

# MATLAB EXPO

November 13–14, 2024 | Online

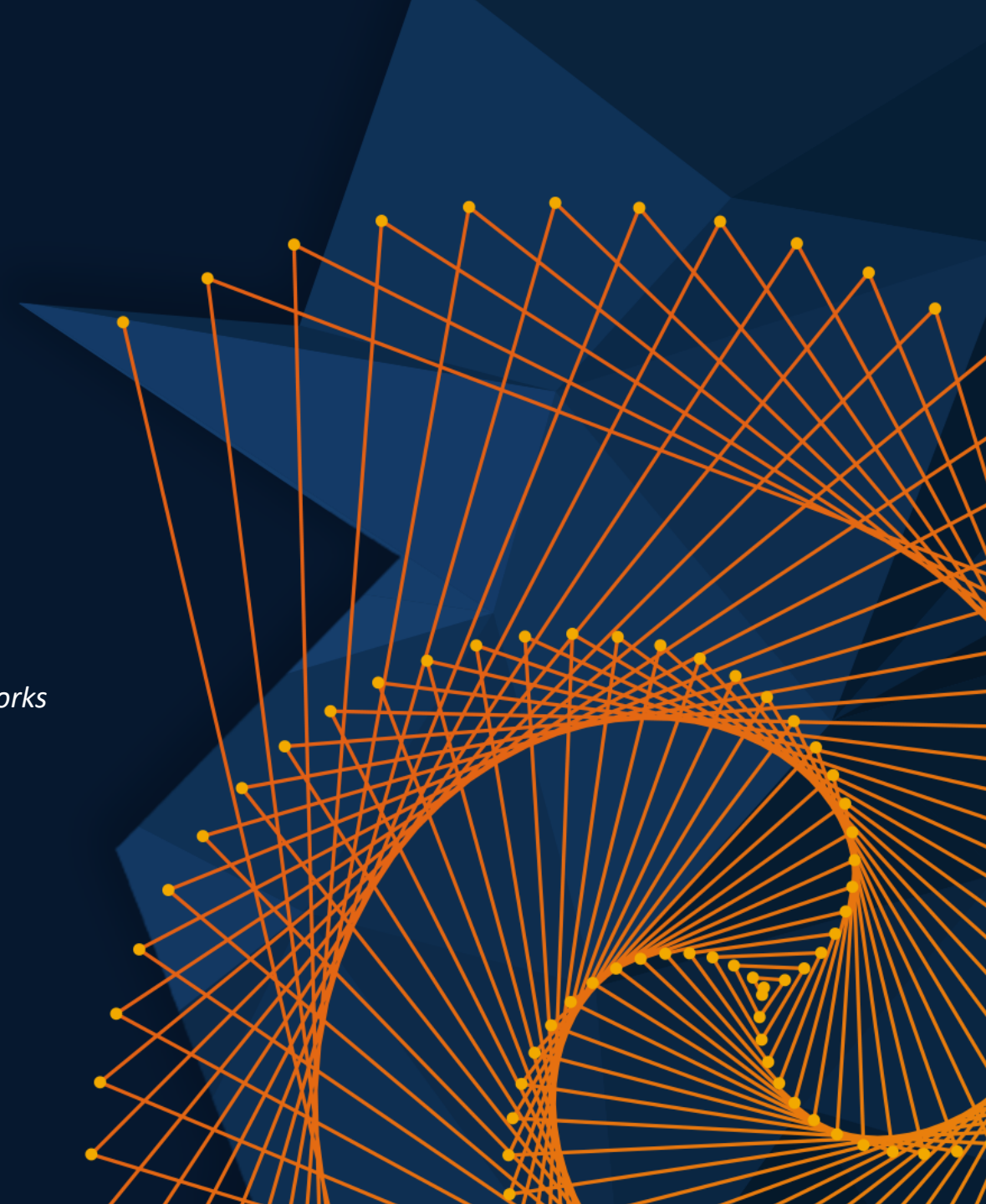
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## Virtual Testing and Simulation to Automate Offroad Heavy Machinery Using MATLAB

*YJ Lim, PhD, MathWorks*



*Christoph Kammer, PhD, MathWorks*



# Offroad vehicle industries are adopting autonomy and intelligence for process optimization, safety, and sustainability



Construction



Agriculture



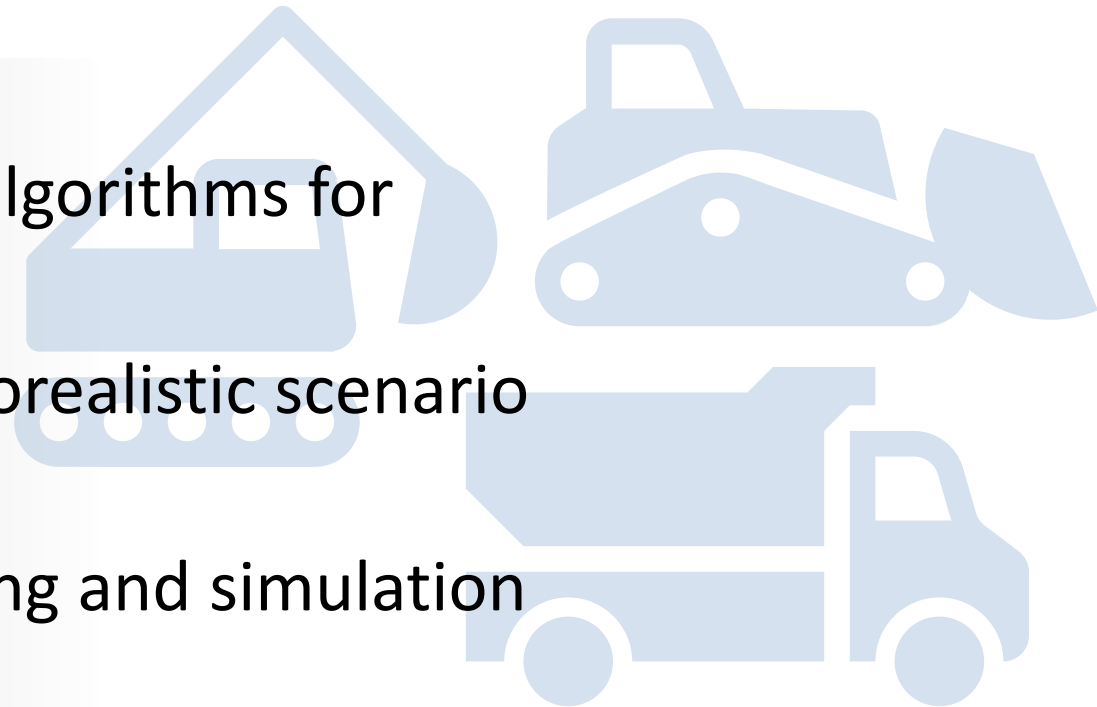
Mining





## Key Takeaways - **Virtual testing** and **simulation** are essential for developing autonomous offroad heavy machinery

- Developing and validating autonomous algorithms for offroad heavy machinery in simulation
- Testing offroad heavy machinery in photorealistic scenario simulations
- Performing high-fidelity dynamic modeling and simulation



# What are the key drivers behind interest in autonomy and intelligence for offroad heavy machinery?



## Workforce

- Widespread skilled operator shortage
- Aging workforce



## Tasks

- Inherently high-fatality tasks
- Precision and accuracy



## Technology

- Perceived successes of autonomy in automotive industry
- The rise of the Internet of Things (IoT) and better connectivity



## Economics

- ROI despite high initial costs
- Competitive advantage via operational efficiency, cost reduction, and improved quality and safety

