



# Morphology Optimization of a Tilt-Rotor MAV

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Master Thesis performed at the Autonomous System Lab

Supervised by Karen Bodie and Zachary Taylor



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>



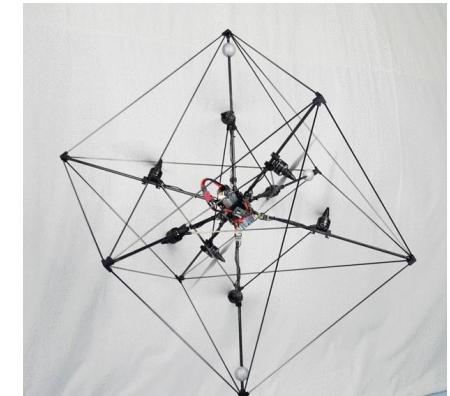
# State of the Art

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. Elkhattib, C. Sprecher, P. Wulkop, Z. Taylor, R. Siegwart, and I. Gilitschenski, "Voliro: An Omnidirectional Hexacopter With Tilttable Rotors," *arXiv:1801.04581 [cs]*, Jan. 2018, arXiv: 1801.04581.

S. Rajappa, M. Ryll, H. H. Bülfhoff, 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.



# Problem Statement

- Design of a micro aerial vehicle (MAV) with tilting propellers as a result of an optimization problem
  - Omnidirectionality
  - Flight efficiency
  - Controlability



# Optimization Tool User Guide

Choose parameters to optimize



Specify design parameters



Specify an initial solution



Specify a cost function



Launch optimization



Obtain result

**Parameters to optimize:**

- $\beta$  (angles that the arm form in the vertical plane)
- $\theta$  (angles that the arm form in the horizontal plane)
- $L$  (arm length)
- $n$  (number of rotors)

**Initial solution representation:**

**Initial solution:**

$\beta_1: 35.2^\circ$	$\beta_2: -35.2^\circ$	$\beta_3: 35.26^\circ$	$\beta_4: -35.21^\circ$	$\beta_5: 0^\circ$	$\beta_6: 0^\circ$	$\beta_7: 0^\circ$	$\beta_8: 0^\circ$
$\theta_1: 0^\circ$	$\theta_2: 0^\circ$	$\theta_3: 0^\circ$	$\theta_4: 0^\circ$	$\theta_5: 0^\circ$	$\theta_6: 0^\circ$	$\theta_7: 0^\circ$	$\theta_8: 0^\circ$
$L: 0.3 \text{ m}$	<b>Design parameters:</b>						
	$L: 0.3 \text{ m}$	<b>Number of rotors:</b>		$4 \frac{1}{2}$			

**Parameters bounds:**

$\beta_{\min}: -90^\circ$	$\theta_{\min}: -90^\circ$	$L_{\min}: 0.2 \text{ m}$	<b>Minimum number of rotors:</b>	$3 \frac{1}{2}$
$\beta_{\max}: 90^\circ$	$\theta_{\max}: 90^\circ$	$L_{\max}: 0.4 \text{ m}$	<b>Maximum number of rotors:</b>	$8 \frac{1}{2}$

**Cost function:** Maximize the minimal torque and force that the drone can apply  
Maximize the minimal torque and force 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 (d)  
Maximize the force and torque that the drone can apply in one direction (d), with a hover in any orientation condition

**Advanced parameters of fmmincom:**

<b>Algorithm:</b>	<b>sqp</b> <b>sqp-legacy</b> <b>interior-point</b> <b>active-set</b>	<b>Display:</b>	displays no output displays output at each iteration displays output only if the function does not converge displays only the final output
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**Maximum iterations of the algorithm:**

<b>1e+04</b>
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**Tolerance on the constraint violation:**

<b>1e-06</b>
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**Termination tolerance on the opt. arg.:**

<b>1e-06</b>
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**Direction d:** x:  $0 \frac{1}{2}$ , y:  $0 \frac{1}{2}$ , z:  $1 \frac{1}{2}$

**Maximal number of times fmmincom is iterated to find the optimal solution:**

**Parameters for the plot of the force and torque space:**

<b>Number of points of the torque and force space:</b>	<input type="text" value="7490"/>	<b>Design number:</b>	<input type="text" value="1"/>
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Perform an optimization on the tilting angles and on the rotor speed for every points of the torque/force space (time consuming):

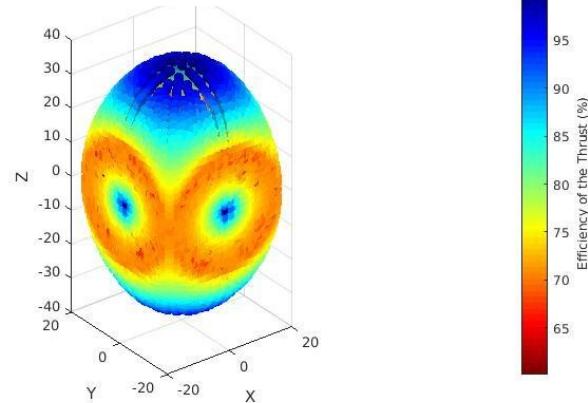
**Start optimization**

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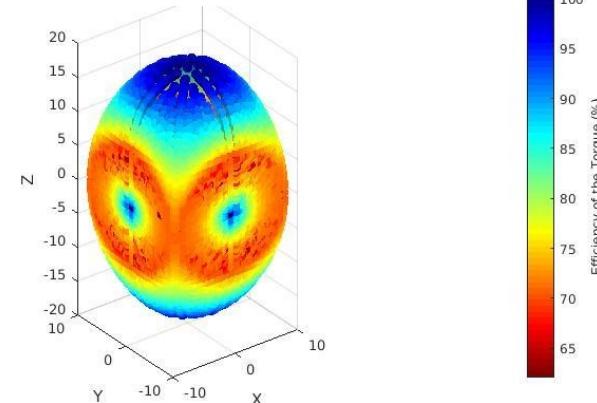
Luca Rinsoz | 9. September 2018 | 5

