Modeling and control of multi-rotor UAVs

Presentation

Francesco Peracchia - 1906895

Francesco Starna - 1613660

Francesco Vincelli - 1727959

SAPIENZA
UNIVERSITÀ DI ROMA

Sapienza University of Rome

Team Francesco^3

Francesco Peracchia

Francesco Starna

Francesco Vincelli

External Wrench Estimation in Multi-rotor UAVs

Simulation and experiments results

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Outline

- Introduction
- Contact Detection
- Modeling and Control
- External Wrench Estimation
- Experiments
- Conclusions
- References

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Motivations

Related Work

Physical modelling

Blade flapping model and propeller induced drag

Data driven modelling

Learn a Regressor from data

Wind tunnel measurements integration

Aerodynamic model estimation based on Blade-flapping(Physical modelling)

Data-driven wind speed estimation

Contact Detection

Aerodynamic Wrench

A learned Aerodynamic Matrix is used to describe the Aerodynamic Wrech $\mathbf{m}_d(\mathbf{f}_e)$

Experiments on a wind tunnel are used to build the aerodynamic model

Residuals based approach $\boldsymbol{\tau}_e = \boldsymbol{\tau}_d + \boldsymbol{\tau}_i + \boldsymbol{\tau}_f$

An accurate aerodynamic model allows a residuals computation as : $\tilde{\mathbf{m}}_d = \mathbf{m}_d(\mathbf{f}_e) - \mathbf{m}_e$

If only the wind effect is acting $\mathbf{m}_d(\mathbf{f}_e) = \mathbf{m}_e$ hence $\tilde{\mathbf{m}}_d = \mathbf{m}_d(\mathbf{f}_e) - \mathbf{m}_e = \mathbf{0}$

Threshold

Uncertainty: both **aerodynamic** and **external wrech** are estimated

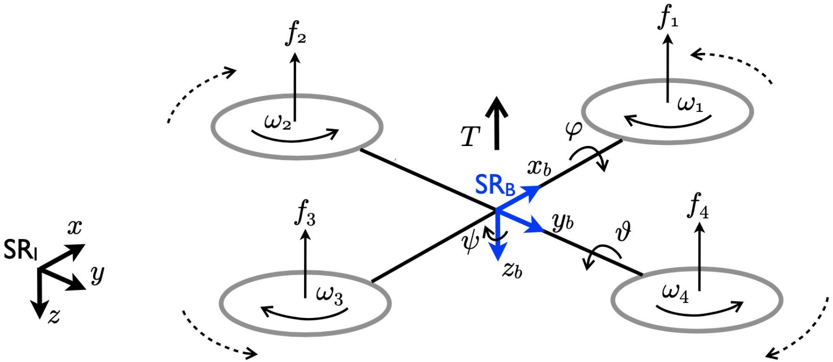
Tuning the **threshold** by experiments

$$||\tilde{\mathbf{m}}_d|| > CD_{threshold} \qquad \tilde{\mathbf{m}}_d = \underline{\mathbf{m}_d(\mathbf{f}_e)} - \mathbf{m}_e = \mathbf{0}$$

Modeling

Newton-Euler formalism

Convenient for control algorithm



Translational and Rotational Dynamics

Expressed in the inertial RF$_I$ and body RF$_B$ frames

$$\sum \mathbf{f}_I = \mathcal{M}\ddot{\mathbf{r}}$$

$$\sum \mathbf{m}_B = \mathbf{I}\dot{\boldsymbol{\omega}} + (\mathbf{I}\boldsymbol{\omega}) \times \boldsymbol{\omega}$$

Equation of motion

Rbi rpy rotation matrix from body to inertial frame

$$\boxed{\begin{aligned} \mathcal{M}\ddot{\mathbf{r}} &= \mathcal{M}g\mathbf{e}_3 + \mathbf{R}_b^i\mathbf{f} + \mathbf{R}_b^i\mathbf{f}_e \\ \mathbf{I}\dot{\boldsymbol{\omega}} &= -(\mathbf{I}\boldsymbol{\omega}) \times \boldsymbol{\omega} + \mathbf{m} + \mathbf{m}_e \\ \dot{\mathbf{R}}_b^i &= \mathbf{R}_b^i(\boldsymbol{\omega})_\times \end{aligned}}$$

