

MATLAB EXPO

2021

Mission Planning of a Quadcopter Using a Digital Twin

Maria Gavilan



Sara Nambi



MATLAB EXPO

2021

Mission Planning of a Quadcopter Using a Digital Twin

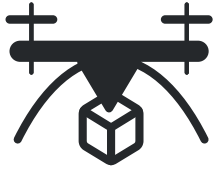
Kritika Ramani



Ameya Rajendra Godbole



Before we start, let's prepare to participate in this workshop



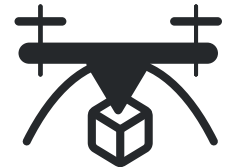
Use your laptop and a web browser to run exercises



Download instructions using the “Handouts” Tab




A group of TAs will assist with questions



Access MATLAB Online

1. Create your MathWorks account

Sign in to your MathWorks Account or create a new one.

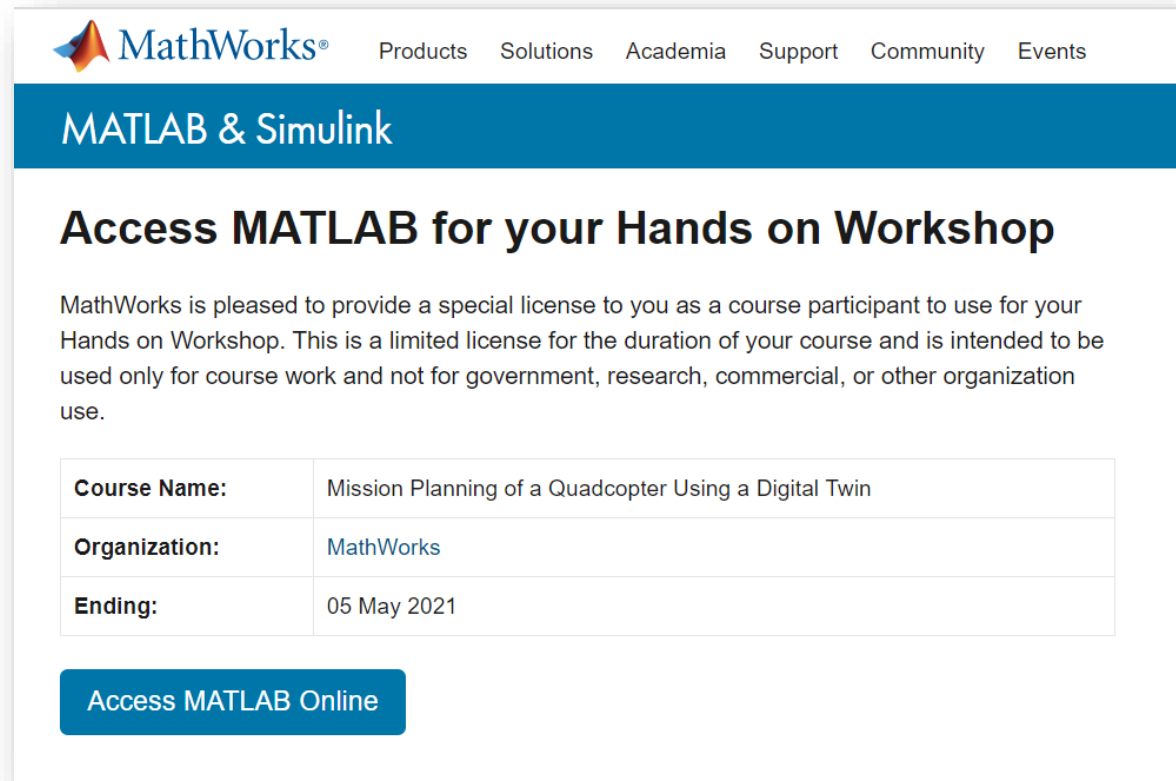


Email

[No account? Create one!](#)
By signing in you agree to our [privacy policy](#).

Next

2. Access your license
<https://tinyurl.com/DigitalTwinWorkshop>



MathWorks® Products Solutions Academia Support Community Events

MATLAB & Simulink

Access MATLAB for your Hands on Workshop

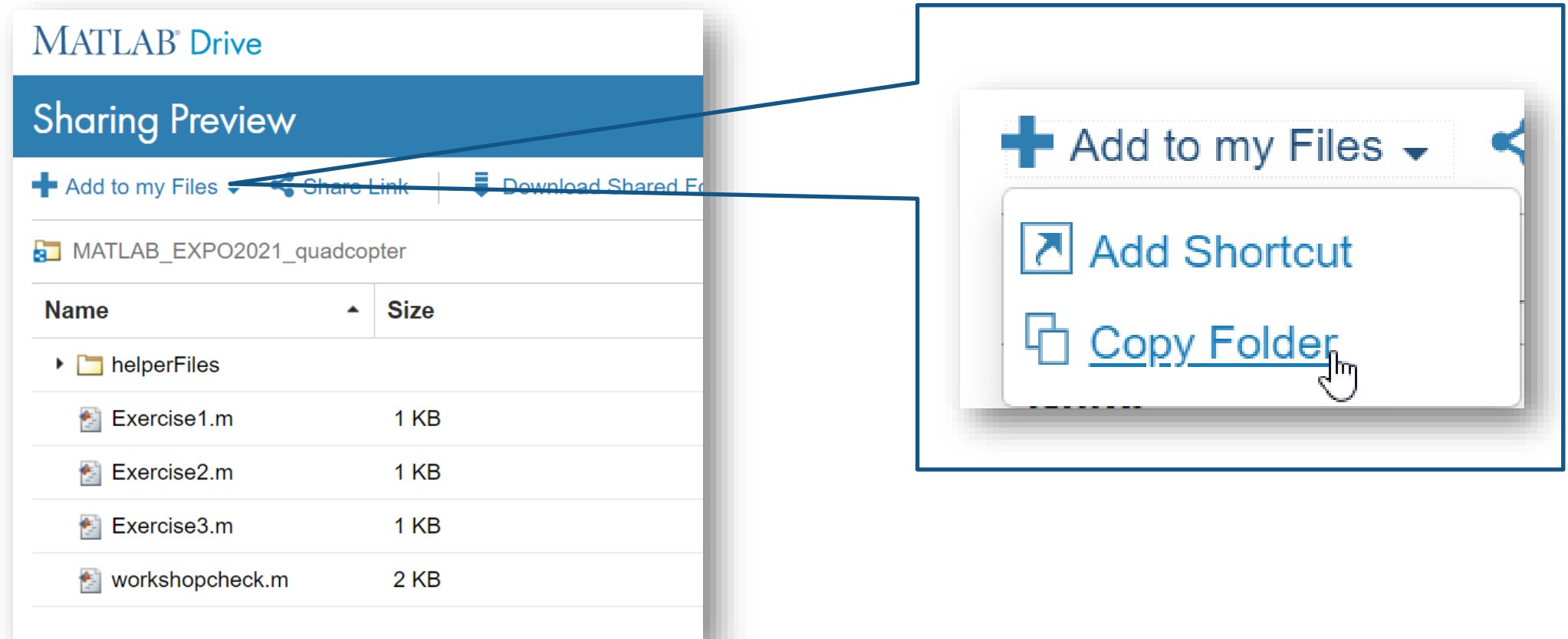
MathWorks is pleased to provide a special license to you as a course participant to use for your Hands on Workshop. This is a limited license for the duration of your course and is intended to be used only for course work and not for government, research, commercial, or other organization use.

Course Name:	Mission Planning of a Quadcopter Using a Digital Twin
Organization:	MathWorks
Ending:	05 May 2021

Access MATLAB Online

Access workshop files in MATLAB Drive

<https://tinyurl.com/DigitalTwinWorkshopFiles>



MATLAB Drive

Sharing Preview

+ Add to my Files | Share Link | Download Shared Files

MATLAB_EXPO2021_quadcopter

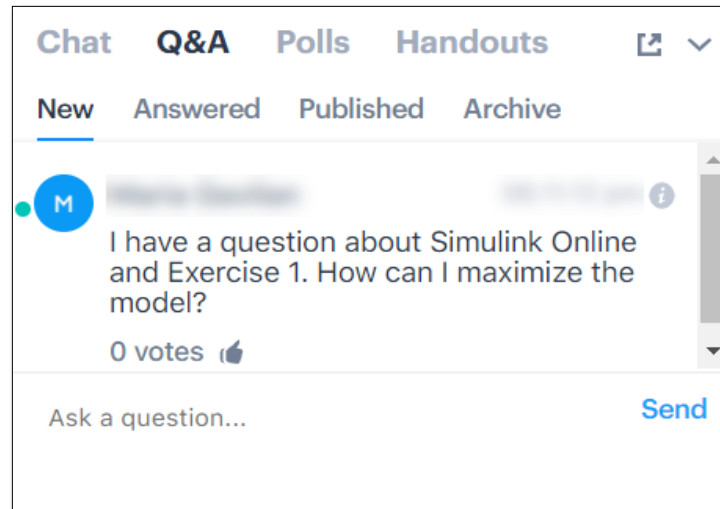
Name	Size
▶ helperFiles	
Exercise1.m	1 KB
Exercise2.m	1 KB
Exercise3.m	1 KB
workshopcheck.m	2 KB

+ Add to my Files ▾

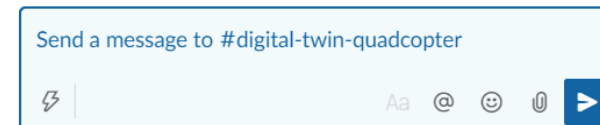
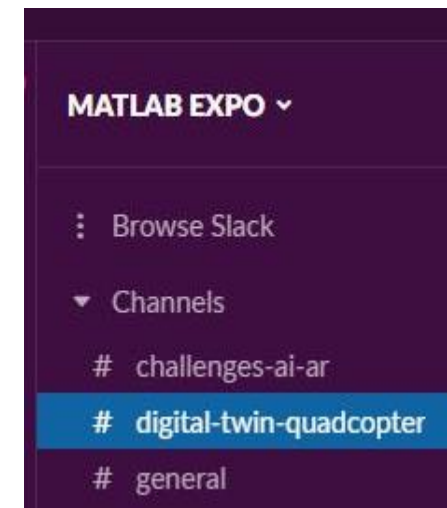
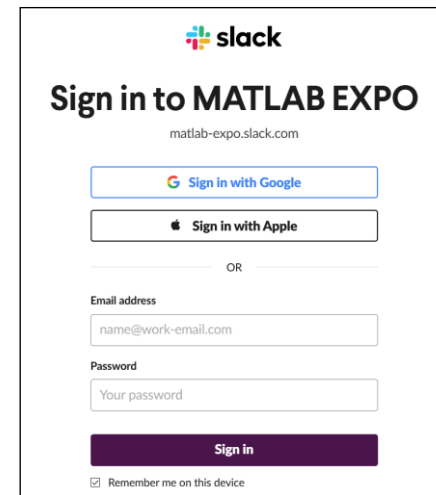
- ▶ Add Shortcut
- ▶ Copy Folder

How to get assistance during the workshop

BigMarker (use Q&A)

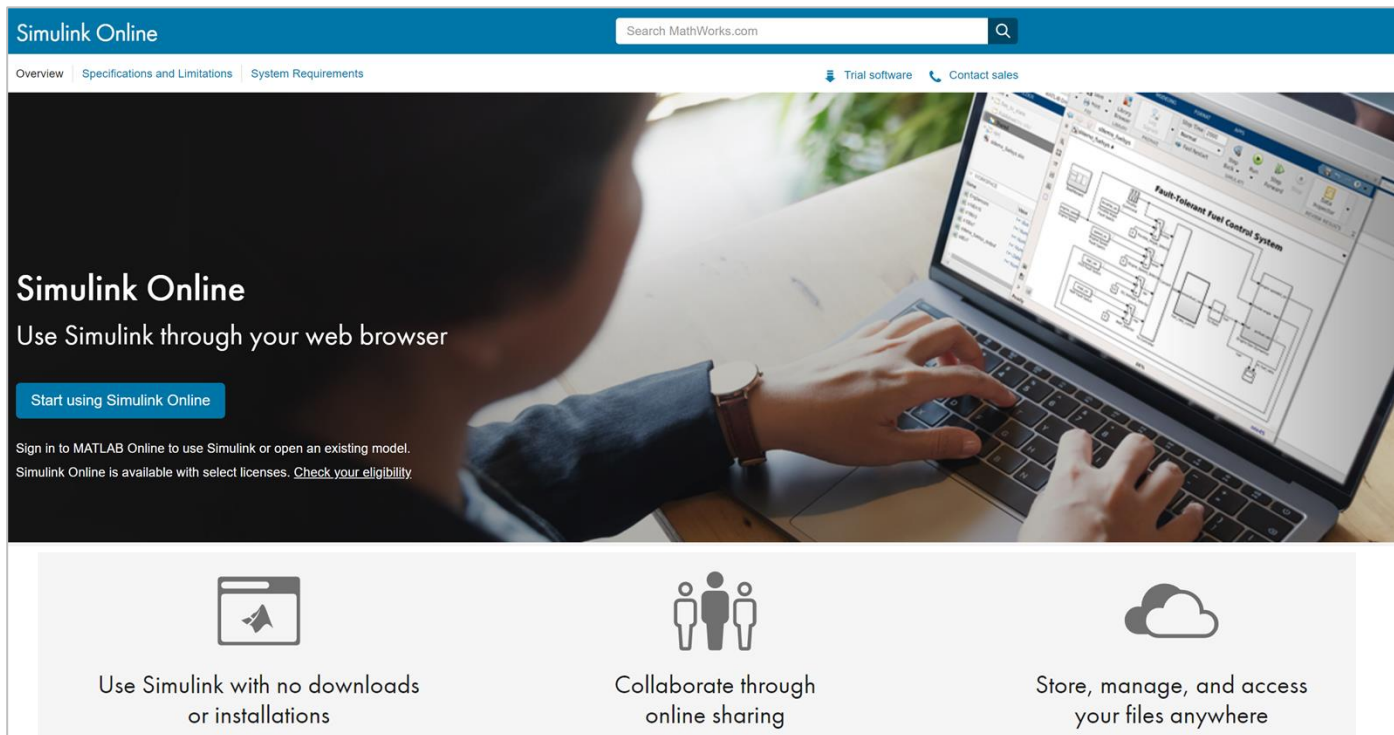


Slack



Products used in this workshop

Today we will be using **Simulink Online**



Simulink Online

Search MathWorks.com

Overview | Specifications and Limitations | System Requirements

Trial software | Contact sales

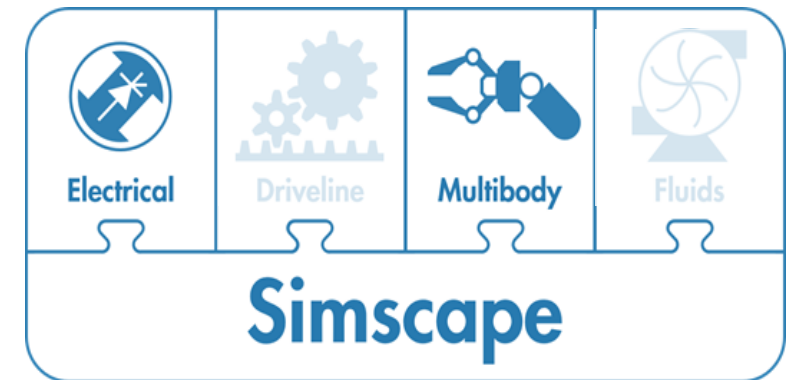
Simulink Online

Use Simulink through your web browser

[Start using Simulink Online](#)

Sign in to MATLAB Online to use Simulink or open an existing model.
Simulink Online is available with select licenses. [Check your eligibility.](#)

- Use Simulink with no downloads or installations
- Collaborate through online sharing
- Store, manage, and access your files anywhere



Navigation Toolbox™

**Predictive Maintenance
Toolbox™**

The problem we'll be tackling in this workshop



Design a delivery drone



Valuable cargo

What if the need is too critical and failure is not an option?

How to "fail fast" so we can address issues before deploying to real devices?