# Industry examples transforming offroad vehicle operations include ...



Construction



**Sumitomo Heavy Industries** Speeds Development of Embedded Model Predictive Control Software for Hydraulic Excavators [LINK](#)



Agriculture



**CNH Industry** Develops Intelligent Filling System for Forage Harvesters [LINK](#)



Mining



**Caterpillar** Uses Machine and Deep Learning to Build Ground-Truth for Training, Validation, and Deploying Classifiers [LINK](#)

# The core elements of Autonomy – perception, planning, and control – are powering offroad vehicles on all terrains

## Tasks

**Survey**



**Detection /  
Identification**

**Earth Moving**



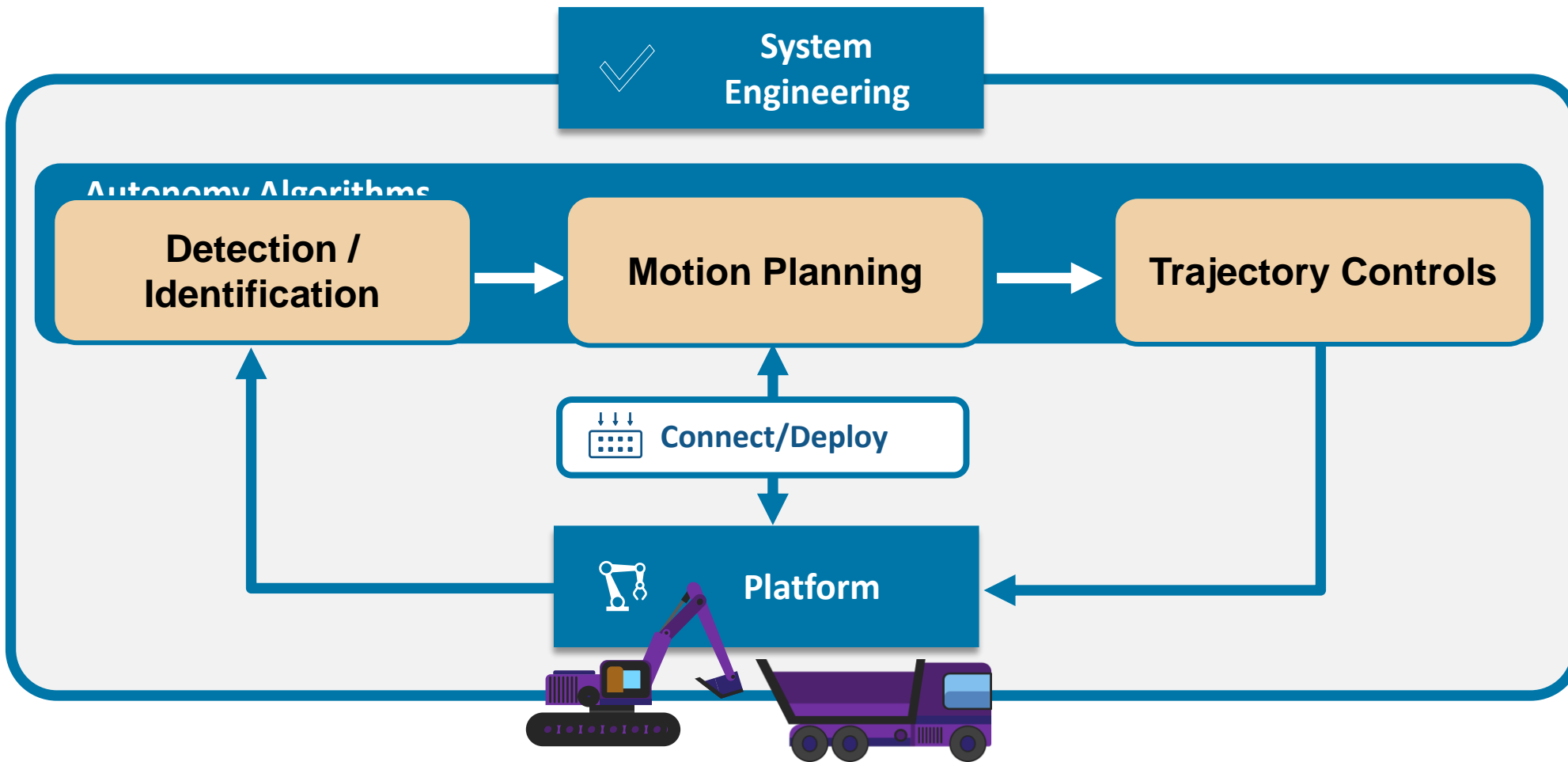
**Motion Planning**

**Transport**

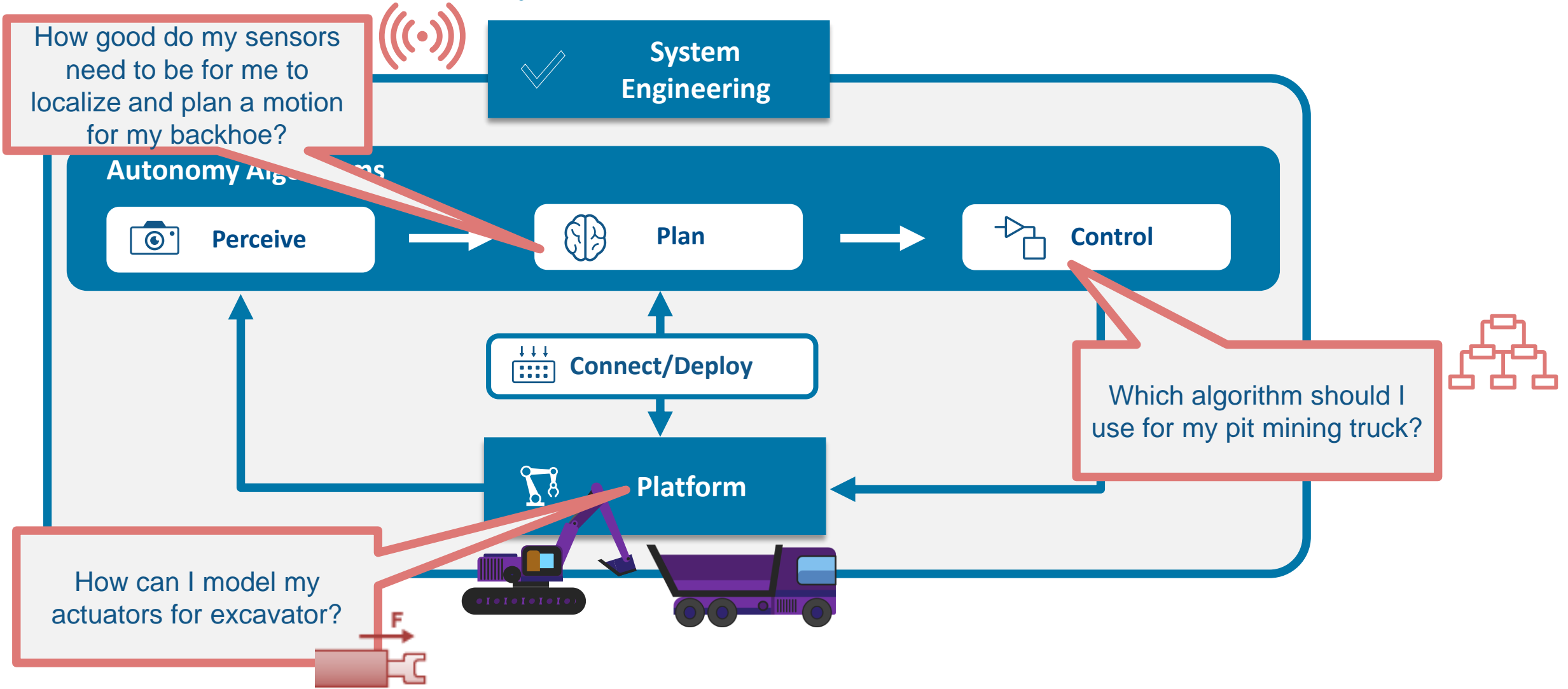