Control

System model

Affine system linear in the input u

Position and attitude control

Output a control thrust T and torque **m**

Cascaded control scheme

Efficient for basic maneuvers

state

$$\xi = (x,\, y,\, z,\, v_x,\, v_y,\, v_z,\, \varphi,\, \vartheta,\, \psi,\, p,\, q,\, r)'$$

inputs

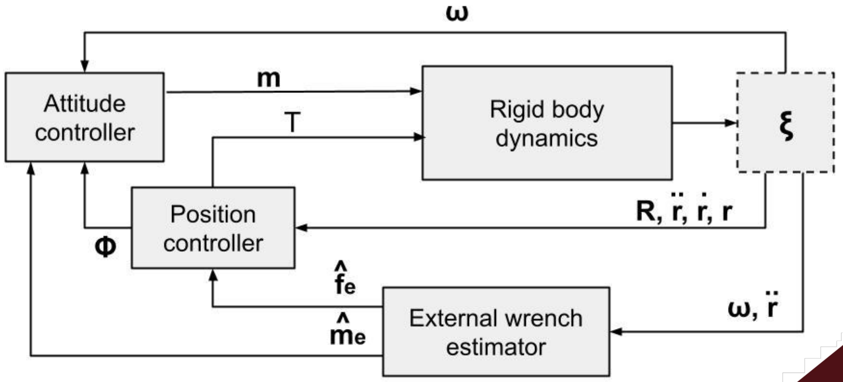
u = (T, **m**)

control

$$\mathbf{f}_i = \mathbf{R}_{di}\mathbf{f} = M(\dot{r}_d - K_{fd}\,\mathbf{e}_{\dot{r}} - K_{fp}\,\mathbf{e}_r) - Mg\mathbf{e}_3 - \mathbf{f}_e$$

$$\mathbf{m} = \mathbf{I}(K_{mp}\,\mathbf{e}_\mathbf{R} - K_{md}\,\boldsymbol{\omega}) + (\mathbf{I}\boldsymbol{\omega}) \times \boldsymbol{\omega} - \mathbf{m}_e$$

scheme



Lagrangian Formalism

twist

control wrench

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{g} = \mathbf{J}^T\boldsymbol{\tau} + \boldsymbol{\tau}_e$$

aerodynamic drag forces

external wrench

where $\mathbf{g} = \begin{bmatrix} -\mathcal{M}g\mathbf{e}_3 & 0 \end{bmatrix}^T$, $\boldsymbol{\nu} = \begin{bmatrix} \dot{\mathbf{r}} & \boldsymbol{\omega} \end{bmatrix}^T$ is the twist, $\mathbf{J} = blockdiag\left\{\mathbf{R}_b^i, \mathbf{I}_{3\times3}\right\}$ and

$$\mathbf{M} = \begin{bmatrix} \mathcal{M}\mathbf{I}_{3\times3} & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \mathbf{I} \end{bmatrix}, \mathbf{C}(\boldsymbol{\nu}) = \begin{bmatrix} \mathbf{0}_{3\times3} & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & -(\mathbf{I}\boldsymbol{\omega})\times \end{bmatrix}$$

Momentum-based External Wrench Estimation

Generalized momentum

Differentiation according to Lagrangian form

$$\boldsymbol{p} = \boldsymbol{M}\boldsymbol{\nu}$$

$$\dot{\mathbf{p}} = \mathbf{M}\dot{\boldsymbol{\nu}} = \mathbf{J}^T\boldsymbol{\tau} + \boldsymbol{\tau}_e - \mathbf{N}$$

Residual vector

Definition following **[De Luca et al.]**

Requires a direct measure of the twist

$$\boldsymbol{\rho} = K_I\left[\mathbf{p} - \int\left(\mathbf{J}\boldsymbol{\tau} + \boldsymbol{\tau}_e - \mathbf{N} + \boldsymbol{\rho}\right)dt\right]$$

Residual dynamics

Linear exponentially stable system

$$\dot{\boldsymbol{\rho}} = K_I\boldsymbol{\tau}_e - K_I\boldsymbol{\rho}$$

Acceleration-based External Wrench Estimation

Rearranging the Lagrangian form

Needs a direct measure of acceleration

$$\hat{\boldsymbol{\tau}}_e = \mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{g} - \boldsymbol{\tau}$$

Hybrid External External Wrench Estimation

Only momentum-based

Requires more sensors and fusion algorithm

$$\hat{\boldsymbol{\tau}}_e = K_I \left[\mathbf{p} - \int \left(\mathbf{J}\boldsymbol{\tau} + \boldsymbol{\tau}_e - \mathbf{N} + \boldsymbol{\rho}\right) dt\right]$$

Only acceleration-based

Requires numerical differentiation

$$\hat{\boldsymbol{\tau}}_e = \mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{g} - \boldsymbol{\tau}$$

Combining the two methods

Requires only accelerometer

$$\boxed{\hat{\boldsymbol{\tau}}_e = \begin{bmatrix} \hat{\mathbf{f}} \\ \hat{\mathbf{m}}_e \end{bmatrix} = \begin{cases} \int K_f \left(\mathcal{M}\mathbf{a} - \mathbf{f} - \hat{\mathbf{f}}_e\right) dt \\ K_m \left(\mathbf{I}\boldsymbol{\omega} + \int \left((\mathbf{I}\boldsymbol{\omega}) \times \boldsymbol{\omega} - \mathbf{m} - \hat{\mathbf{m}}_e\right) dt\right) \end{cases}}$$