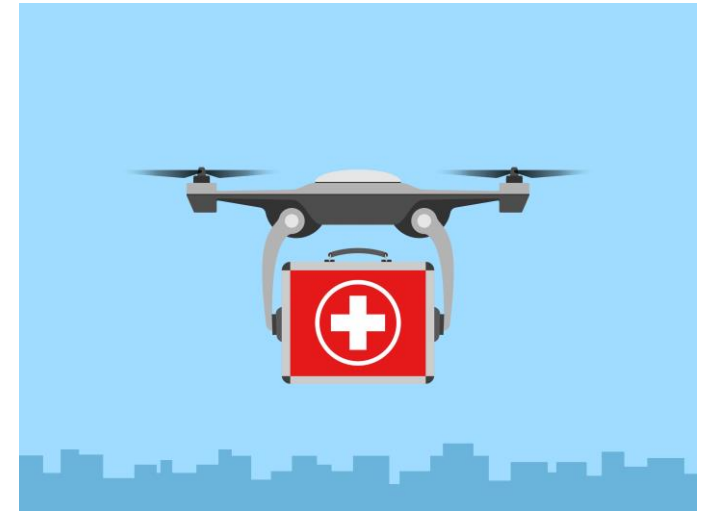
The problem we'll be tackling in this workshop



Design a delivery drone



Valuable cargo



Digital Twin

Workflow

Use your data to build models and predict failures

Data



Collect Data
Create Datastores

(both real + digital models)

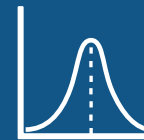
Model



Physical Modeling
(digital twin)

Behavior Modeling

Act



Predict
Fault Detection, RUL

Change Control

Integrate

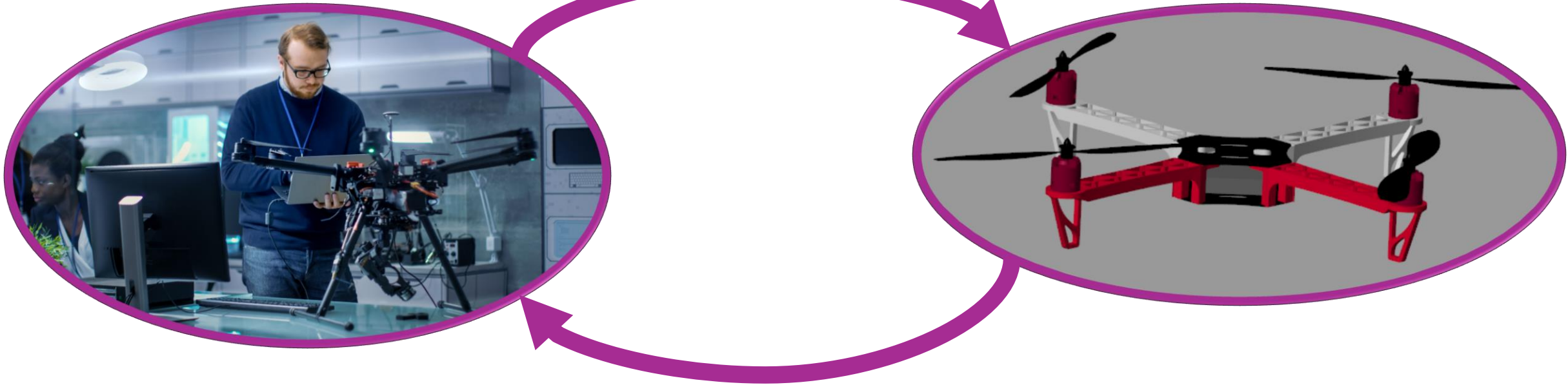


Code generation
Deploy

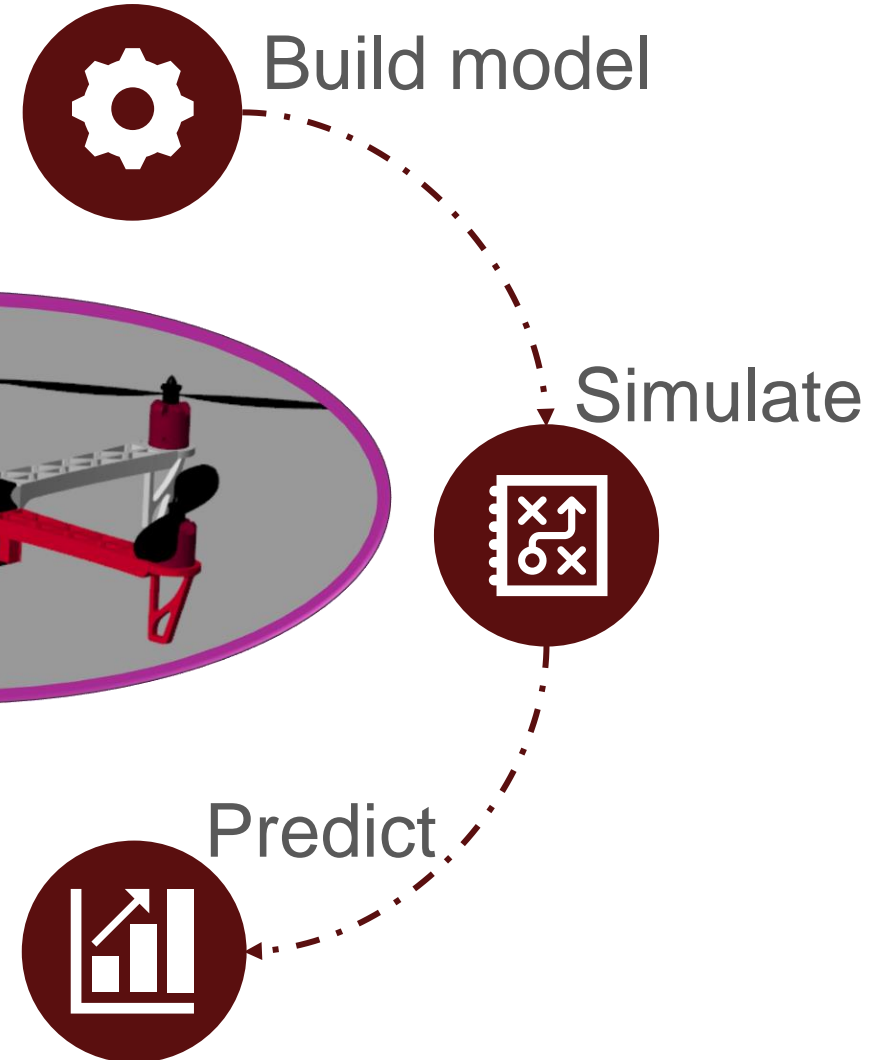
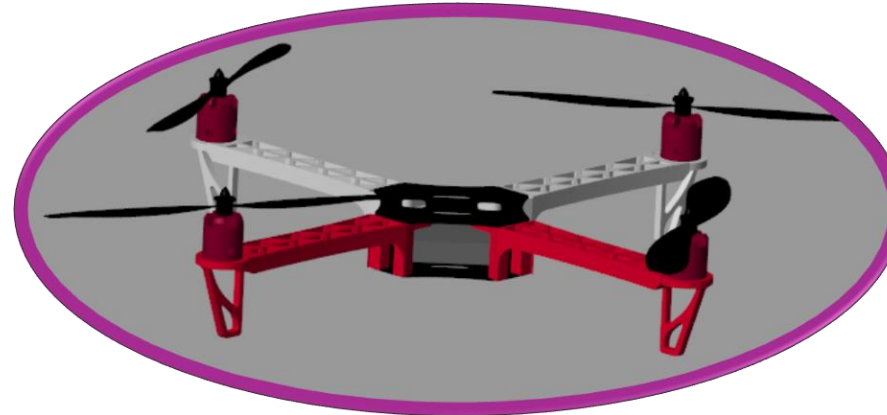
Digital twins connect the virtual world of simulation to real world operation.

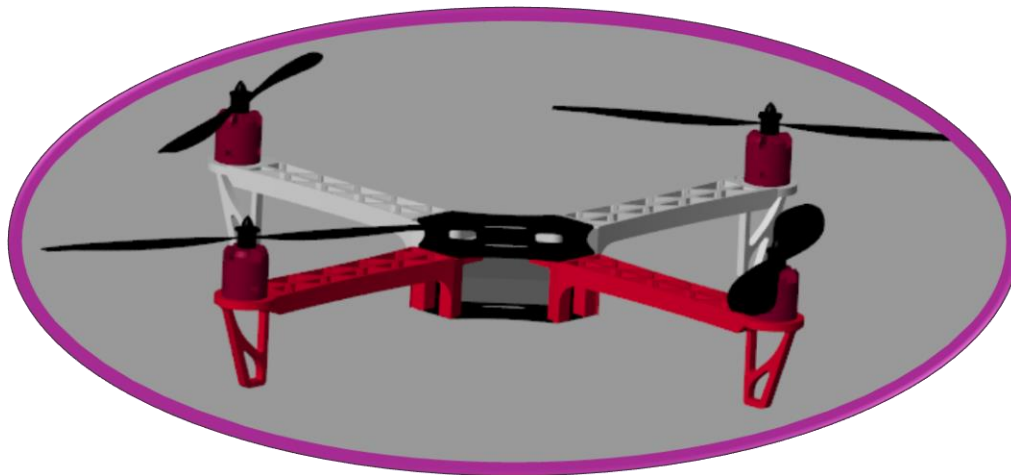


Real world data informs simulation, and simulation data informs operation.



You can use digital twin simulation data to build data-driven behavioral models.





**Exercise 1:
Meet the Digital
Twin**




**Exercise 2:
Plan the
Mission**



**Exercise 3:
Fault Detection**



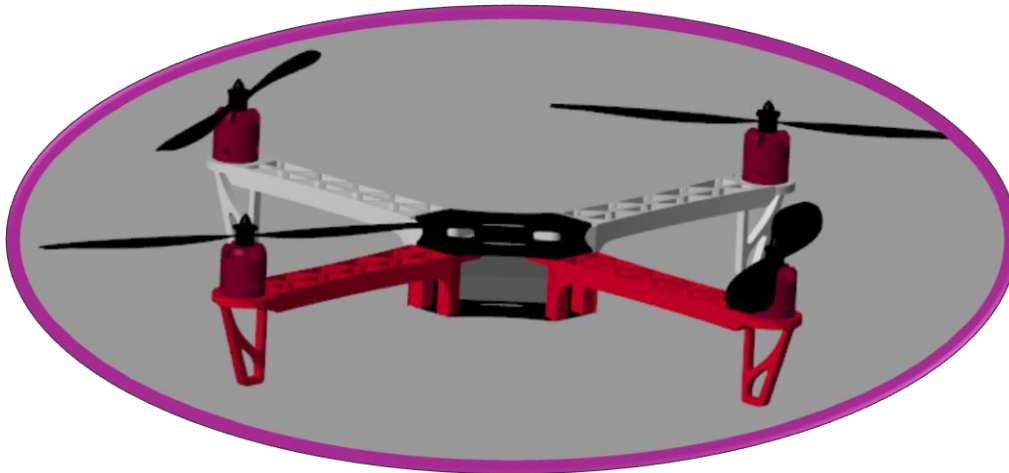
Exercise 1: Meet the Digital Twin



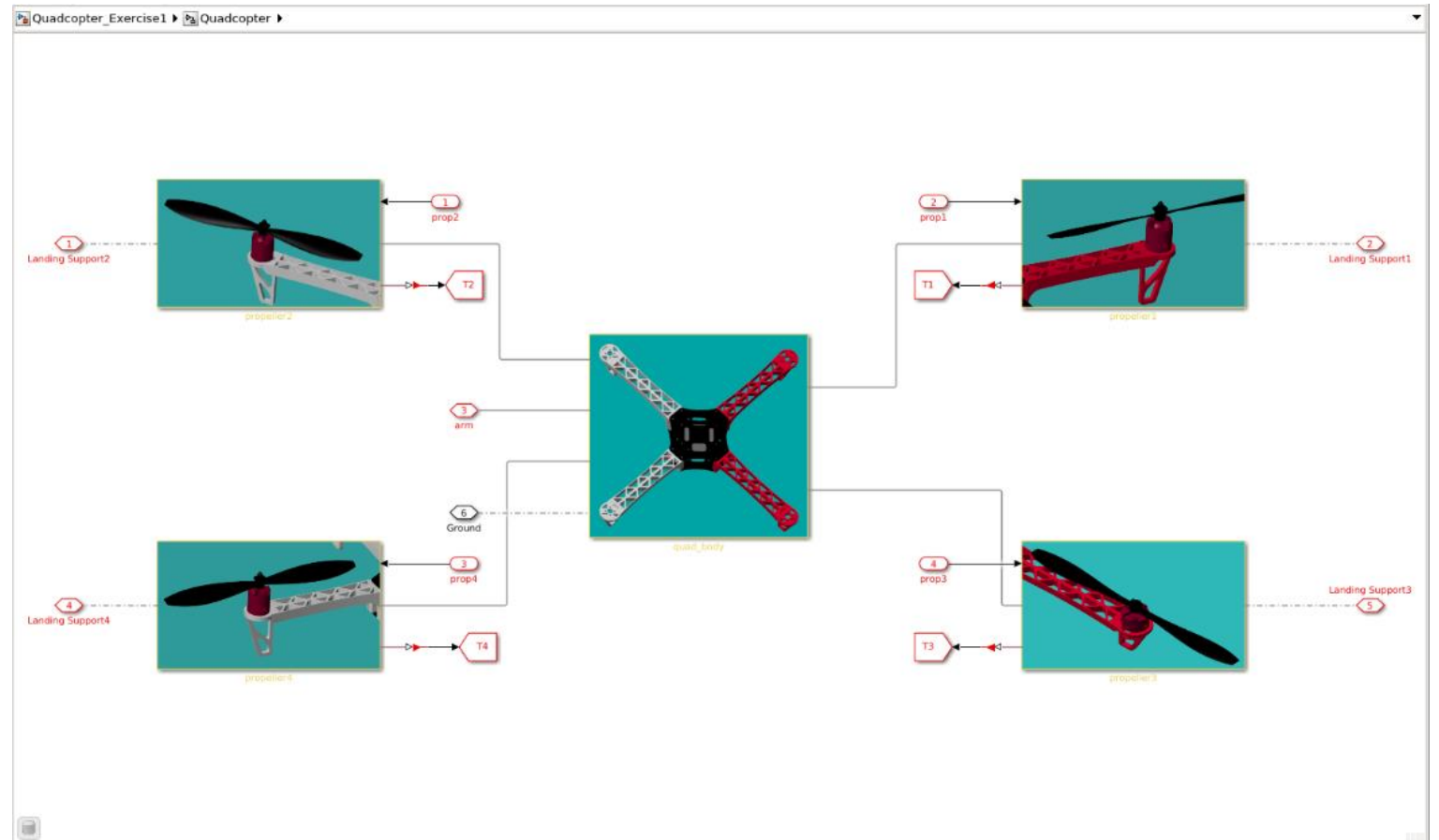
Exercise 2: Plan the Mission



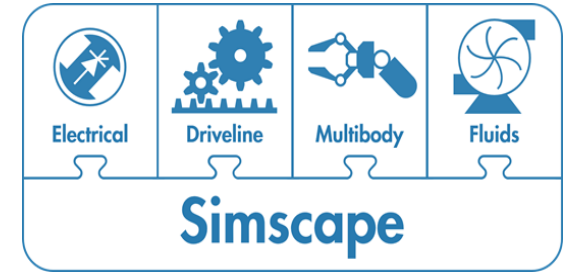
Exercise 3: Fault Detection



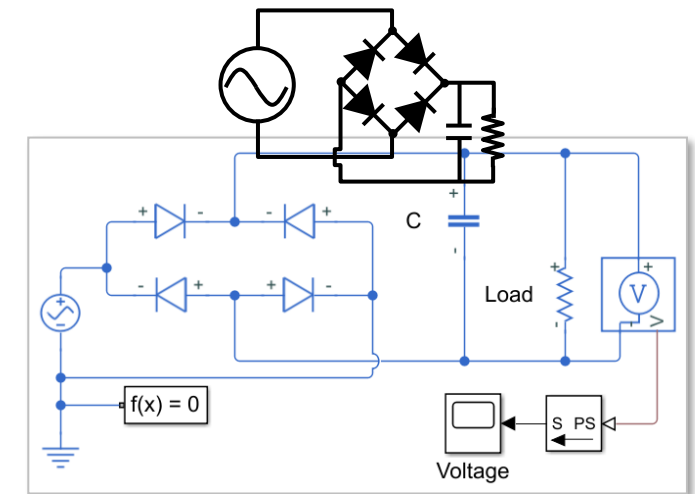
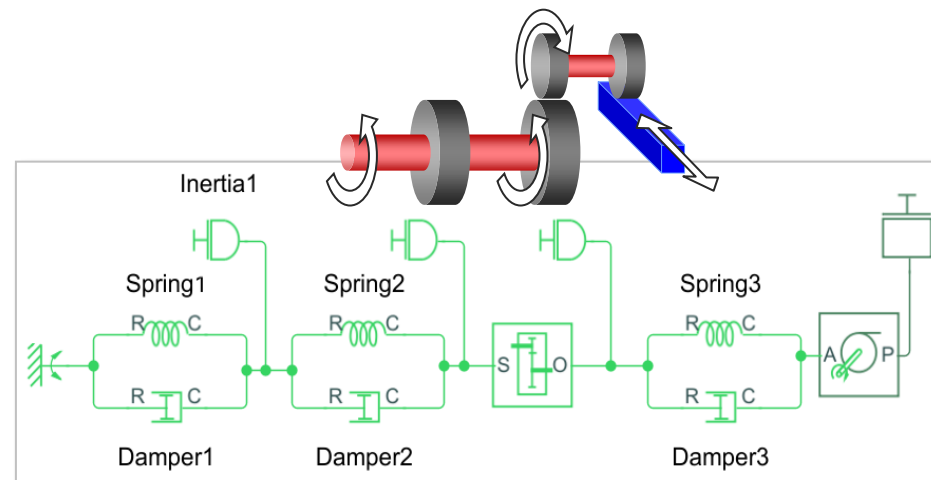
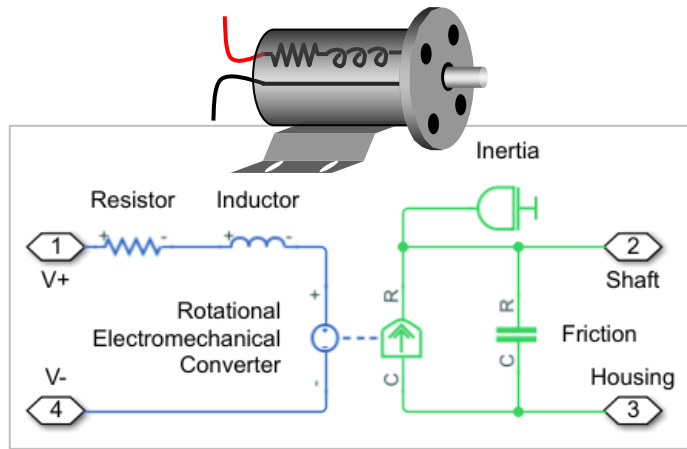
Modeling the Quadcopter



We used Simscape to build the digital twin of our quadcopter




Simscape allows us to model a multidomain system as a physical network that reflects the structure of the actual system.

