# Short Course: Quadcopter Modeling and Simulation

By Author

Date

# Few Things to Note

- This course is spread across 8 lectures
- First 6 lectures will be delivered in-person and last two will be online
- A few simple tasks as assignments
- This is NOT a mathematics-heavy course; we will focus more on implementation
- Simulation Platform: MATLAB and Simulink
- Suitable for
  - All UG, PG and PhD students with an engineering background
- Pre-requisites:
  - Basic knowledge of engineering mathematics (Mandatory)
  - Exposure to MATLAB and Simulink (Nice to have)

# Before we start…

1. Which department are you from?
2. Do you have any background in robotics/drones (courses, projects etc.)?
3. What do you expect to learn out of this course?
4. Your experience with MATLAB and Simulink

# Pre-Course Survey

https://tinyurl.com/SC361Survey

# Course Outline and Schedule

| Date | Lecture | Time | Topic |
|---|---|---|---|
| Sep 12 | Lecture 1 | 6:00 – 7:30 pm | Introduction to UAVs and Overview of MATLAB and Simulink |
| Sep 13 | Lecture 2 | 6:00 – 7:30 pm | First principle modeling of a quadcopter and basics of control |
| Sep 14 | Lecture 3 | 10:30 am – 12:00 noon | Quadcopter control |
| | Lecture 4 | 2:00 – 3:30 pm | Introduction to Simscape and Multidomain Physical Modeling |
| Sep 15 | Lecture 5 | 10:30 am – 12:00 noon | Scenario Generation and Path Planning |
| | Lecture 6 | 2:00 – 3:30 pm | Introduction to ROS and hardware deployment |
| Sep 20 | Lecture 7 (Online) | 6:00 – 7:30 pm | Introduction to Perception and State Machines |
| Sep 27 | Lecture 8 (Online) | 6:00 – 7:30 pm | Case Study |

# What are UAVs?

- Unmanned Aerial Vehicles
- Class of Robotic Systems
- Generally fixed-wing or multi-rotor (quadcopter type) configuration
- Wide variety of payloads and sizes: from “insect-like” to “flying cars”
- Huge range of applications

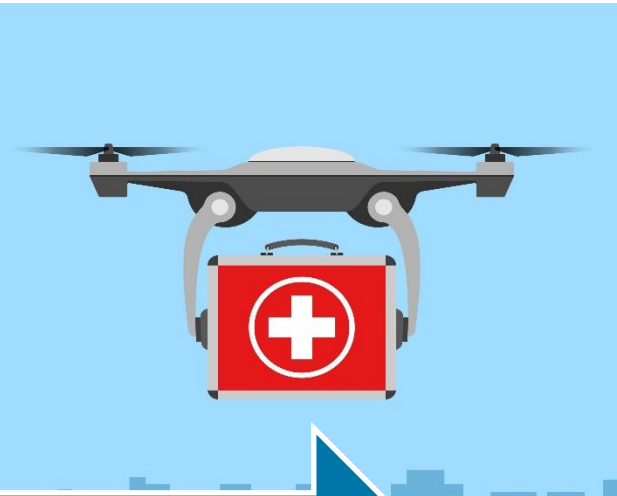
# Current Trend: Increase in usage of UAVs across sectors

**Education**

**Surveying**

**Inspection**

**Delivery**



**Manual Operations** → **Autonomous Flight**

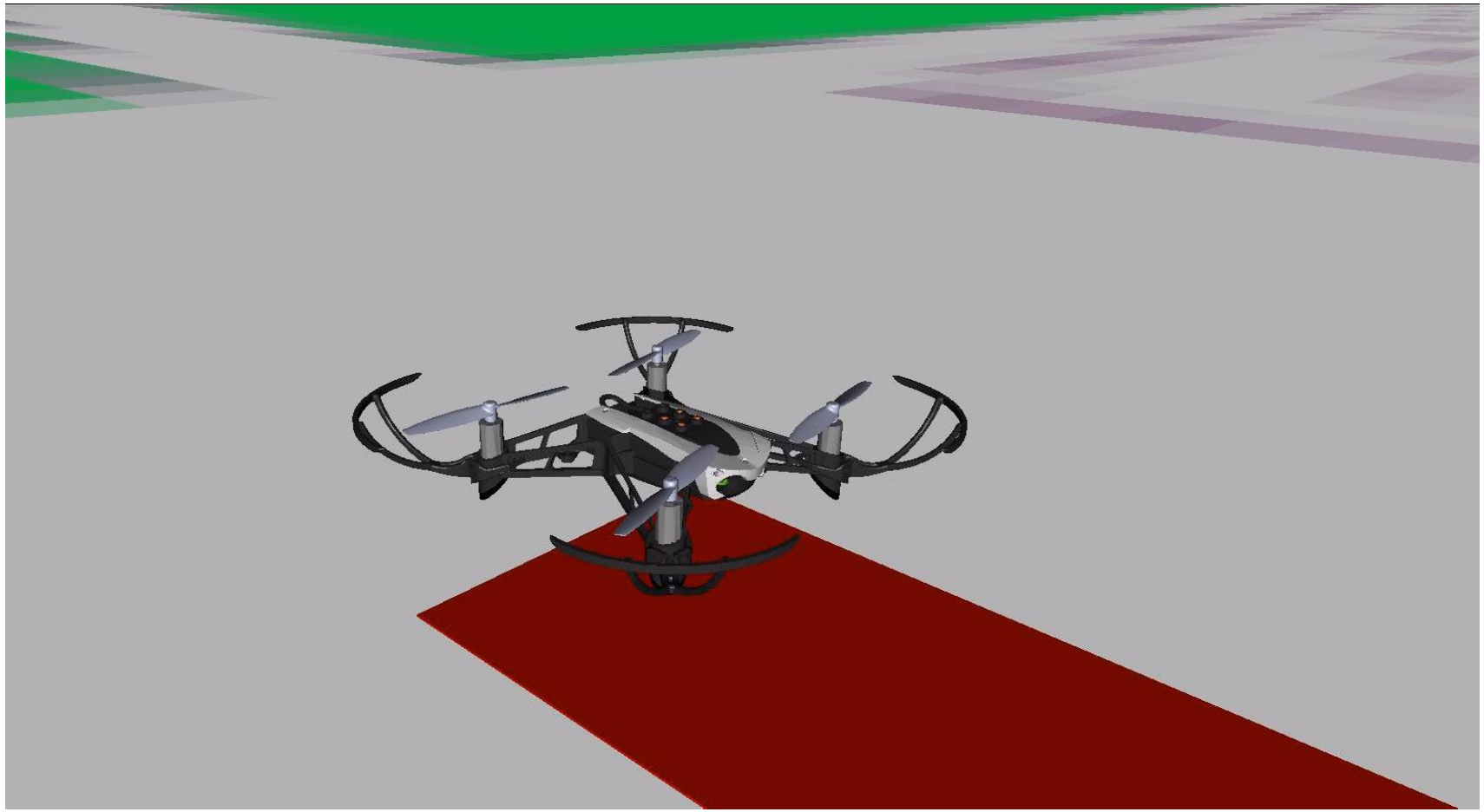
**Filming**

**Measurement**

**Monitoring**

**Transport**

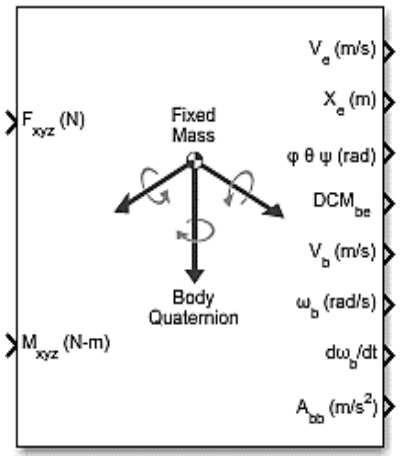
# Drone following a defined path



# Common tasks for UAV Development

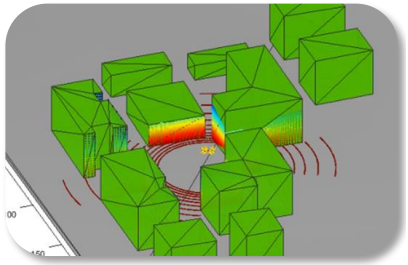
## Platform

- Modeling Kinematics & Dynamics
- Sizing and Configuration
- Vibration Analysis



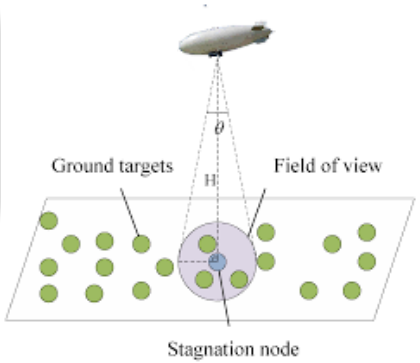

## Sense

- Camera/LIDAR etc.
- Sensor filtering
- Sensor calibration
- Co-simulation



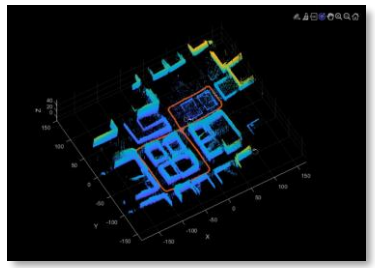
## Perceive

- Environment mapping
- Classification
- Segmentation
- Object Detection
- Sensor Fusion