Discrimination

Data-driven approach

Train a perceptron over the wind-tunnel dataset

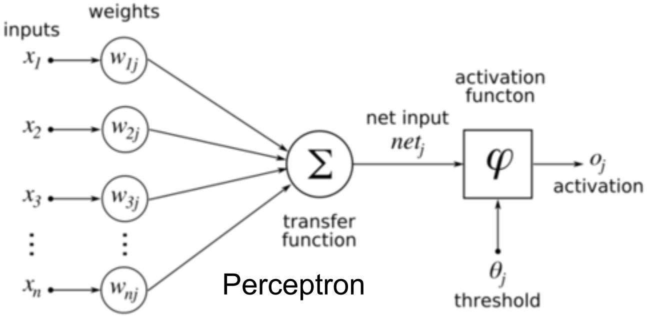
Physical modeling approach

Exploiting propeller aerodynamics

Attempts

- Using a linear model $\mathbf{v}_r = \mathbf{u}$
- Guessing propeller physical characteristics

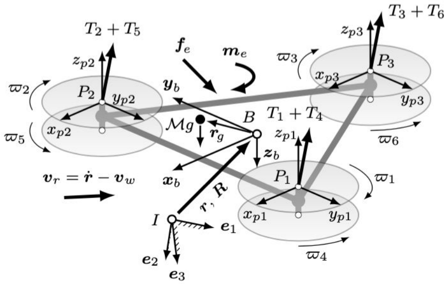
wind-tunnel experiment



Perceptron

$$\mathbf{f}_d = \mathbf{A}_d \mathbf{v}_r c_T \sum_i \varpi_i$$

Blade flapping model **[Omari et al.]**



$$v_{\infty,k} = \mathbf{R}_{bp,k}^T(\mathbf{R}_{bi}^T \mathbf{v}_r + \boldsymbol{\omega} \times \mathbf{r}_k)$$

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Simulation Environment

Applications and Tools

The project is developed using Matlab and CoppeliaSim framework

Matlab

Matlab is a computational framework optimized for iterative analysis and design processes

CoppeliaSim

CoppeliaSim is a robot simulator used in industry, education and research

MATLAB®

CoppeliaSim
from the creators of V-REP

Implementation

System Architecture

The project consists of two main modules:

- the **Matlab client application**, implementing the **core logic** of the system
- the **Coppelia simulation scene**, providing the **experimental environment** and simulation settings

Matlab Client Structure

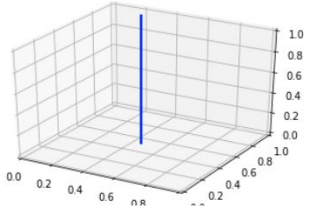
The Matlab application is made up of three main classes:

- **Quadrotor** : implements the system dynamics and provides the control design for tracking task
- **Aerodynamics** : contains the wrench estimation algorithm and the contact detection procedure
- **QuadrotorSim** : acts as an interface between Matlab logic and Coppelia simulation environment

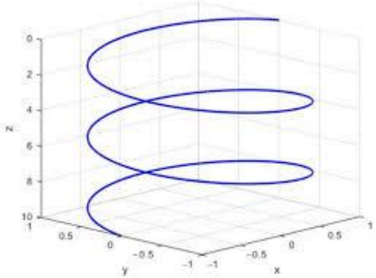
Problem Settings

Task Trajectories

Two task trajectories are considered: a **hovering** and an **elicoidal trajectory**



Hovering



Elicoidal trajecotry

Hovering

We tested the external wrench estimation and contact detection, in the following cases:

- in **presence** of **wind action only**
- in **presence** of a **continuous** contact action but in **absence** of **wind action**
- in **presence** of a **continuous contact** action and of **wind action**
- in **presence** of **wind action** and **not uniformly distributed load** mass

