ETH zürich

Morphology Optimization of a Tilt-Rotor MAV

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Master Thesis
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Autonomous Systems Lab

Motivation

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

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

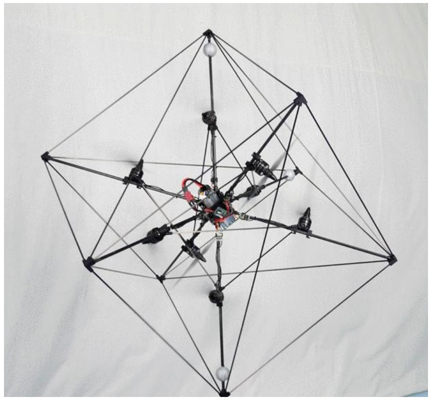
https://www.duluthnewstribune.com/news/3849087-mndot-test-bridge-inspecting-drones-duluth

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 omnidirectional 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. Gilitschenski, "Voliro: An Omnidirectional Hexacopter With Tiltable Rotors," *arXiv:1801.04581 [cs]*, Jan. 2018, arXiv: 1801.04581.

S. Rajappa, M. Ryll, H. H. Bülthoff, 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

↓

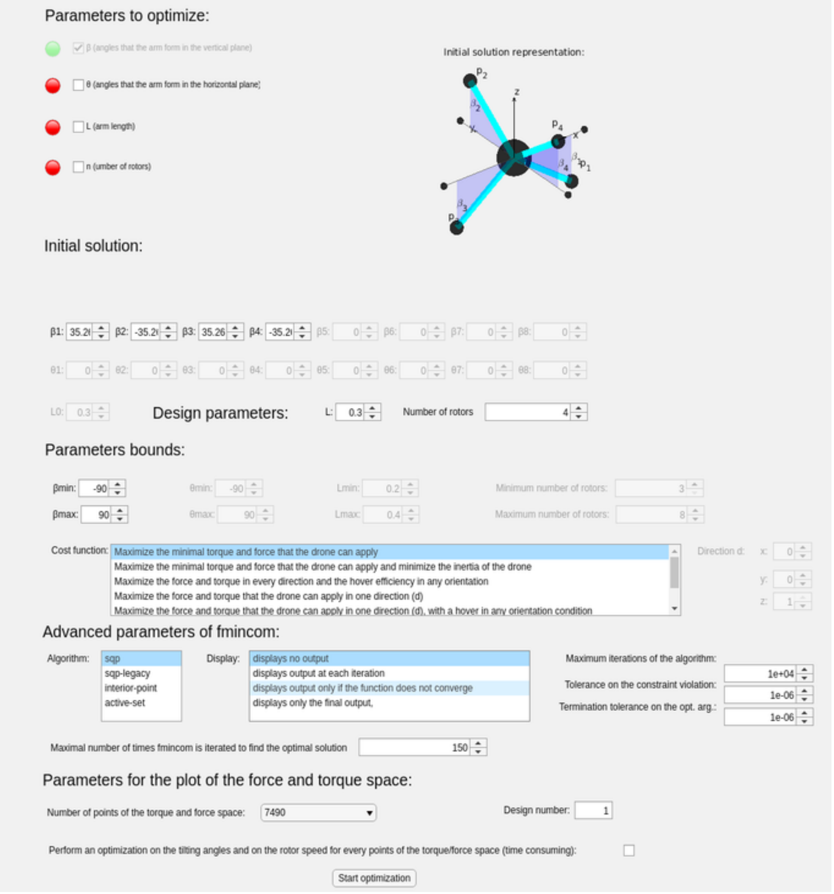
Specify a cost function

↓

Launch optimization

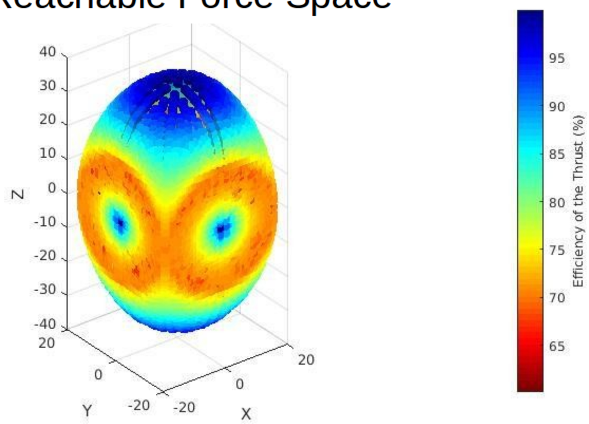
↓

Obtain result

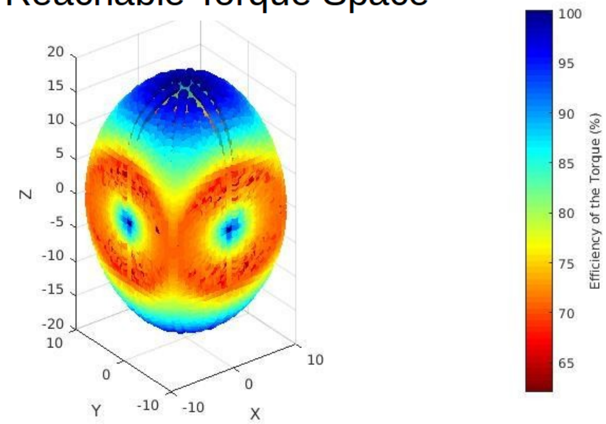


Optimization Tool Output

Reachable Force Space