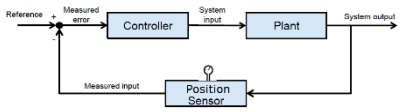

## Decide & Plan

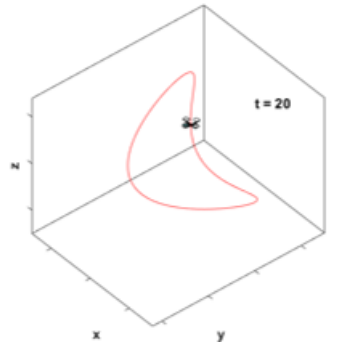
- Localization
- Path & motion planning
- SLAM
- Map management
- Object Avoidance



## Control

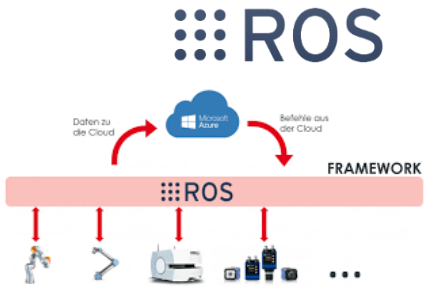
- Guidance, Navigation & Control
- Multi-robot co-ordination
- Impedance Control




## Connect

- Code Generation
- Networked Robots
- Communication models
- Multi-agent communication





PX4®

# MathWorks Tools to Accelerate Autonomous System Development

Platform

Sense

Perceive

Decide & Plan

Control

Connect

Robotics System Toolbox™

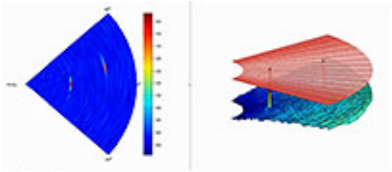
Simscape™

UAV Toolbox®

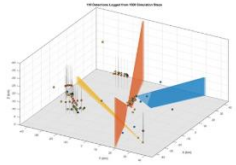
MATLAB® & SIMULINK®

Computer Vision Toolbox™

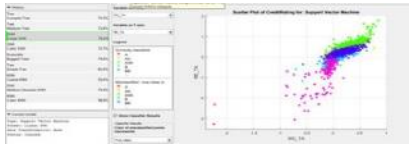
Phased Array System Toolbox™



Sensor Fusion and Tracking Toolbox™



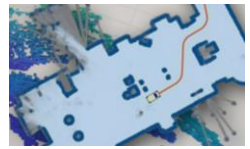
Statistics and Machine Learning Toolbox™