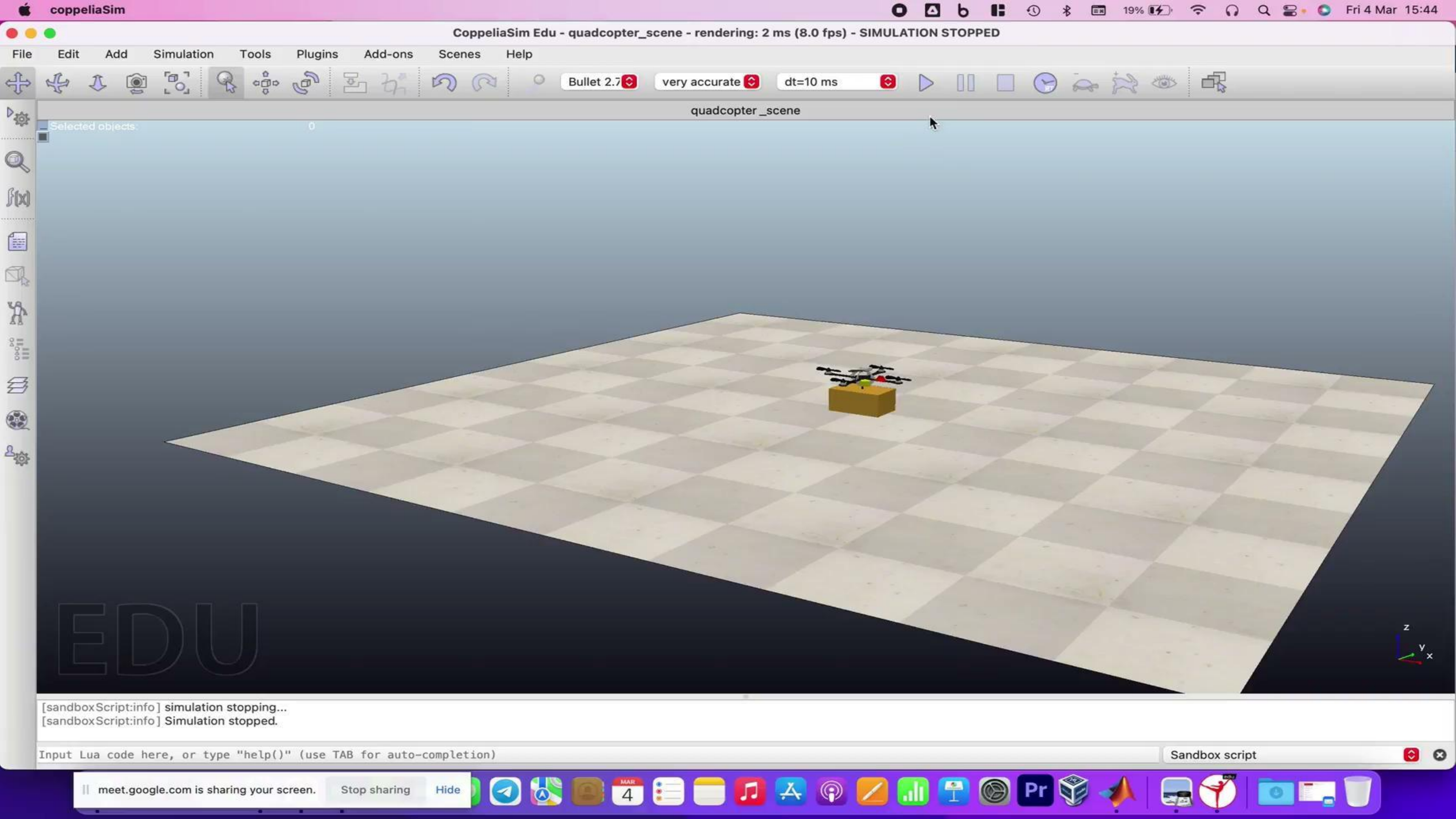
Spiral

We tested this task in **presence of wind action only**.