Reachable Torque Space



Hover Efficiency in every direction

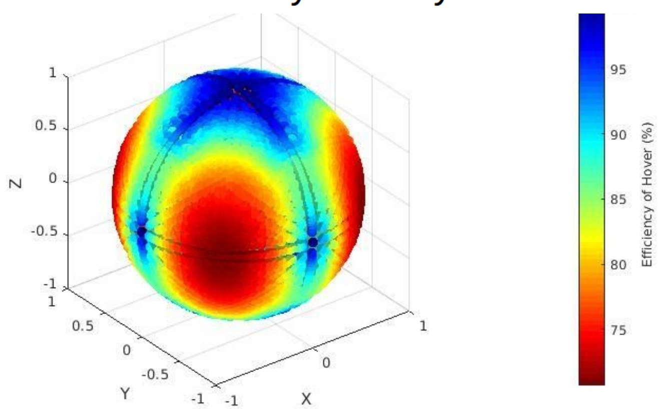
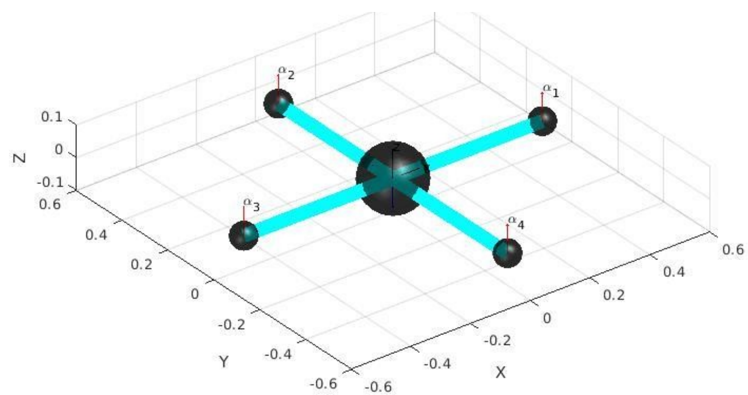
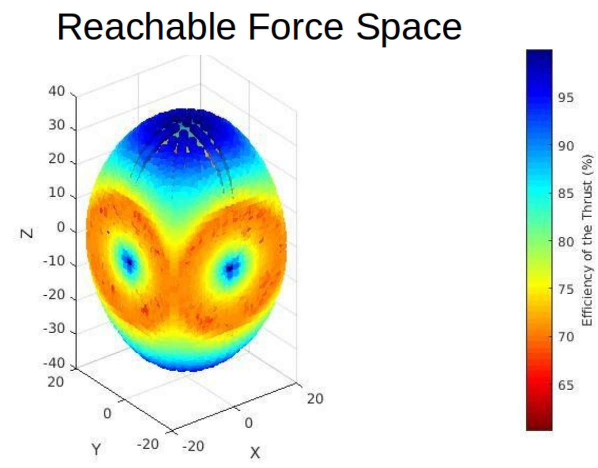


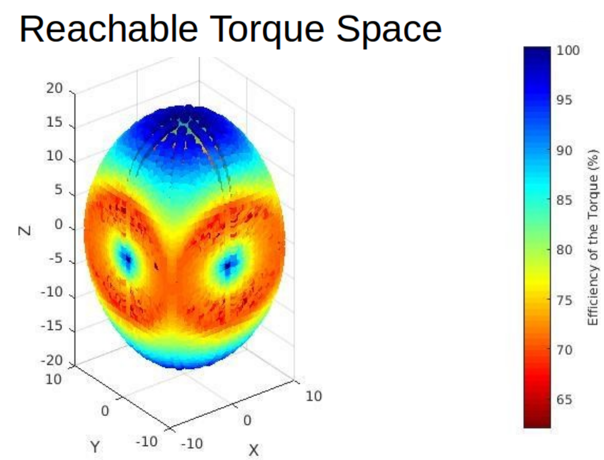
Illustration of the design



Optimization Tool Output

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

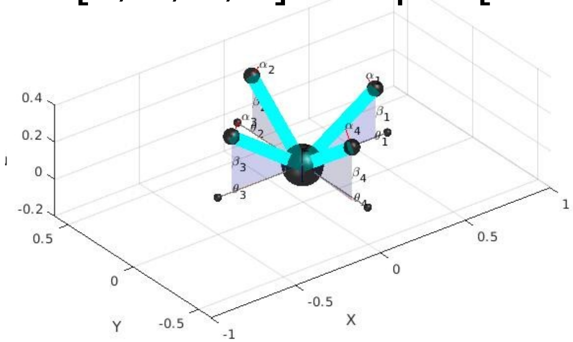
- Non-linear cost functions
- Algorithm provides local minima
- Solution dependent on the chosen initial solution
- The more parameters to optimize the more it gets stuck in local optima

Results

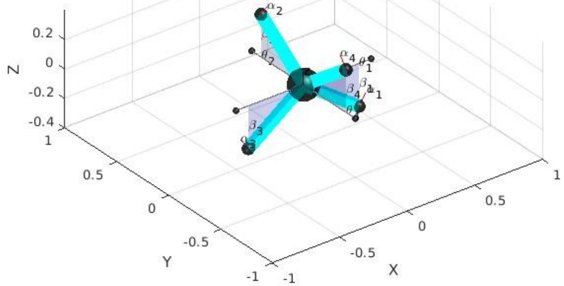
- Drone design obtained for different numbers of propellers
  - Three propellers → Tri-copter
  - Four propellers → Quad-copter
  - Five propellers → Penta-copter
  - Six propellers → Hexa-copter
  - Seven propellers → Hepta-copter
  - Eight propellers → Octa-copter

Results

- Quad-copter
  - Maximizing the minimal force and torque
  - Starting as with β0 = [0, 0, 0, 0] ⟶ β = [-32.42, -35.49, -35.44, -35.49]