# Optimization Tool Output

Reachable Force Space



Reachable Torque Space



Hover Efficiency in every direction

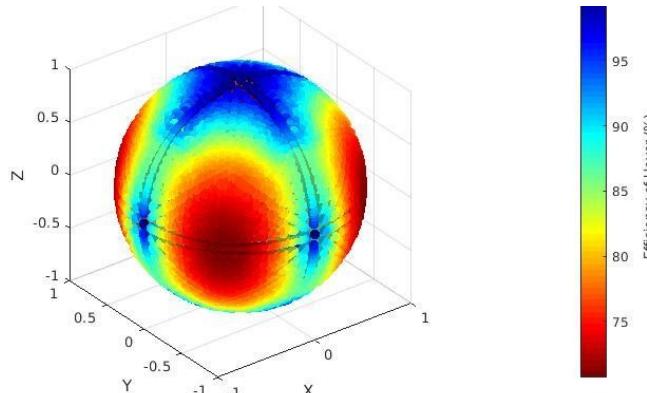
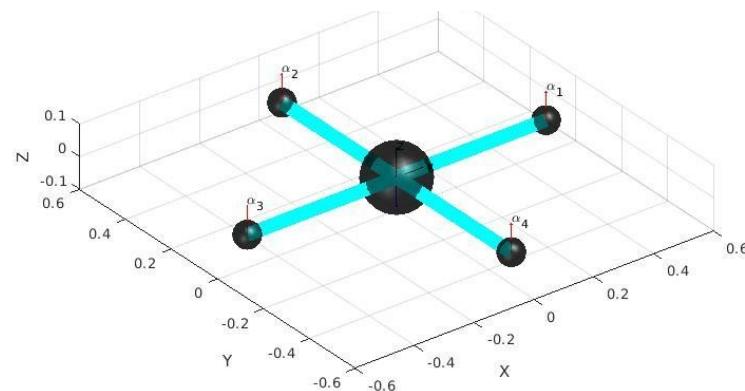


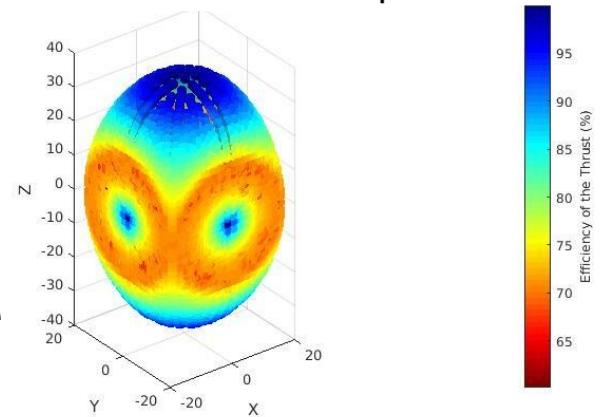
Illustration of the design



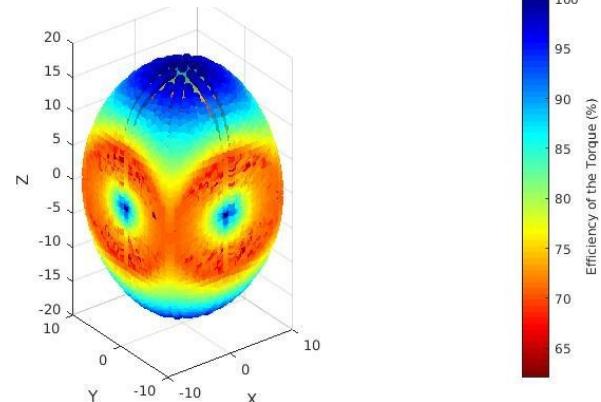
# Optimization Tool Output

- 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
  - Mean absolute deviation of the force, torque and hover efficiency

Reachable Force Space



Reachable Torque Space



# 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 minimal force and the minimal torque, and minimize the inertia
- 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



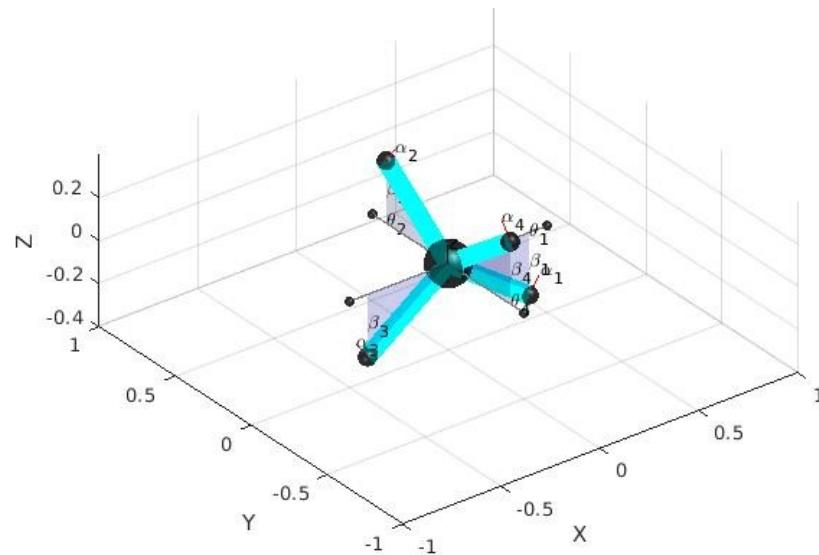
# Results

- 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

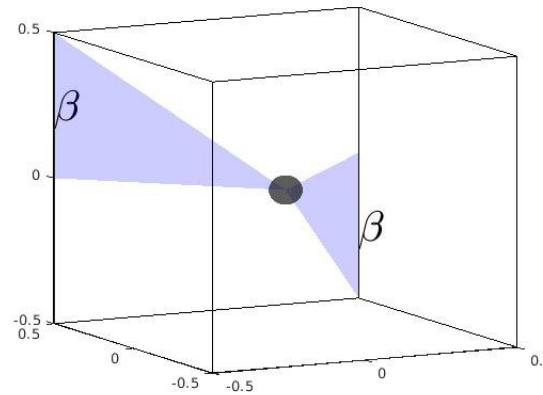
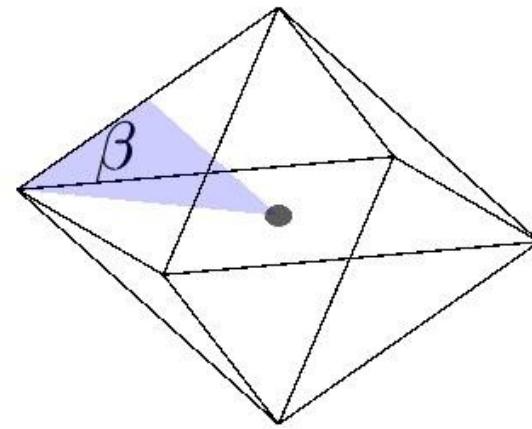
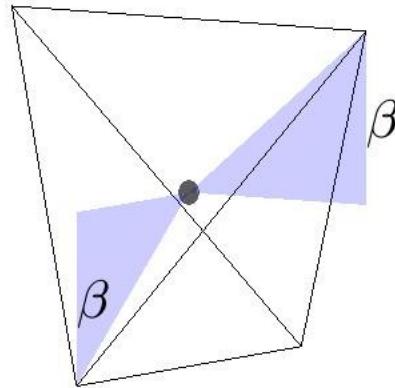
# Results