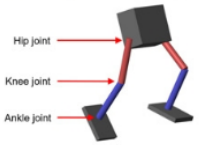
Deep Learning Toolbox™


Automated Driving Toolbox™

Navigation Toolbox™

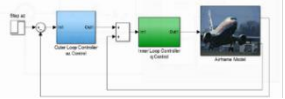


Reinforcement Learning Toolbox™

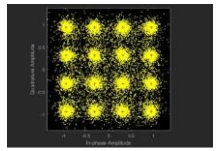



Model Predictive Control Toolbox™

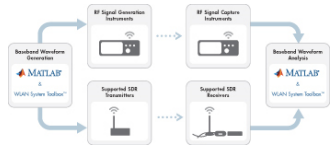
Control System Toolbox™



WLAN Toolbox™



Communications Toolbox™

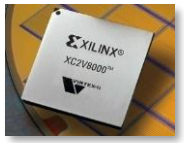


HW Support Packages

Embedded Coder™


Simulink Real-Time™

HDL Coder™




GPU Coder™

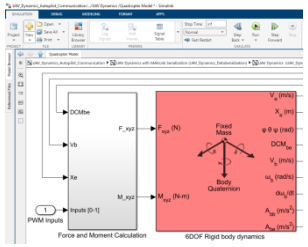
ROS Toolbox

# Building Blocks for UAV Simulation

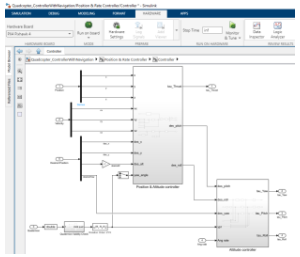
## Design/Model

**Model flight dynamics and design flight controller**

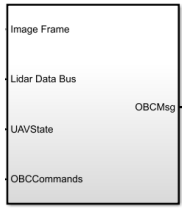
### Plant Model



### Flight Controller



### Autonomy Algorithms



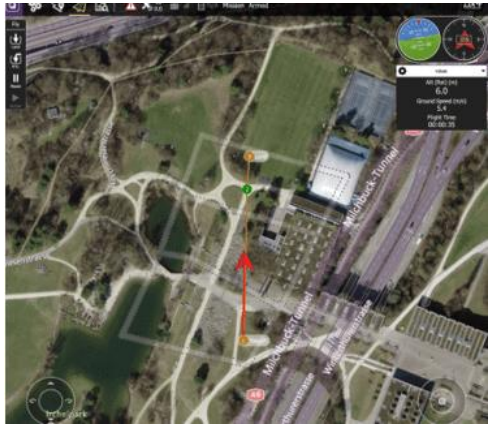

Obstacle Avoidance

## Simulate

**Simulate plant behavior in virtual scenarios with simulated flight paths**

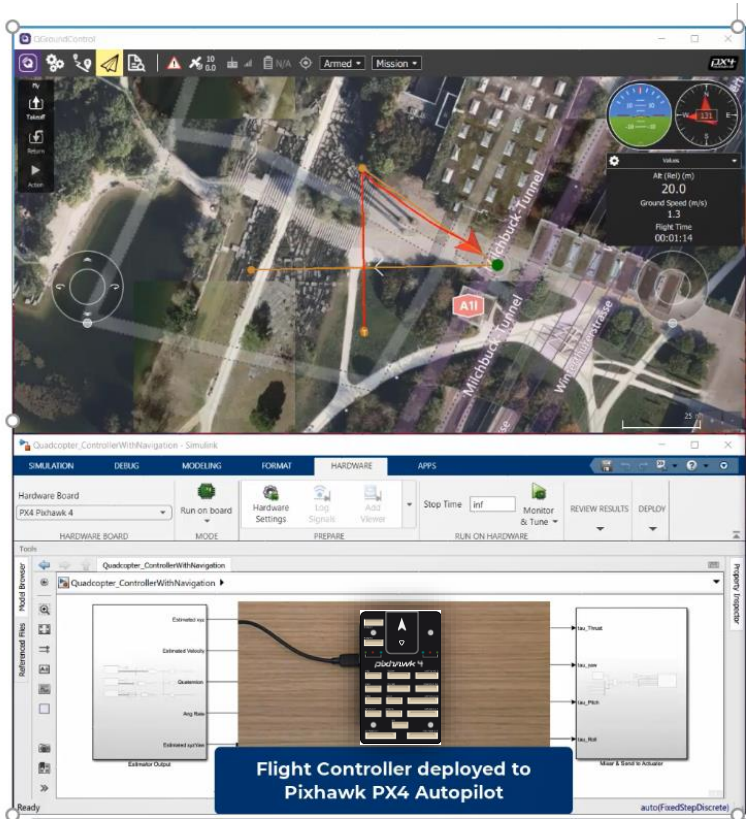
### Scenario Simulation

### Ground Control Station

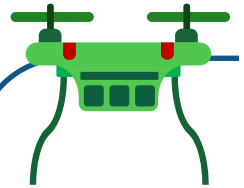


## Deploy

**Deploy flight controller and autonomy algorithms to the platform**



# Integrated workflows for developing UAV applications



MATLAB®

Simulink®

System Architecture

## Model UAV

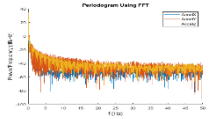
## Design Algorithms

Perception

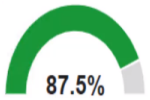
Planning & Decision

Control

## Analyze Data



## Verification & Validation

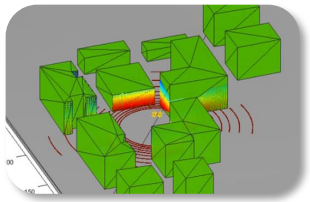



DO-178

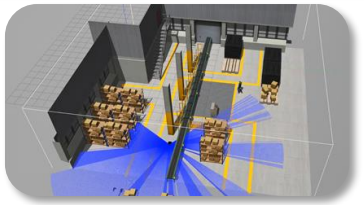
Implement

Connect

## Simulate with Sensor Models



Cuboid



Gazebo

Unreal Engine

## Deploy to Hardware


PX4®

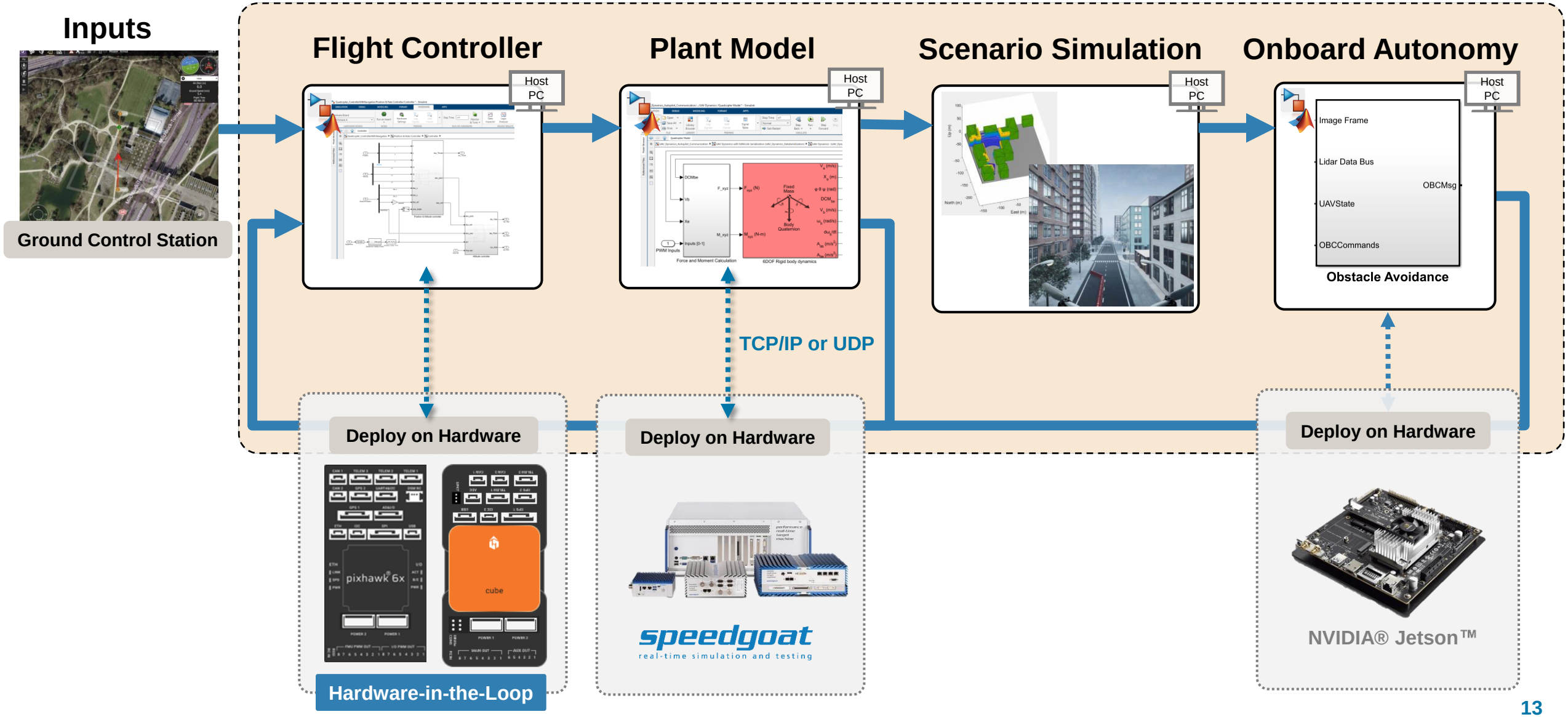
NVIDIA® Jetson®

## Connect

UAV

Ground Control Station

# Typical UAV Development Workflows



# #1 question of the UAV design process:

## *What level of the development are we working at?*

Are we:

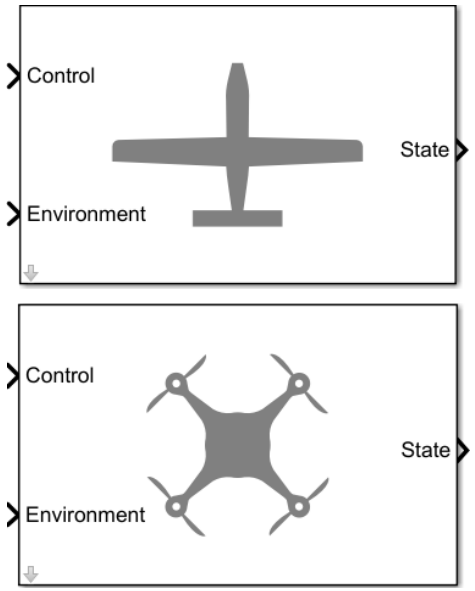
- Building the Flight Hardware?
- Programming the Control and Navigation system?
- Sizing the Battery and/or Payload properly?
- Developing Sensing hardware and Perception algorithms?
- Or all of the above?

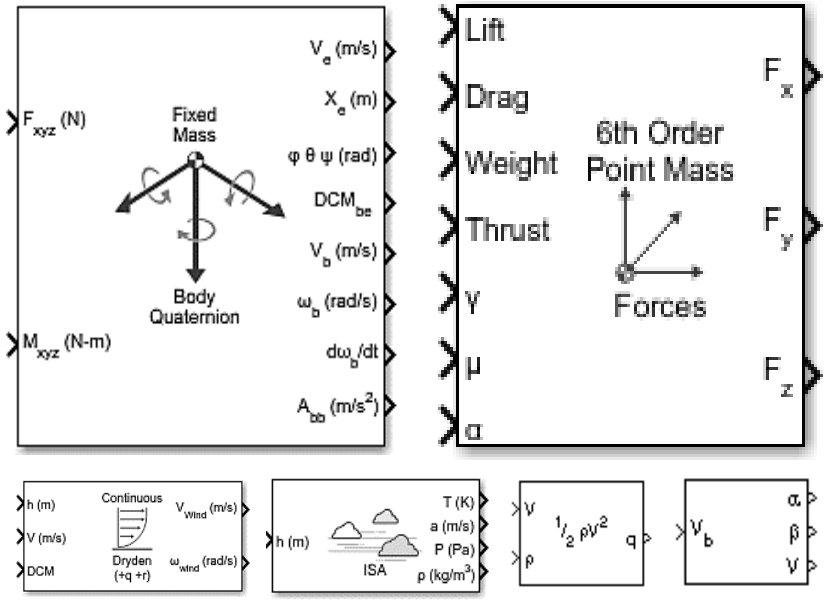
Developing a ‘systems-level’ understanding is key to selecting the right *fidelity*.

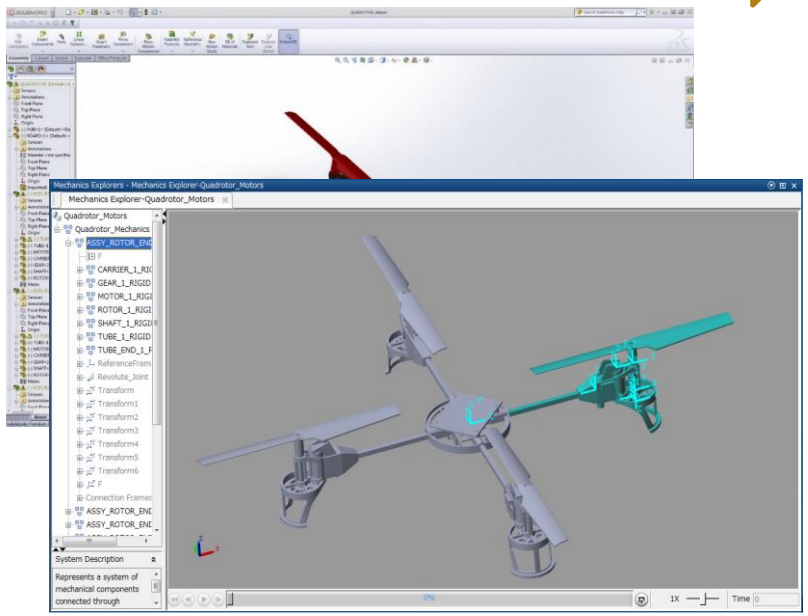
# UAV Plant Modeling: Selecting the appropriate fidelity