**Trajectory Controls**

Autonomy



# There are a variety of challenges in developing autonomous offroad systems





## System Engineering

### Autonomy Algorithms



Perceive



Plan



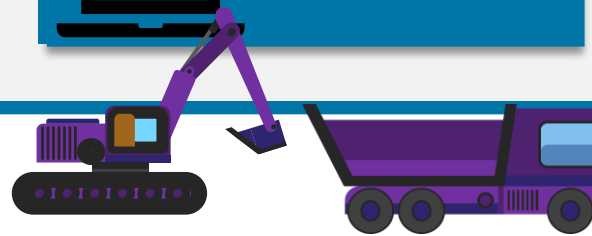
Control



Connect/Deploy



Platform



***“Simulation is essential for all stages of development process and entire product lifecycle”***

System Engineering

Autonomy Algorithms



Perceive



Plan



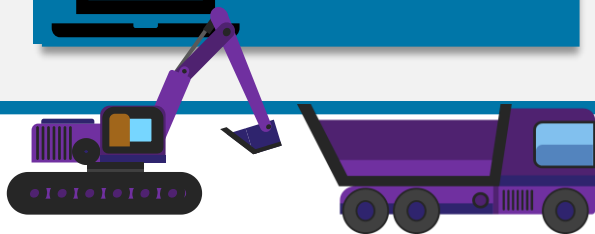
Control



Connect/Deploy



Platform



Scenario Simulation

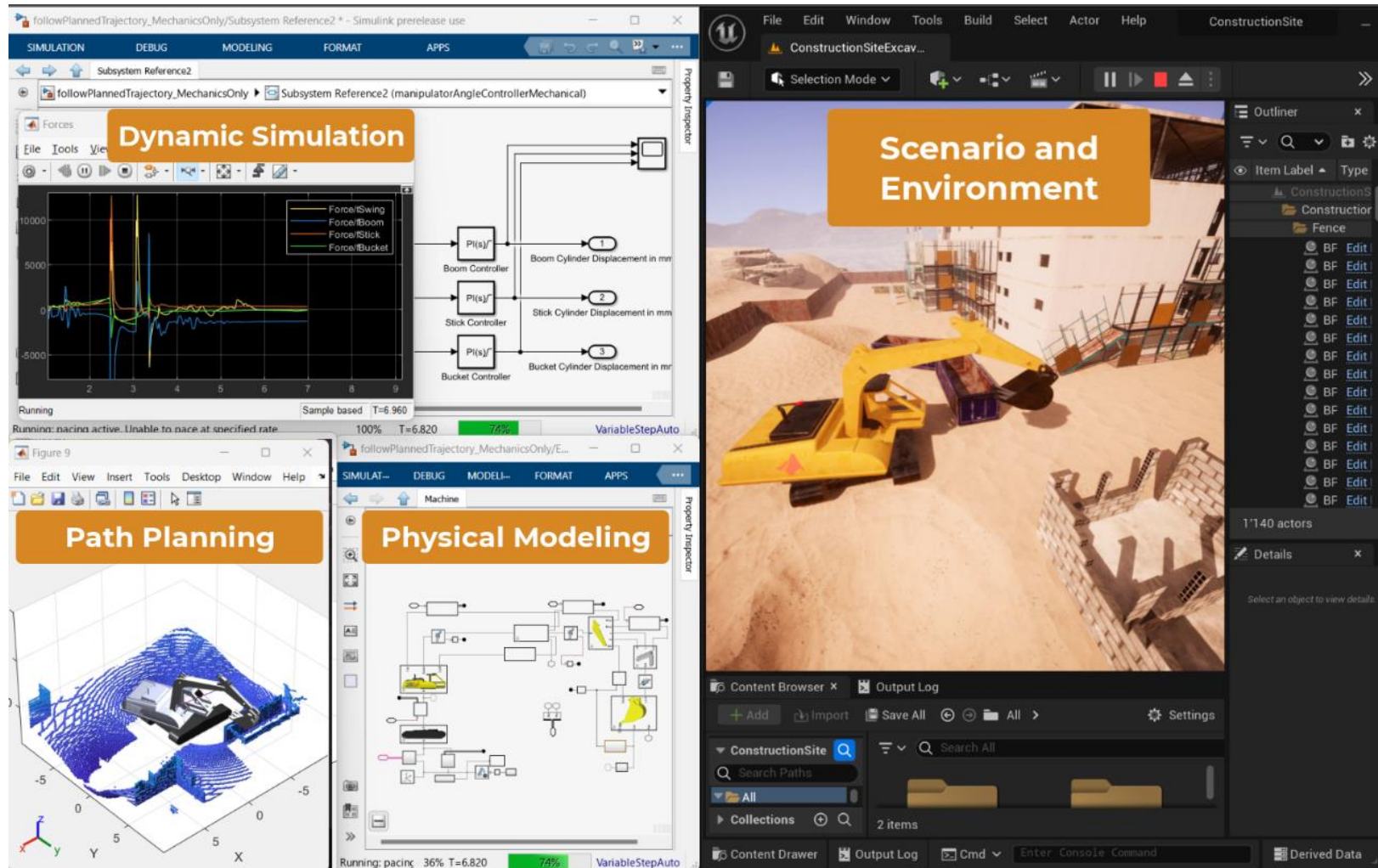
Autonomous Algorithm Development

Physical Modeling

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# System-Level Closed-Loop Dynamic Simulation of Autonomous Offroad Machinery