- Quad-copter
  - Maximizing the minimal force and torque

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



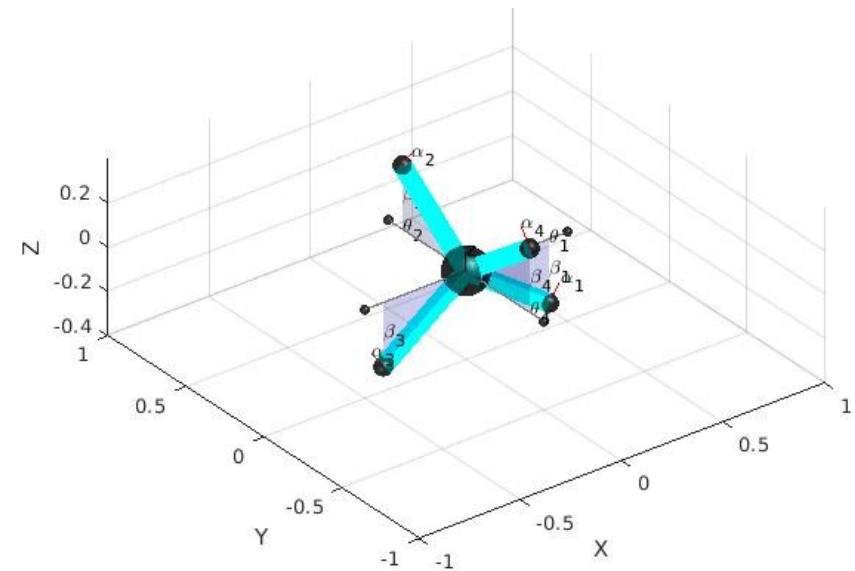
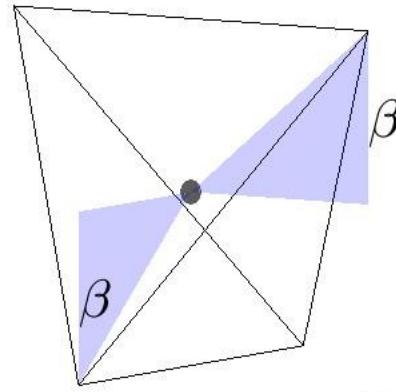
# Platonic solids



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

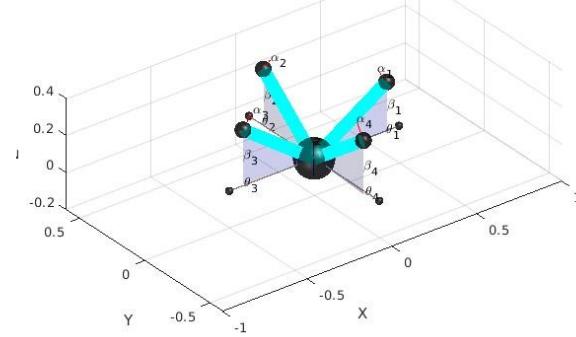
# Results

- Quad-copter

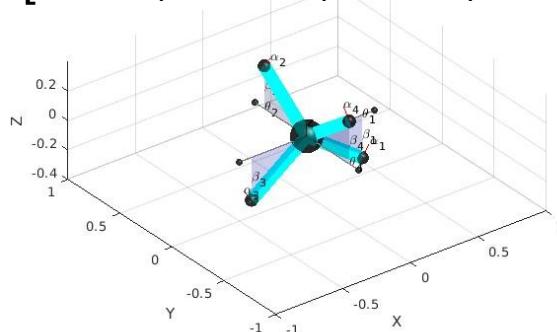


# Results

- Quad-copter
  - Maximizing the minimal force and torque
  - Starting as with  $\beta_0 = [0, 0, 0, 0]$   $\rightarrow \beta = [-32.42, -35.49, -35.44, -35.49]$



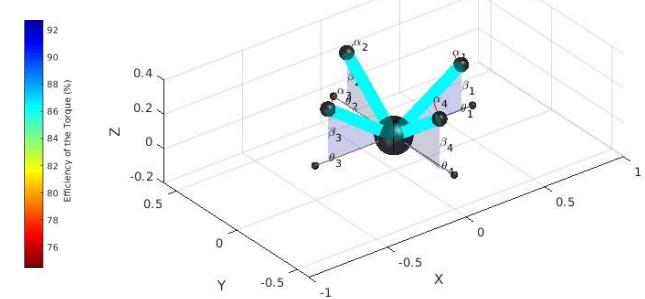
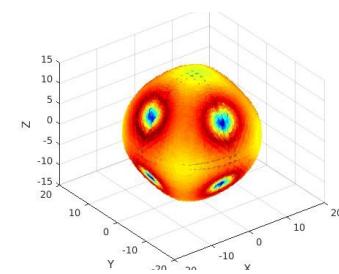
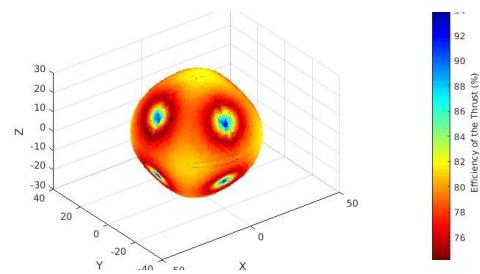
- Starting with  $\beta_0 = [35.26, -35.26, 35.26, -35.26]$   $\rightarrow \beta = [35.26, -35.26, 35.26, -35.26]$



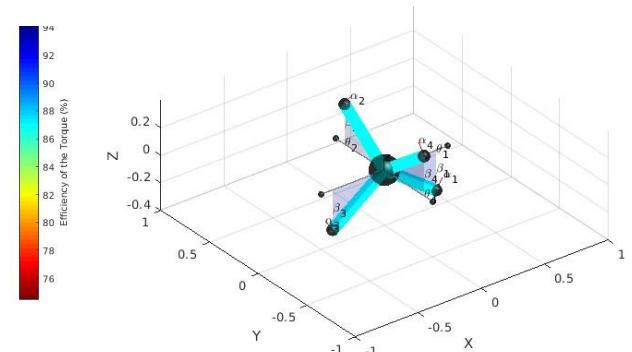
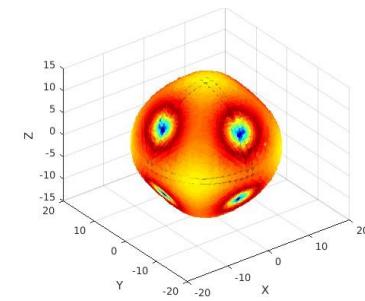
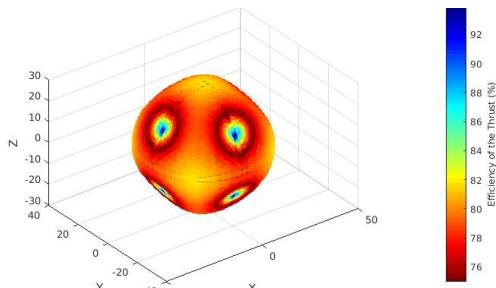
# Results