**Approximate**
*Programming UAV*

**High-Fidelity**
*Building UAV*



## Guidance Model [Link]

Reduced-order model for UAV

## Vehicle Dynamics [Link]

Model aerodynamics, propulsion, and motion of aircraft and spacecraft

## Physical Modeling [Link]

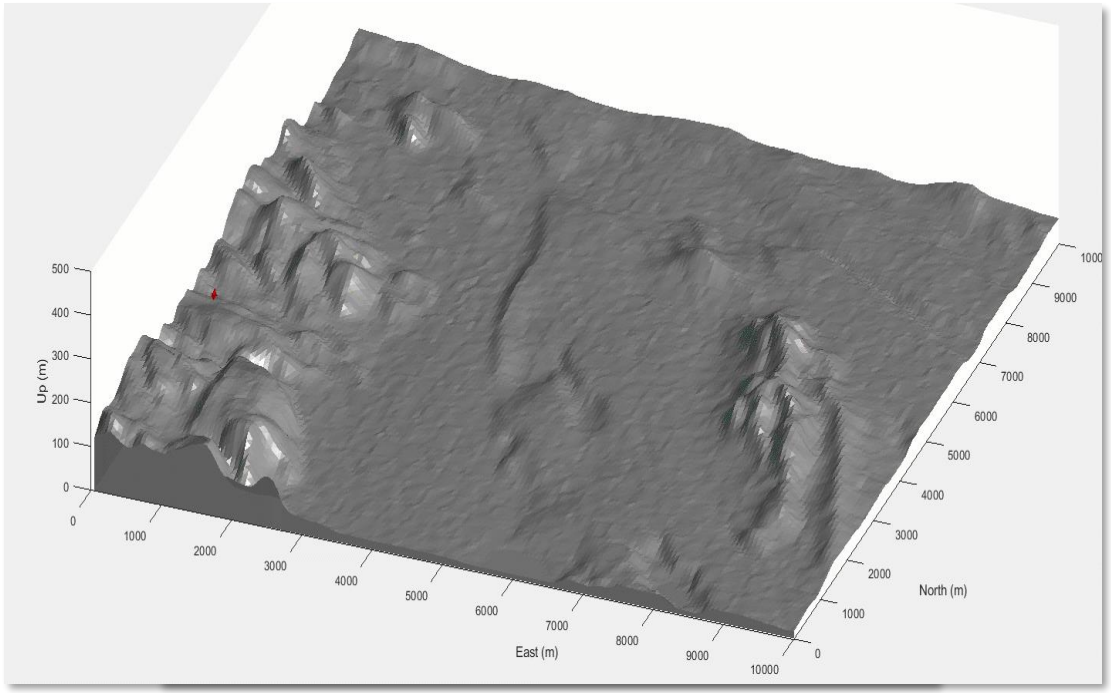
Model construction techniques and best practices, domain-specific modeling, physical units

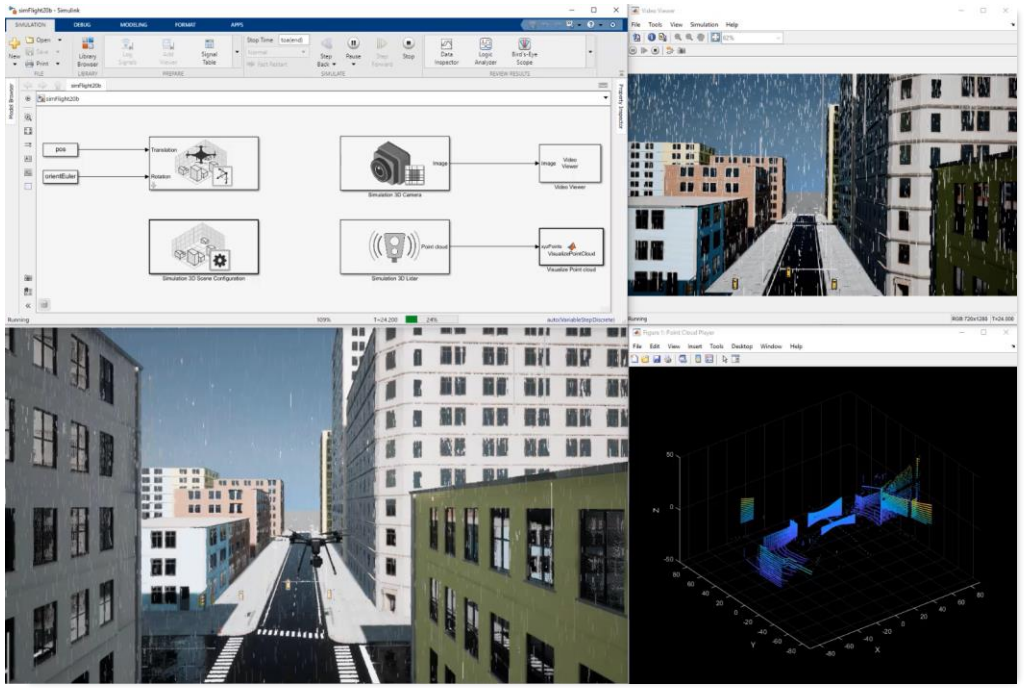
*UAV Toolbox, Aerospace Blockset, Simscape Multibody*