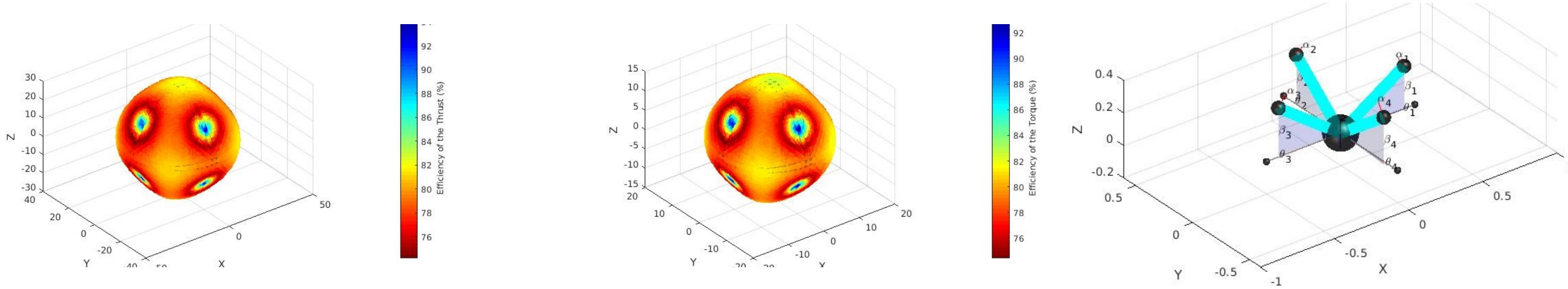
  - Starting with β0 = [35.26, -35.26, 35.26, -35.26] ⟶ β = [35.26, -35.26, 35.26, -35.26]



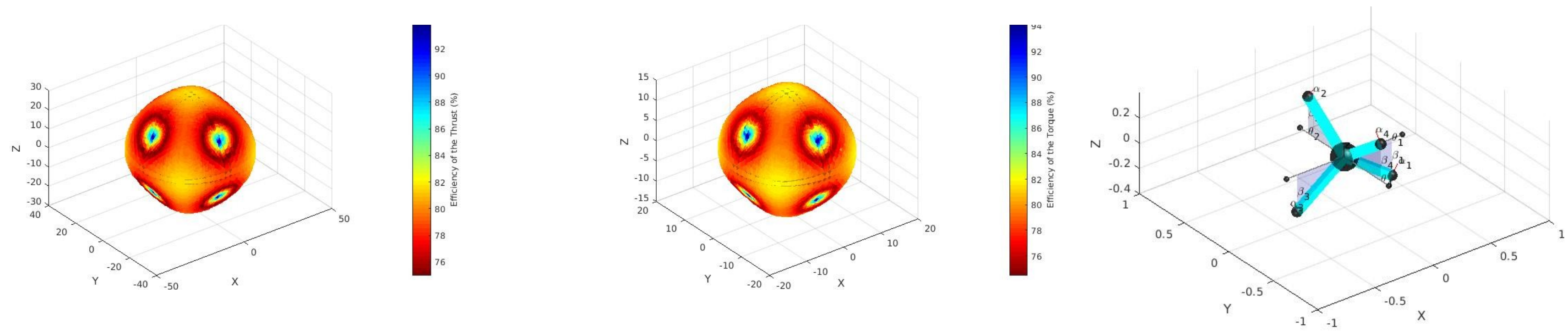
Results

- Quad-copter

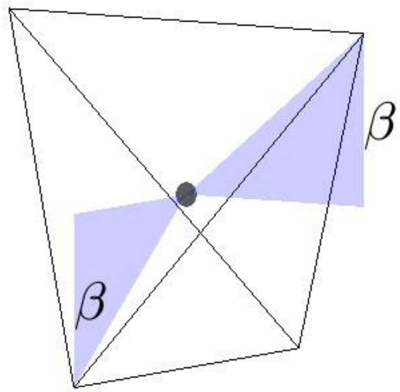
Design 1: $F_{min} = 23.18, F_{max} = 28.56, M_{min} = 11.61, M_{max} = 14.3, H_{eff,min} = 81.11\%, H_{eff,max} = 95.2\%$

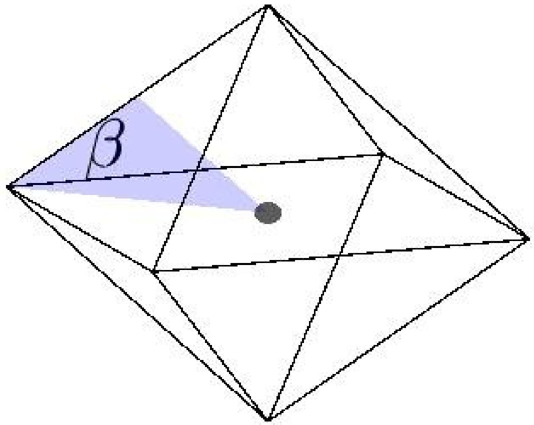


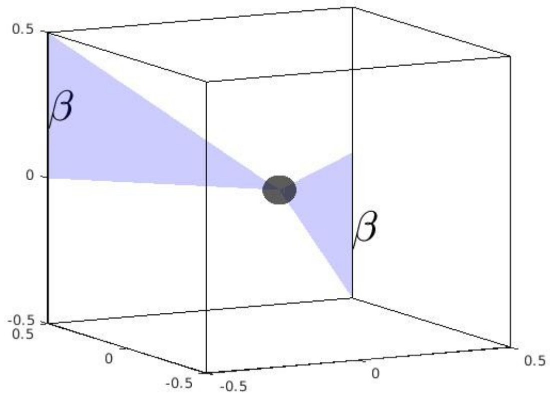
Design 2: $F_{min} = 23.22, F_{max} = 28.37, M_{min} = 11.65, M_{max} = 14.23, H_{eff,min} = 81.65\%, H_{eff,max} = 94.73\%$