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

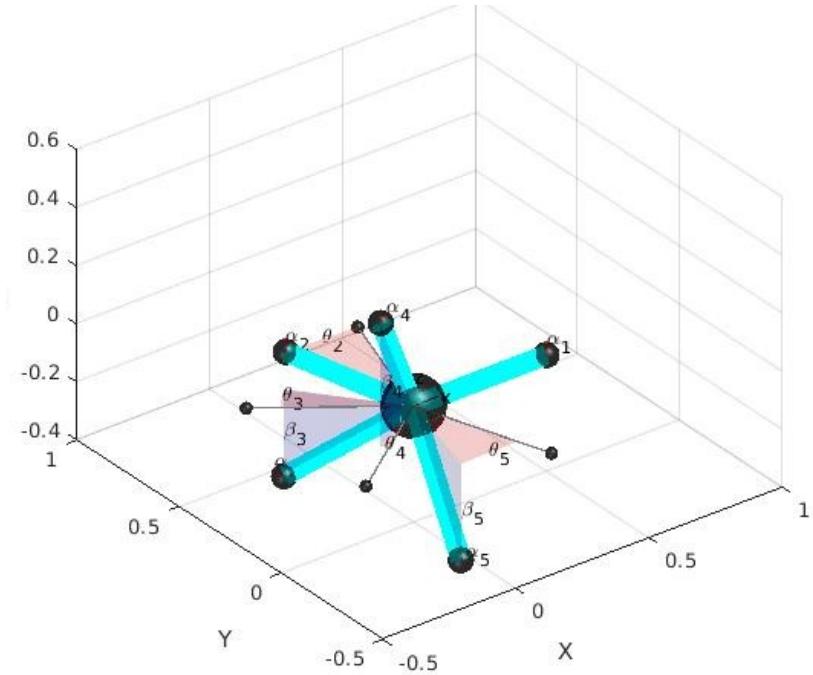


# Results

- Penta-copter
  - Maximizing the force, the torque and hover efficiency in every direction
  - Starting with  $\beta_0 = [0, 0, 0, 0, 0]$

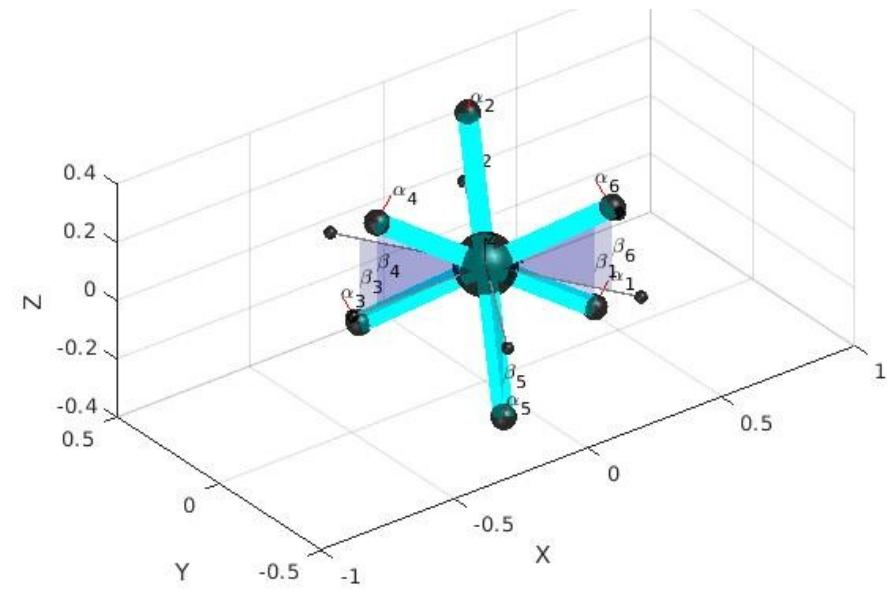
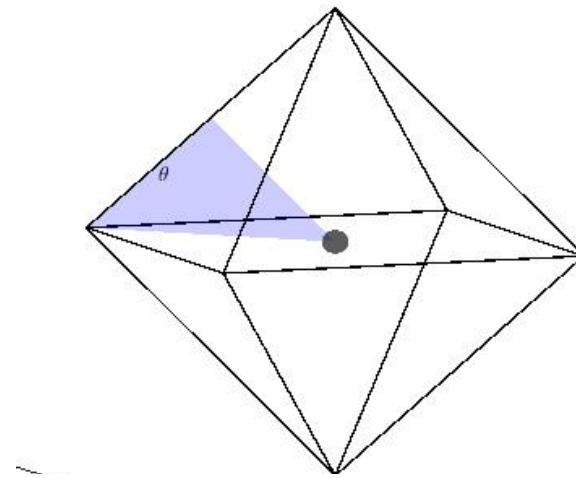


Solution  $\beta = [0, 0, 36.9, -58.4, -41.5]$



# Results

- Hexa-copter
  - Obtained maximizing the volumes of the force and torque spaces
    - Solution  $\beta = [35.26, -35.26, -35.26, 35.26, -35.26, 35.26]$