# Integrated simulations with sensor models

**Cuboid**
*Performance*

**Unreal Engine®**
*Photorealistic*



Rapidly author scenarios and generate sensor data

Realistic graphics to test autonomous algorithms in closed-loop simulations

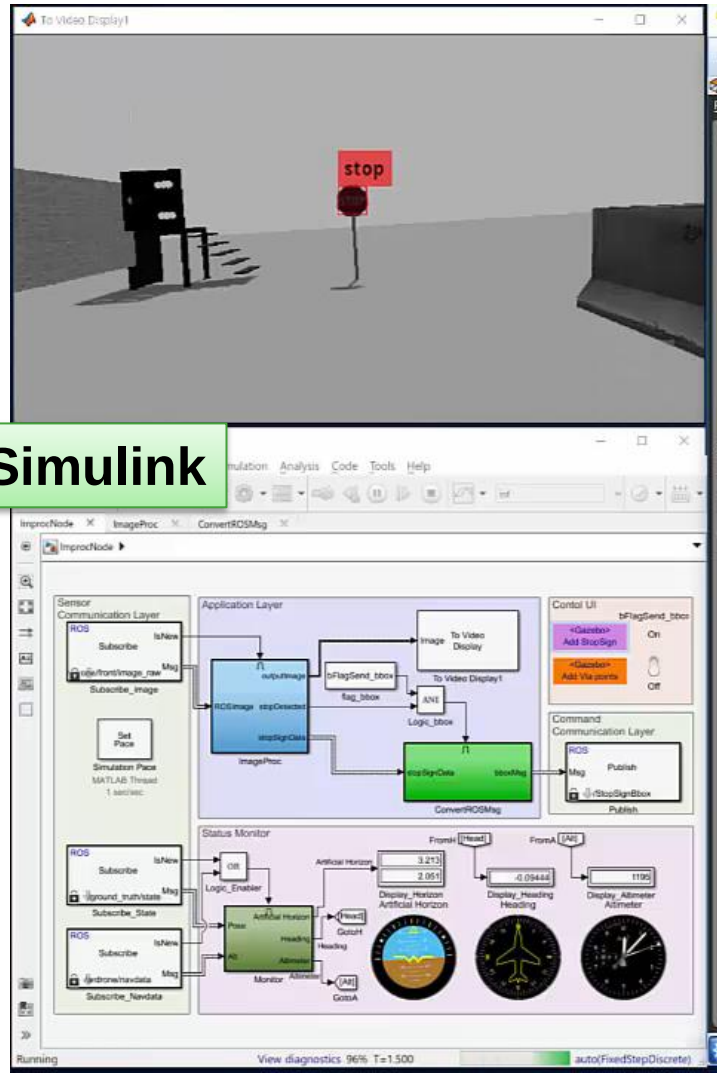
Link

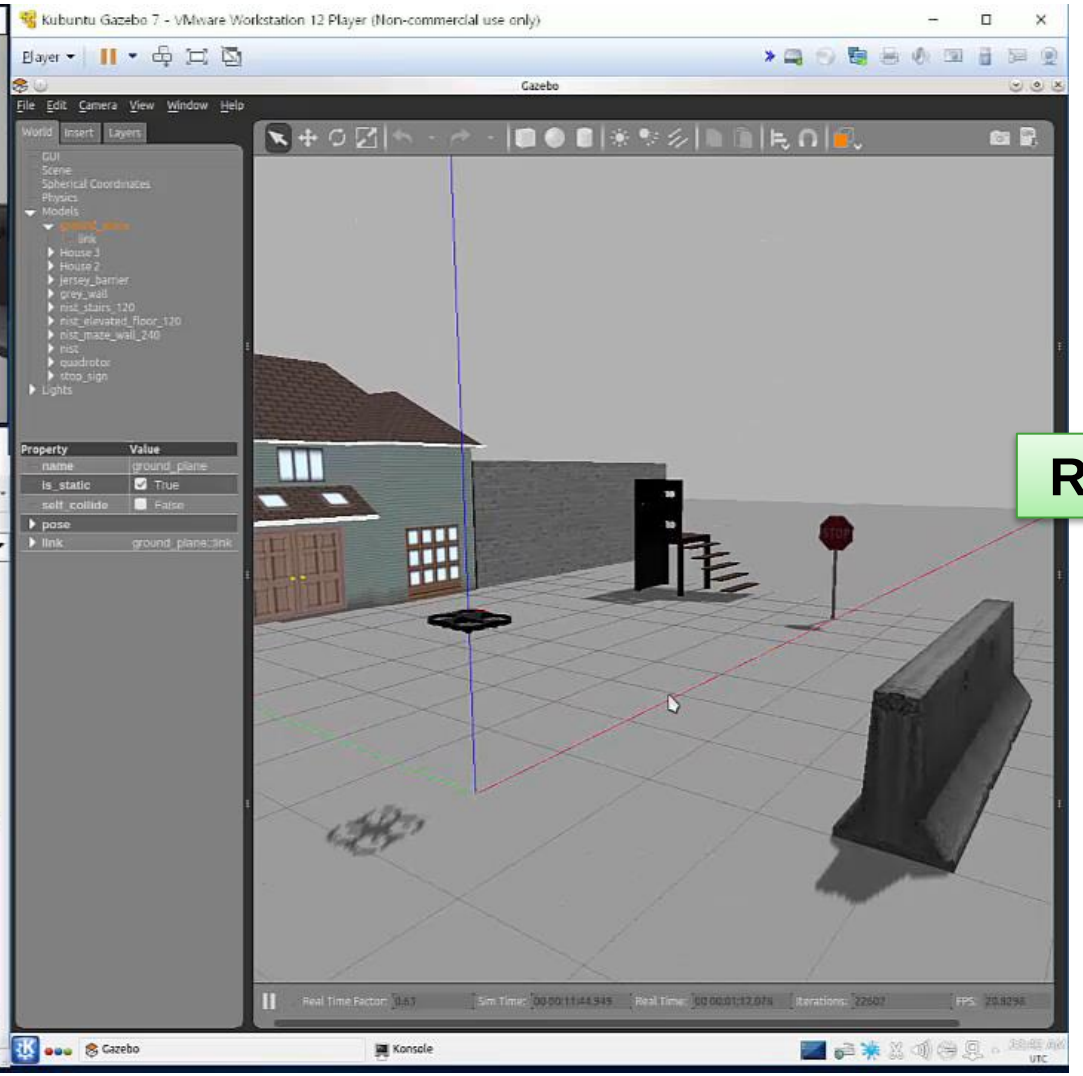
Link

# Simulate and verify autonomous algorithm

**Evaluate algorithms with Robotics System Toolbox, ROS, and Gazebo**

**MATLAB/Simulink**




**ROS + Gazebo**

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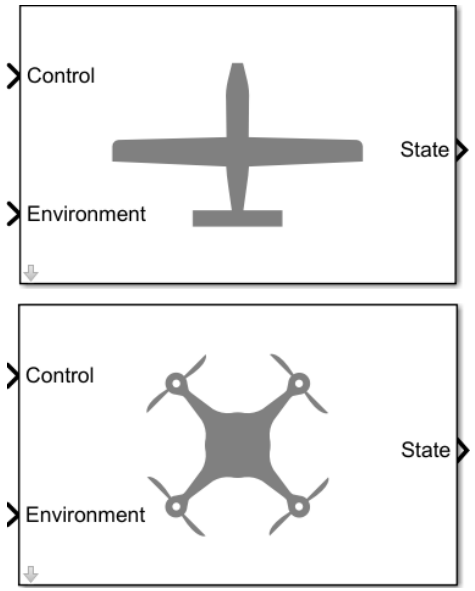
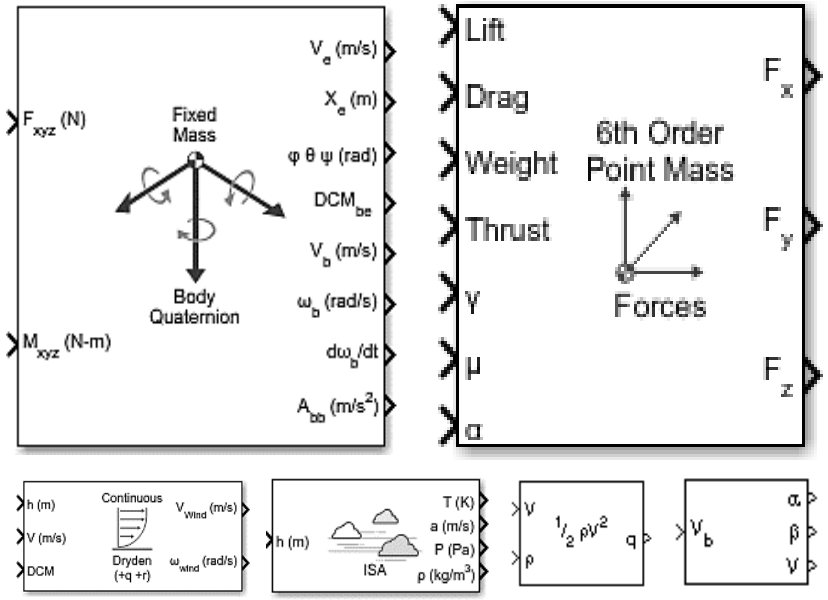
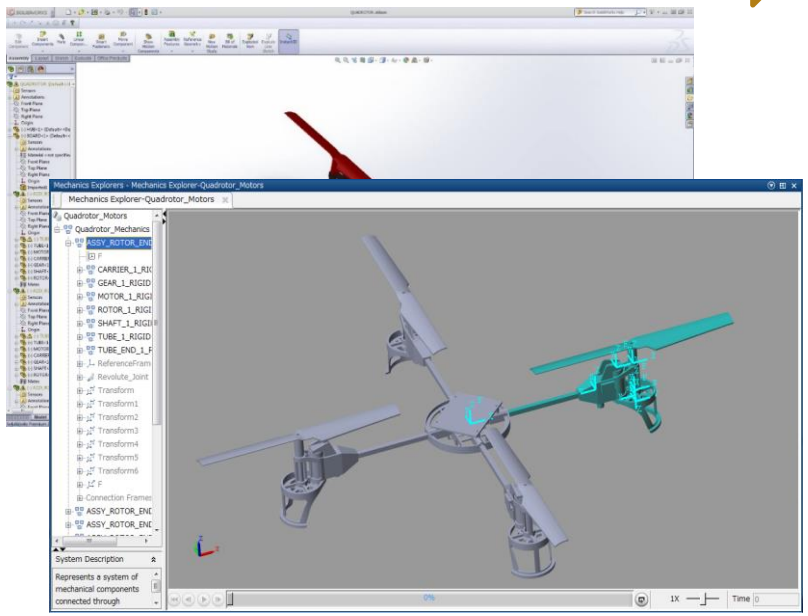
**Approximate**
*Programming UAV*

**High-Fidelity**
*Building UAV*



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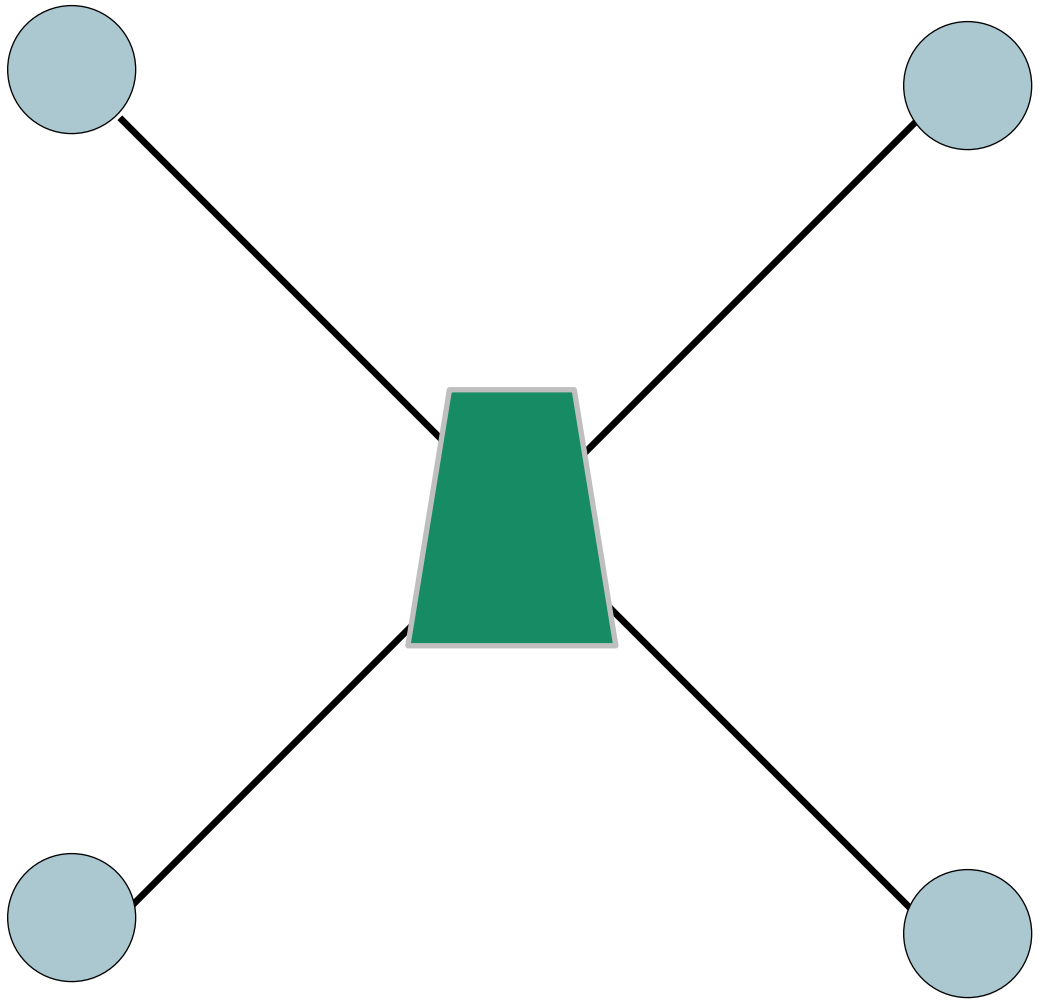
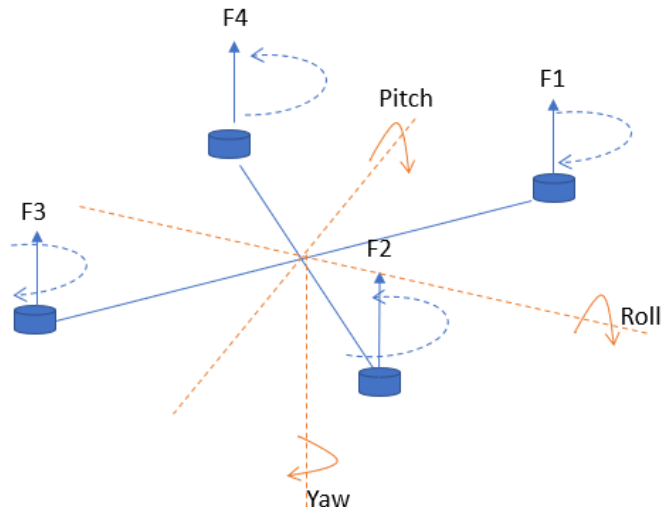
*UAV Toolbox, Aerospace Blockset, Simscape Multibody*