Platonic solids and Tetrahedron angle



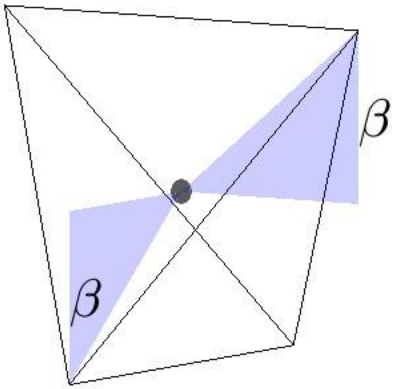


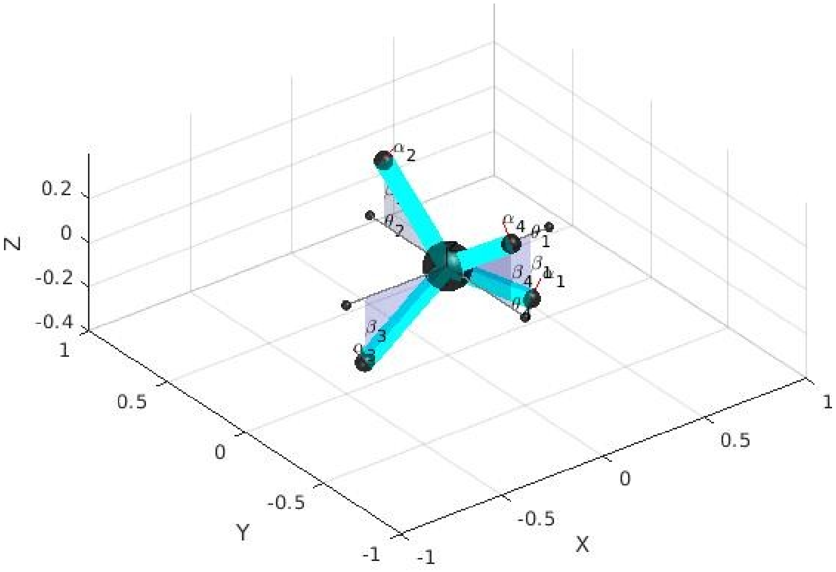


$$\cos(\beta) = \sqrt{\left(\frac{2}{3}\right)} => \beta = 35.26°$$

Results

- Quad-copter

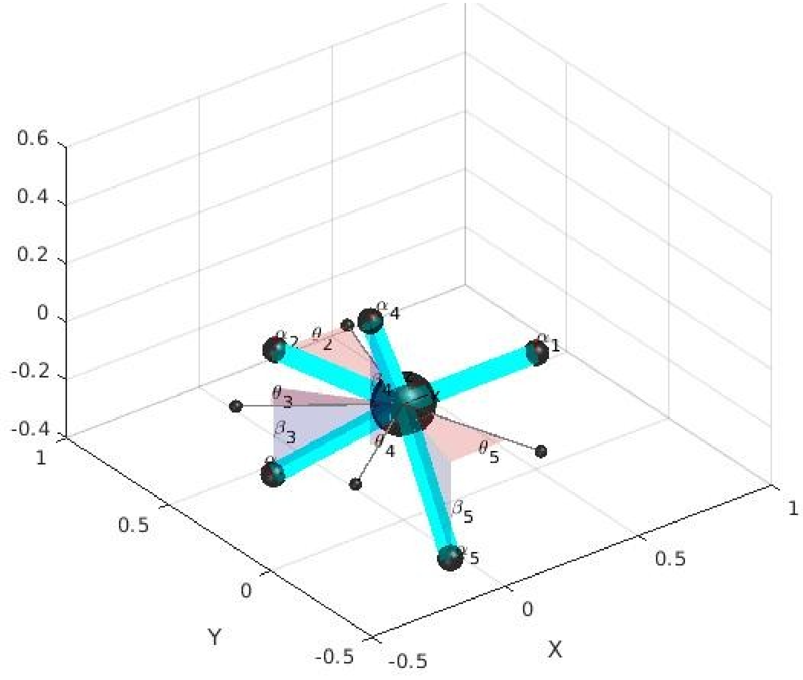




Results

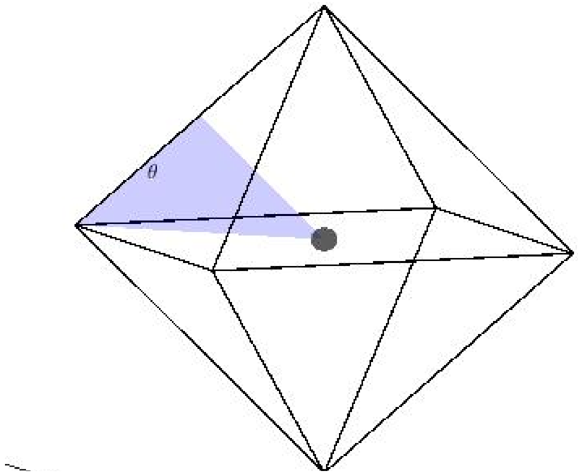
- Penta-copter
  - Maximizing the minimal force and torque and minimzing the drone inertia
  - Starting with β0 = [0, 0, 0, 0, 0]

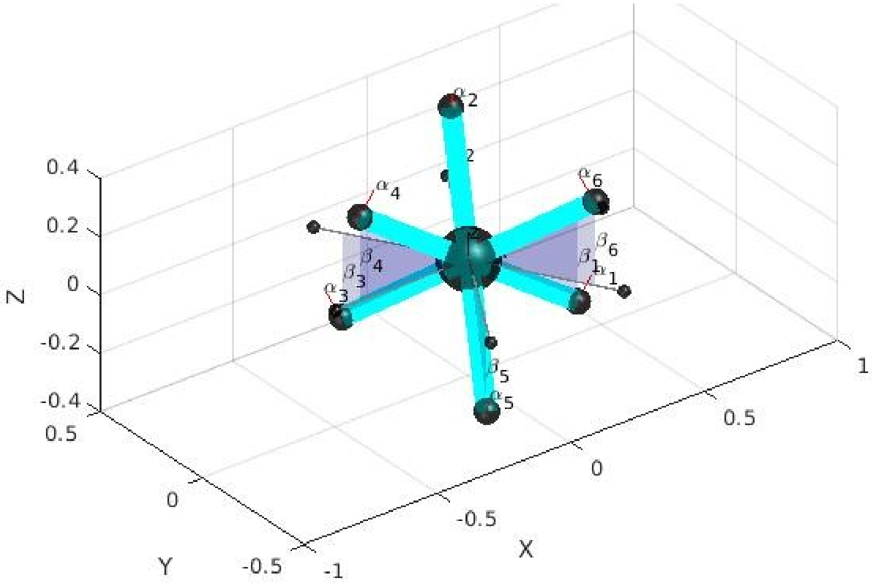
Solution β = [0, 0, 36.9, -58.4, -41.5]



