\%$

- Voliro

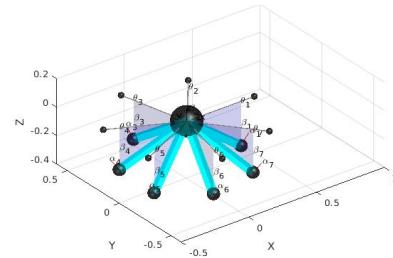
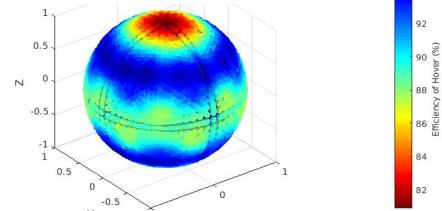


$F_{min} = 26.6, F_{max} = 52.11, M_{min} = 15.1, M_{max} = 26.13, H_{eff,min} = 75\%, H_{eff,max} = 100\%$

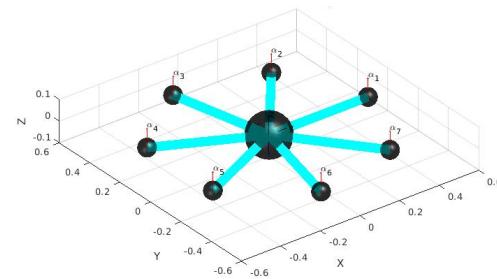
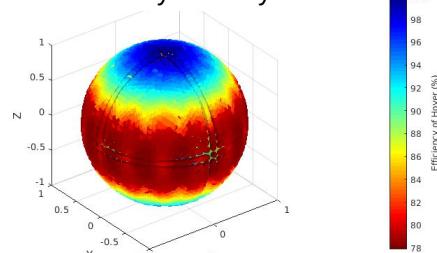
Results

- Hepta-copter

Hover Efficiency in every direction

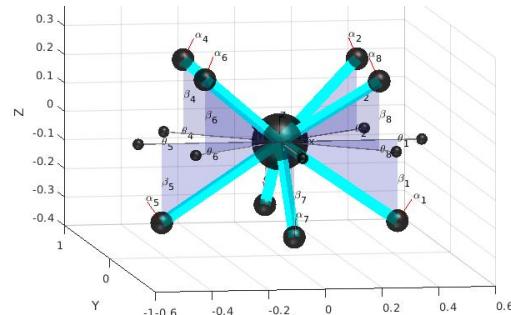


Hover Efficiency in every direction



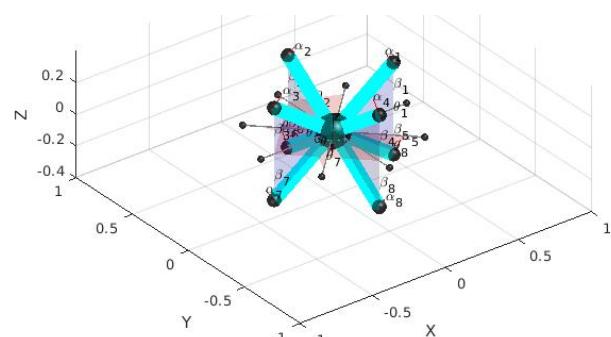
Results

- Octa-copter



$$F_{min} = 44.7, F_{max} = 58.8, M_{min} = 22.4, M_{max} = 29.5, H_{eff,min} = 81.78\%, H_{eff,max} = 96.65\%$$