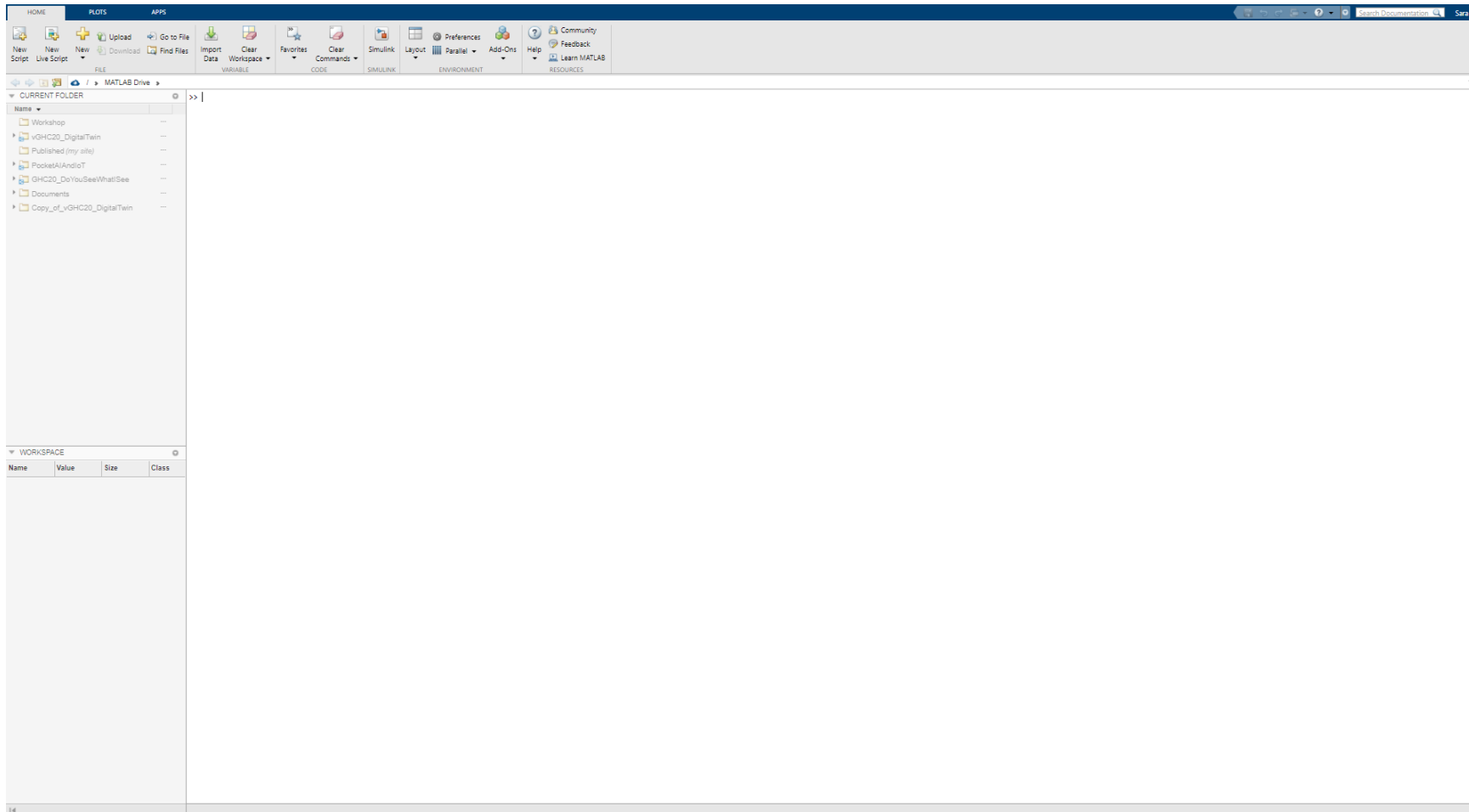




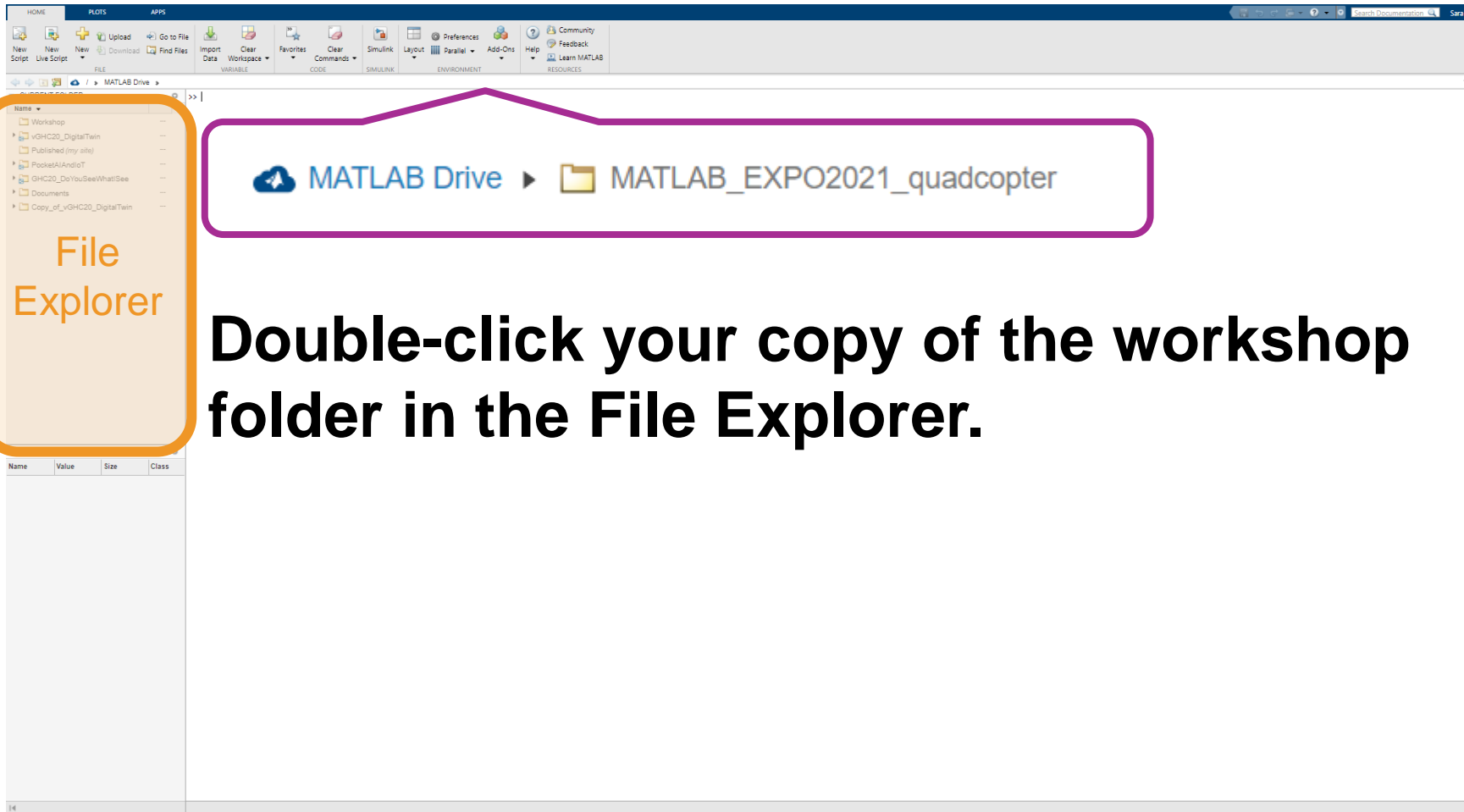
Exercise 1



In your browser, navigate to:
<https://tinyurl.com/DigitalTwinWorkshop>



Navigate inside the copy you made of the workshop folder.

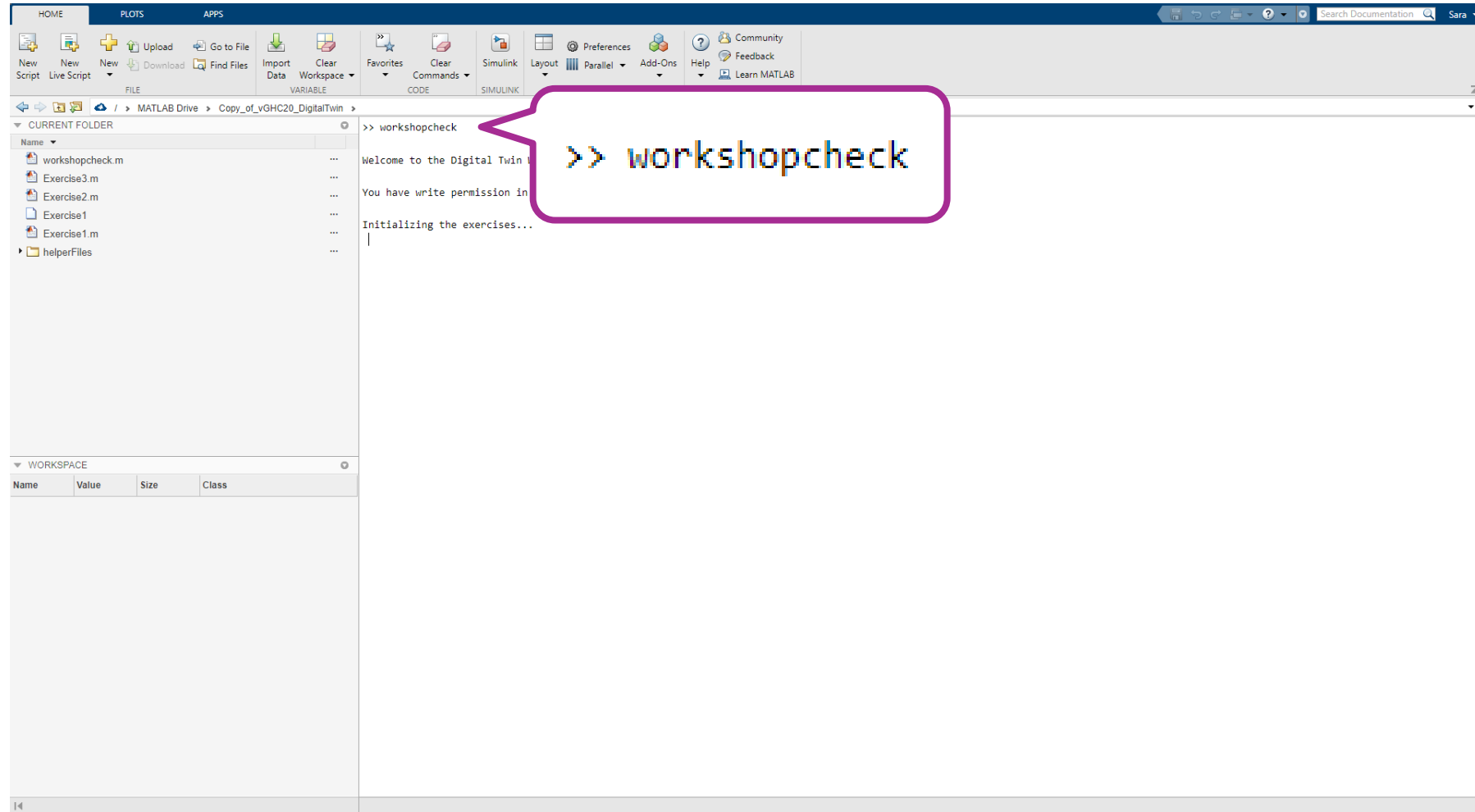


The screenshot shows the MATLAB R2021a File Explorer interface. The address bar displays the path: **MATLAB Drive** > **MATLAB_EXPO2021_quadcopter**. A purple callout box highlights this path. On the left, an orange callout box labeled **File Explorer** points to the file list on the left side of the window. The file list includes folders such as **Workshop**, **vGHC20_DigitalTwin**, **Published (my site)**, **PocketAIAndIoT**, **GHC20_DoYouSeeWhatISee**, **Documents**, and **Copy_of_vGHC20_DigitalTwin**. Below the file list is a table with columns for **Name**, **Value**, **Size**, and **Class**.

Name	Value	Size	Class
Workshop			
vGHC20_DigitalTwin			
Published (my site)			
PocketAIAndIoT			
GHC20_DoYouSeeWhatISee			
Documents			
Copy_of_vGHC20_DigitalTwin			

Double-click your copy of the workshop folder in the File Explorer.

Type `workshopcheck` into the Command Window and press Enter



The screenshot shows the MATLAB Command Window interface. The Command Window contains the following text:

```
>> workshopcheck  
Welcome to the Digital Twin  
You have write permission in  
Initializing the exercises...
```

A callout box highlights the command `>> workshopcheck` in the Command Window.

The Workspace window is visible at the bottom, showing a table with columns for Name, Value, Size, and Class.

Name	Value	Size	Class
------	-------	------	-------

Type `Exercise1` in the Command Window and press Enter



The screenshot shows the MATLAB Command Window with the command `>> Exercise1` entered. The workspace table is visible at the bottom of the window.

Name	Value	Size
Ah	7.6000	1x1
ans	12.8282	1x1
BreakTor	40	1x1
BreakVel	2	1x1
column	6	1x1
CombFric	10	1x1
contact...	300000	1x1
contact...	350000000	1x1
counter	20	1x1
dx	-0.1000	1x1
dy	-0.1000	1x1
DynaFri...	0.5000	1x1
dz	0	1x1
i	6	1x1
lmax	35	1x1
initialAlt...	0.0600	1x1
j	3	1x1

When model opens, maximize the window. Then, click anywhere on the Model Canvas and **press the space bar to Fit to View.**

Let's walk through the model for Exercise 1...



Quadcopter_Exercise1 - Simulink

SIMULATION DEBUG MODELING FORMAT APPS

Open Save Library Browser Log Signals Add Viewer Signal Table Stop Time: T_stop Normal Step Back Run Step Forward Stop Data Inspector Logic Analyzer

FILE LIBRARY PREPARE SIMULATE REVIEW RESULTS

Model Browser

Quadcopter_Exercise1

MATLAB EXPO 2021

Mission planning of a quadcopter using a Digital Twin

Exercise 1

Objective:
In Exercise 1, you meet the quadcopter digital twin and become acquainted with the model using Simulink Online. Your task is to attach the payload to the body of the quadcopter and run the simulation. You can also explore the electromechanical model of the propellers. Use the additional resource (scopes) to monitor and analyze simulation results.

Step 1: Attach your payload
Click here to attach payload

Step 2: Run your simulation (Simulation Tab)

Resource: Visualize results

Additional task: Examine one of the propellers
Inside the quadcopter subsystem, navigate to one of the propeller subsystems

Quadcopter

Notes - Quadcopter_Exercise1_notes.mldatx

Write Notes

Model notes

The simulation model of a package delivery quadcopter contains a Multibody model of a quadcopter which is connected to the world frame via 6-DOF joint. A Maneuver Controller subsystem is used to control the motion of the quadcopter. Additionally, the propulsion system of the quadcopter is modelled using Simscape Electrical toolbox. A package is attached to the quadcopter via weld joint and is released using the Joint Disengagement feature in Simscape Multibody toolbox. Further, contact forces between the package and the ground are modelled so that whenever the quadcopter delivers the package, it stays on the ground surface instead of sinking below it.

This first exercise focuses on the physical modeling of the device, which includes mechanical and electrical domains.

Ready 40% ode1

Notes provide detailed info about the model

Quadcopter system modeled in Simscape

Let's walk through the model for Exercise 1...



Quadcopter_Exercise1 - Simulink

SIMULATION DEBUG MODELING FORMAT APPS

Open Save Library Browser Log Signals Add Viewer Signal Table Stop Time T_stop Normal Fast Restart Step Back Run Step Forward Stop Data Inspector Logic Analyzer

FILE LIBRARY PREPARE SIMULATE REVIEW RESULTS

Model Browser

Quadcopter_Exercise1

MATLAB EXPO 2021
Mission planning of a quadcopter using a Digital Twin
Exercise 1

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Quadcopter

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Click here to attach payload

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Notes - Quadcopter_Exercise1_notes.mldatx

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This first exercise focuses on the physical modeling of the device, which includes mechanical and electrical domains.

Ready 40% ode1

Exercise 1 Steps



Exercise 1

- **Objective:** Attach the payload to the quadcopter body and run the simulation

Step 1: Attach your payload

Click here to attach payload



Hyperlink opens up the quadcopter body subsystem

Quadcopter Body Subsystem



Quadcopter_Exercise1/Quadcopter/quad_body - Simulink

SIMULATION DEBUG MODELING FORMAT APPS

Stop Time: T_stop
Normal
Fast Restart

Step Back Run Step Forward Stop

Data Inspector Logic Analyzer Bird's-Eye Scope

Model Browser

quad_body

Add blocks in this area

Click here to open Custom Library

Back to Main Level

Ready 59%

Notes - Quadcopter_Exercise1_notes.mldatx

Write Notes

To demonstrate the package delivery using a quadcopter, the package is attached to the quadcopter via a weld joint and it is released using the joint disengagement feature in Simscape Multibody.

The goal in this exercise is to finalize the model:

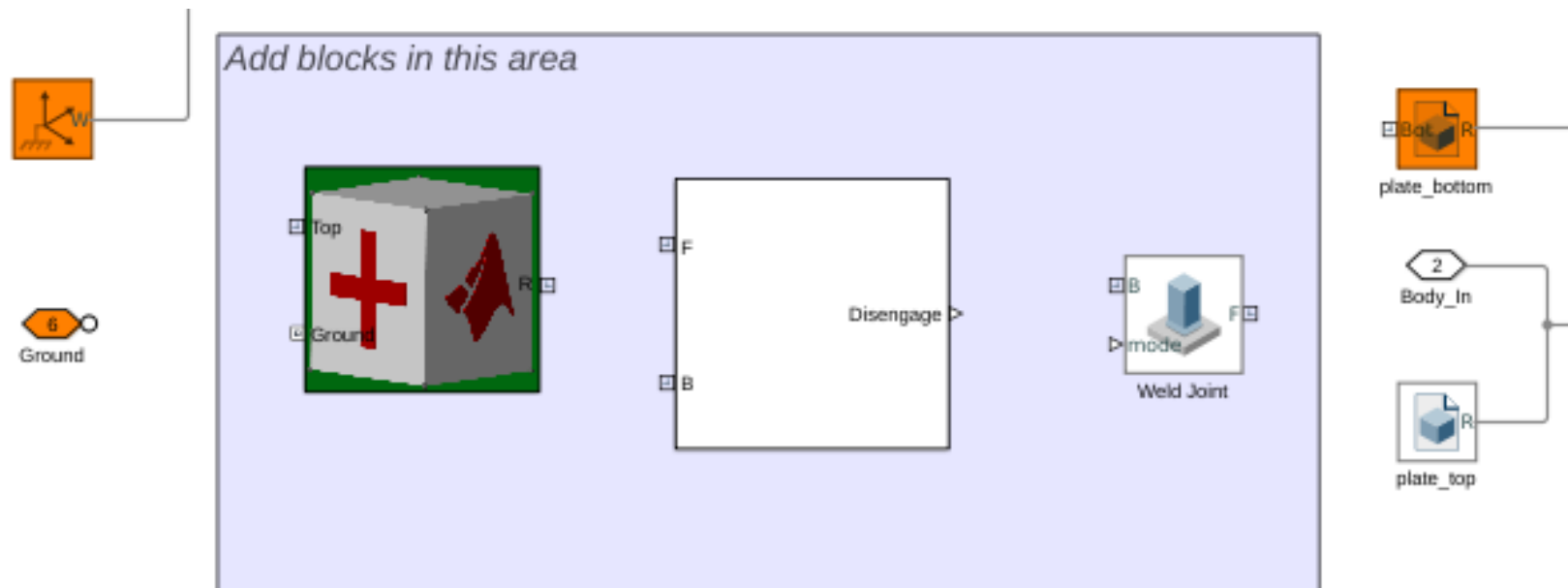
1. Open the Custom Library
2. Drag the blocks
3. Connect the medical kit (to ground, weld joint and disengage logic)
4. Connect the weld joint (to plate_bottom and disengage logic)
5. Connect the disengage subsystem to the existing world frame block

A schematic is provided below:

Follow these instructions to add and connect the blocks in the correct sequence!