Results

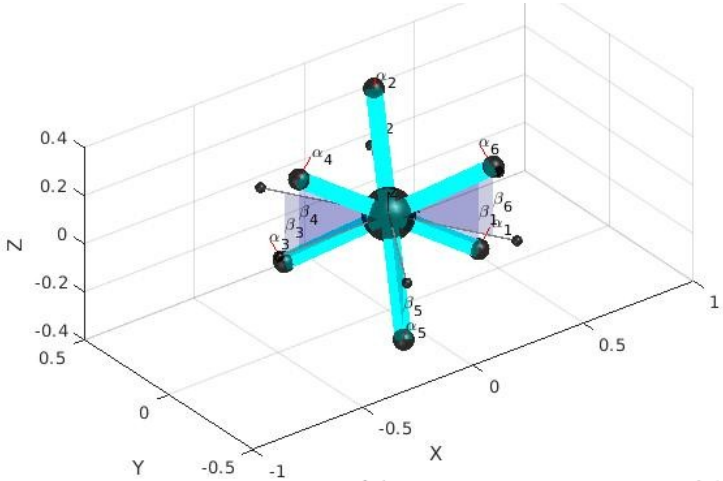
- Hexa-copter
  - Solution β = [35.26, -35.26, -35.26, 35.26,-35.26, 35.26]





Results

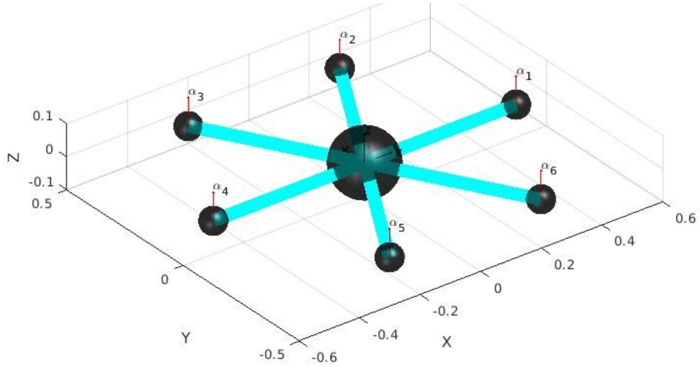
- Hexa-copter



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

  - Obtained maximizing the volumes of the force and torque spaces

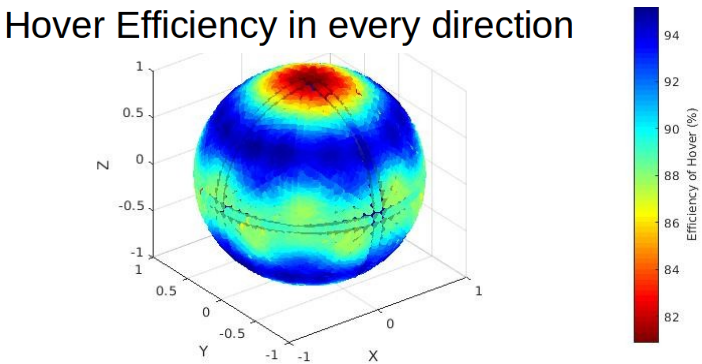
- Voliro

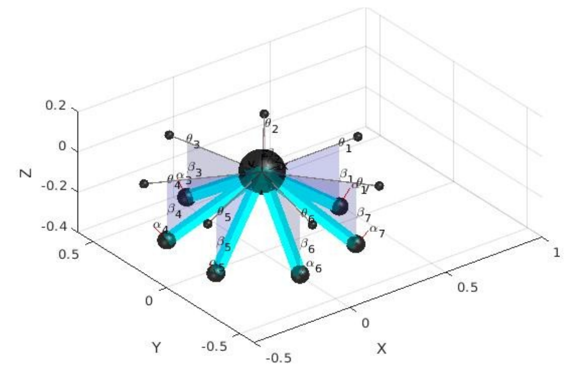


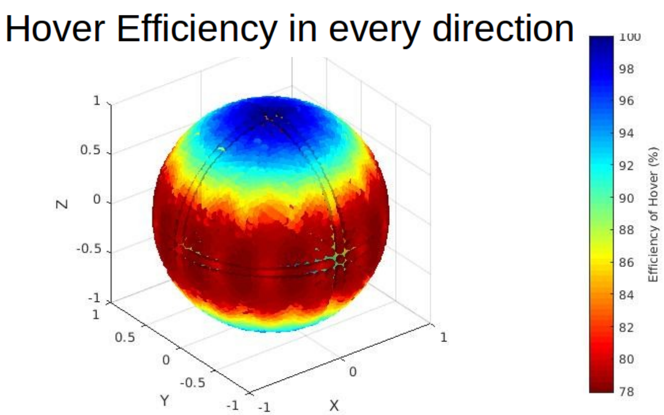
$$F_{min} = 26.6, F_{max} = 52.11, M_{min} = 15.1, M_{max} = 26.13, H_{eff,min} = 75\%, H_{eff,max} = 100\%$$