# System-Level Closed-Loop Dynamic Simulation of Autonomous Offroad Machinery

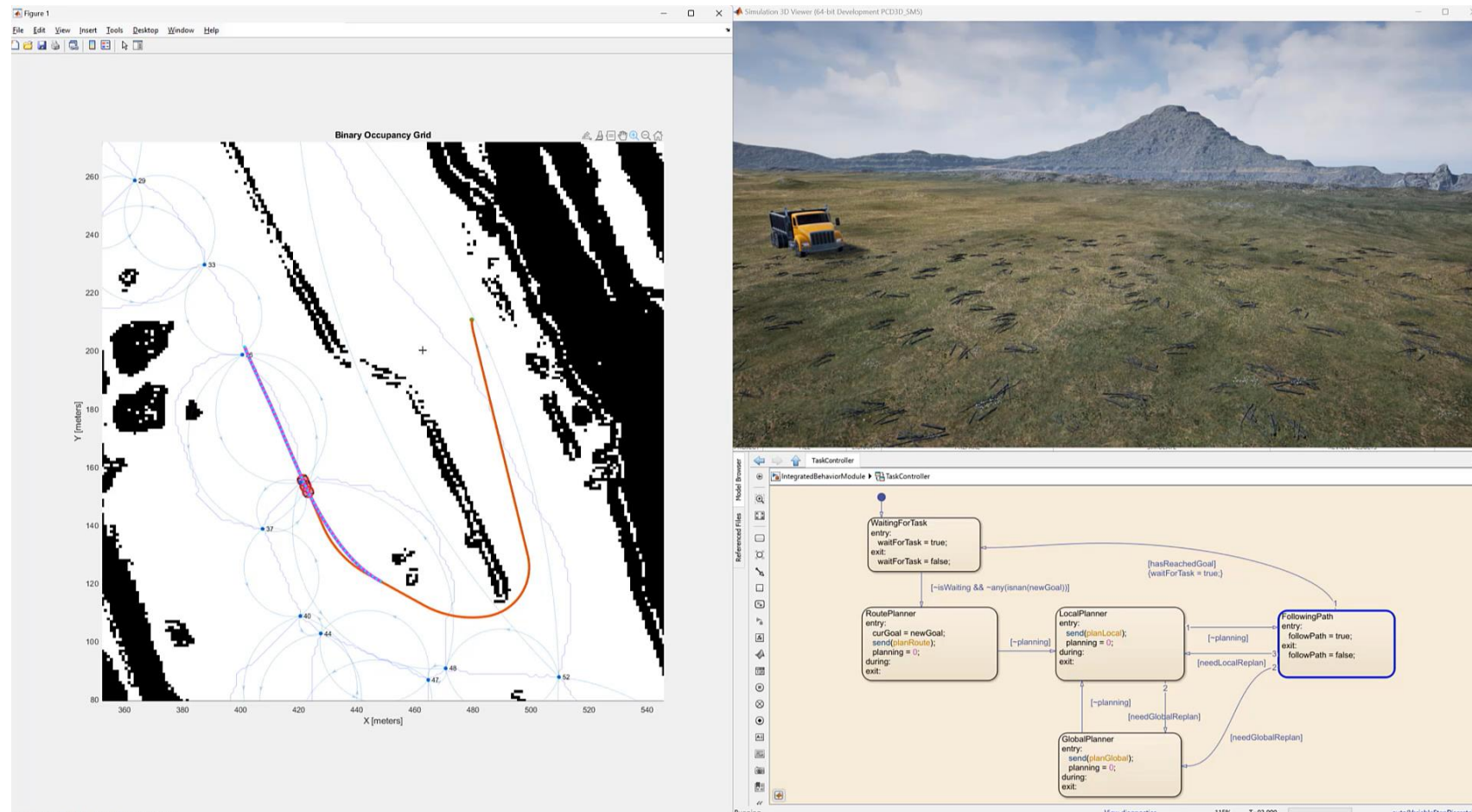




# System-Level Closed-Loop Dynamic Simulation of Autonomous Offroad Machinery

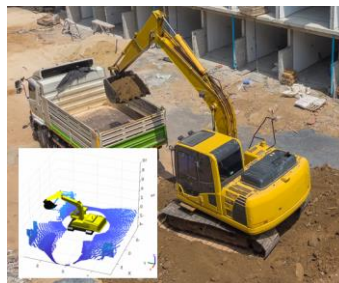
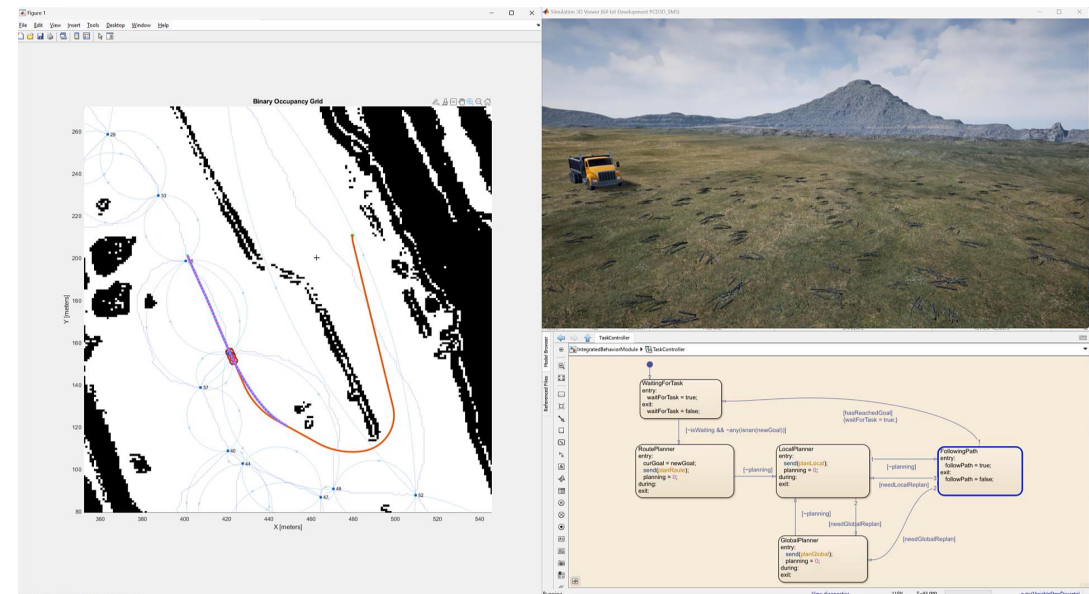
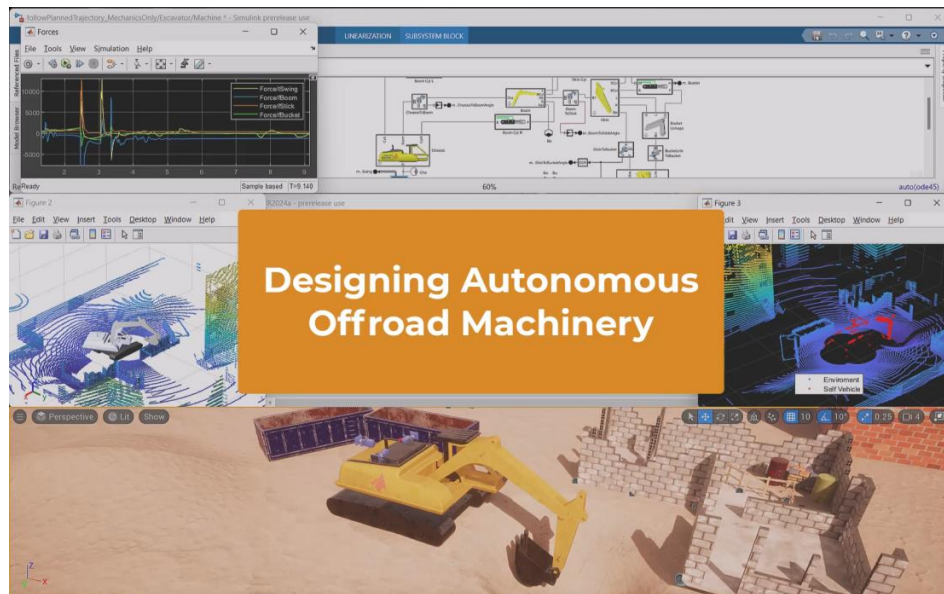