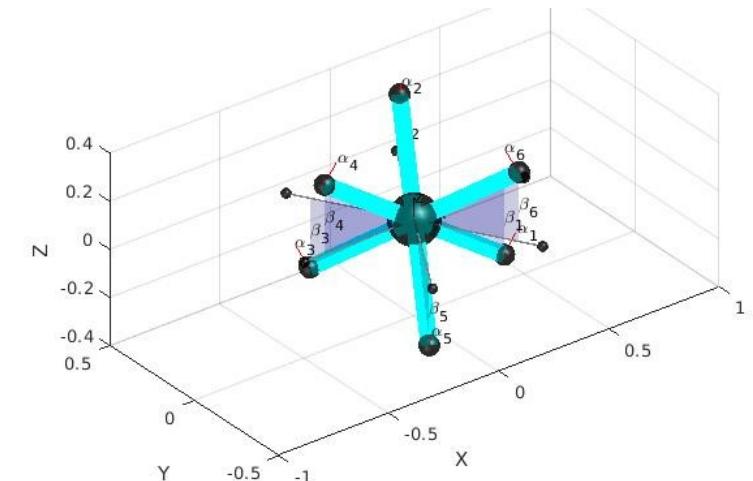
# Results

- Hexa-copter

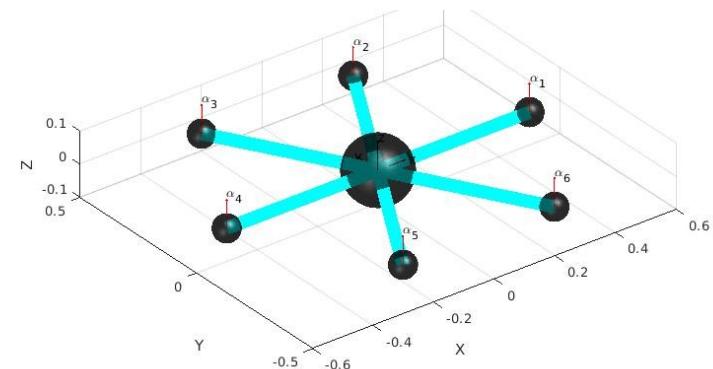
$F_{min} = 34.74, F_{max} = 42.55, M_{min} = 17.42, M_{max} = 21.34, H_{eff,min} = 81.65\%, H_{eff,max} = 100\%$

- Obtained maximizing the volumes of the force and torque spaces

- Voliro



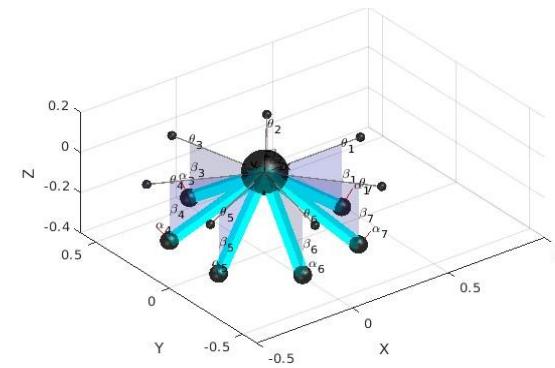
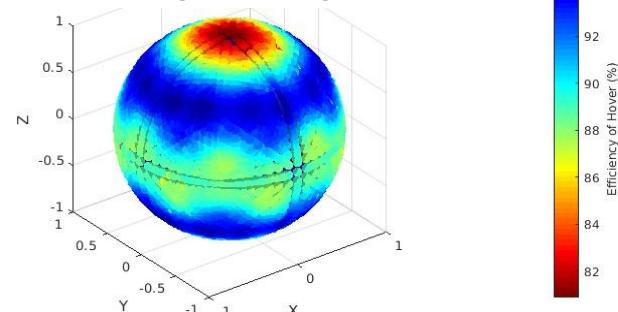
$F_{min} = 26.6, F_{max} = 52.11, M_{min} = 15.1, M_{max} = 26.13, H_{eff,min} = 75\%, H_{eff,max} = 100\%$



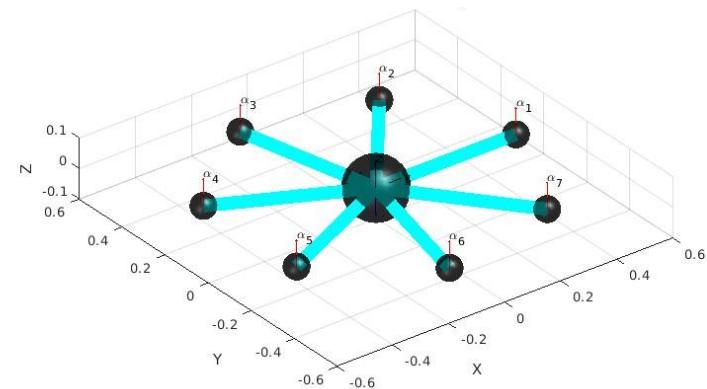
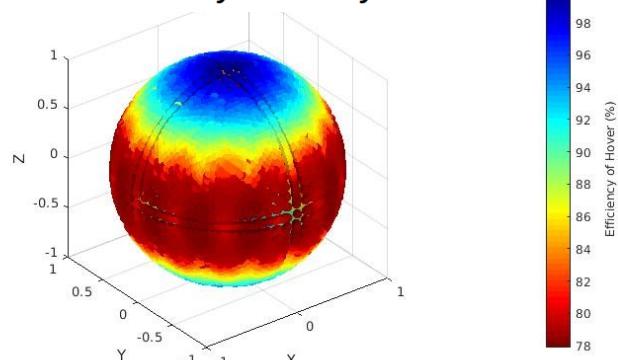
# Results