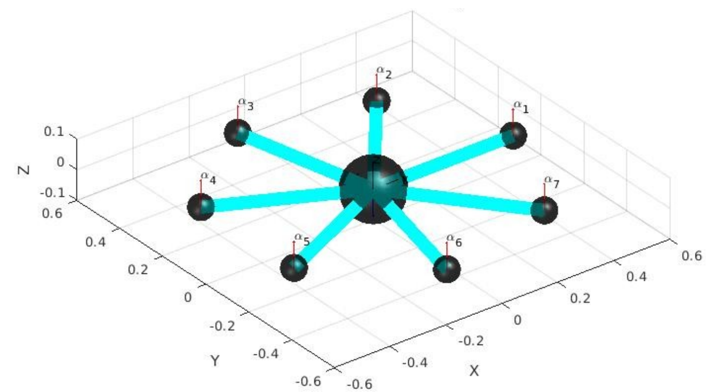
Results

- Hepta-copter



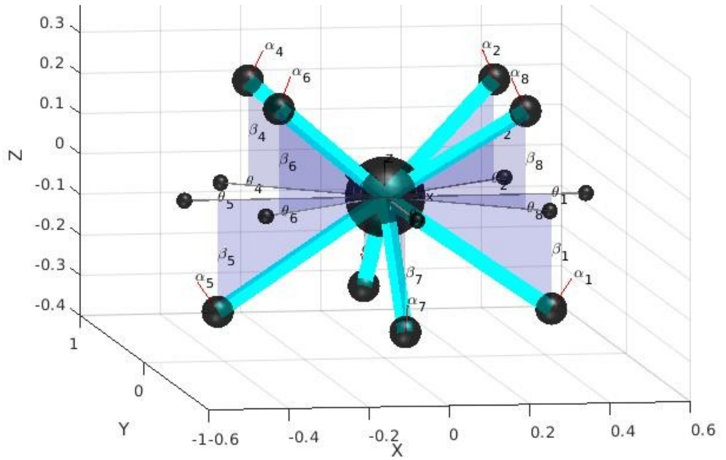






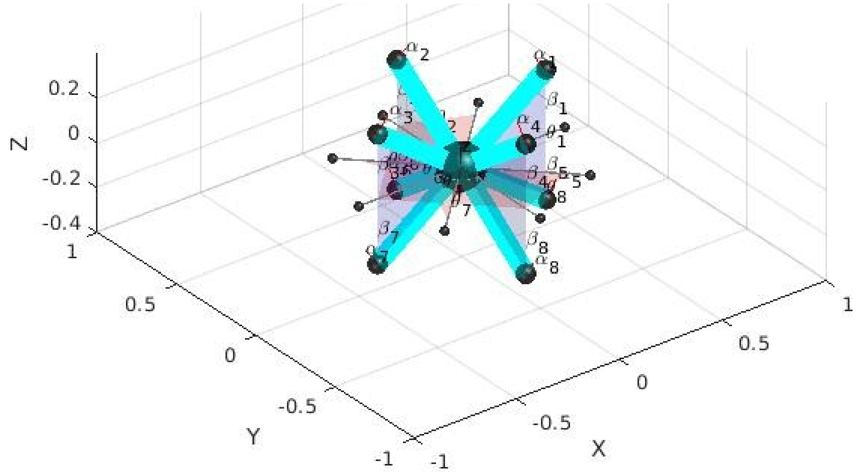
Results

- 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



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

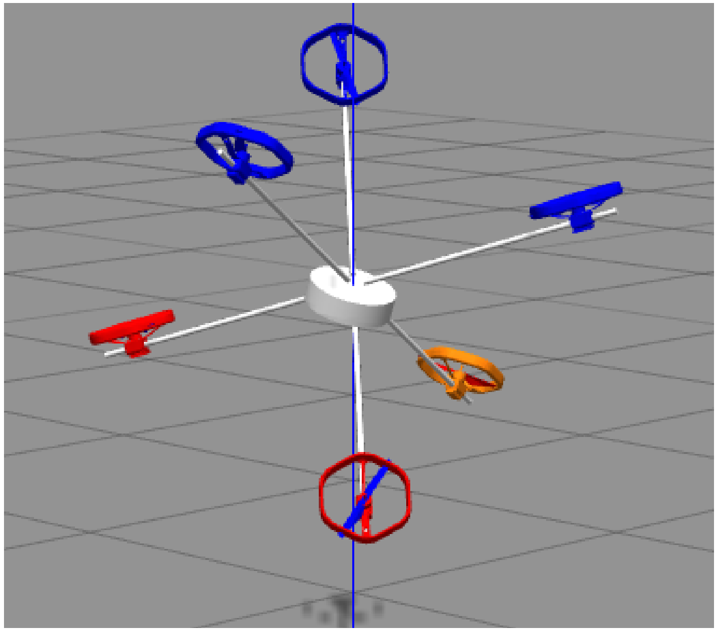
Results

- Comparison

MAV Design	$F_{min}[N]$	$F_{max}[N]$	$F_{mean}[N]$	$M_{min}[Nm]$	$M_{max}[Nm]$	$M_{mean}[Nm]$	$H_{eff,mean}[\%]$
Tri-copter	17.17	21.21	17.95	8.61	10.64	9	85.46
Quad-copter	23.22	28.37	26.87	11.65	14.23	13.47	87.1
Penta-copter	28.95	35.46	29.4	14.52	17.78	14.74	85.35
Hexa-copter	34.74	42.55	39.52	17.42	21.34	19.82	88.9
Hepta-copter	39.96	49.44	47.2	20.04	24.8	23.66	91.1
Octa-copter	44.7	58.8	53.95	22.4	29.48	27.06	91.42