# System-Level Closed-Loop Dynamic Simulation of Autonomous Offroad Machinery





# System-Level Closed-Loop Dynamic Simulation of Autonomous Offroad Machinery



## Robotics System Toolbox Offroad Autonomy Library

by MathWorks Robotics and Autonomous Systems Team **STAFF**

Design, Simulate, and Test Autonomous Offroad Vehicle Applications

# Autonomous Offroad Heavy Machinery Development



**Perceive**

1. Scenario Simulation using Unreal Engine
2. Sensor Modeling and Synthetic Data Generation



**Plan**

3. Motion planning for Excavator



**Control**

4. Autonomous navigation algorithm development



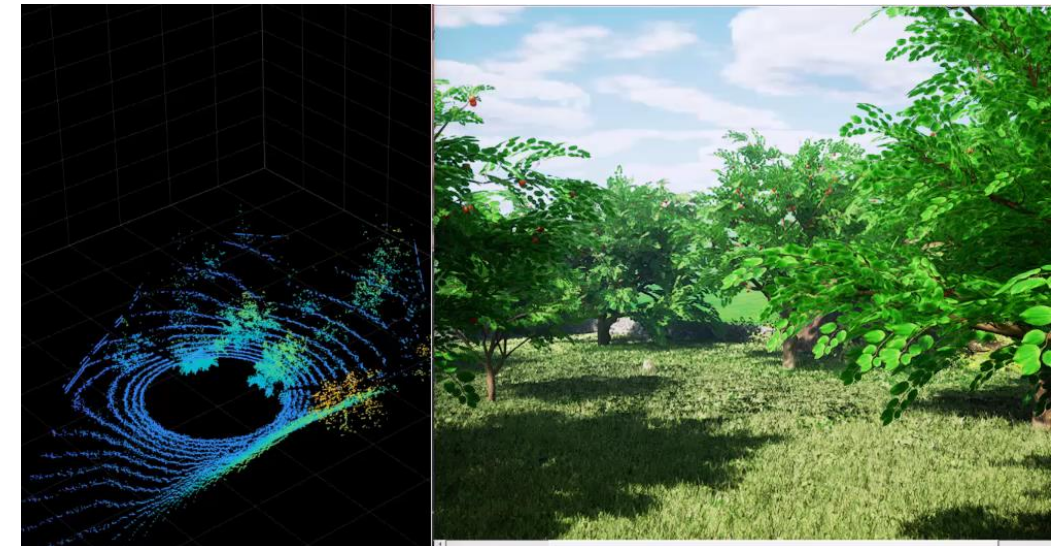
**Platform**

5. High-fidelity multi-domain physics models



# Why 3D Scenario Simulation?

- Visuals are universal
  - Easily debug issues
  - Sell your concept or product
- 3D environments are data-rich
  - Simulate camera, radar, or lidar data
  - Ray tracing enables other sensor simulations
- Complex scenario simulation
  - Create complex scenes with multiple actors
  - Test and validate complete system in simulation



# You can perform closed-loop, deterministic simulations with Unreal Engine

## MATLAB & Simulink

- Physics of main actor(s)
- Perception, Planning, Control Algorithms

actor position

sensor location

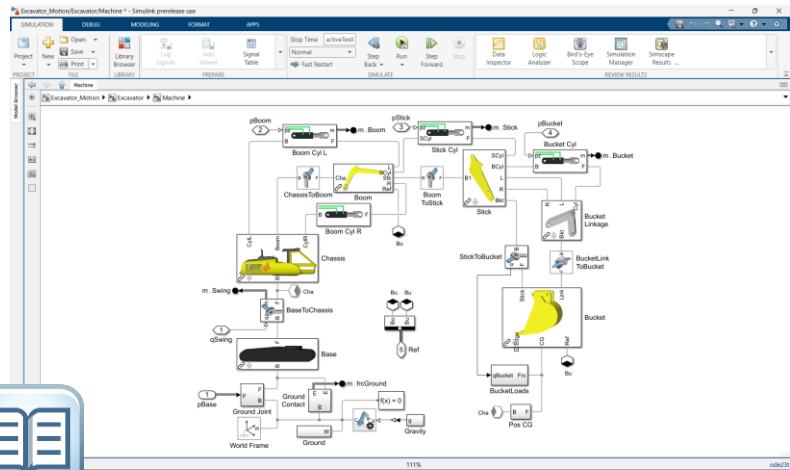
sensor information

collision information

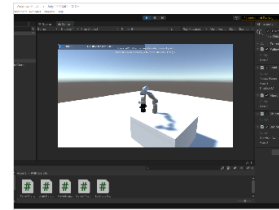
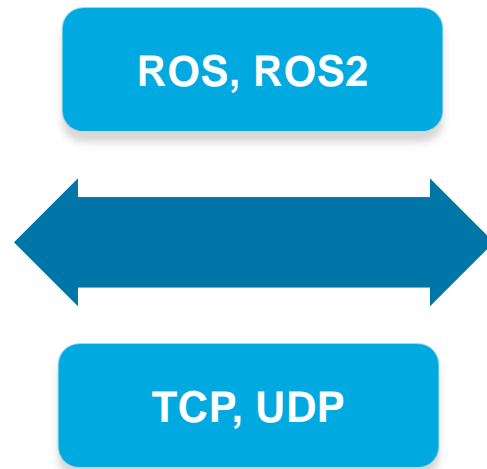
## Unreal Engine

- Rendering / lighting
- Physics of non-Simulink actors
- Collision detection

Lock-step co-simulation (solvers take turns) provides **deterministic results**

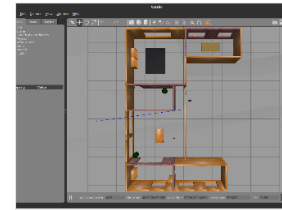


# MathWorks supports other simulators as well



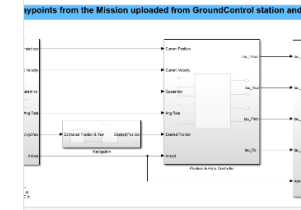
## Pick-and-Place Workflow in Unity 3D Using ROS

Set up an end-to-end pick-and-place workflow for a robotic manipulator like the Kinova Gen3, and simulate the robot in the Unity game engine.



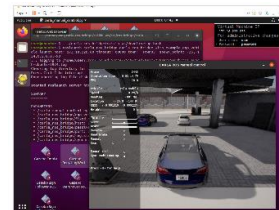
## Get Started with Gazebo and Simulated TurtleBot

Set up the Gazebo® simulator engine and further explore Gazebo with a simulated TurtleBot.



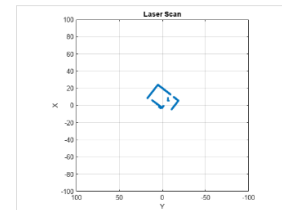
## PX4 in Hardware-in-the-Loop (HITL) Simulation with jMAVSim Simulator

Use the UAV Toolbox Support Package for PX4 Autopilots to verify the controller design by deploying on the Pixhawk hardware board, in HITL



## Emergency Braking of Ego Vehicle in CARLA Simulator Using Simulink and CARLA...

Emergency braking of ego vehicle in CARLA using Simulink.



## Control NVIDIA Carter Robot in Isaac Sim Using ROS 2

Publish ROS 2 messages from MATLAB to NVIDIA Carter robot and subscribe to the published topics



## HL-20 Project with Optional FlightGear Interface

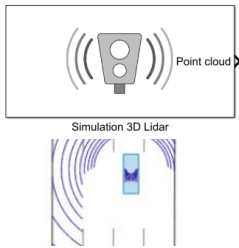
Model NASA HL-20 lifting body and controller modeled in Simulink and Aerospace Blockset, using FlightGear for visualization.