- Hepta-copter

Hover Efficiency in every direction

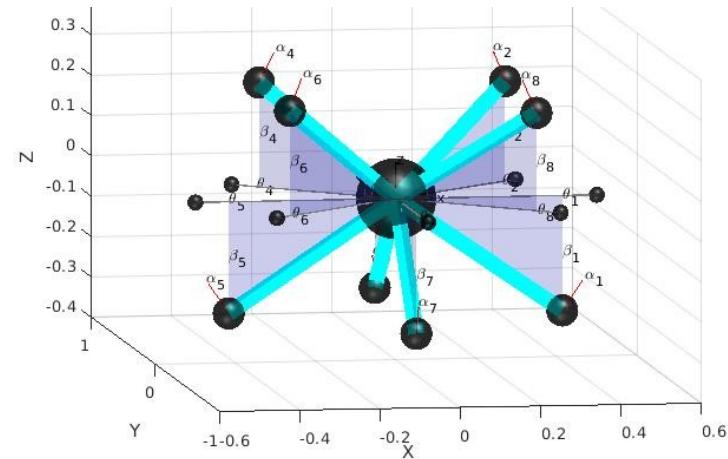


Hover Efficiency in every direction



# Results

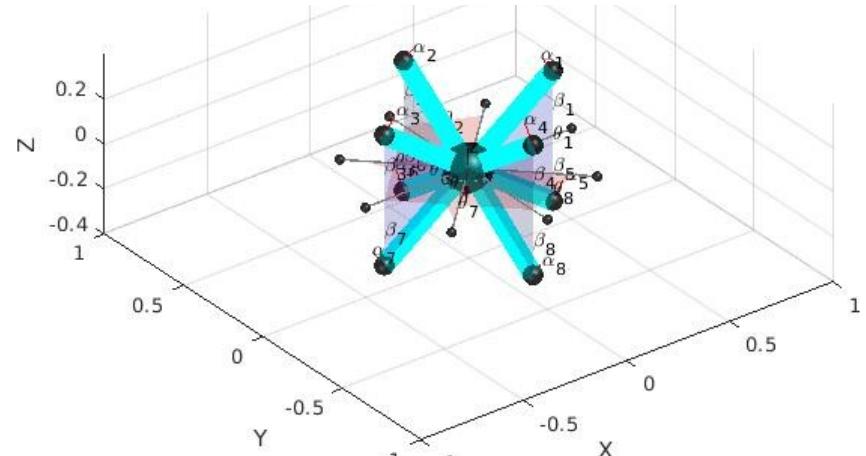
- Octa-copter



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

- Obtained maximizing the minimal force and torque that the drone can apply

- IDSC's Omnicopter



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

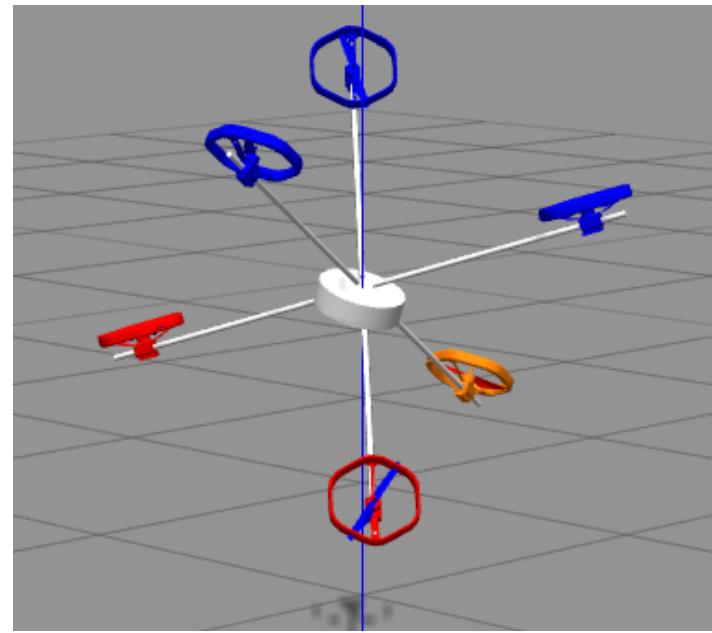
# Results

- 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

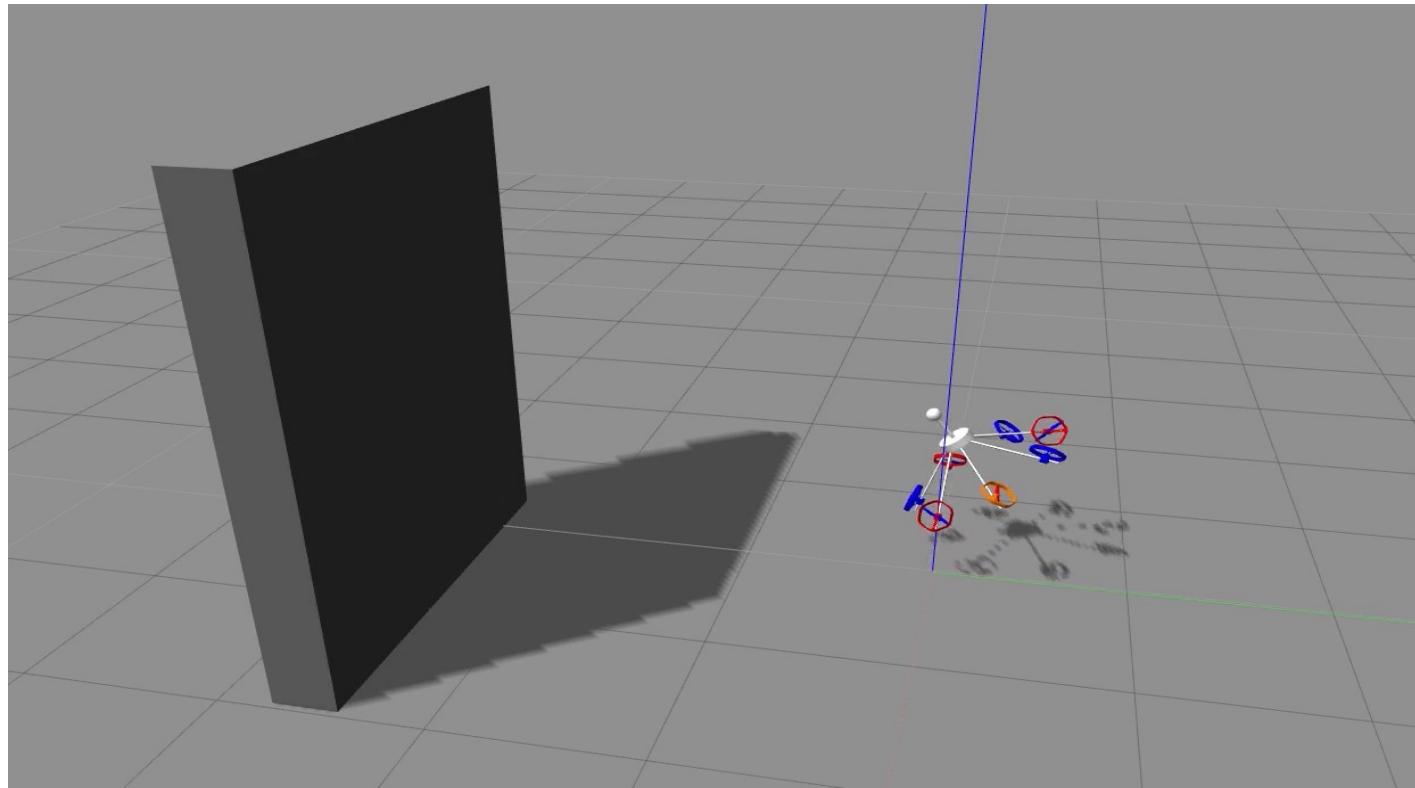
# Simulation

- Simulated different design in ROS to test them



# Simulation

- Hepta-copter interaction with a wall



# Conclusion

- Developped a design optimization tool

**Parameters to optimize:**

(  $\beta$  (angles that the arm form in the vertical plane))  
  $\theta$  (angles that the arm form in the horizontal plane)  
  $L$  (arm length)  
  $n$  (number of rotors)