- IDSC's Omnicopter



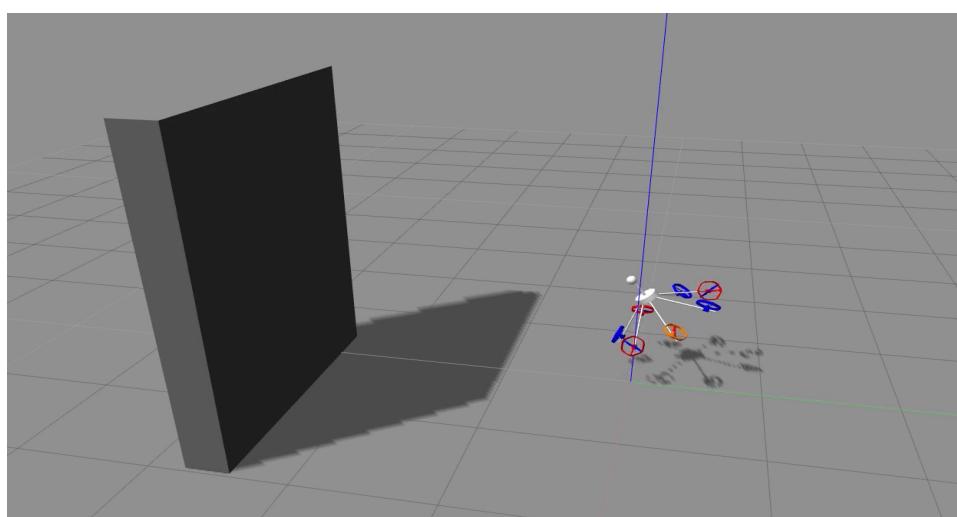
$$F_{min} = 46.46, F_{max} = 56.73, M_{min} = 23.3, M_{max} = 28.45, H_{eff,min} = 81.64\%, H_{eff,max} = 94.77\%$$

Results

- Comparison

Simulation

- Hepta-copter interaction with a wall



Conclusion

- Developped a design optimization tool

Parameters to optimize:

- β angles that the arm form in the vertical plane
- θ angles that the arm form in the horizontal plane
- L (arm length)
- n (number of rotors)

Initial solution representation:

Initial solution:

p1: 35.21°	p2: -35.26°	p3: 35.26°	p4: -35.21°	p5: 0°	p6: 0°	p7: 0°	p8: 0°
θ1: 0°	θ2: 0°	θ3: 0°	θ4: 0°	θ5: 0°	θ6: 0°	θ7: 0°	θ8: 0°
L: 0.3	Design parameters: L: 0.3		Number of rotors: 4				

Parameters bounds:

θmin: -90°	θmax: 90°	Lmin: 0.2	Lmax: 0.4	Minimum number of rotors: 3	Maximum number of rotors: 8
θmin: -90°	θmax: 90°	Lmin: 0.1	Lmax: 0.4	Minimum number of rotors: 3	Maximum number of rotors: 8

Cost function:

- Maximize the minimal torque and force that the drone can apply
- Maximize the minimal force and torque that the drone can apply and minimize the inertia of the drone
- Maximize the force and torque in every direction and the hover efficiency in any orientation
- Maximize the force and torque that the drone can apply in one direction (θ_i)
- Maximize the force and torque that the drone can apply in one direction (θ_i), with a hover in any orientation condition

Direction d: x: 0°, y: 0°, z: 1°

Advanced parameters of fmincon:

Algorithm: sqp	Display: displays no output	Maximum iterations of the algorithm: 1e+04
sqp-legacy	displays output at each iteration	Tolerance on the constraint violation: 1e-06
interior-point	displays output only if the function does not converge	Termination tolerance on the opt. arg.: 1e-06
active-set	displays only the final output,	