# What is a quadcopter?

- Rotating wing aircraft (rotorcraft)
- 4 rotating propellers
- Rotors used to generate lift



# Equations of motion





- Work on the concept of balancing forces and torques
- Translational Dynamics:

$$F_{frame} = F_{gravity} - F_{thrust} - F_{drag}$$

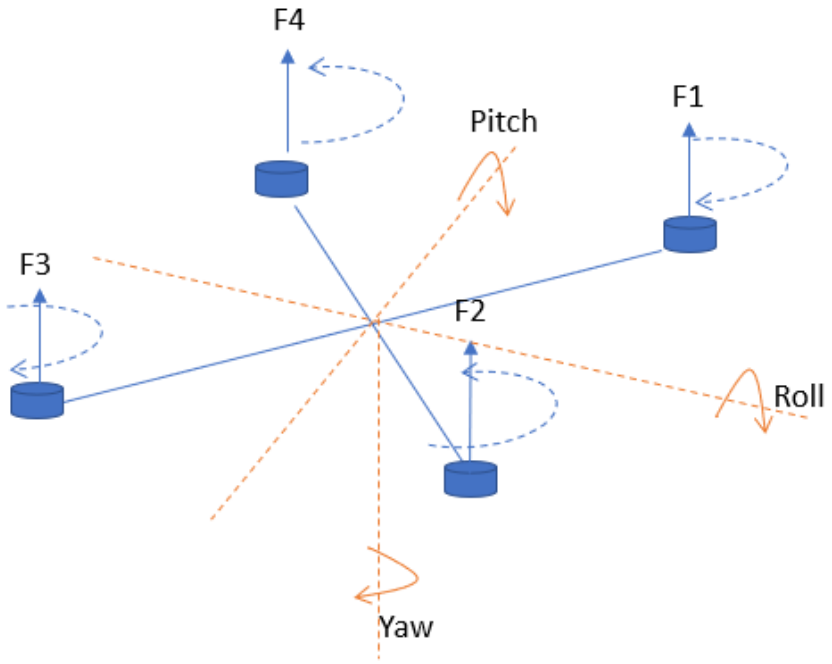
- Rotational Dynamics:

$$\tau_{frame} = \tau_{motors} - \tau_{gyro} - \tau_{inertia}$$

# Drone motions

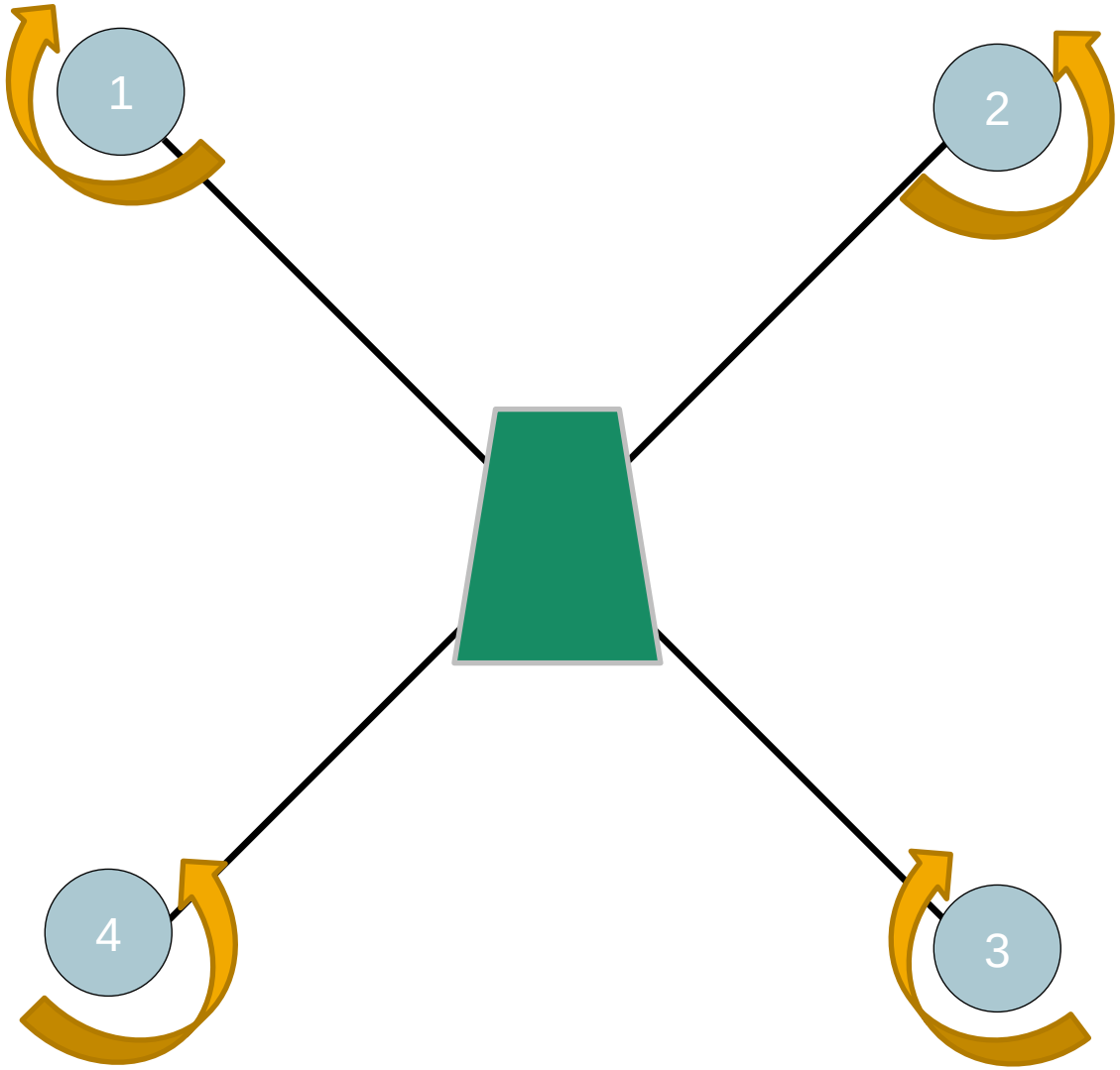
- 6 degrees of freedom
  1. Up-down
  2. Left-right
  3. Forward-backward
  4. Rotation around X-axis: Roll
  5. Rotation around Y-axis: Pitch
  6. Rotation around Z-axis: Yaw