**Initial solution representation:**

**Initial solution:**

$\beta_1: 35.21^\circ$	$\beta_2: -35.21^\circ$	$\beta_3: 35.26^\circ$	$\beta_4: -35.21^\circ$	$\beta_5: 0^\circ$	$\beta_6: 0^\circ$	$\beta_7: 0^\circ$	$\beta_8: 0^\circ$
$\theta_1: 0^\circ$	$\theta_2: 0^\circ$	$\theta_3: 0^\circ$	$\theta_4: 0^\circ$	$\theta_5: 0^\circ$	$\theta_6: 0^\circ$	$\theta_7: 0^\circ$	$\theta_8: 0^\circ$
$L: 0.3\text{ m}$	<b>Design parameters:</b>	$L: 0.3\text{ m}$	Number of rotors	4			

**Parameters bounds:**

$\beta_{\min}: -90^\circ$	$\theta_{\min}: -90^\circ$	$L_{\min}: 0.2\text{ m}$	Minimum number of rotors: 3
$\beta_{\max}: 90^\circ$	$\theta_{\max}: 90^\circ$	$L_{\max}: 0.4\text{ m}$	Maximum number of rotors: 8

**Cost function:** Maximize the minimal torque and force that the drone can apply  
Maximize the minimal torque and force 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 (d)  
Maximize the force and torque that the drone can apply in one direction (d), with a hover in any orientation condition

**Direction d:** x:  $0^\circ$ , y:  $0^\circ$ , z:  $1^\circ$

**Advanced parameters of fmincon:**

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

Maximal number of times fmincon is iterated to find the optimal solution: 150

**Parameters for the plot of the force and torque space:**

Number of points of the torque and force space: 7490 Design number: 1

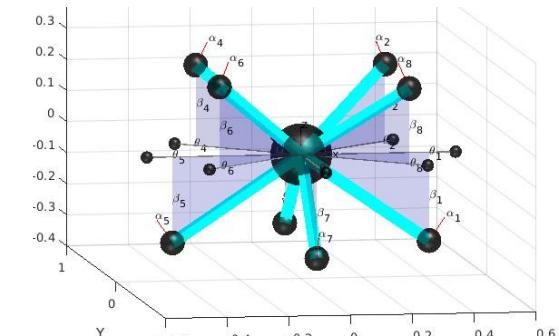
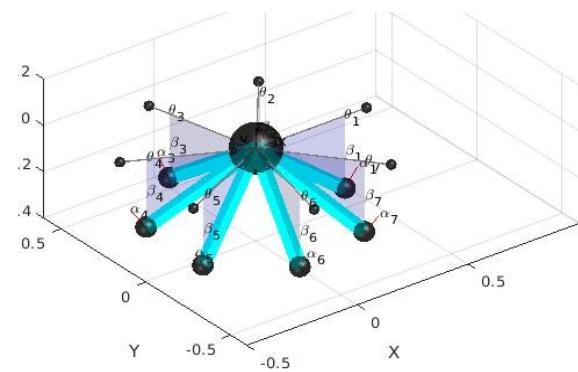
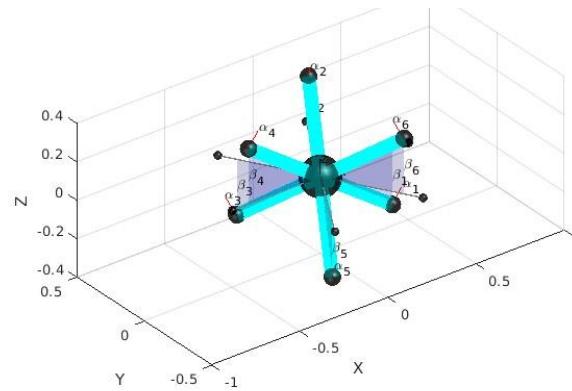
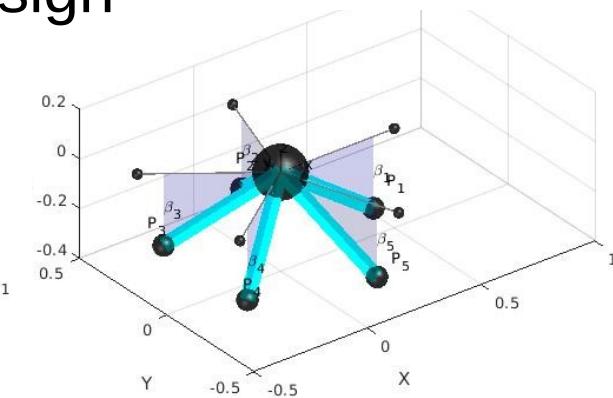
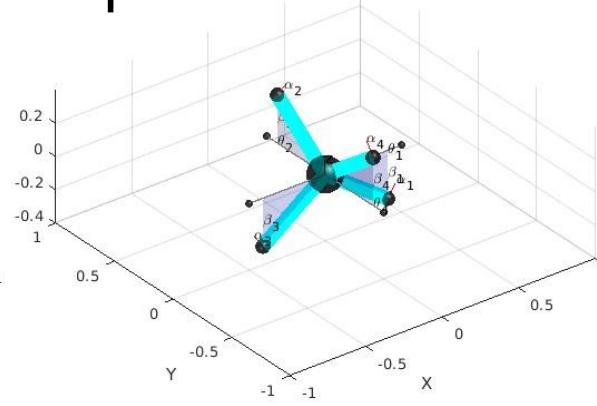
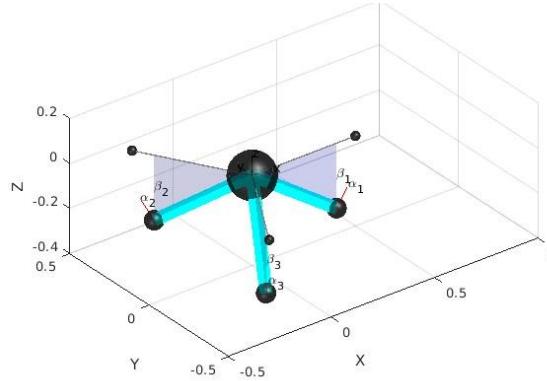
Perform an optimization on the tilting angles and on the rotor speed for every points of the torque/force space (time consuming):