Number of points in the torque and force space: 7490

Start optimization

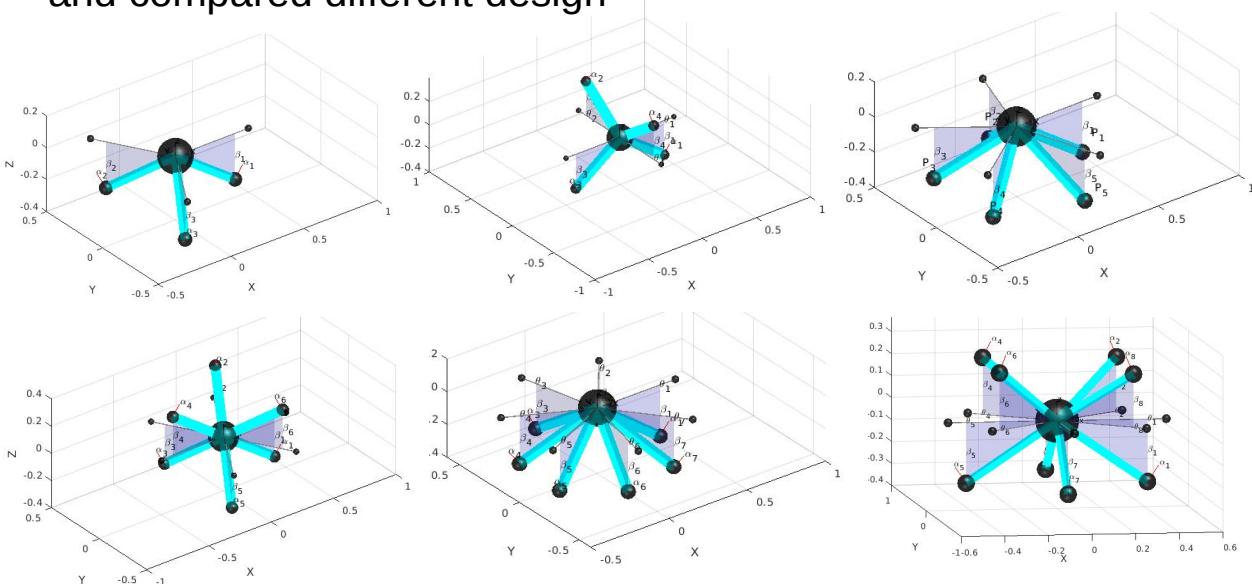
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Conclusion

- Obtained results using different cost functions and parameters and compared different design



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Conclusion

- Simulated some of the results in ROS environment

Outlook

- Improvement to the project
- Further development

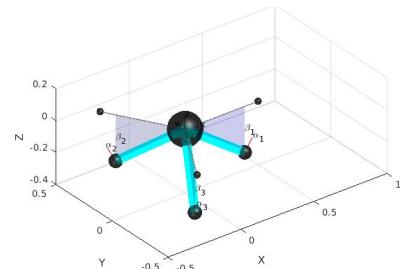
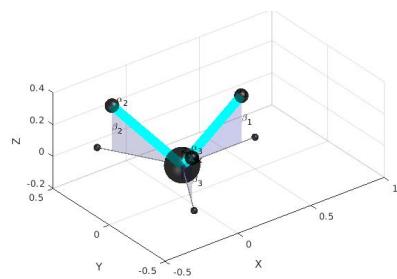
Thank you for your attention !

Questions ?



Supplementary Slides

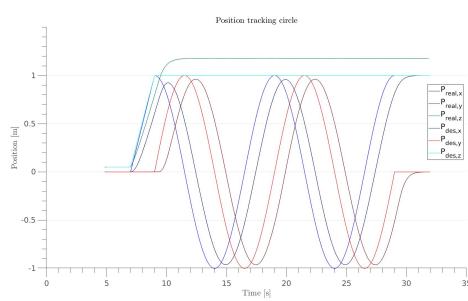
- Tri-copter
 - Starting optimization $\beta_0 = [0, 0, 0]$
 - Solution $\beta = [-35.81, -34.32, -34.35]$
 - Solution with $\beta_0 = [35.26, 35.26, 35.26]$
 - Solution $\beta = [35.26, 35.26, 35.26]$