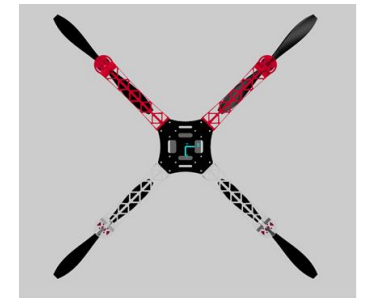
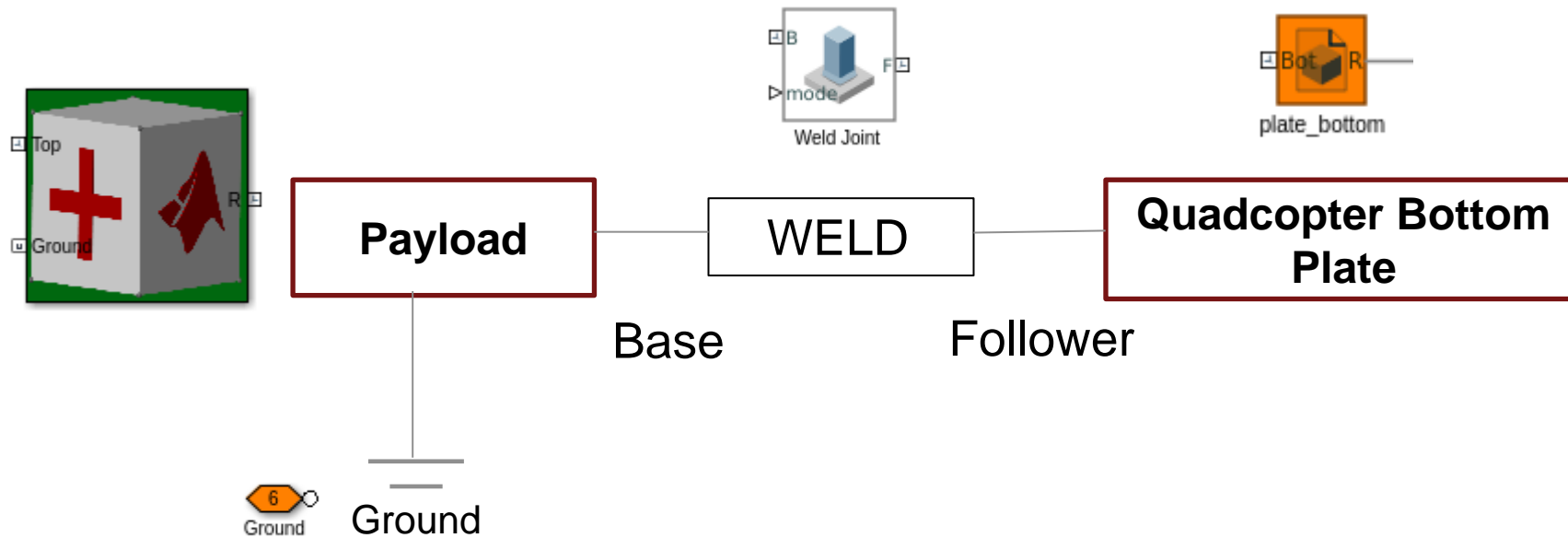
Exercise 1 – Step 1 in more detail

1. Drag all the blocks from the Custom Library into the blue area and get ready to make the connections



Exercise 1 – Step 1 in more detail

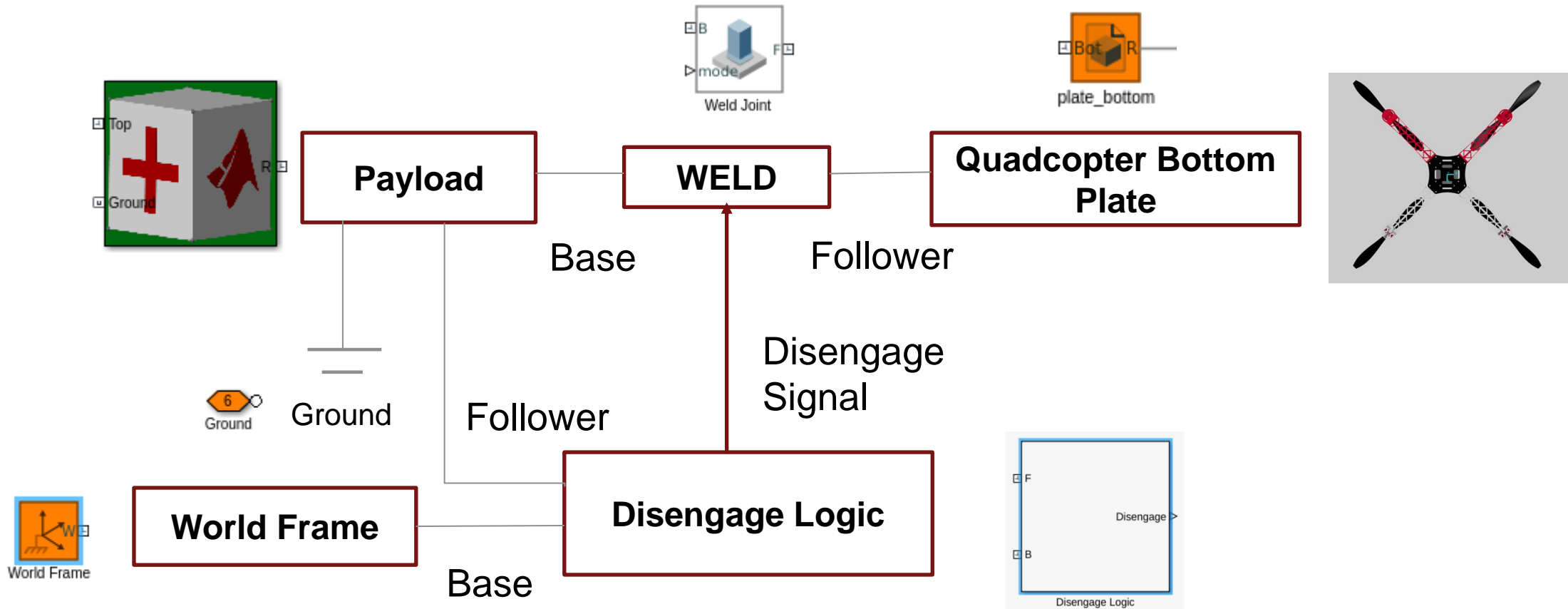
2. Connect the Payload Top to the ground and to the Quadcopter Bottom Plate via the Weld Joint





Exercise 1 - Step 1 in more detail

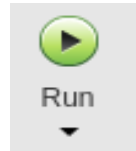
3. Ensure the Weld Joint can be disengaged when Payload reaches near its destination





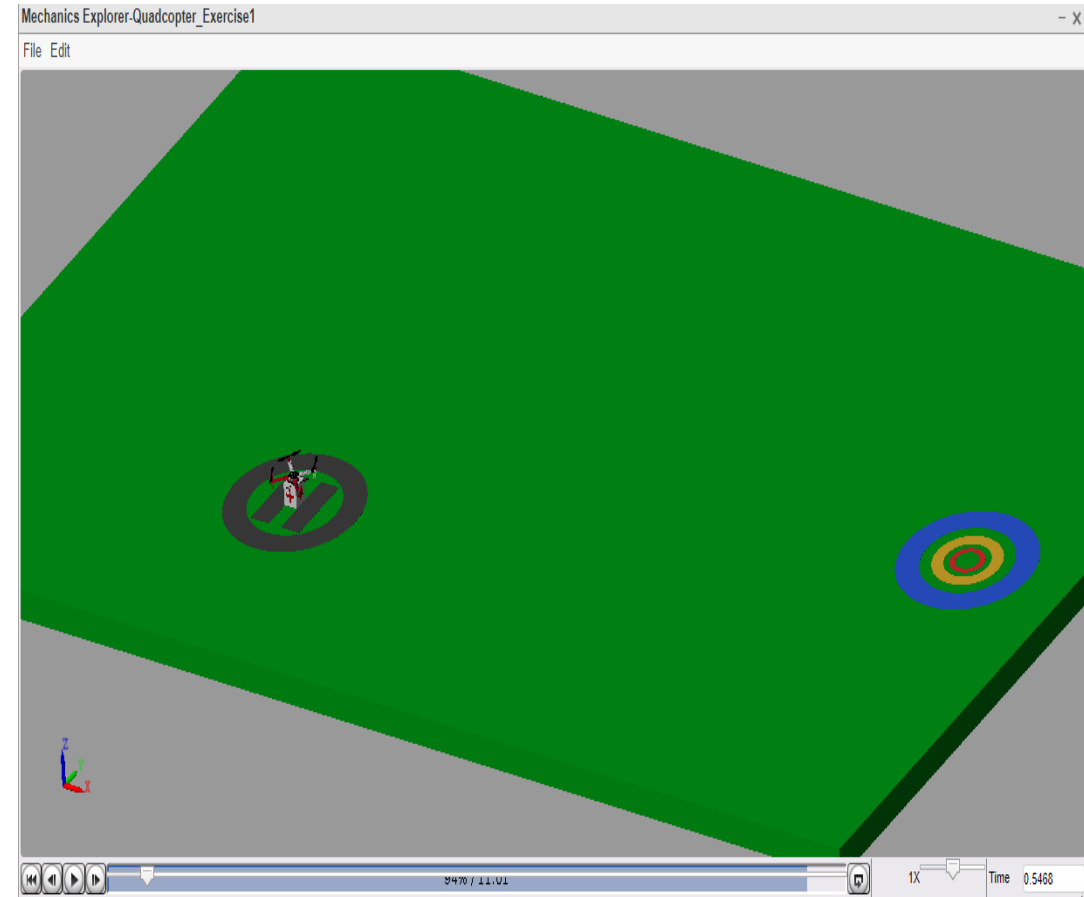
Once you are done connecting the blocks

- Click “Run” to simulate
- Animation opens up in a new window



Rotate	Click and hold the mouse scroll wheel. Move the mouse in the direction you want to rotate the model
Zoom	Use the mouse scroll wheel to zoom in/out.

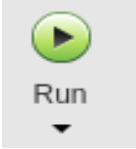
- You can also visualize the results using the provided scopes



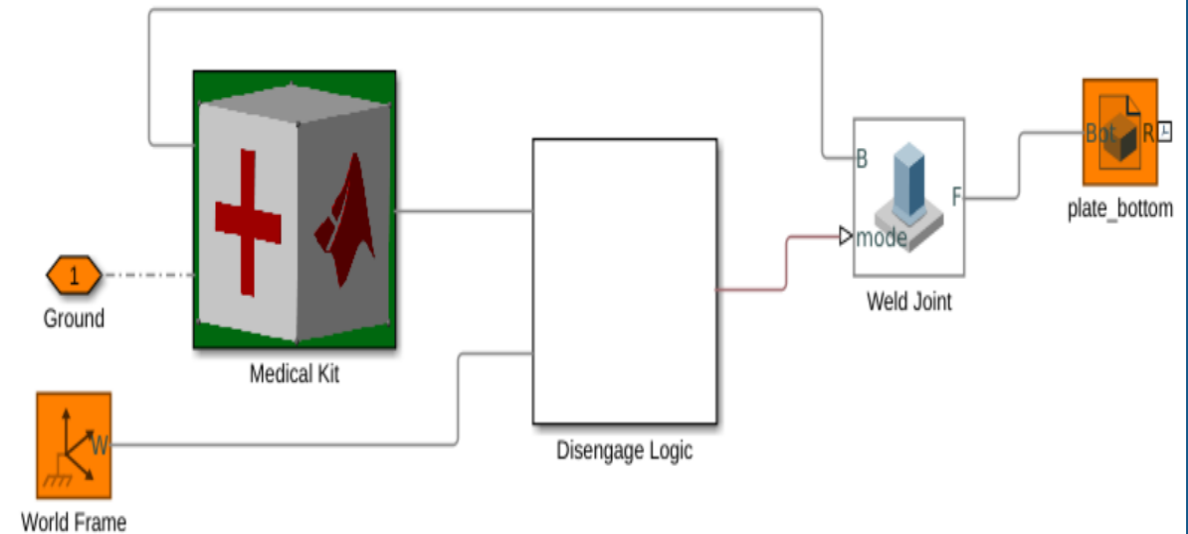
Exercise 1 Summary

- **Objective:** Attach the payload to the quadcopter body and run the simulation

Steps:

1. Click on the hyperlink in **Step 1 : Attach your Payload**
2. Follow the instructions in the quad_body subsystem
3. Once you are done connecting the package, click **“Run”** to simulate 
4. View the animation to confirm pickup and delivery

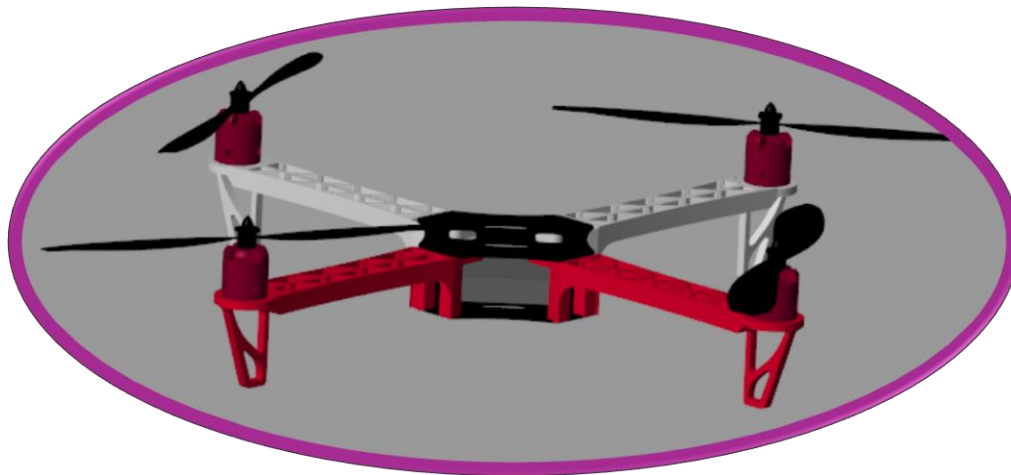
Schematic:





What did you observe?

- Did the quadcopter pickup the package?
- Did it drop the package to its destination?
- Anything else?



**Exercise 1:
Meet the Digital
Twin**



**Exercise 2:
Plan the
Mission**



**Exercise 3:
Fault Detection**

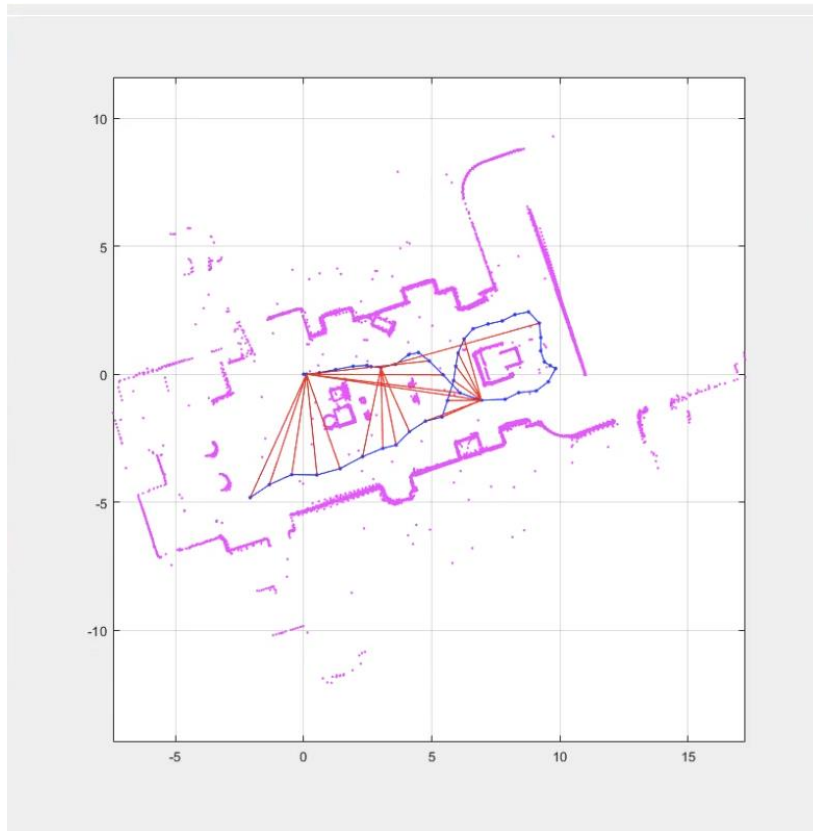
Use navigation to plan your route



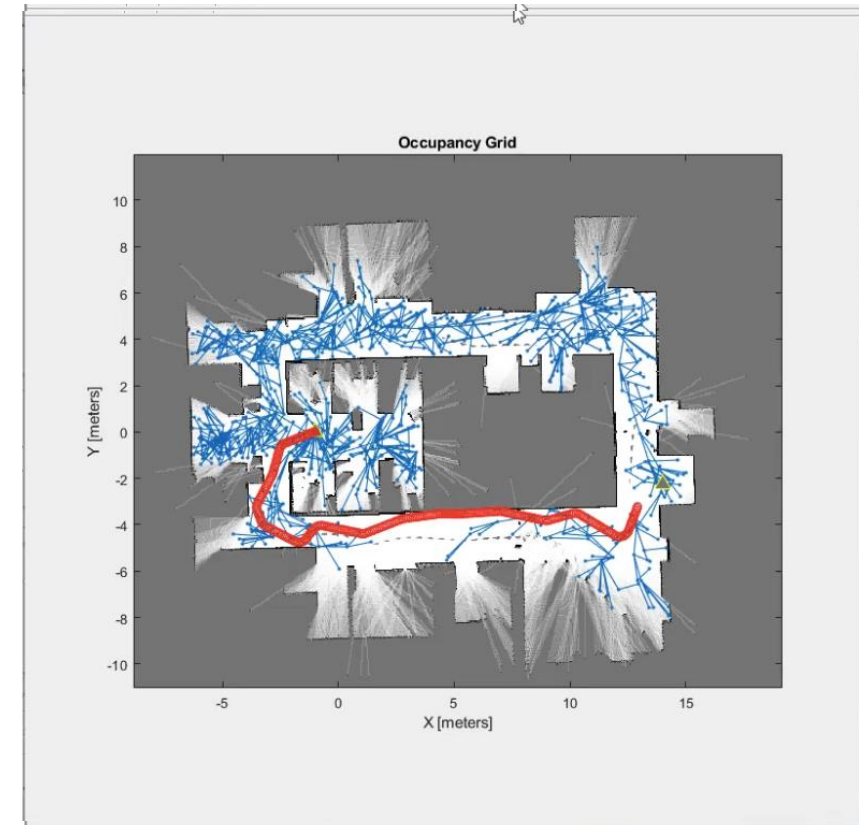
Fully autonomous navigation has no human in the loop



Autonomous navigation is complex in changing environments.