Results

Experiment 1

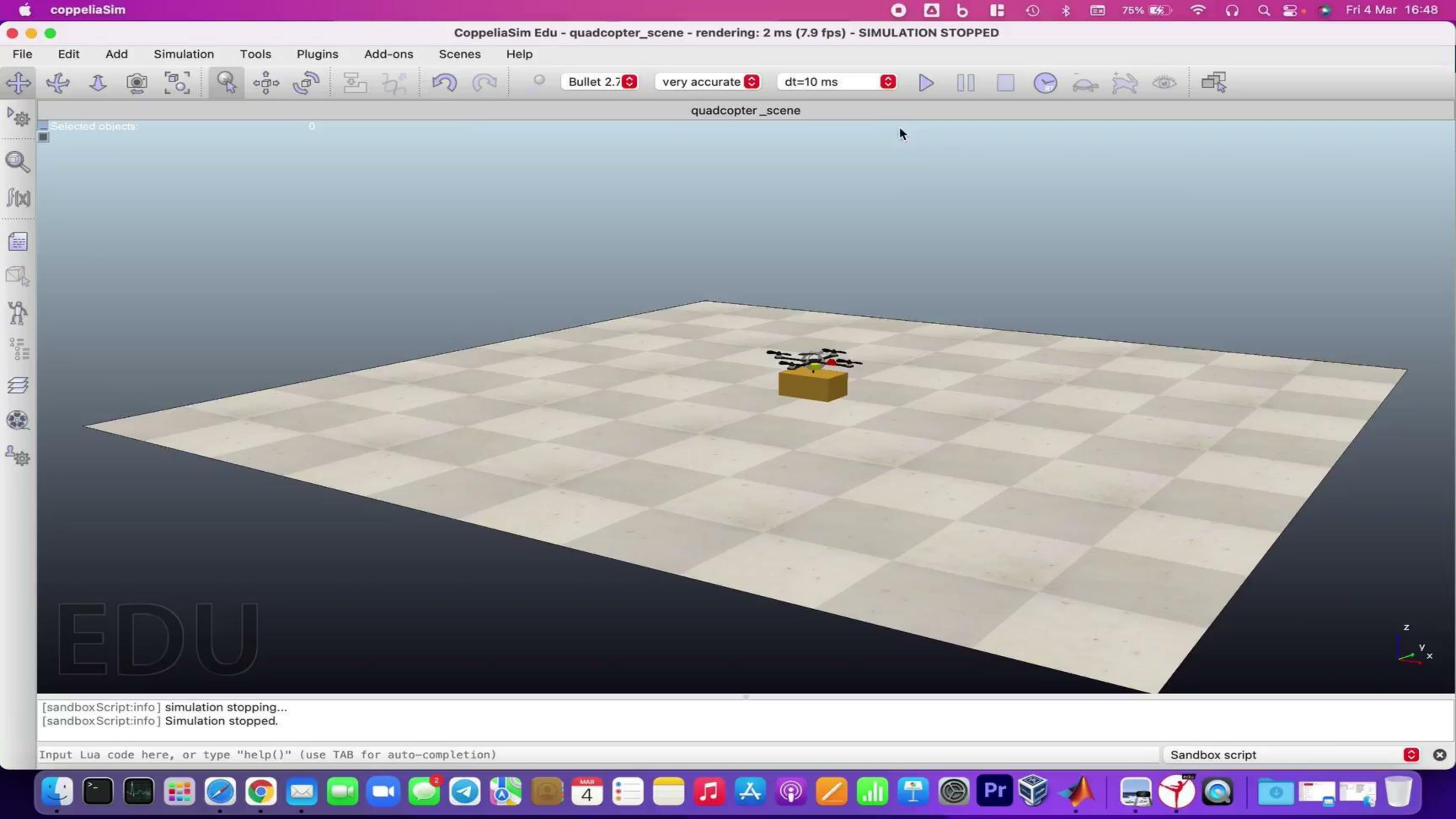
Hovering with wind action only (aerodynamic external wrench)


coppeliaSim
Fri 4 Mar 15:44
CoppeliaSim Edu - quadcopter_scene - rendering: 2 ms (8.0 fps) - SIMULATION STOPPED
File Edit Add Simulation Tools Plugins Add-ons Scenes Help
Bullet 2.7
very accurate
dt=10 ms
quadcopter _scene
Selected objects: 0
EDU
[sandboxScript:info] simulation stopping...
[sandboxScript:info] Simulation stopped.
Input Lua code here, or type "help()" (use TAB for auto-completion)
Sandbox script
meet.google.com is sharing your screen.
Stop sharing
Hide