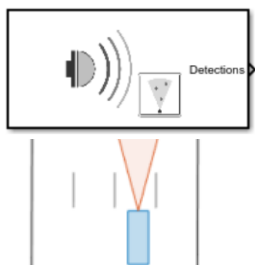
# Perceive

# Simulate virtual sensors models and generate synthetic sensor data

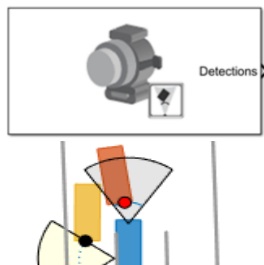
## Lidar



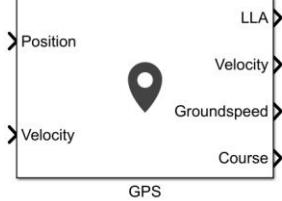
## Radar



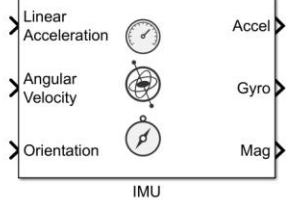
## Ultrasonic



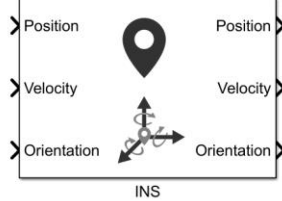
## GPS



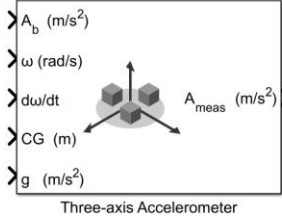
## IMU



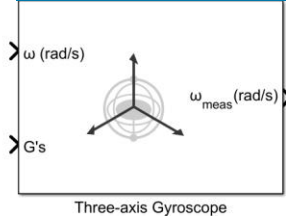
## INS



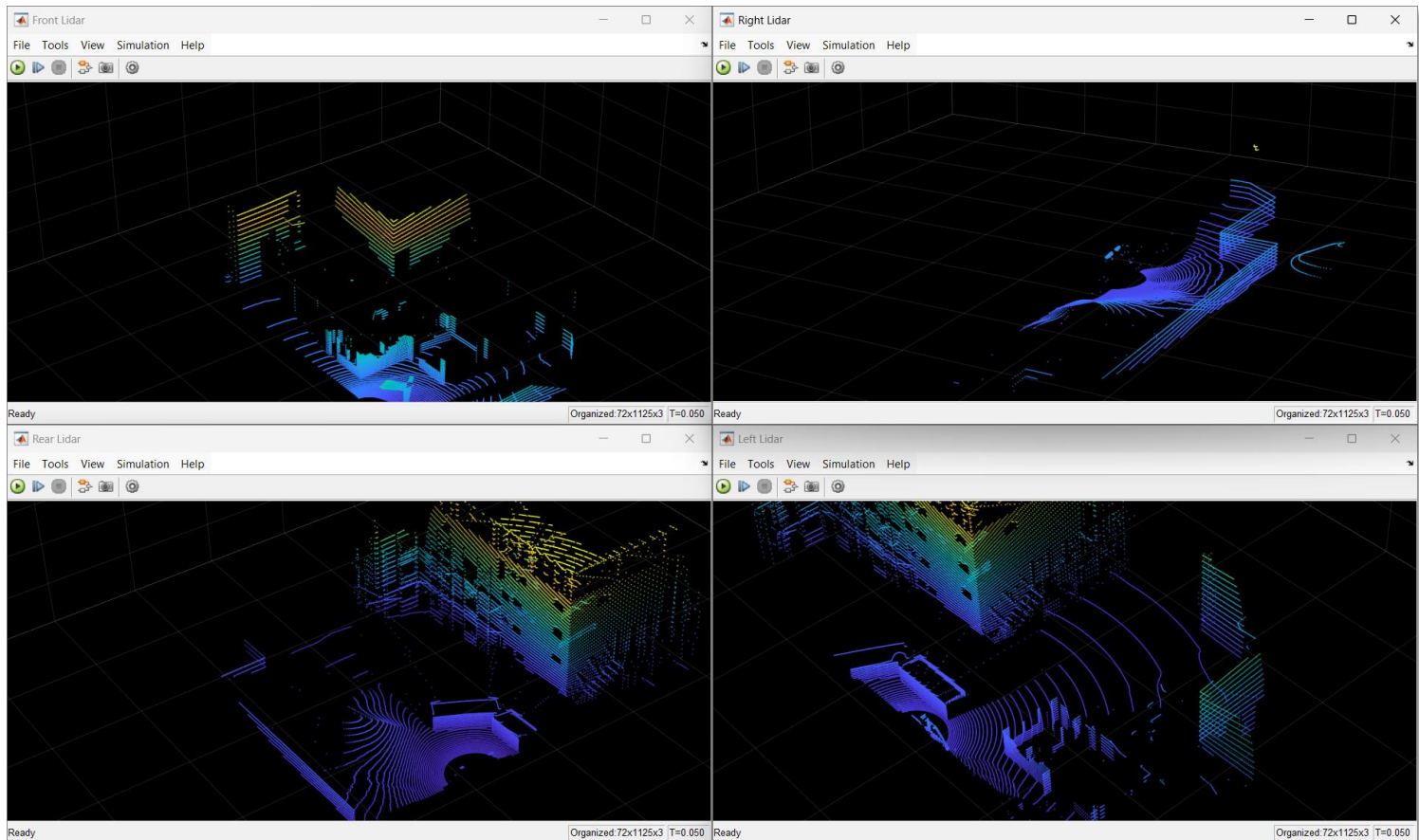
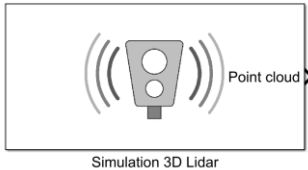
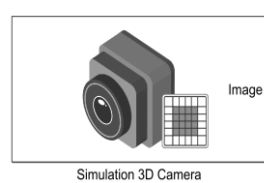
## Accel