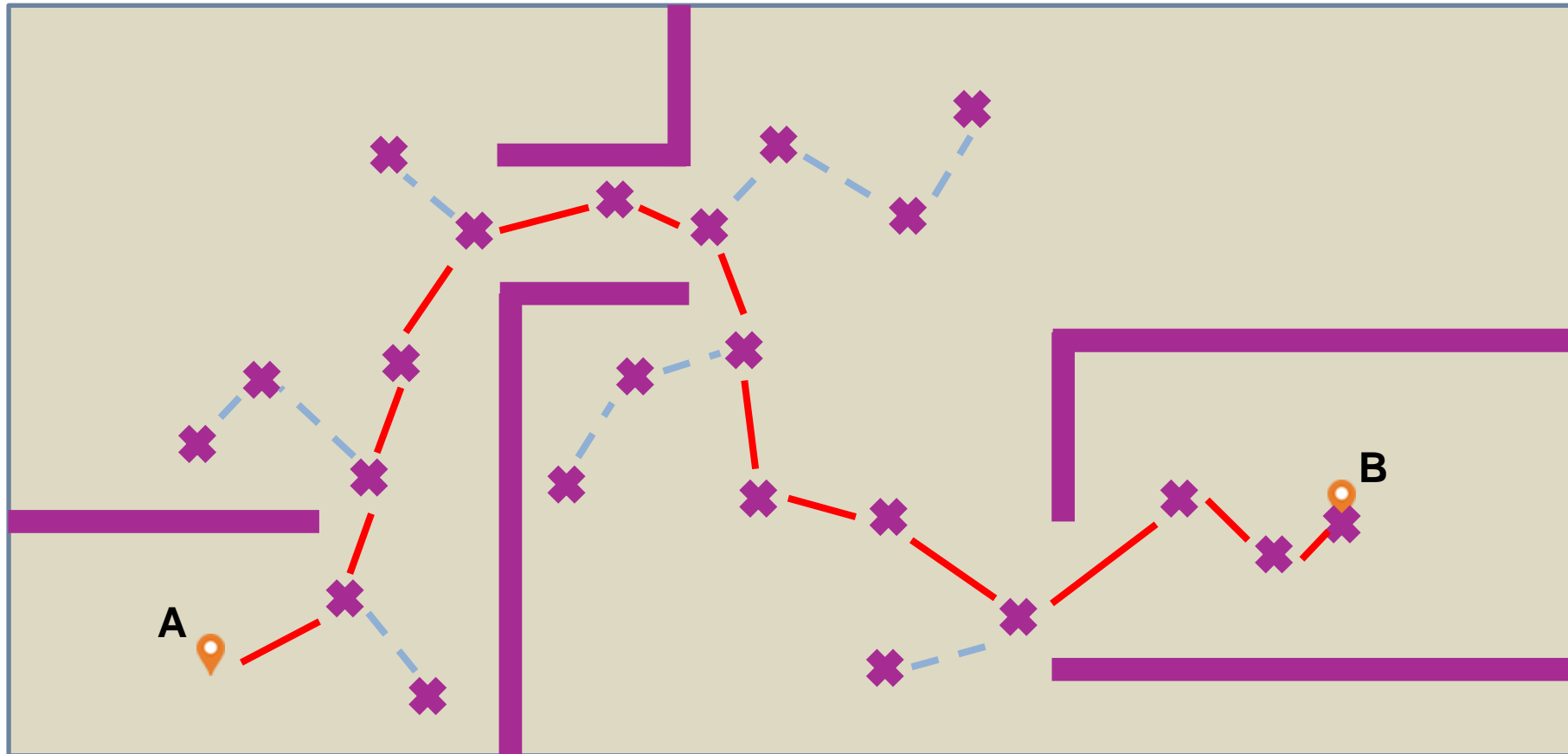


Simultaneous Localization
and Mapping (SLAM)



Static Environment
and
Preplanned Path

Path Planning Algorithms: Find an optimal path and select waypoints



You will use an RRT planner to generate the optimal path for the quadcopter.



pathplanning.m

```
image = imread(scenario);
```

```
bwimage = rgb2gray(image) < 0.5;
```

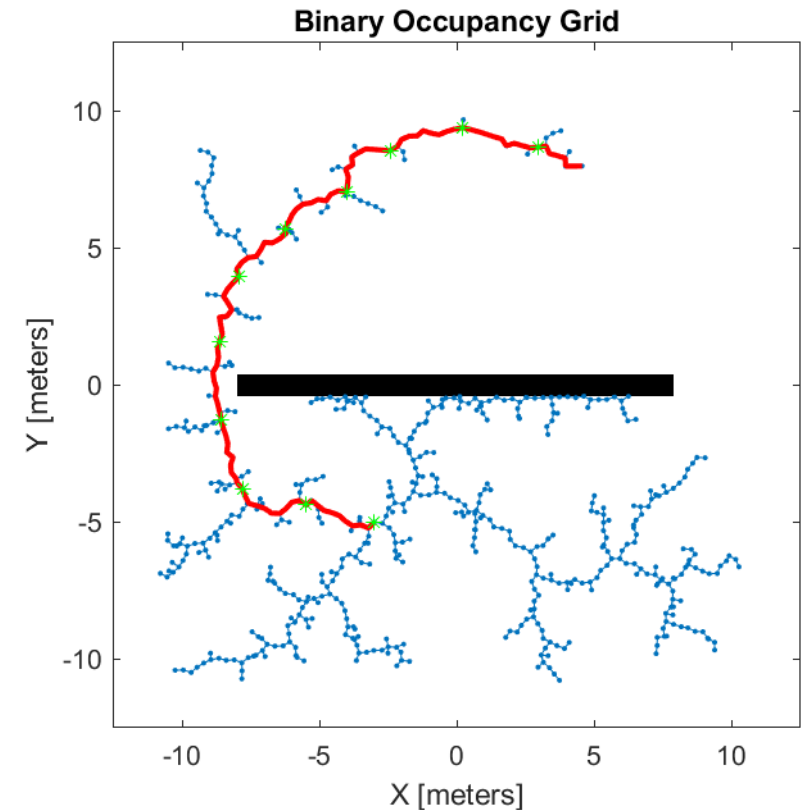
```
grid = binaryOccupancyMap(bwimage,10);
```

```
ss = StateSpaceSE2;
```

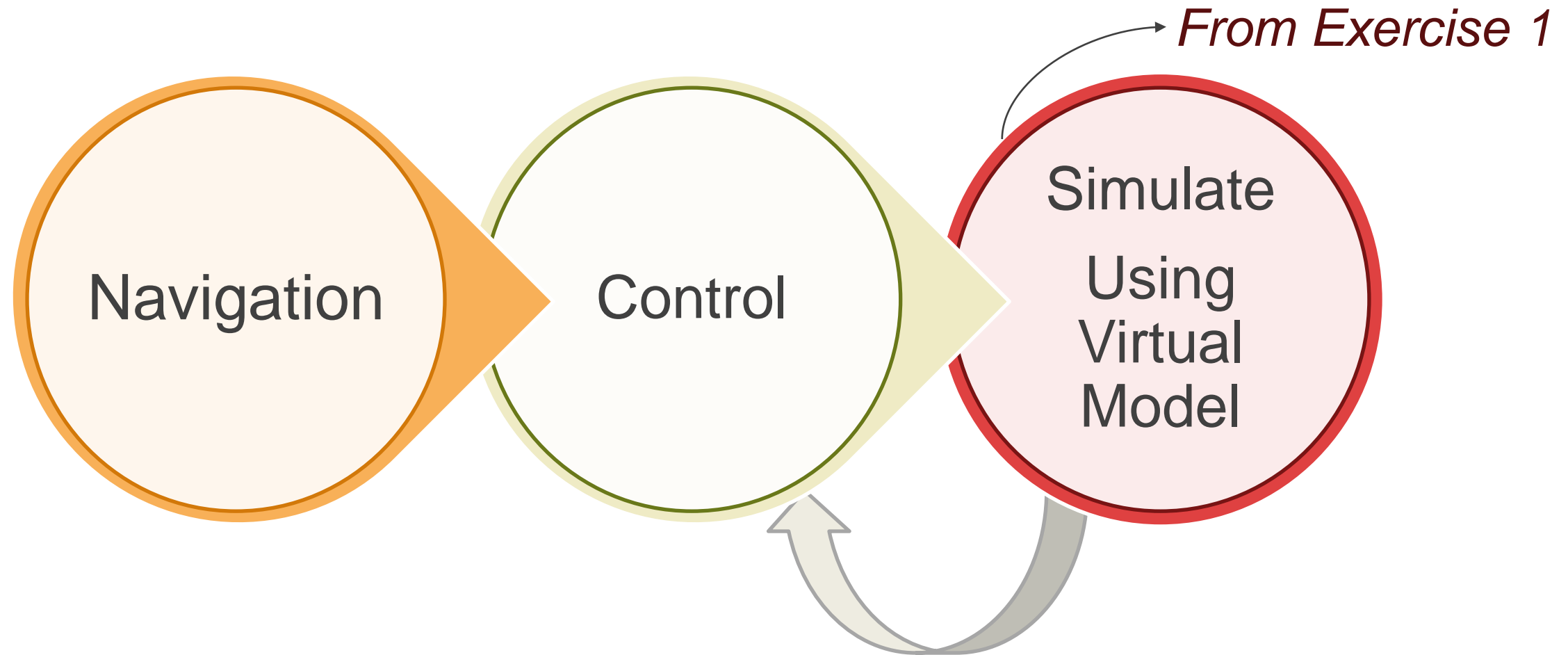
```
sv = validatorOccupancyMap(ss);
```

```
sv.Map = grid;
```

```
planner = plannerRRT(ss,sv);
```



Navigation is just the beginning – control and simulation are next!

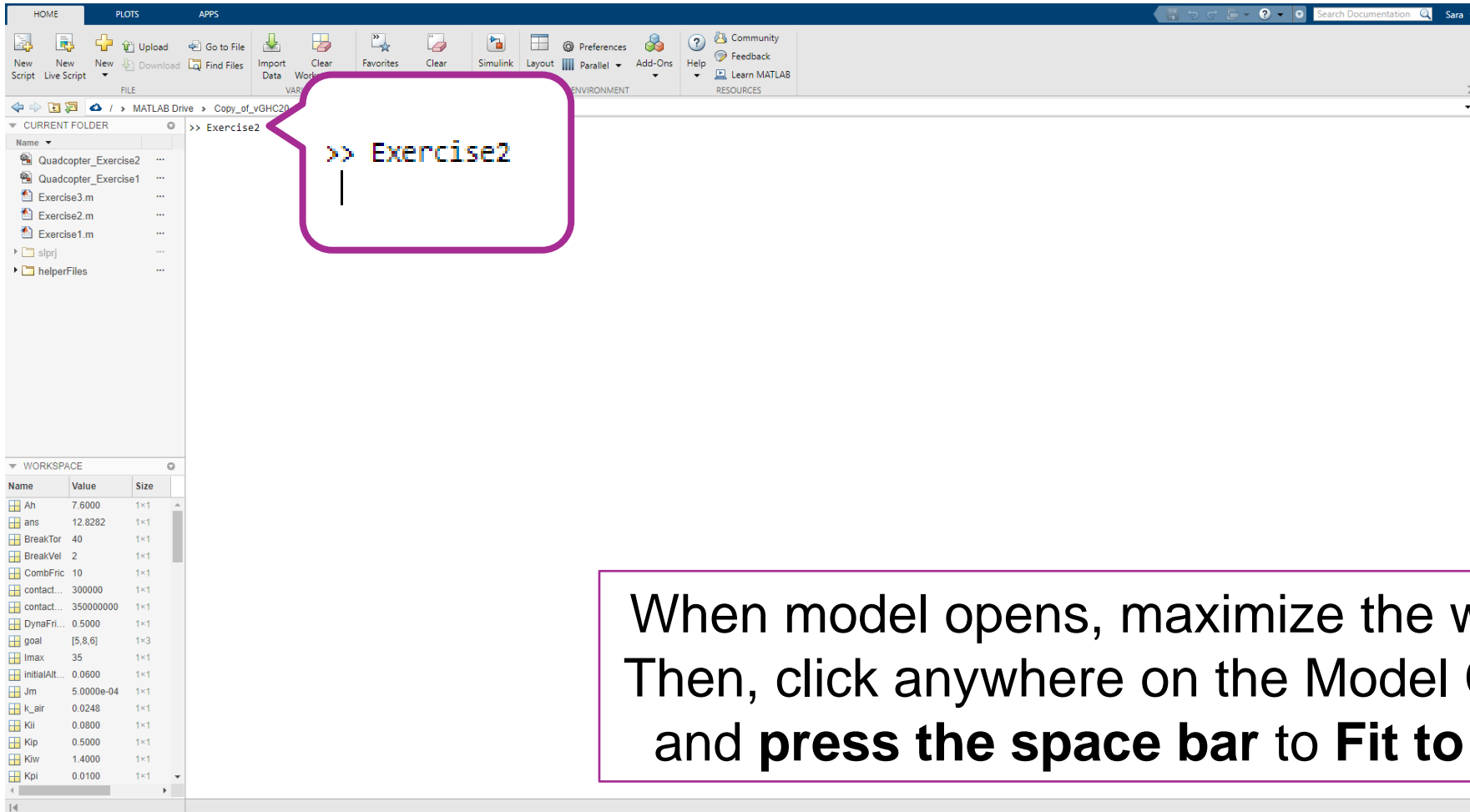




Exercise 2



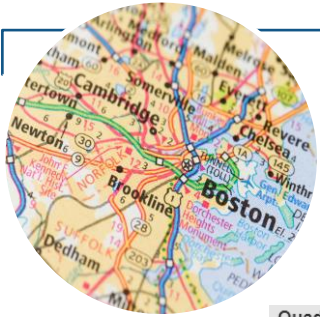
Type **Exercise2** in the Command Window.



The screenshot shows the MATLAB Command Window with the following workspace variables:

Name	Value	Size
Ah	7.6000	1x1
ans	12.8282	1x1
BreakTor	40	1x1
BreakVel	2	1x1
CombFric	10	1x1
contact...	300000	1x1
contact...	350000000	1x1
DynaFit...	0.5000	1x1
goal	[5, 8, 6]	1x3
lmax	35	1x1
initialAlt...	0.0600	1x1
Jm	5.0000e-04	1x1
k_air	0.0248	1x1
Kil	0.0800	1x1
Kip	0.5000	1x1
Kiw	1.4000	1x1
Kpl	0.0100	1x1

When model opens, maximize the window. Then, click anywhere on the Model Canvas and **press the space bar to Fit to View.**



Let's walk through the model for Exercise 2

Exercise 2 Steps

Objective:
In Exercise 2, you learn how the quadcopter determines its path from the starting point to the delivery destination. In this exercise, you'll run simulations to see the effect obstacles have on a planned path and the effect that the path has on the battery capacity.

Workshop instructions

Step 1: Select your flight path
Click here to generate path

Step 2: Check visualization
Show 3D view

Take-home exercise

Step 1: Select your flight path
(use link above)

Step 2: Run simulation
[Screenshot of Simulink toolbar with Run button highlighted]

Step 3: Visualize additional results
Show waypoints

Model notes
This package delivery quadcopter system consists of a quadcopter connected to the world frame via 6-DOF joint. A Maneuver Controller subsystem is used to control the motion of the quadcopter. A package is attached to the quadcopter via a weld joint and is released using the Joint Disengagement feature when the quadcopter nears its delivery destination.

This second exercise focuses on modeling the navigation aspect of the device, which in turn has an impact on battery life.

Workshop Instructions:
Generate the path in Step 1. Three different options are provided. The RRT planner algorithm generates the path based on the scenario. In Step 2 check a previously generated 3D view of each case.

Take-home exercise:
After generating the path, run your simulation using the toolstrip. Whenever you're ready simply click "Stop" to finish the current run. Examine the waypoints and check the impact on the battery life.

Ready

46%

ode1



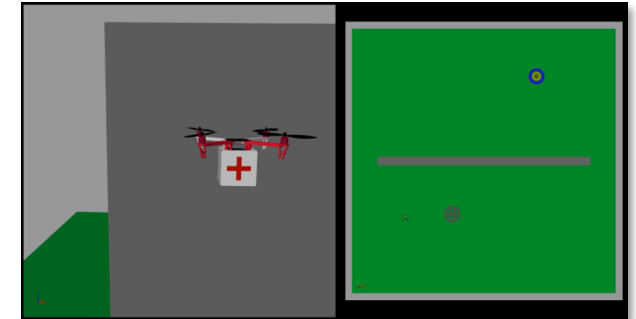
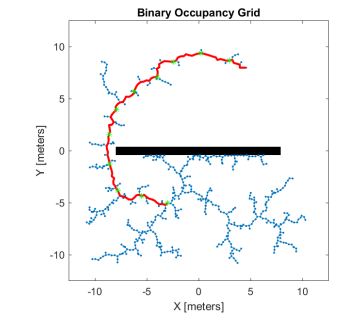
Exercise 2 Summary

- **Objective:** Check the effect of different flight paths

Steps:

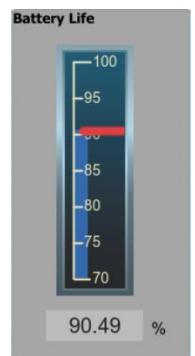
1. Click on the hyperlink in Step 1 open a new window to generate the flight path.
2. In the new window select the scenario and click “Generate path.” When ready, click “Close” to close this window.
3. Check the 3D view for each case.