Results

Experiment 2

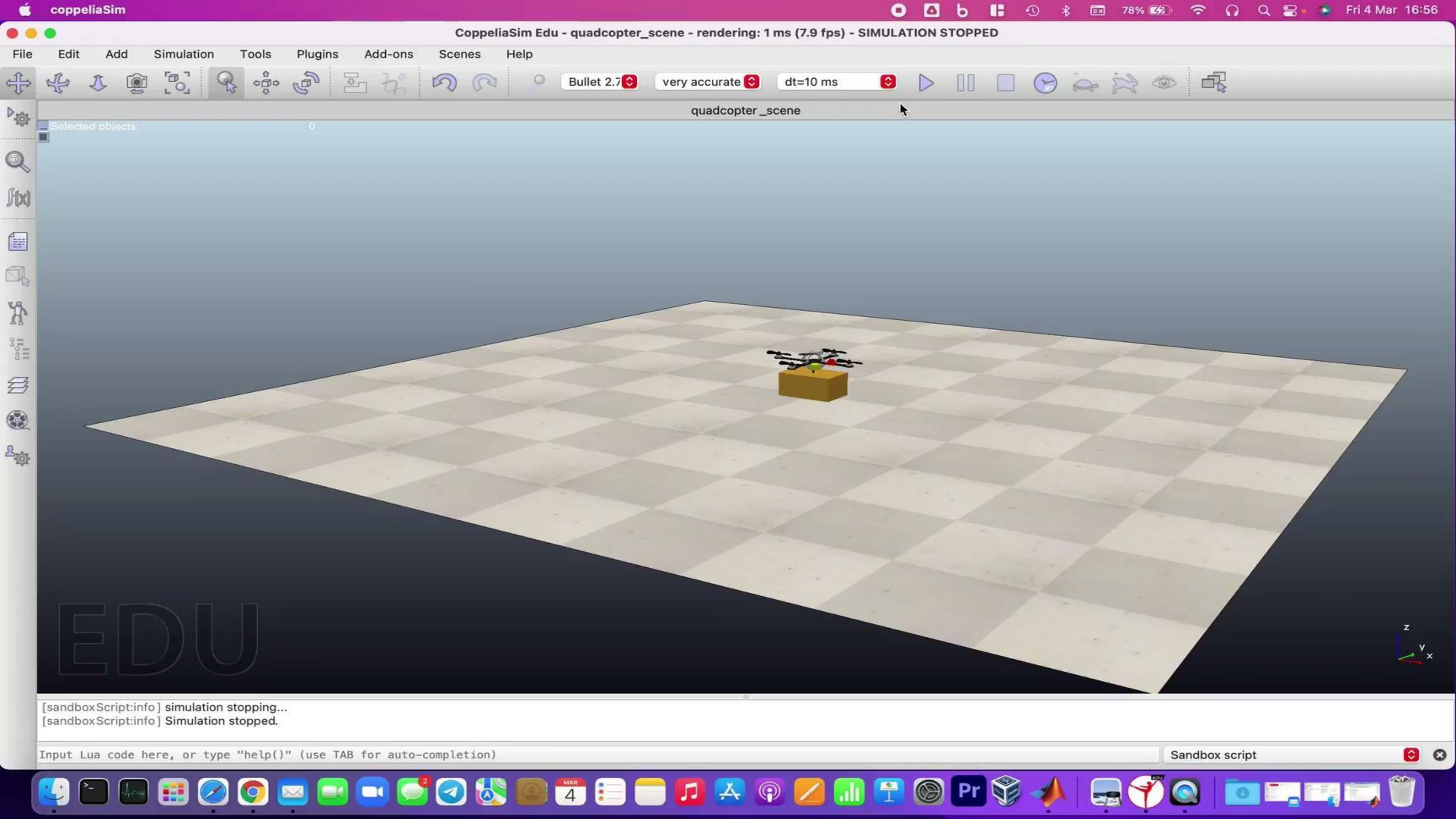
Hovering with continuous external contact force


coppeliaSim
Fri 4 Mar 16:48
CoppeliaSim Edu - quadcopter_scene - rendering: 2 ms (7.9 fps) - SIMULATION STOPPED
File
Edit
Add
Simulation
Tools
Plugins
Add-ons
Scenes
Help
Bullet 2.7
very accurate
dt=10 ms
quadcopter _scene
Selected objects: 0
EDU
[sandboxScript:info] simulation stopping...
[sandboxScript:info] Simulation stopped.
Input Lua code here, or type "help()" (use TAB for auto-completion)
Sandbox script