- What we will control?
  - Thrust, Pitch, Roll, Yaw



# How do we control the drone the motion?

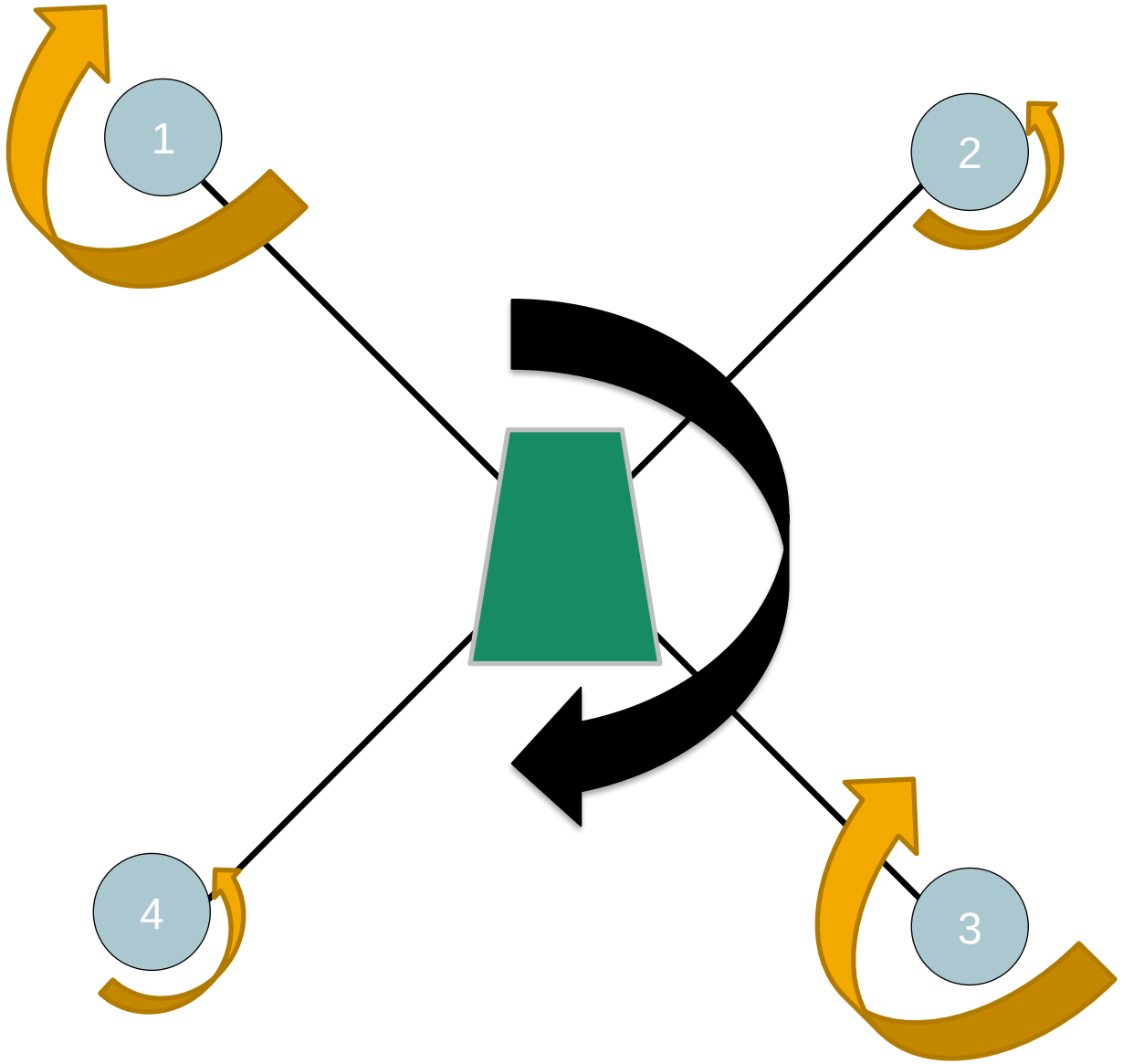
*Thrust*




*Motor arrows indicate motor torque direction*

# How do we control the drone the motion?

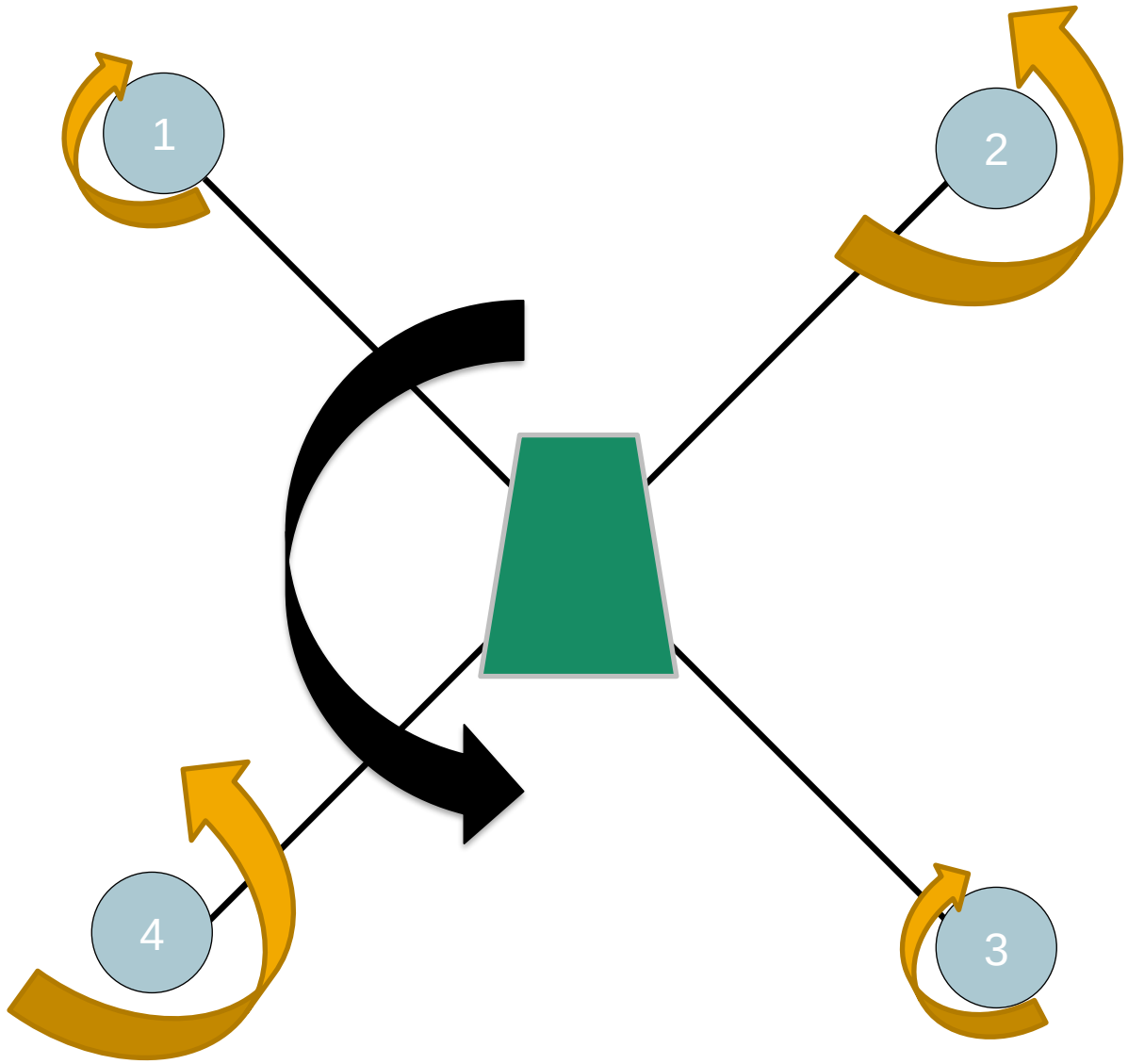
*Yaw*




*Motor arrows indicate motor torque direction*

# How do we control the drone the motion?

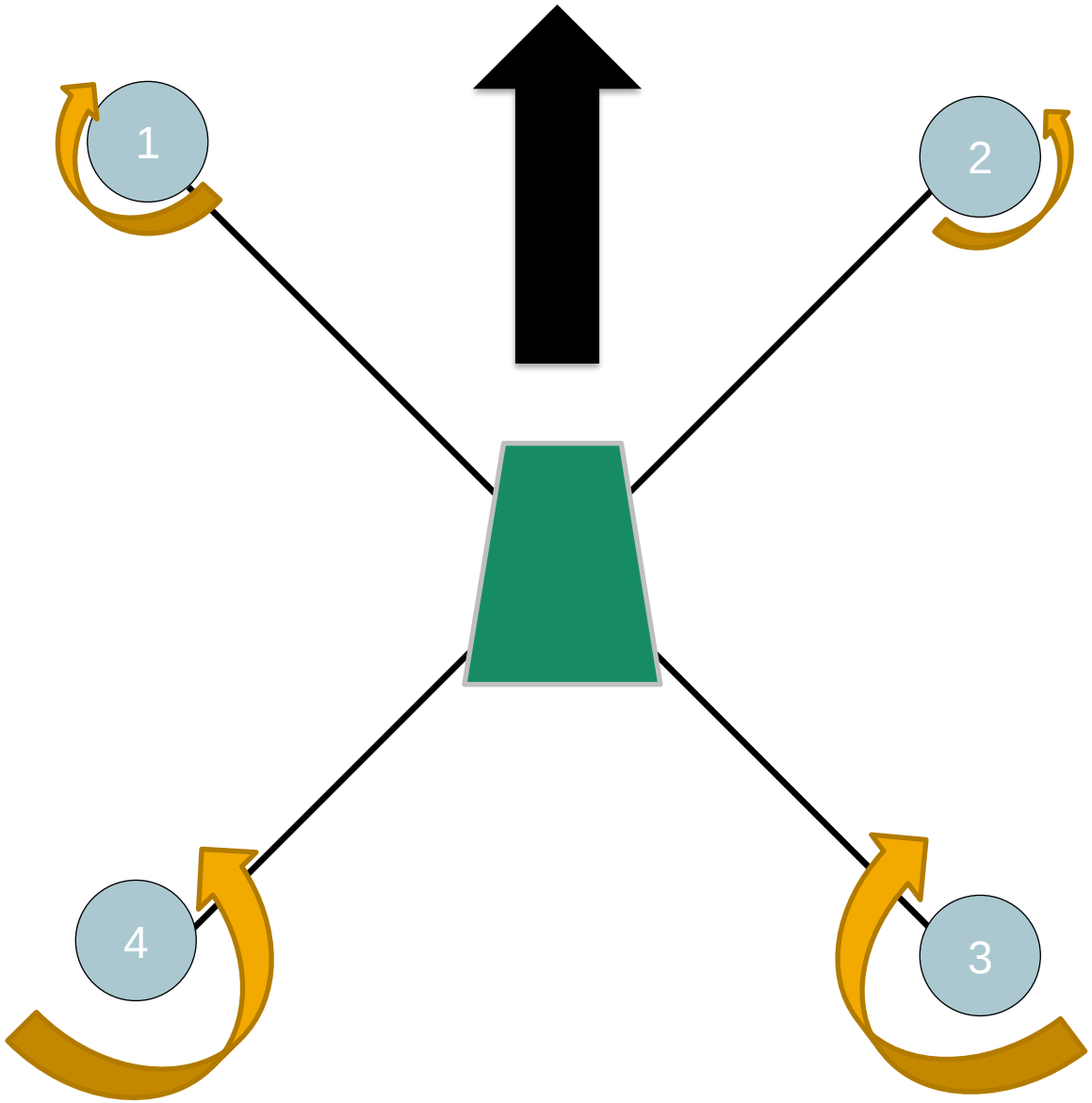
*Yaw*




*Motor arrows indicate motor torque direction*

# How do we control the drone the motion?

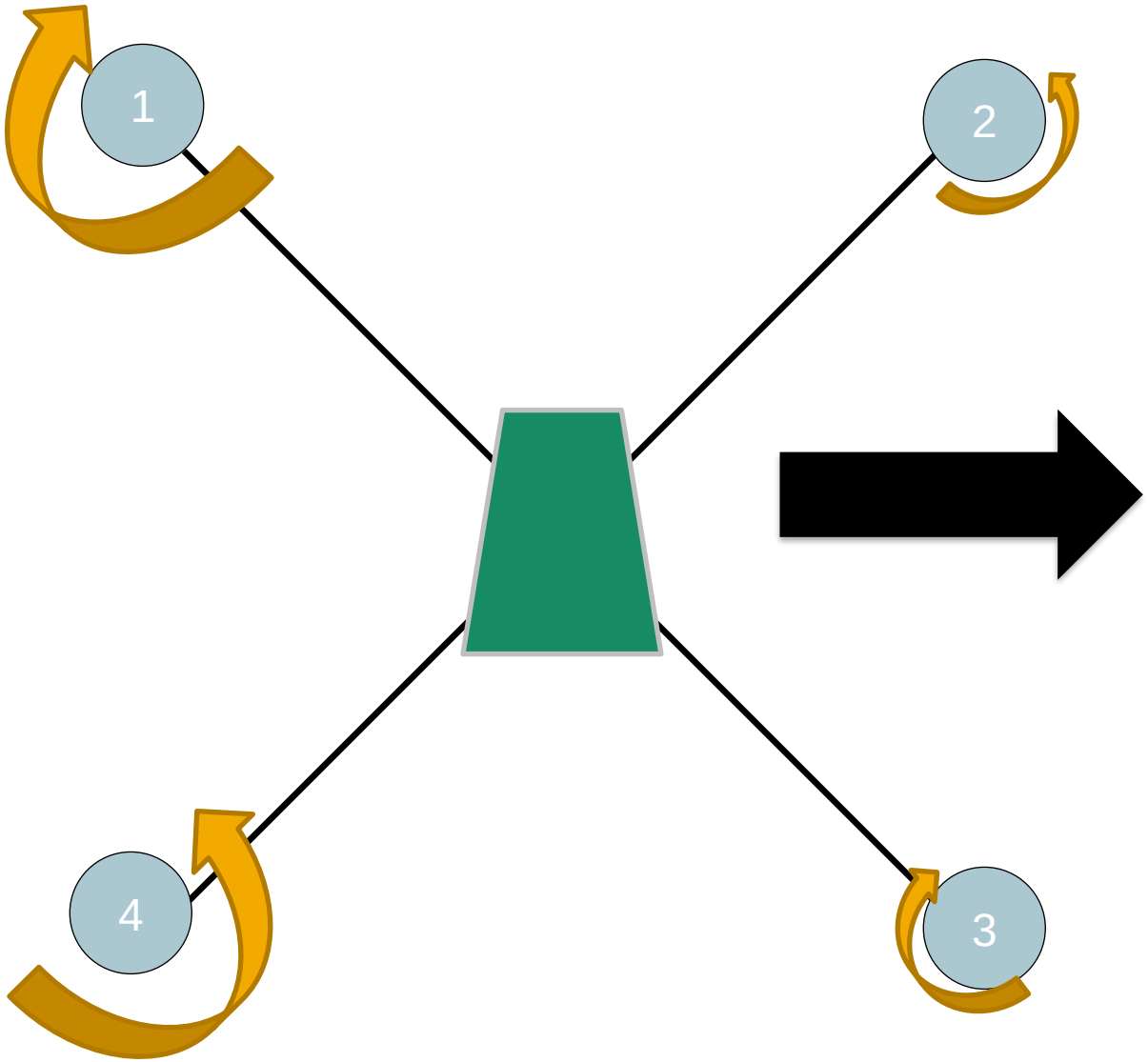
*Pitch*




*Motor arrows indicate motor torque direction*

# How do we control the drone the motion?

*Roll*




*Motor arrows indicate motor torque direction*