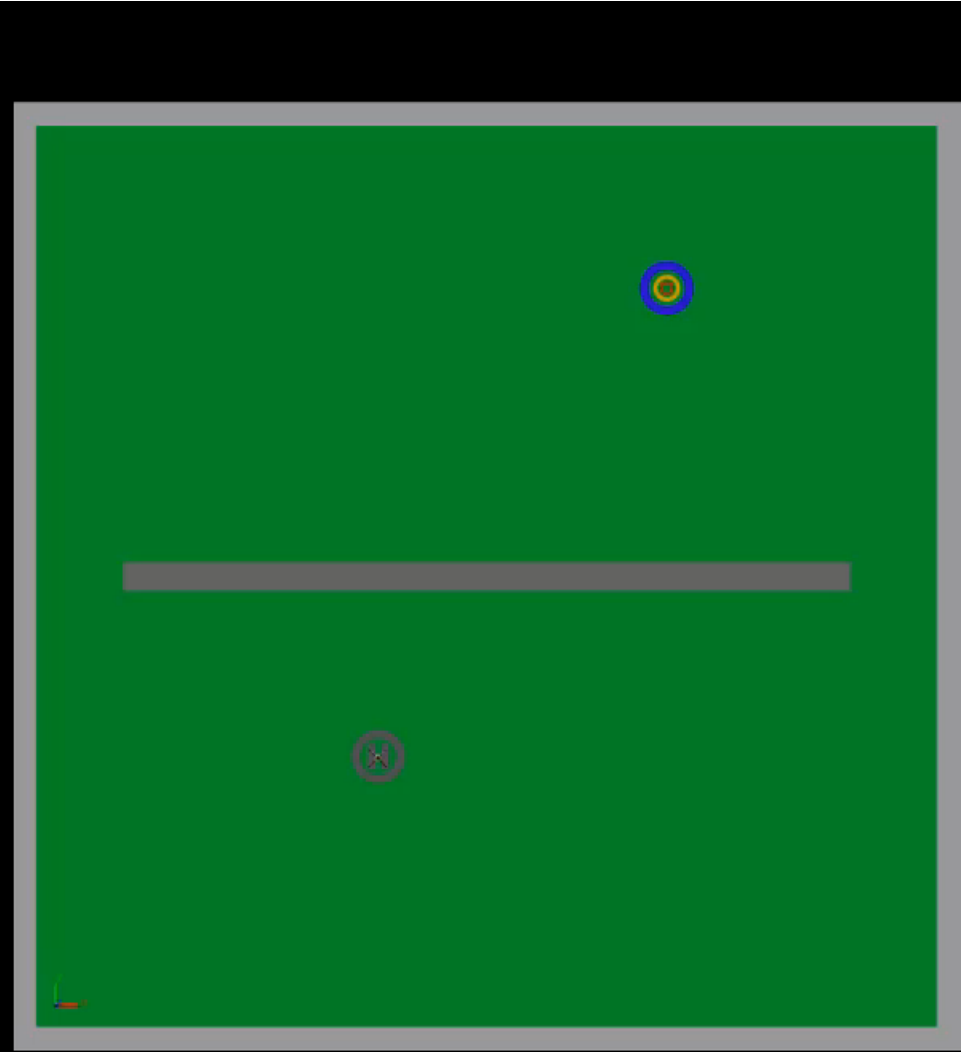
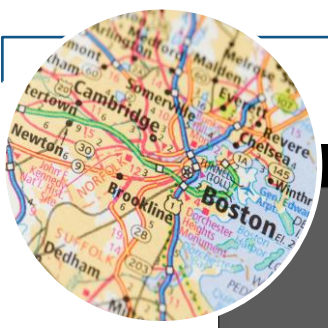
Monitor Results:

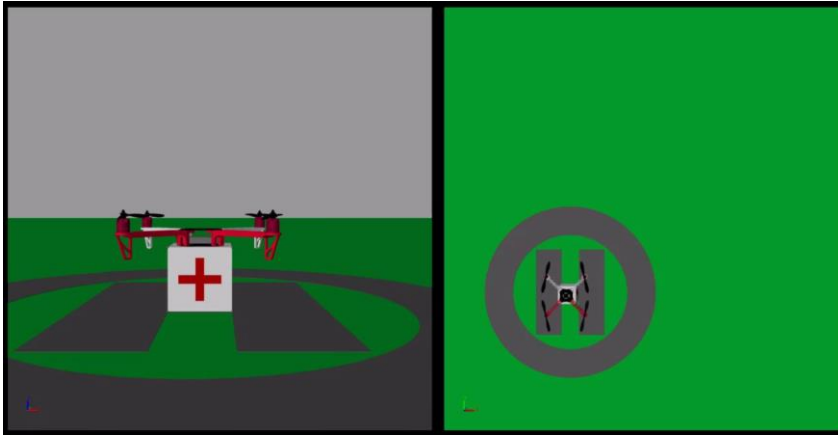
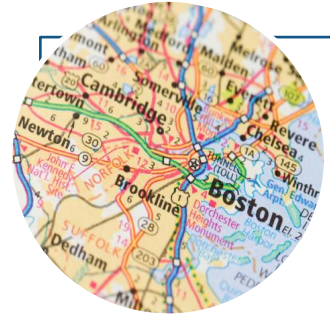


Take-home exercise:

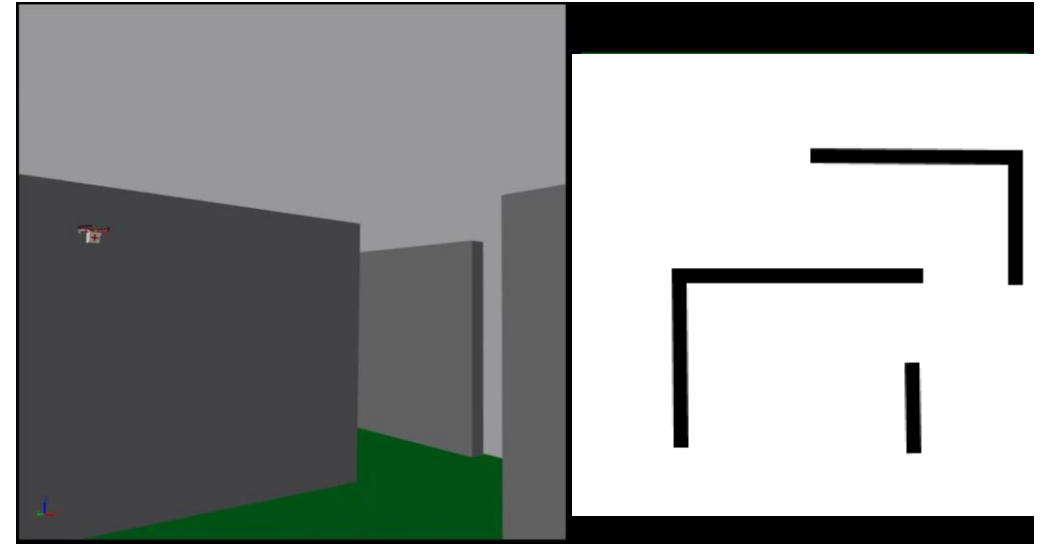
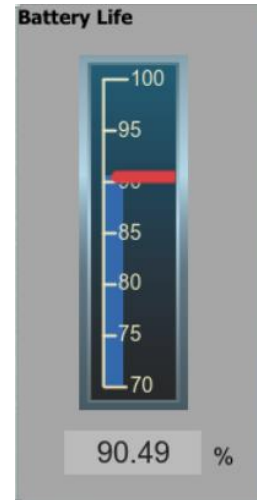
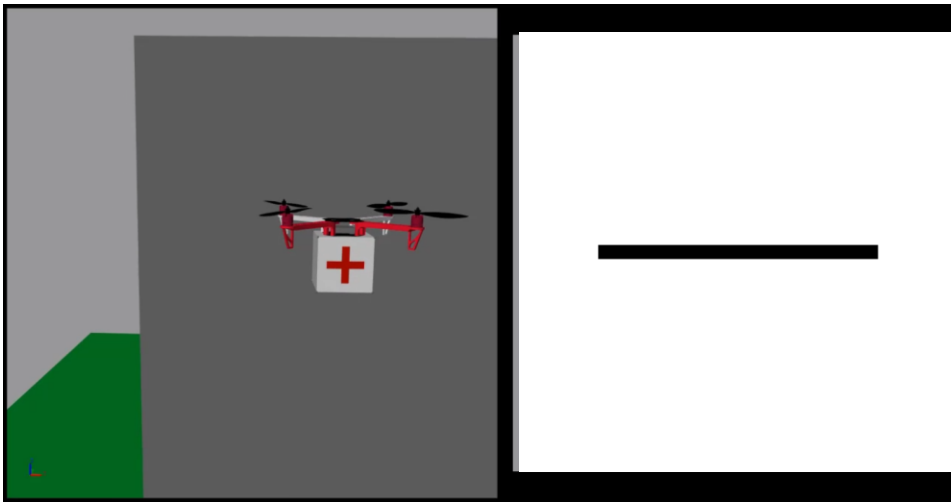
- In the toolbar click the Run button to simulate. Allow simulation to run at least for a few seconds. Use Stop to end the simulation at any time.
- Monitor additional results

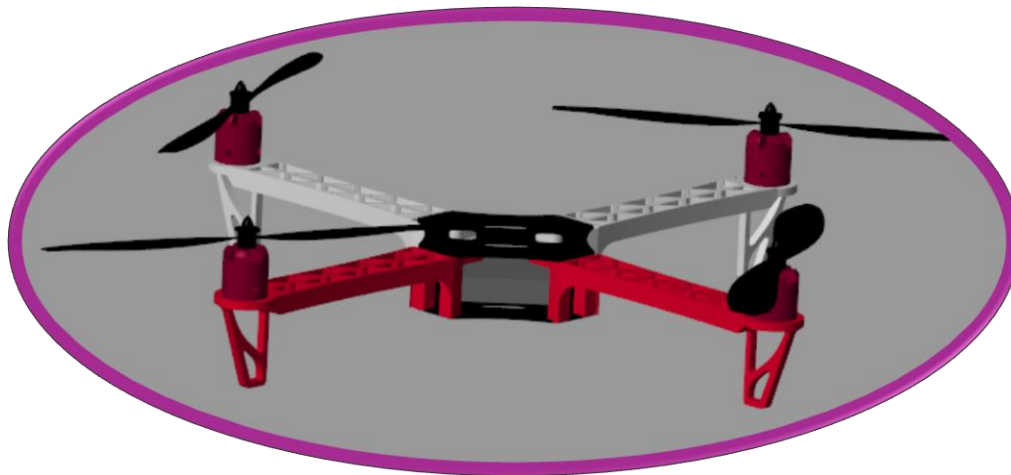






Now that we can plan a mission for the digital twin, how can we test failing scenarios?





**Exercise 1:
Meet the Digital
Twin**

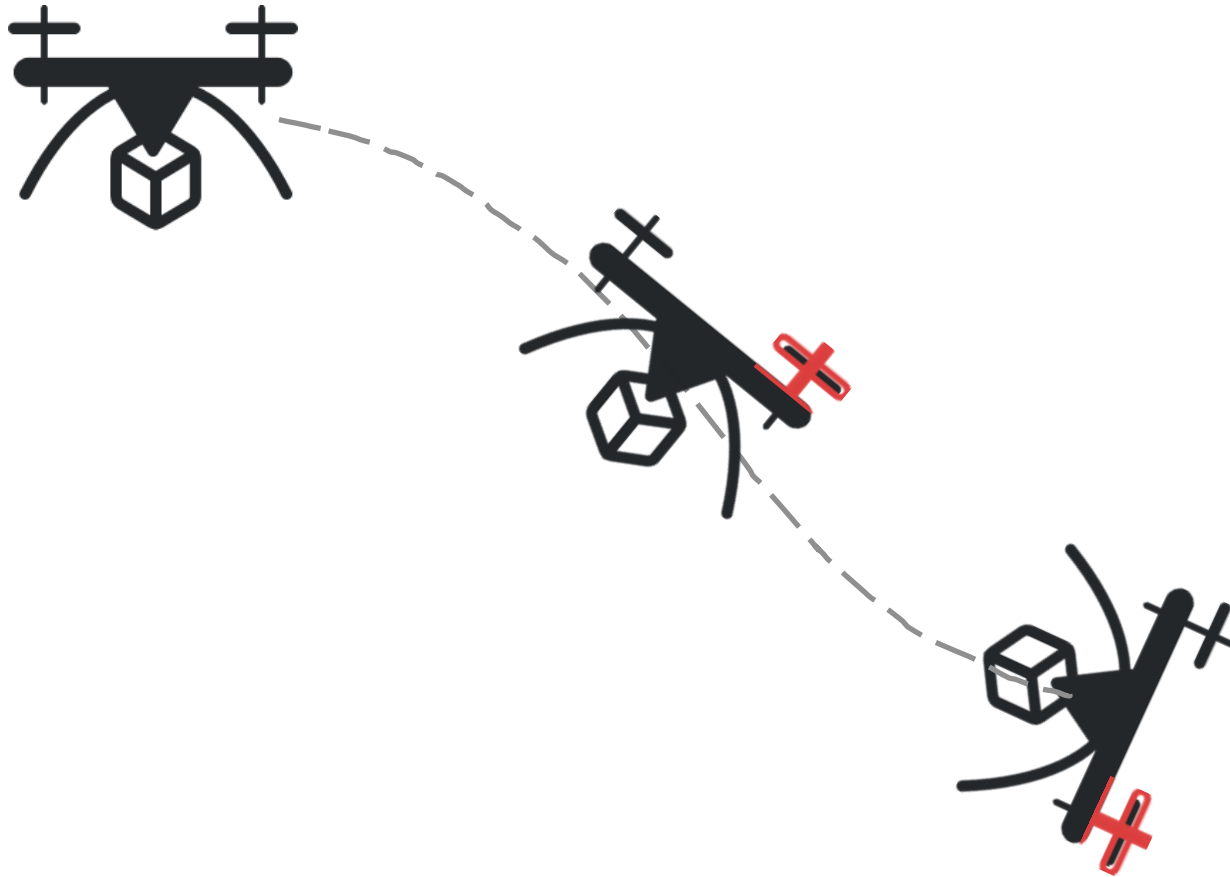


**Exercise 2:
Plan the
Mission**



**Exercise 3:
Fault Detection**

Predictive Maintenance can be used to detect faults in machines

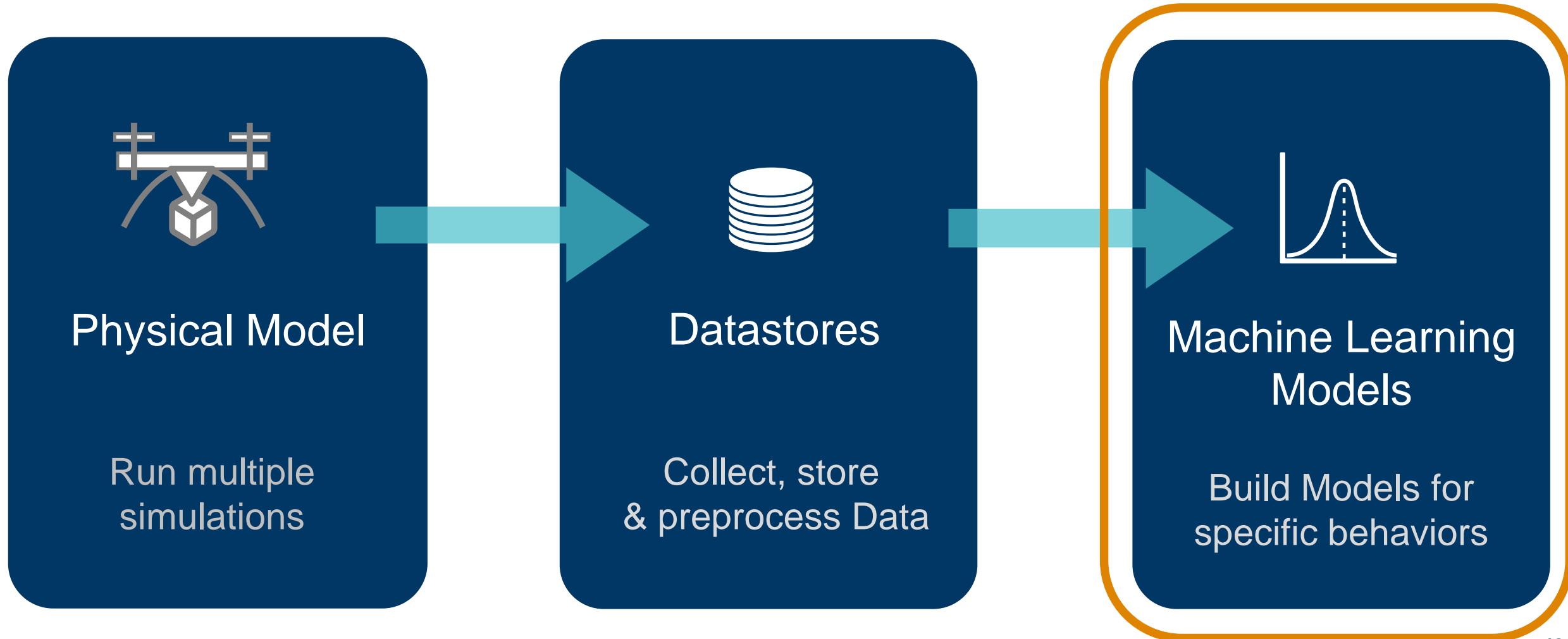


Where did the
Fault Occur?