Results

Experiment 3

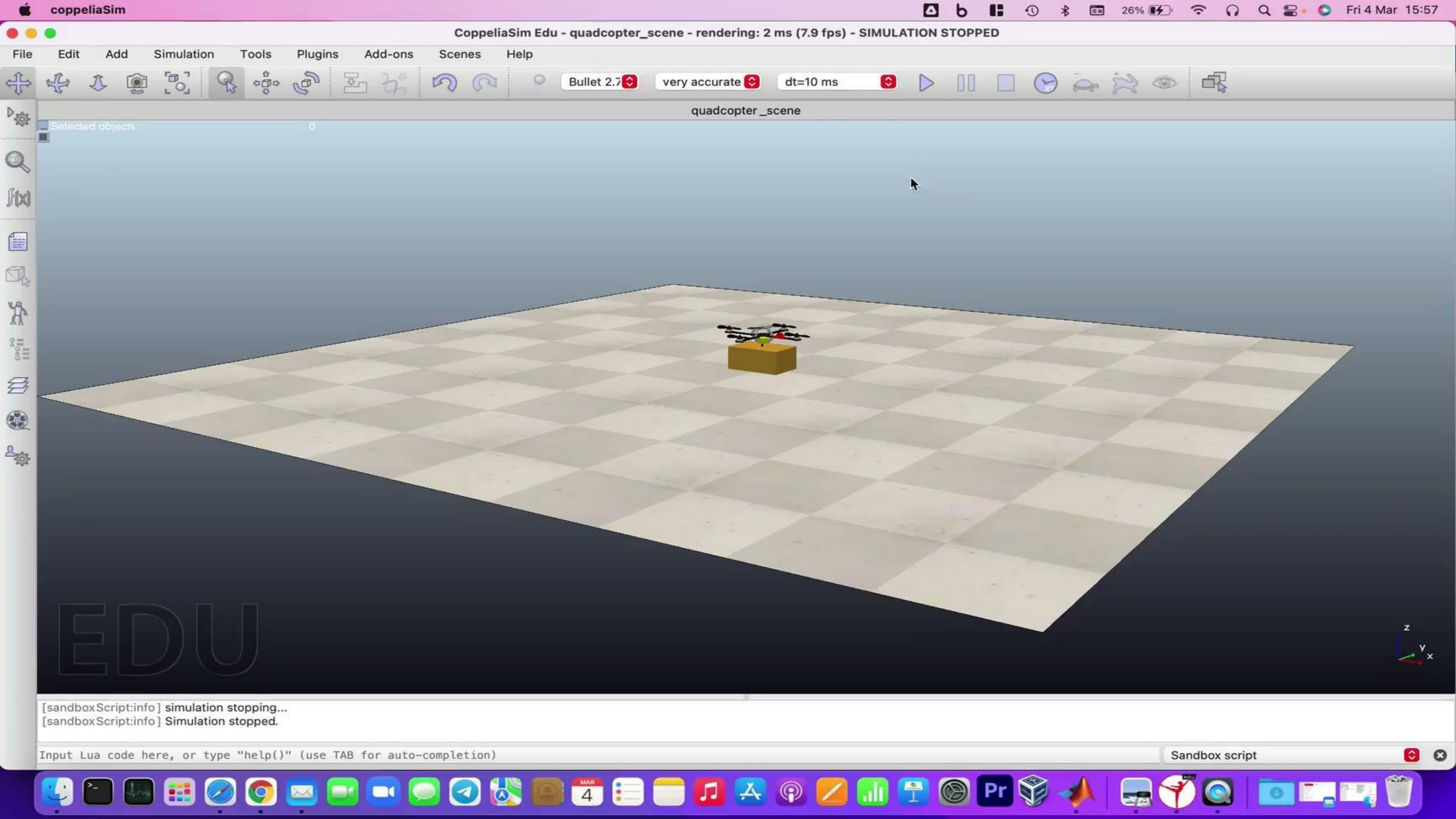
Hovering with both wind and contact force actions


coppeliaSim
Fri 4 Mar 16:56
CoppeliaSim Edu - quadcopter_scene - rendering: 1 ms (7.9 fps) - SIMULATION STOPPED
File
Edit
Add
Simulation
Tools
Plugins
Add-ons
Scenes
Help
Bullet 2.7
very accurate
dt=10 ms
quadcopter _scene
Selected objects:
0
EDU
[sandboxScript:info] simulation stopping...
[sandboxScript:info] Simulation stopped.
Input Lua code here, or type "help()" (use TAB for auto-completion)
Sandbox script