## Gyro



## Camera







Perceive

Simulate with adverse weather and environment conditions



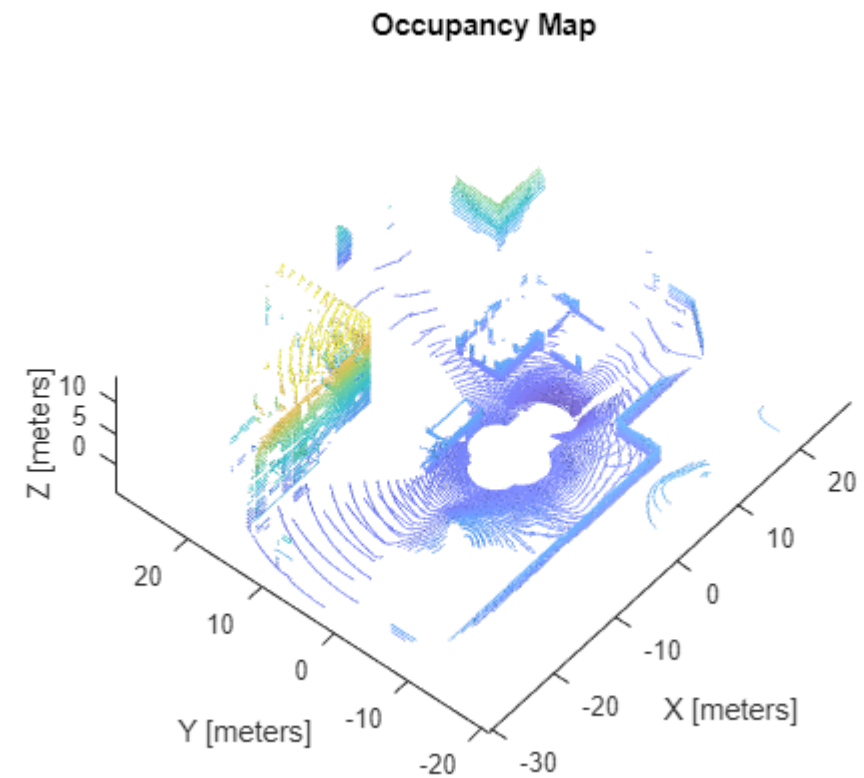
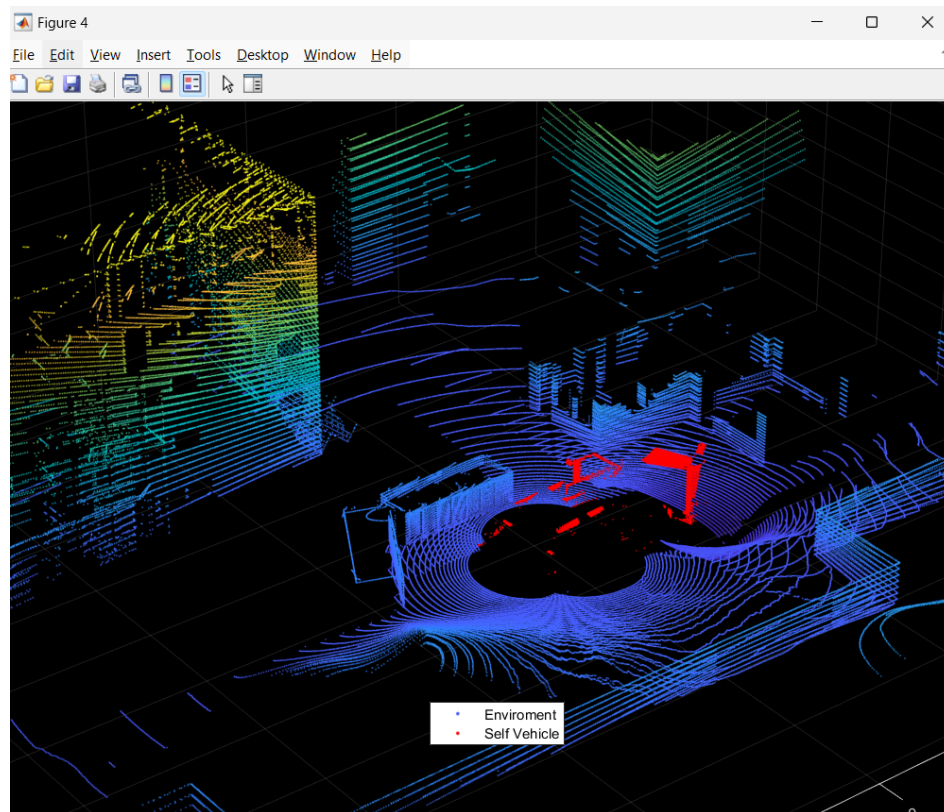