Fault
Detection

Motor

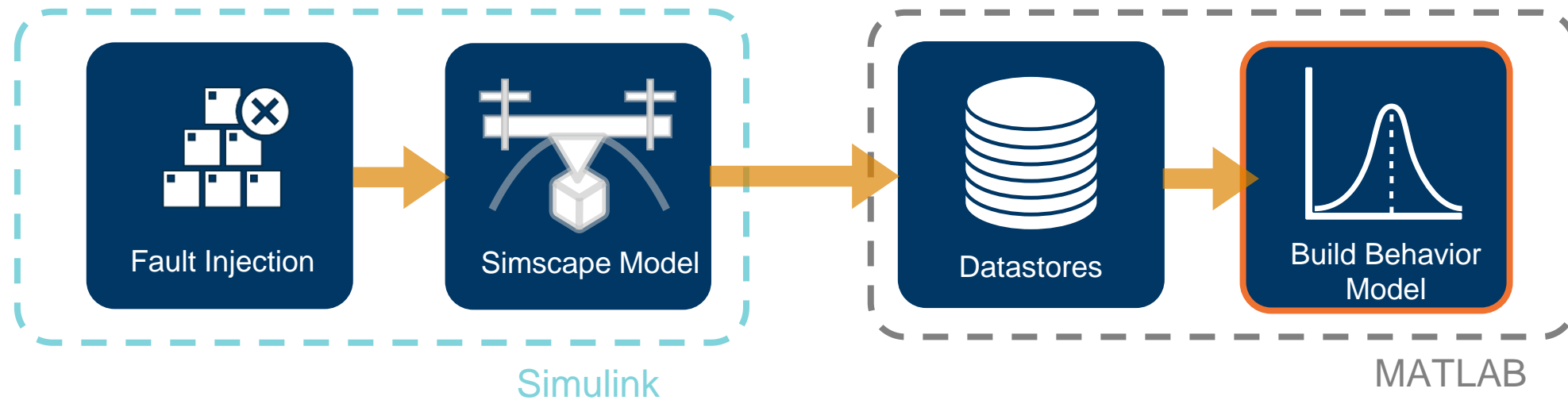
Connecting both worlds of Physical Modeling and Predictive Maintenance



Build and train models using Predictive Maintenance Toolbox

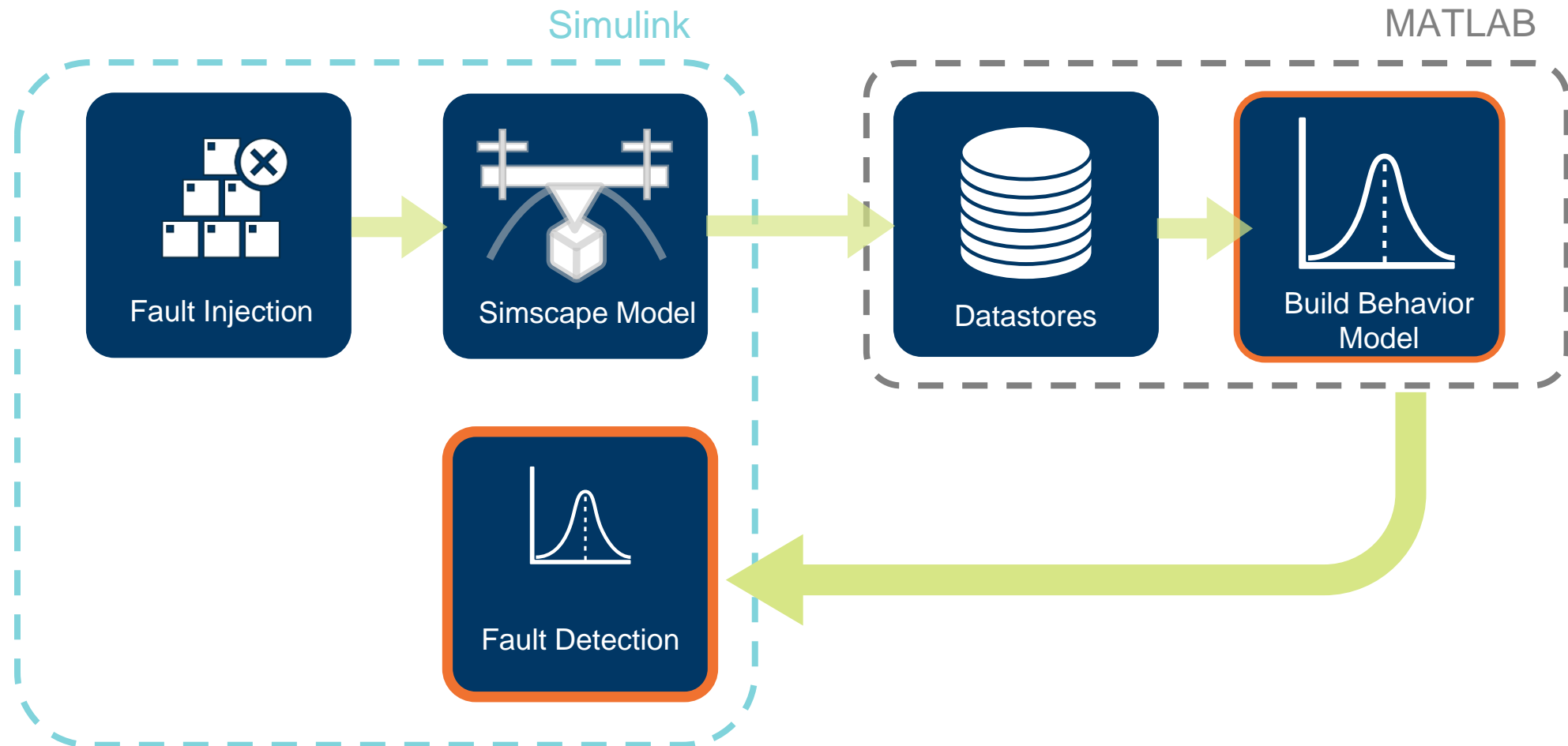
Today's scenario:

- Potential failure of one of the motors
- Offline modeling in MATLAB using data and Predictive Maintenance Toolbox

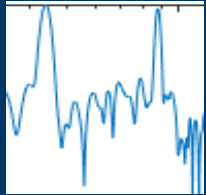


Pre-trained ML models can be exported to Simulink

Export Model to Simulink using Embedded MATLAB function



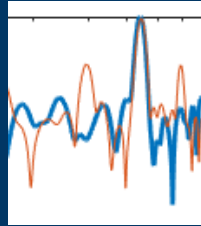
Build a Fault Detection Model using Simulated Data



Preprocessing Data

- Remove outliers
- Remove noise

Your model is only as good as your data



Extract Features

- Identify condition indicators

Time series data

2	0	2	0
0	1	0	0
2	0	7	0
0	2	0	0

Train & Validate

- Classifiers

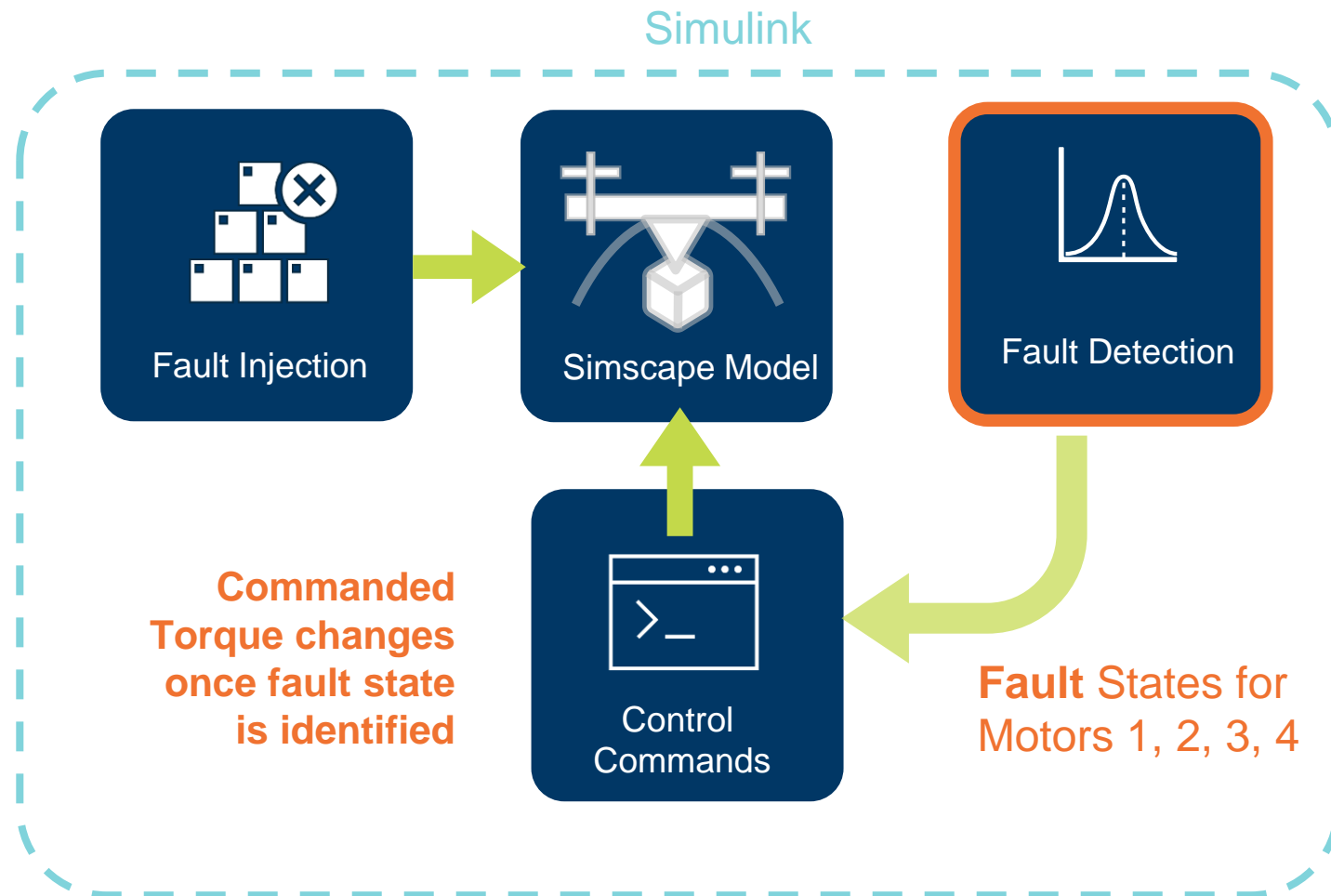


Export to Simulink

- Use Embedded MATLAB functions

Fail fast and design fault tolerant systems

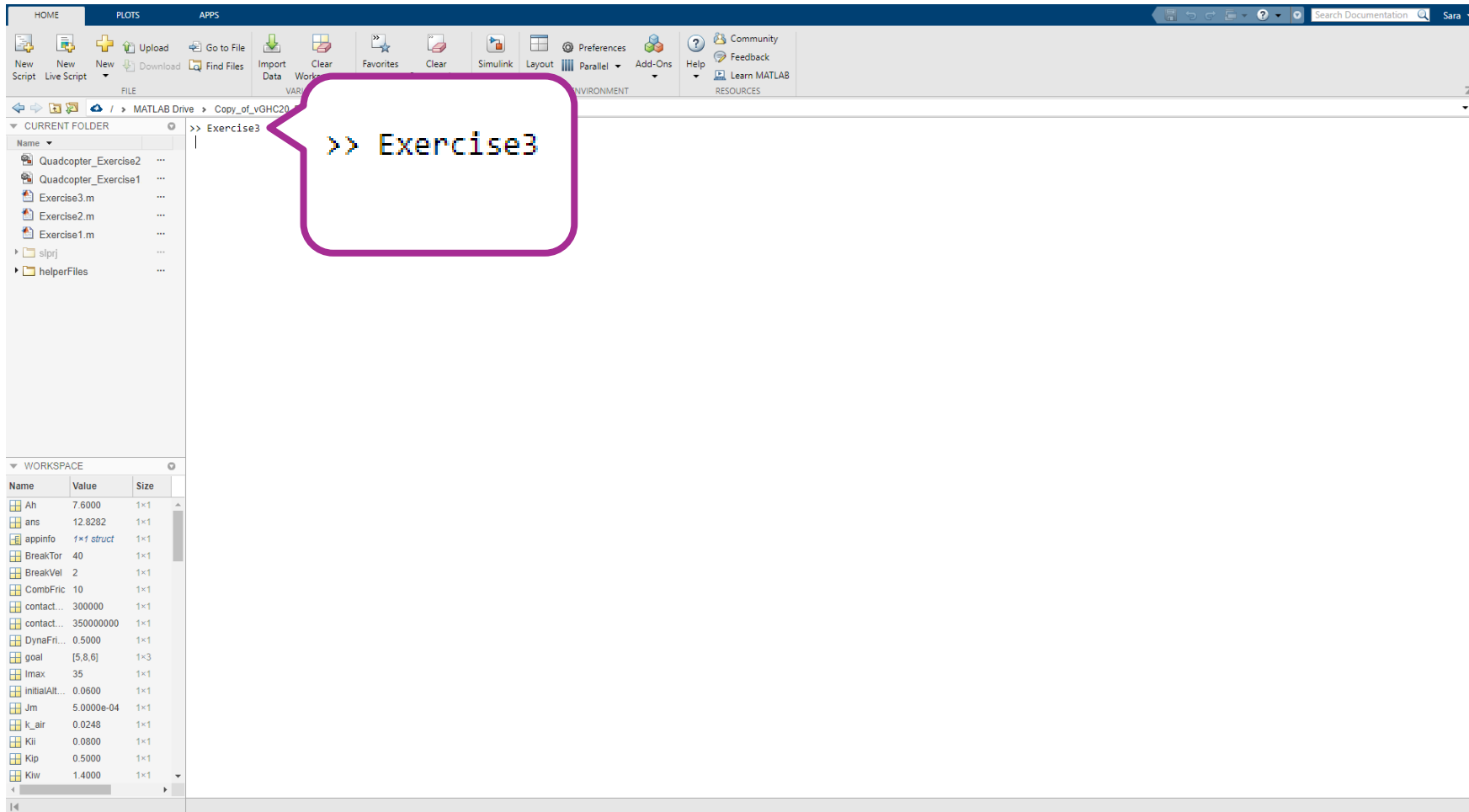
Today's scenario: Potential failure of one of the motors





Exercise 3

Type **Exercise3** in the Command Window



Exercise 3

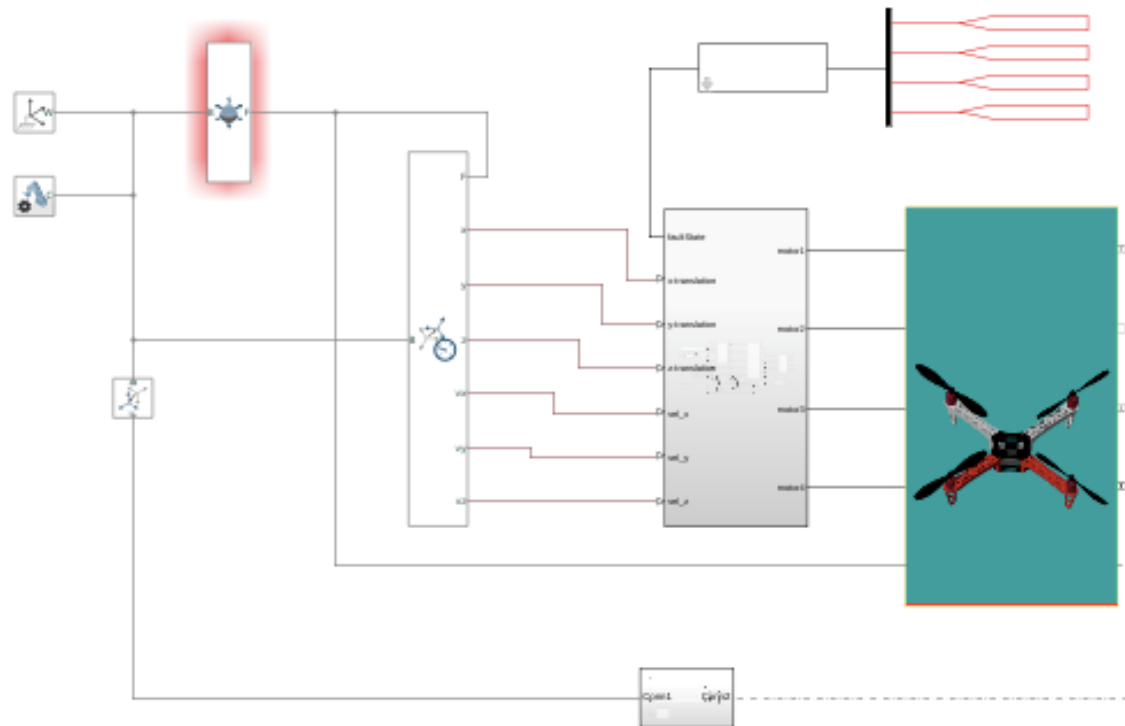
Click on Inject Fault

MATLAB EXPO 2021

Mission planning of a quadcopter using a Digital Twin Exercise 3

Objective:

In Exercise 3, you will understand how to run multiple simulations and create a behavior model to predict the faults that could happen in one of the motors. Your task is to inject faults and observe the failure, following which you will also turn on Fault Detection and observe how the system safely soft crashes.