Results

Experiment 4

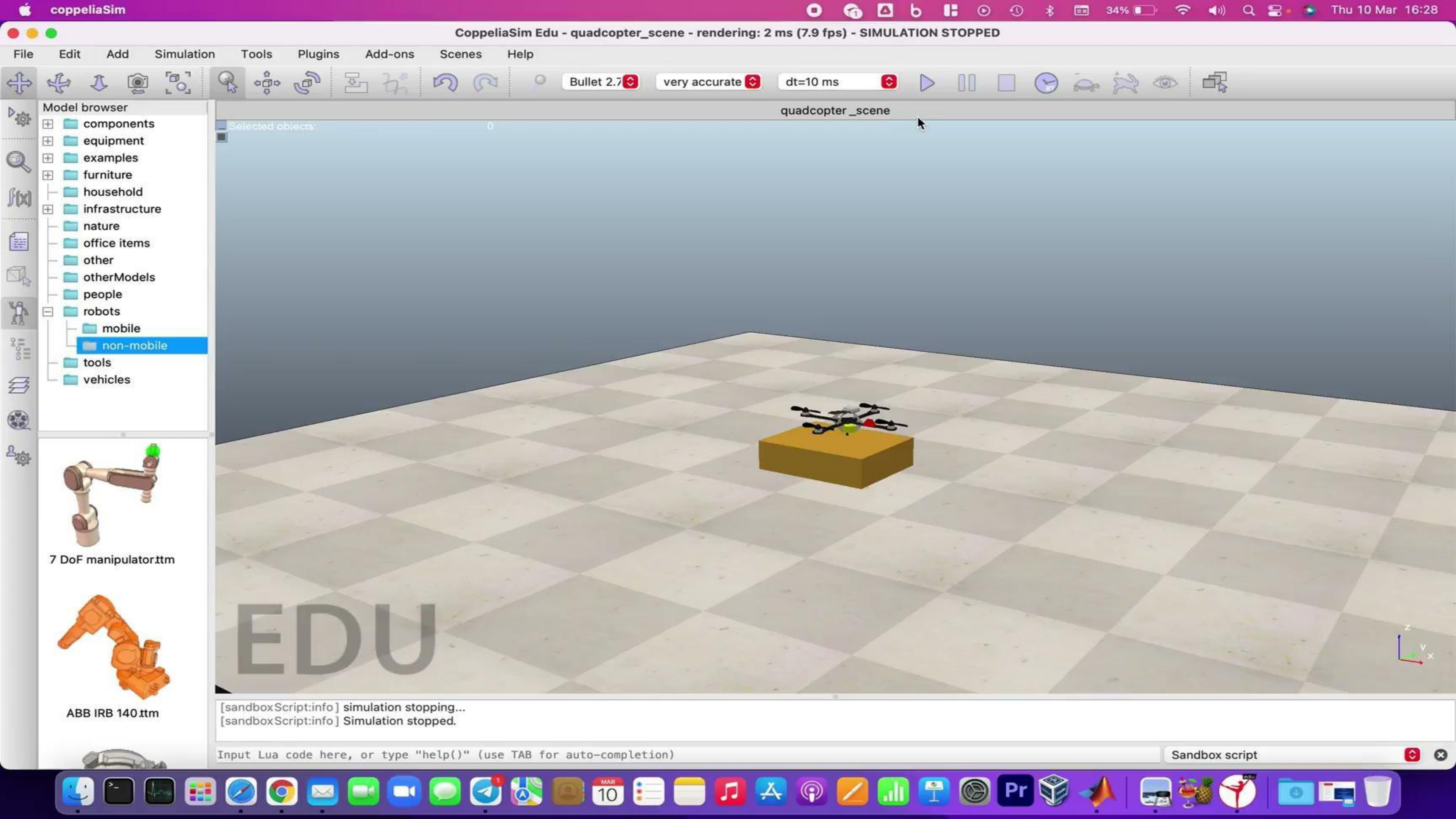
Elicoidal trajectory with wind action only


coppeliaSim
Fri 4 Mar 15:57
CoppeliaSim Edu - quadcopter_scene - rendering: 2 ms (7.9 fps) - SIMULATION STOPPED
File
Edit
Add
Simulation
Tools
Plugins
Add-ons
Scenes
Help
Bullet 2.7
very accurate
dt=10 ms
quadcopter _scene
Selected objects:
0
EDU
[sandboxScript:info] simulation stopping...
[sandboxScript:info] Simulation stopped.
Input Lua code here, or type "help()" (use TAB for auto-completion)
Sandbox script

Results

Experiment 5

Hovering with wind action and not uniformly distributed load mass


coppeliaSim
Thu 10 Mar 16:28
CoppeliaSim Edu - quadcopter_scene - rendering: 2 ms (7.9 fps) - SIMULATION STOPPED
File Edit Add Simulation Tools Plugins Add-ons Scenes Help
Bullet 2.7
very accurate
dt=10 ms
Model browser
components
equipment
examples
furniture
household
infrastructure
nature
office items
other
otherModels
people
robots
mobile
non-mobile
tools
vehicles
7 DoF manipulator.ttm
ABB IRB 140.ttm
quadcopter _scene
Selected objects: 0
EDU
[sandboxScript:info] simulation stopping...
[sandboxScript:info] Simulation stopped.
Input Lua code here, or type "help()" (use TAB for auto-completion)
Sandbox script

Conclusions

Achieved Results

In this project, we provided the implementation and evaluation of a simultaneous contact and external wrench estimation system for aerial robots without the need for additional on-board sensors

Weaknesses

As motivated in the section *Discrimination*, The wrench estimator lacks of the module for discrimination between areodynamics and contact wrenches.

Improvements

A particle filter can be used, as proposed in **[Tomic et al.]**, to directly estimate the contact force position on the robot convex hull

References

Simultaneous Contact and Aerodynamic Force Estimation (s-CAFE) for Aerial Robots

Teodor Tomic, Philipp Lutz, Korbinian Schmid, Andrew Mathers, Sami Haddadin

https://arxiv.org/abs/1810.12908

Collision Detection and Safe Reaction with the DLR-III Lightweight Manipulator Arm

Alessandro De Luca, Alin Albu-Schaffer, Sami Haddadin, Gerd Hirzinger

https://ieeexplore.ieee.org/document/4058607

Nonlinear Control of VTOLs UAVs incorporating Flapping Dynamics

Sammy Omari, Minh-Duc Hua, Guillaume Ducard, Tarek Hamel

https://ieeexplore.ieee.org/document/6696696

Thanks