**Start optimization**



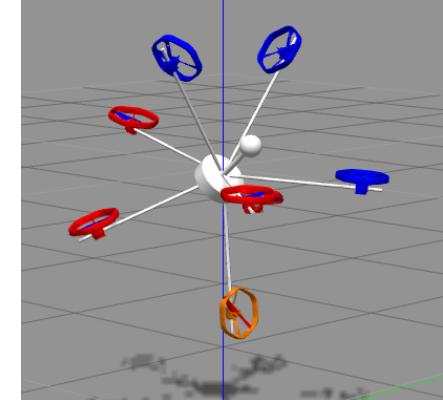
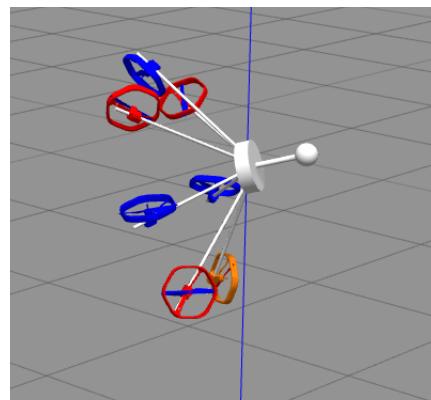
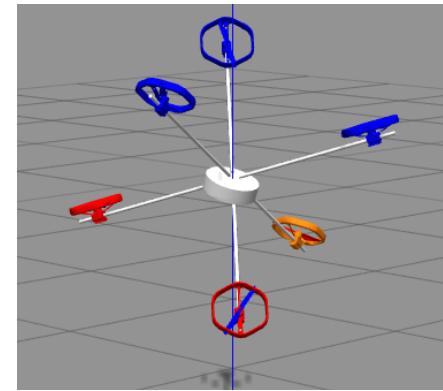
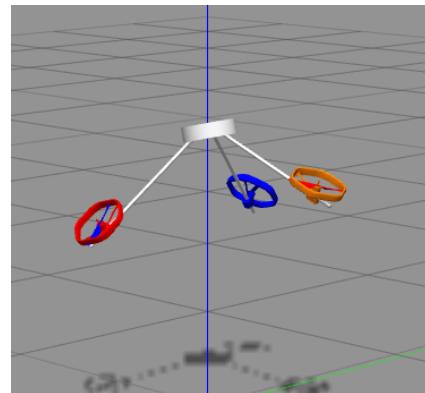
# Conclusion

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



# Conclusion

- Simulated some of the results in ROS environment



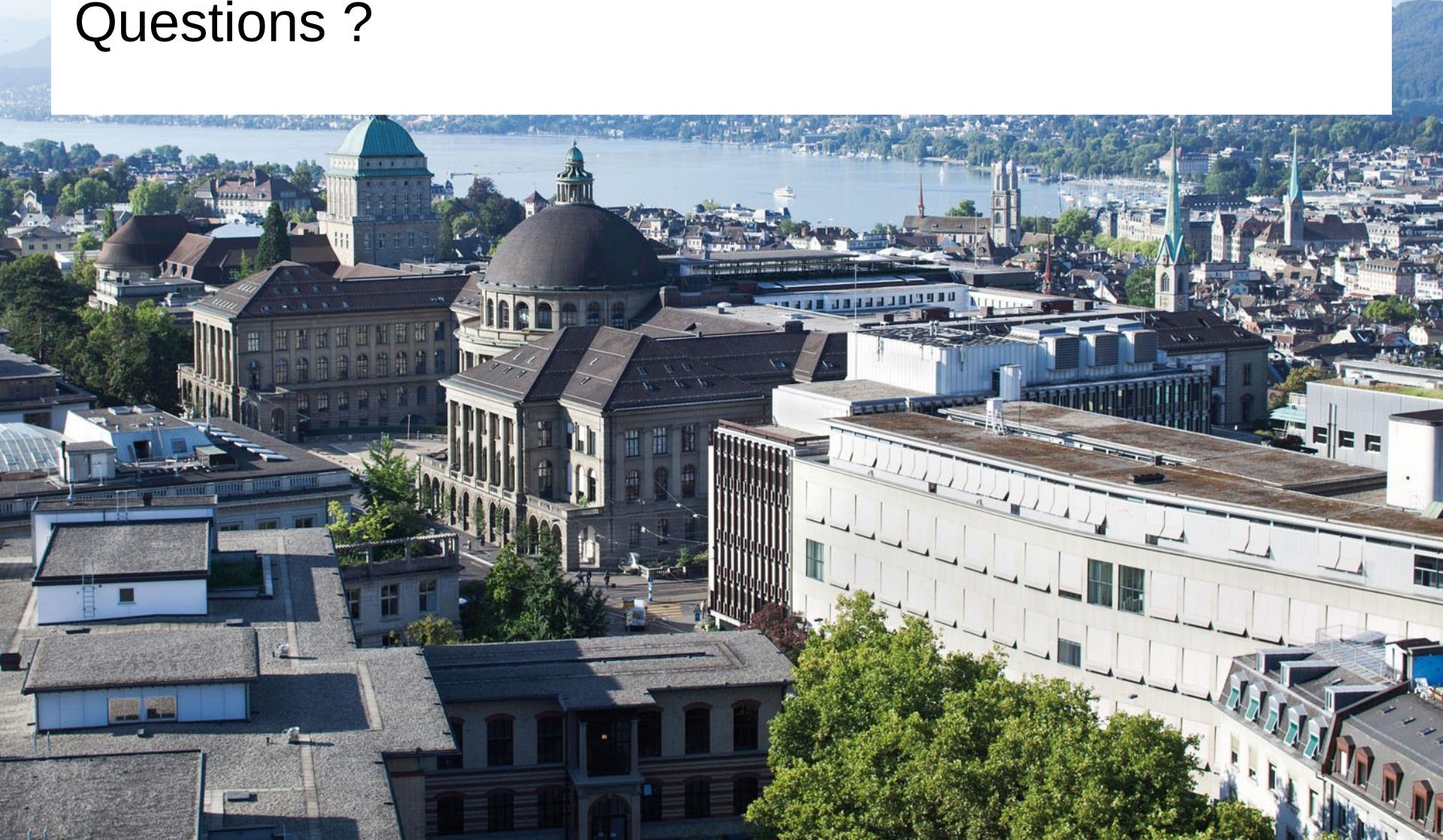
# Outlook

- Further development



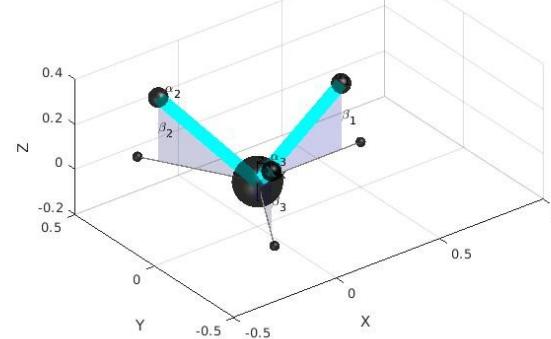
Thank you for your attention !

Questions ?



# Supplementary Slides

- Quad-copter
  - Maximizing the minimal force and torque
  - Starting as with  $\beta_0 = [0, 0, 0]$   $\rightarrow \beta = [-32.42, -35.49, -35.44, -35.49]$



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