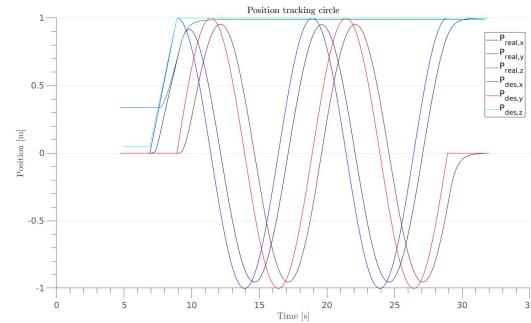
Supplementary Slides

- Position tracking: circle

Voliro



Hexa-copter



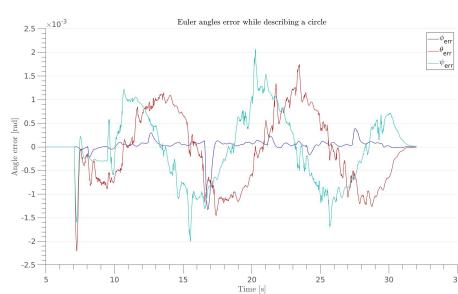
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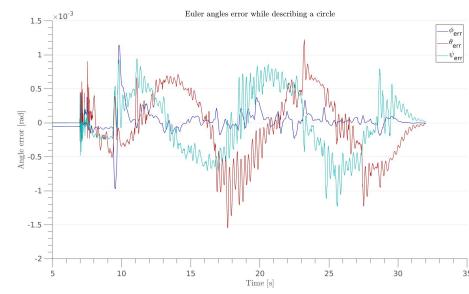
Supplementary Slides

- Angle error while describing a circle

Voliro



Hexa-copter



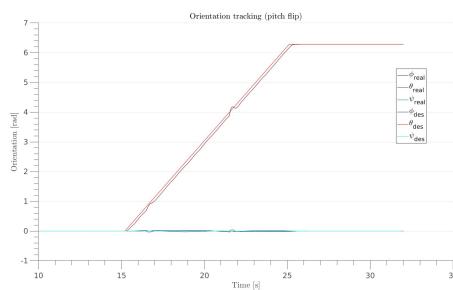
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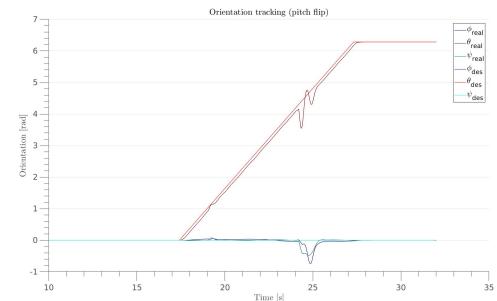
Supplementary Slides

- Orientation tracking: Pitch flip

Voliro



Hexa-copter



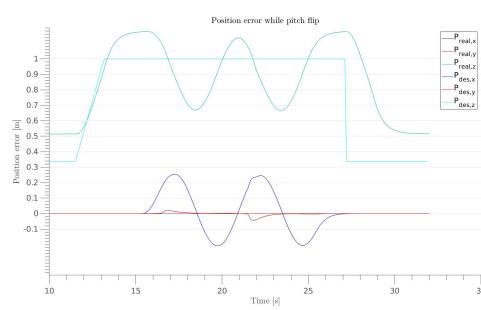
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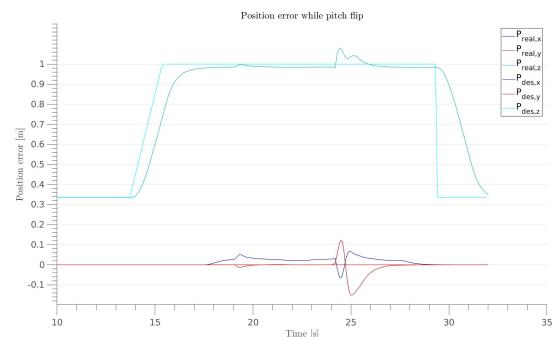
Supplementary Slides

- Position error while doing a pitch

Voliro



Hexa-copter



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