Step 1: Inject your faults

Inject Fault on Motor

Step 2: Run your simulation (Simulation Tab)



Step 3: Turn on Fault Detection

Turn ON Fault Detection

Step 4: Run your simulation again (Simulation Tab)



Additional Resource: Visualizations



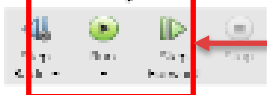
Exercise 3

Inject Fault at a given "time" T secs

Step 1: Inject your faults

Inject Fault on Motor

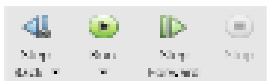
Step 2: Run your simulation (Simulation Tab)



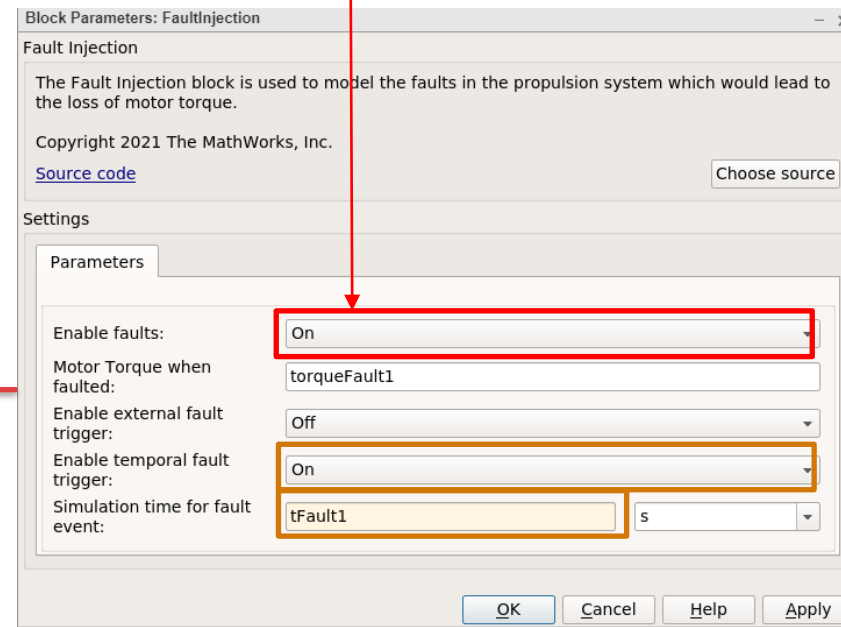
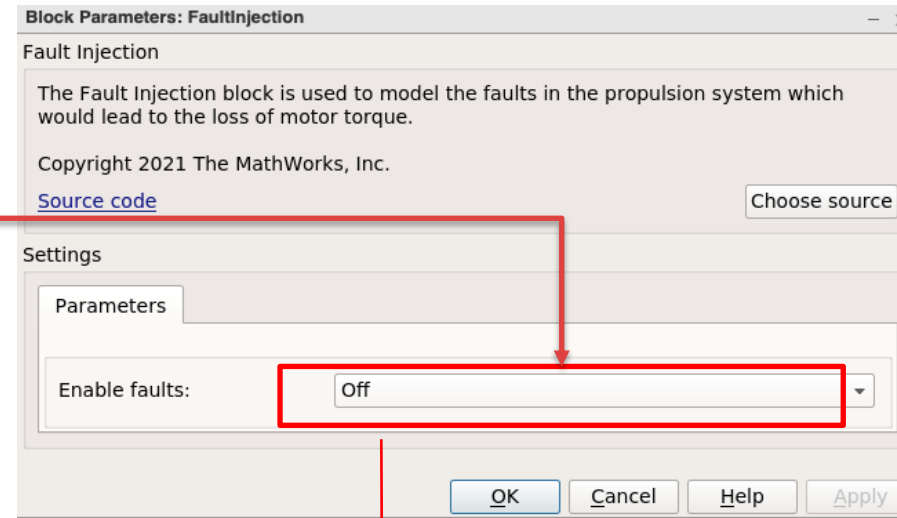
Step 3: Turn on Fault Detection

Turn ON Fault Detection

Step 4: Run your simulation again (Simulation Tab)



Additional Resource: Visualizations



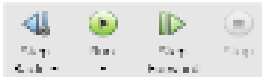
Time to run this part of Ex3-a: 3mins

Exercise 3 Turn ON Fault Detection

Step 1: Inject your faults

Inject Fault on
Motor

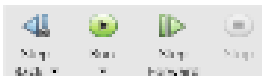
Step 2: Run your simulation (Simulation Tab)



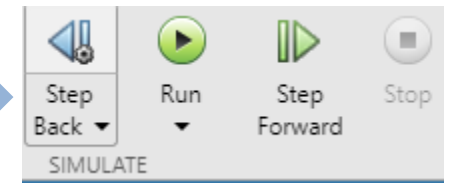
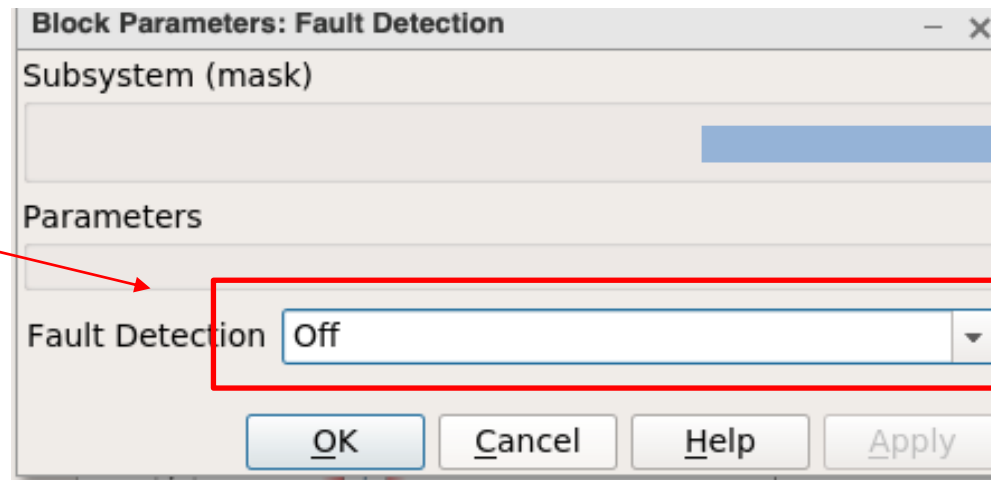
Step 3: Turn on Fault Detection

Turn ON Fault
Detection

Step 4: Run your simulation again (Simulation Tab)

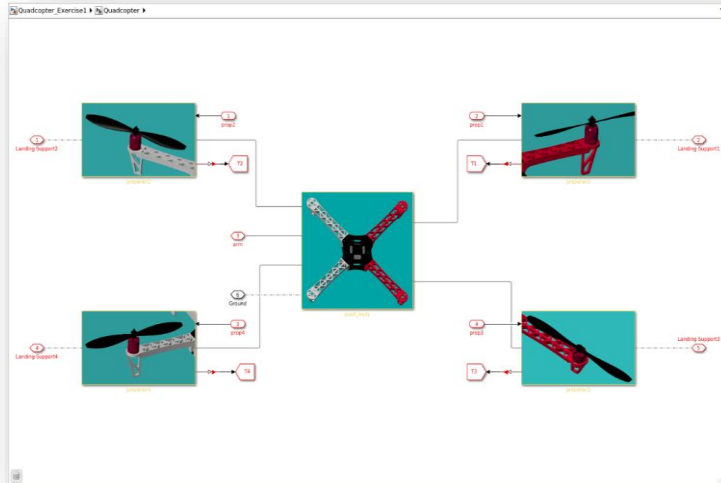


Additional Resource: Visualizations

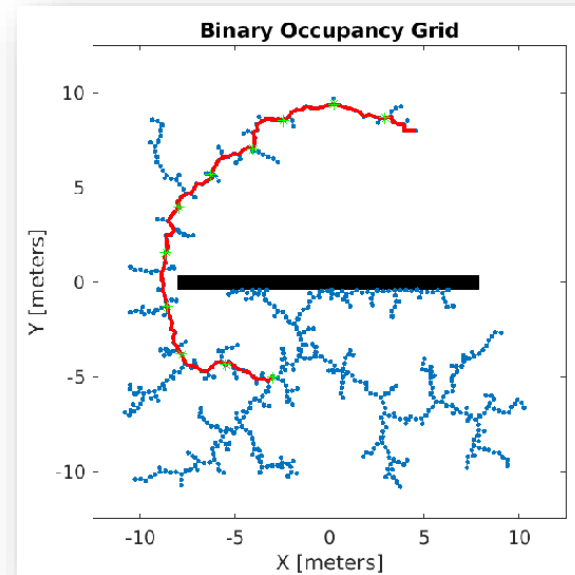


Time to run this part of Ex3-b: 4mins

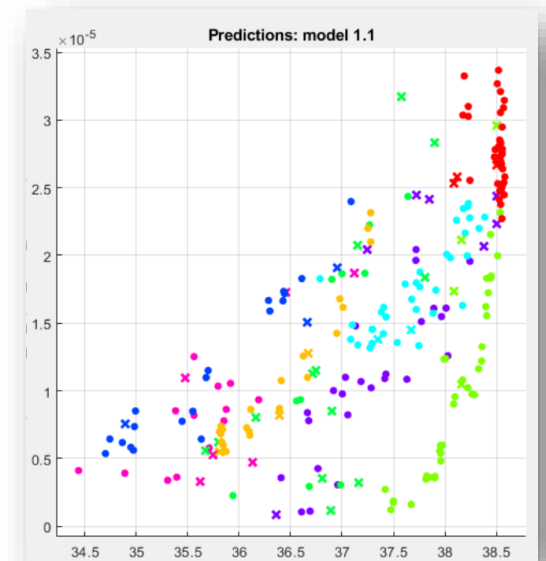
Key takeaways



Physical Modeling
(Digital Twin)



Path planning in
autonomous systems



Predictive
Maintenance for
Digital Twins

Predictive Maintenance evolves within a problem and over applications

Where did the Fault Occur?

Fault Detection

Motor

What was the type of fault?

Condition Monitoring

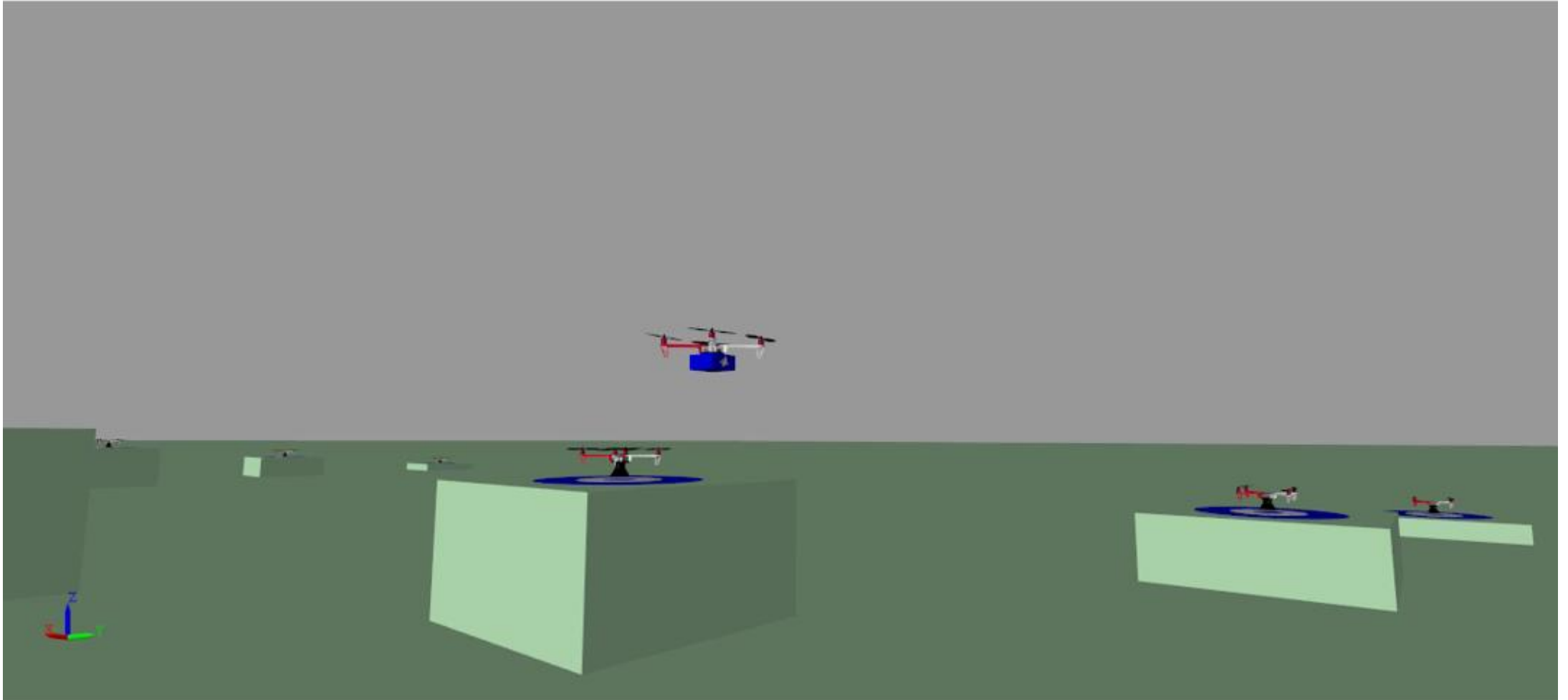
Motor had iron losses

How long can the machine operate?

Remaining Useful Life

Potential Motor Failure in 2 days

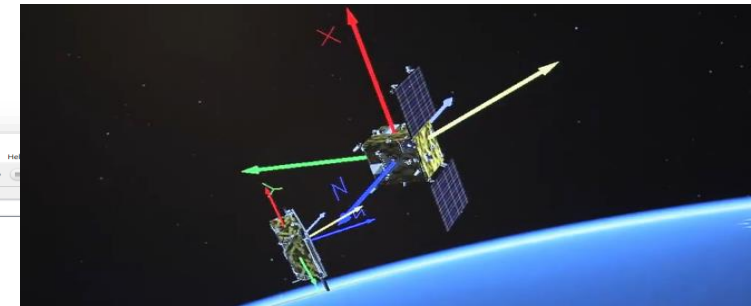
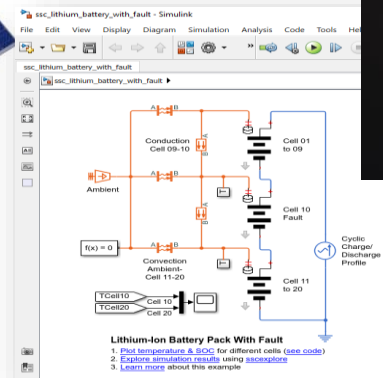
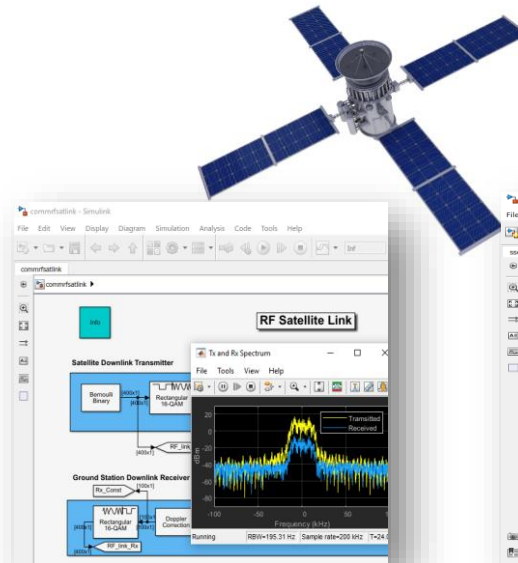
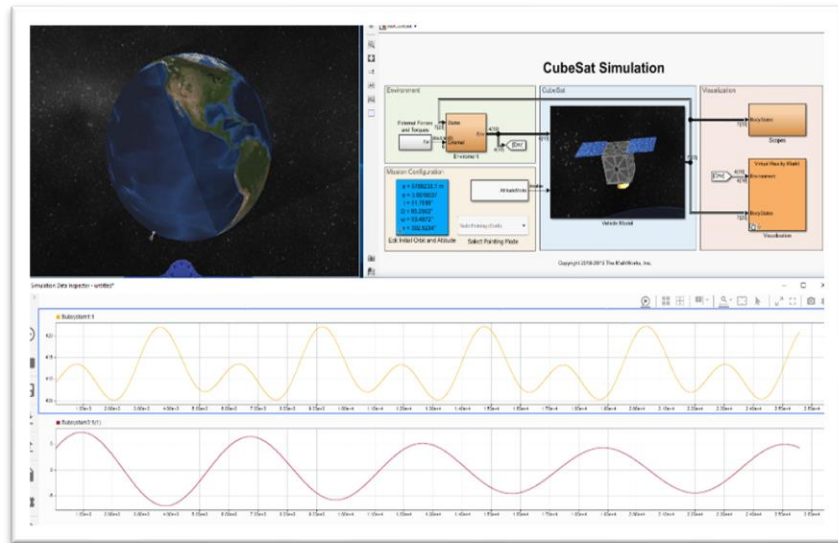
Digital twins join the fleet to meet delivery challenges.



Digital twin is not novel, has been used for expensive assets where reliability is essential.



OT Infrastructure



Digital twins transform technology to be safer, better and cleaner.

Industrial Automation



Automotive



Utilities & Energy



Medical



Aerospace



Robotics



Additional Resources

Learn more:

What Is a Digital Twin?

www.mathworks.com/digital-twin

Robotics and Autonomous Systems

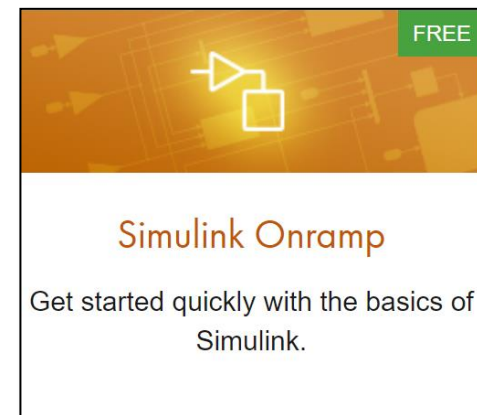
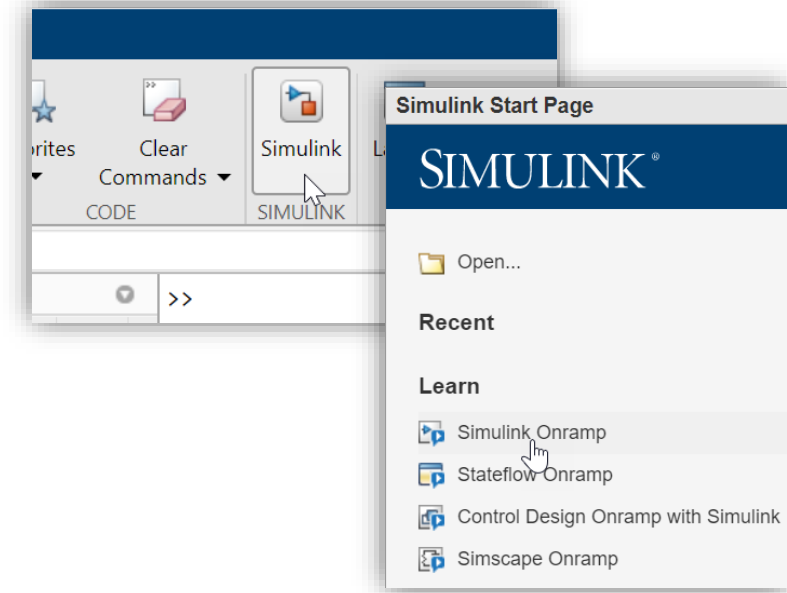
<https://www.mathworks.com/solutions/robotics.html>

Predictive Maintenance with MATLAB and Simulink

<https://www.mathworks.com/solutions/predictive-maintenance.html>



#matlabexpo #digitaltwin #workshop



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2021

Thank you