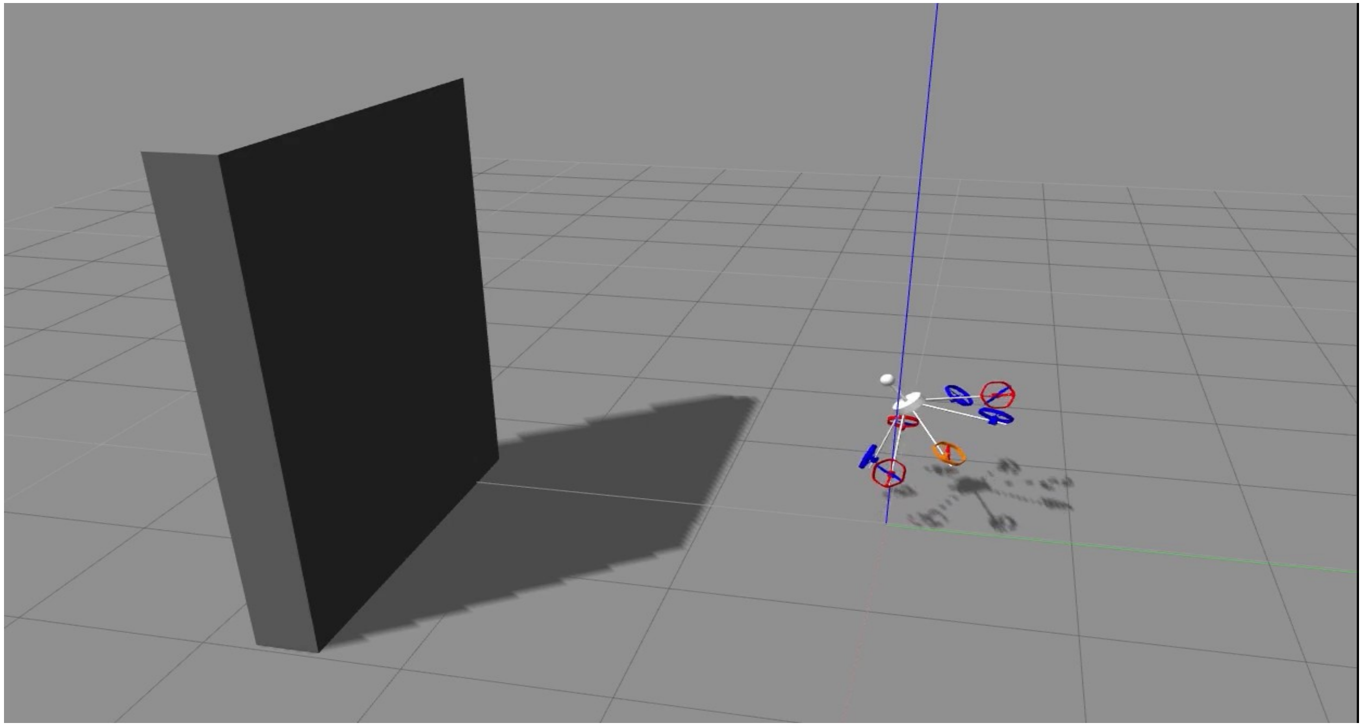
Simulation

- Simulated different model in ROS to test them



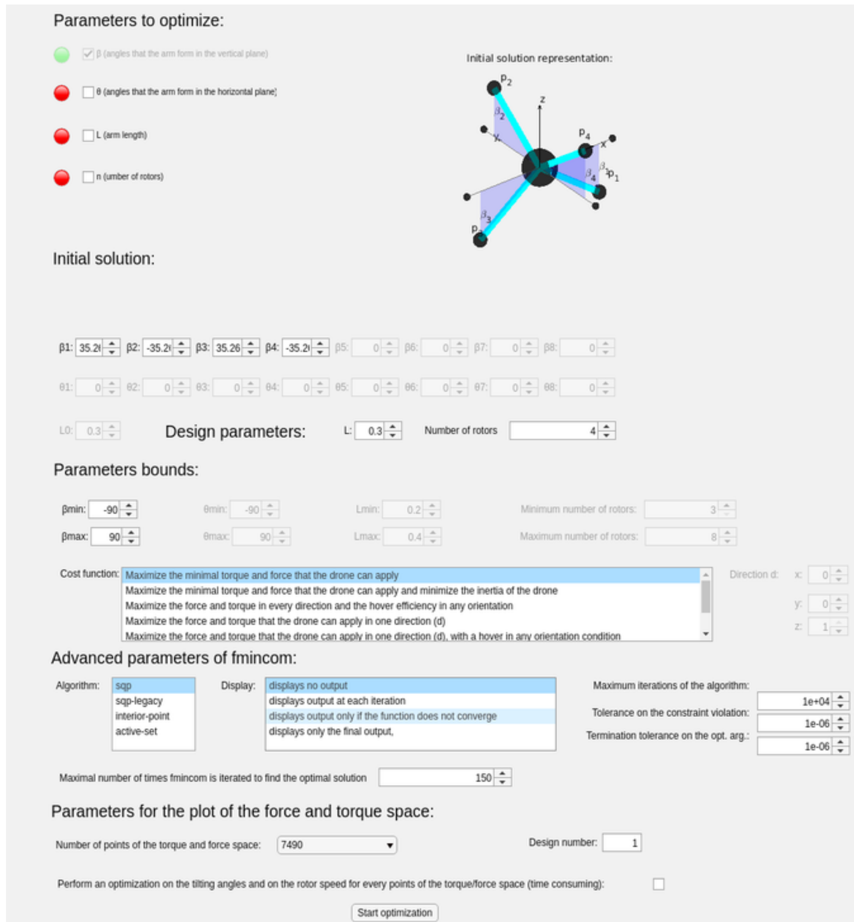
Simulation

- Hepta-copter interaction with a wall



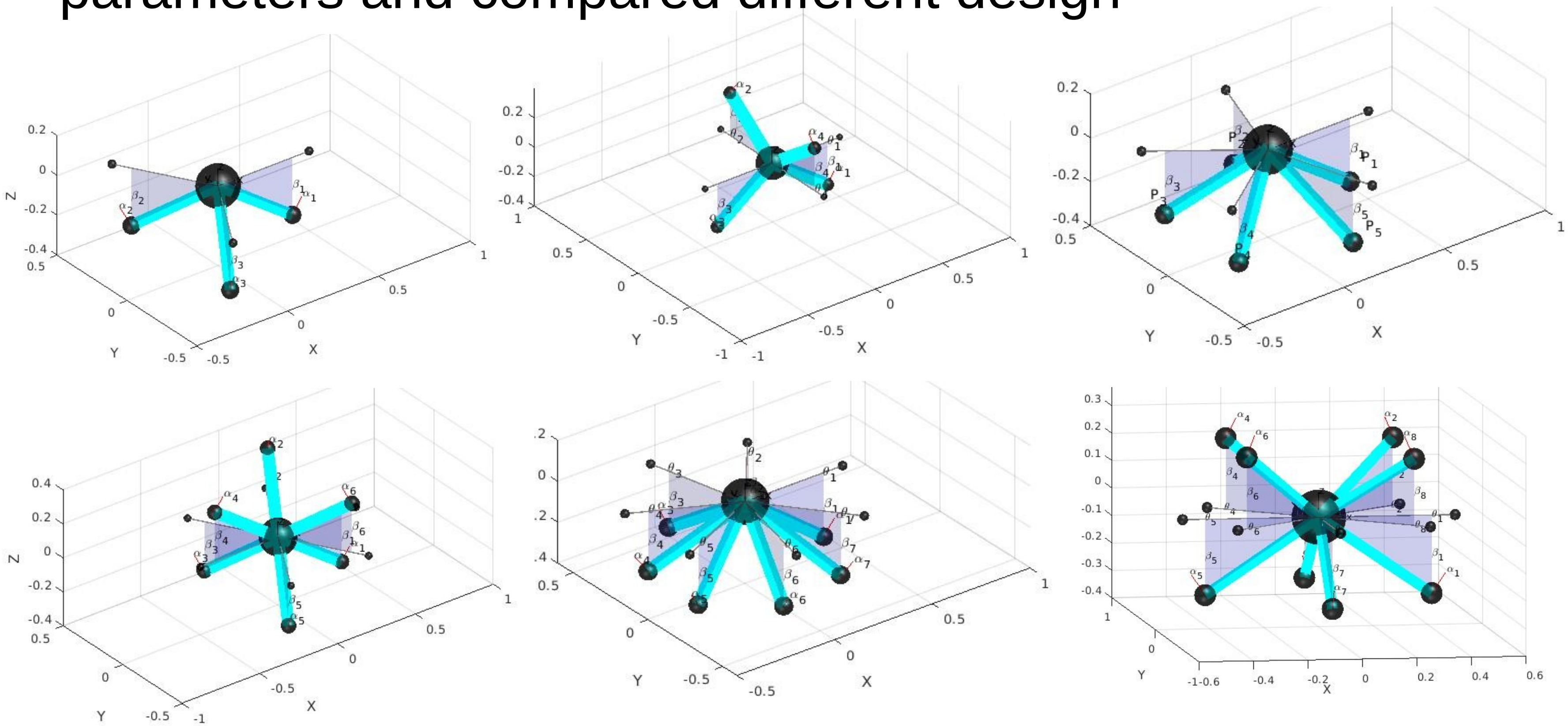
Conclusion

- Developped a design optimization tool



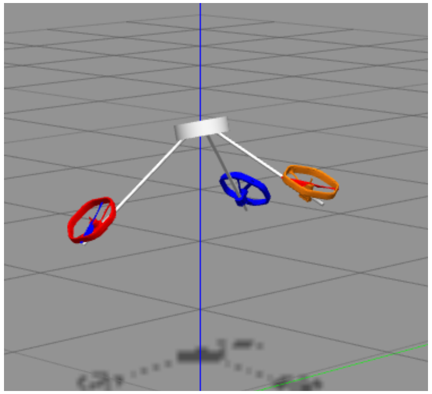
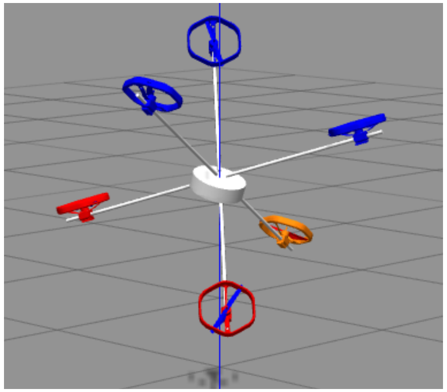
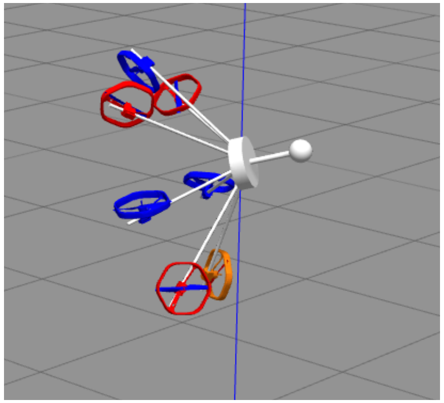
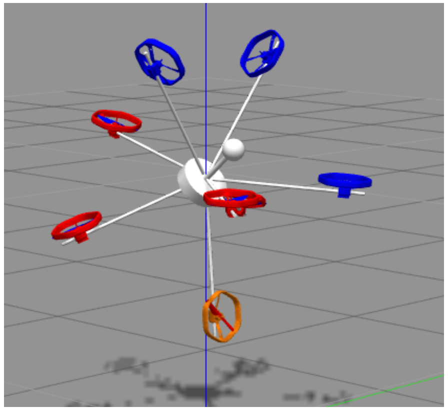
Conclusion

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



Conclusion

- Simulated some of the results in ROS environment

Outlook

- Improvement to the project

- Further development

Thank you for your attention !

Questions ?

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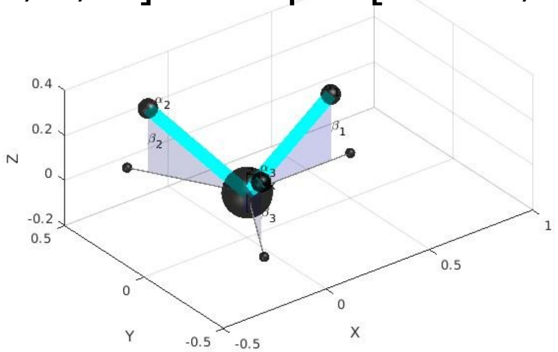
Suplementary Slides

- Quad-copter
  - Maximizing the minimal force and torque
  - Starting as with β0 = [0, 0, 0] ⟶ β = [-32.42, -35.49, -35.44, -35.49]



  - Starting with β0 = [35.26, -35.26, 35.26, -35.26] ⟶ β = [35.26, -35.26, 35.26, -35.26]