# Let’s go to MATLAB

# Simulation and deployment with MathWorks tools across the industry

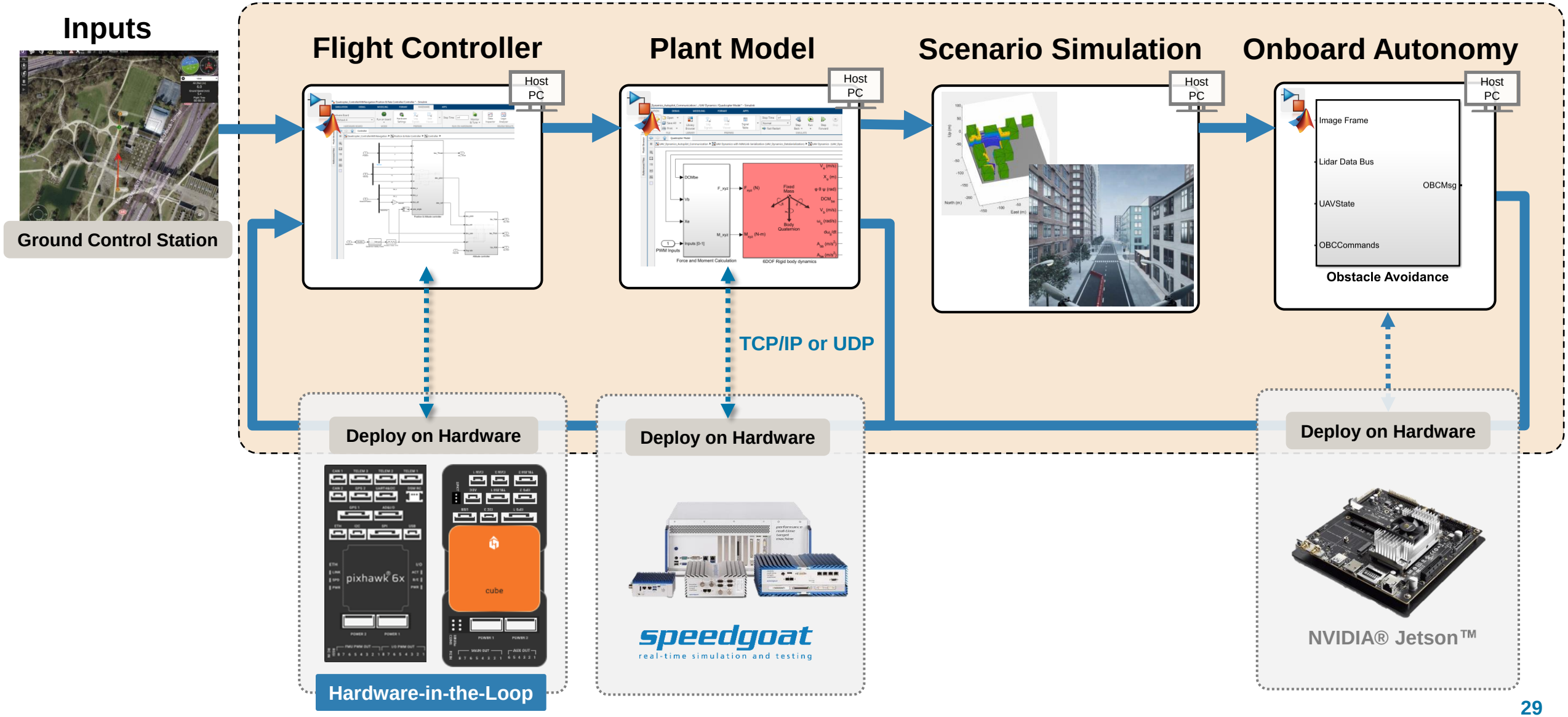
3D Photorealistic Visualization of **Supernal's** eVTOL Platform Over Los Angeles


- Build air taxis
- Simulated in real city environment of LA

**NASA's** Multicopter Test Flight with Simulink Deployed Controller


- Built accurate controllers
- Modelled/simulated in Simulink
- Deployed to physical controller

# Typical UAV Development Workflows



# Homework

- Install the latest version of MATLAB R2024a with all toolboxes
- Complete MATLAB Onramp
- Complete Simulink Onramp
- Link to submit certificates: https://tinyurl.com/IITGNCourse

**Share Certificate URL | Short Course at IITGN**