Plan



Control

# Plan collision-free motion for an excavator



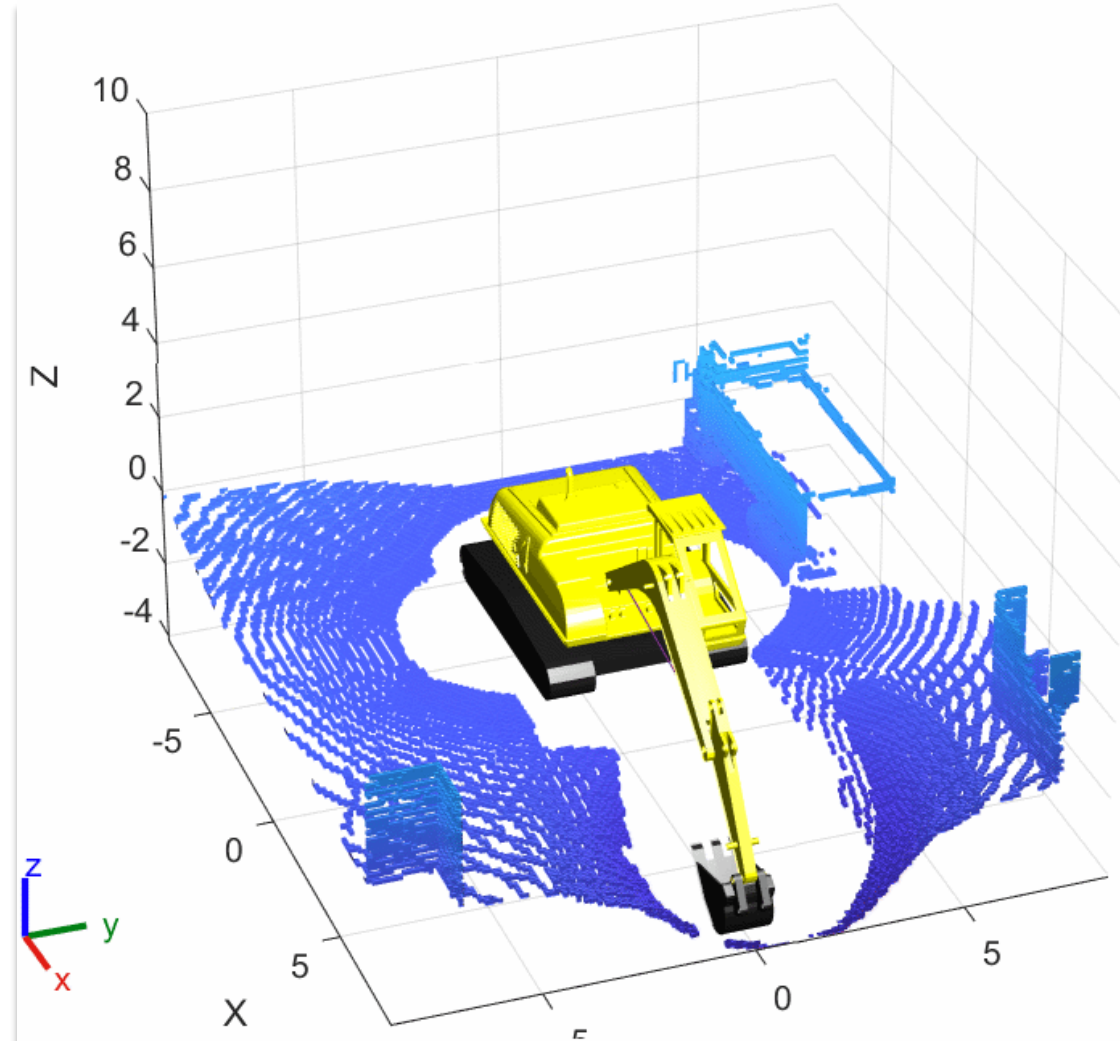


Plan



Control

## Plan collision-free motion for an excavator







Plan



Control

# Convert existing data to maps for planning and navigation on uneven terrain

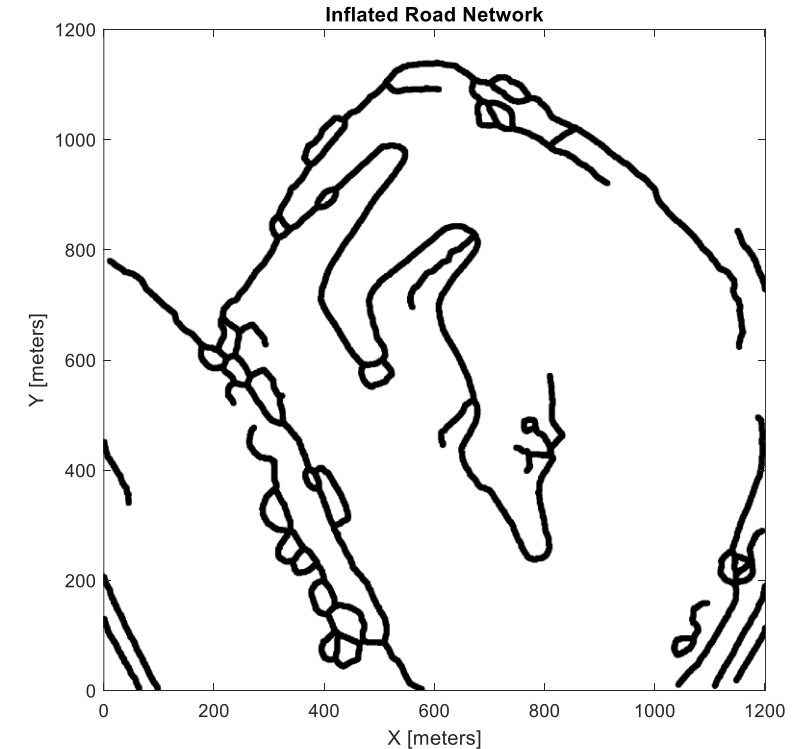
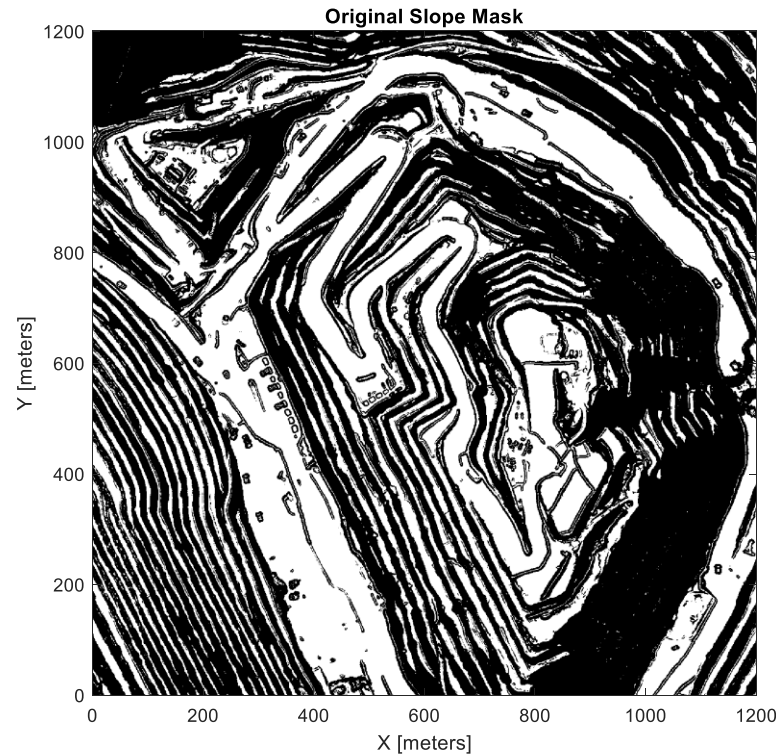
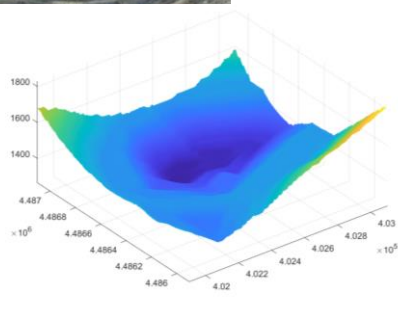
Satellite Imagery



Slope Mask



Road Map





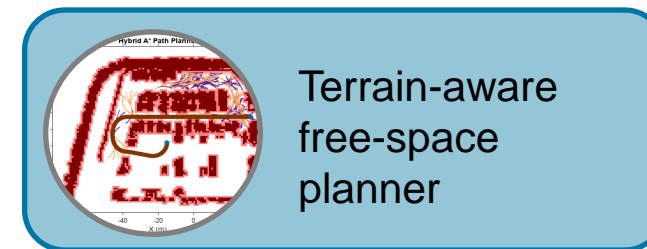
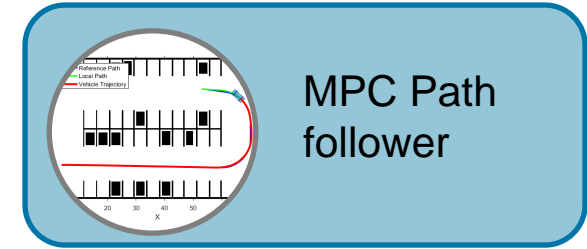
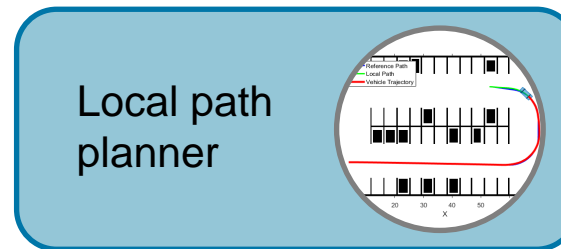
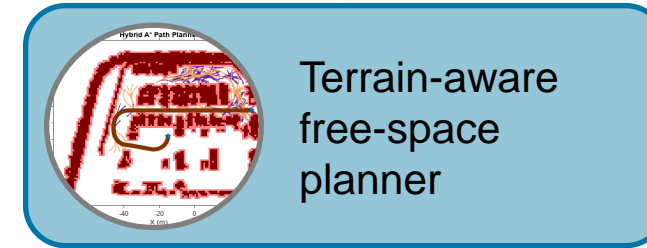
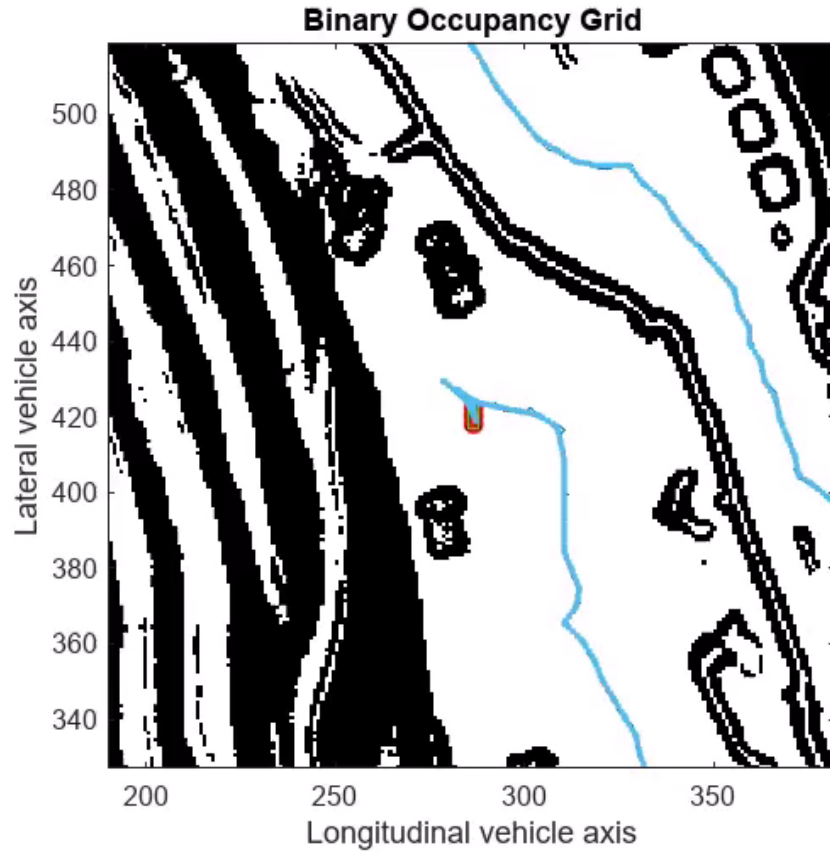


Plan

# Develop an offroad navigation stack



Control

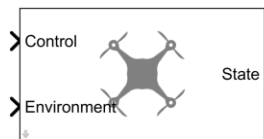
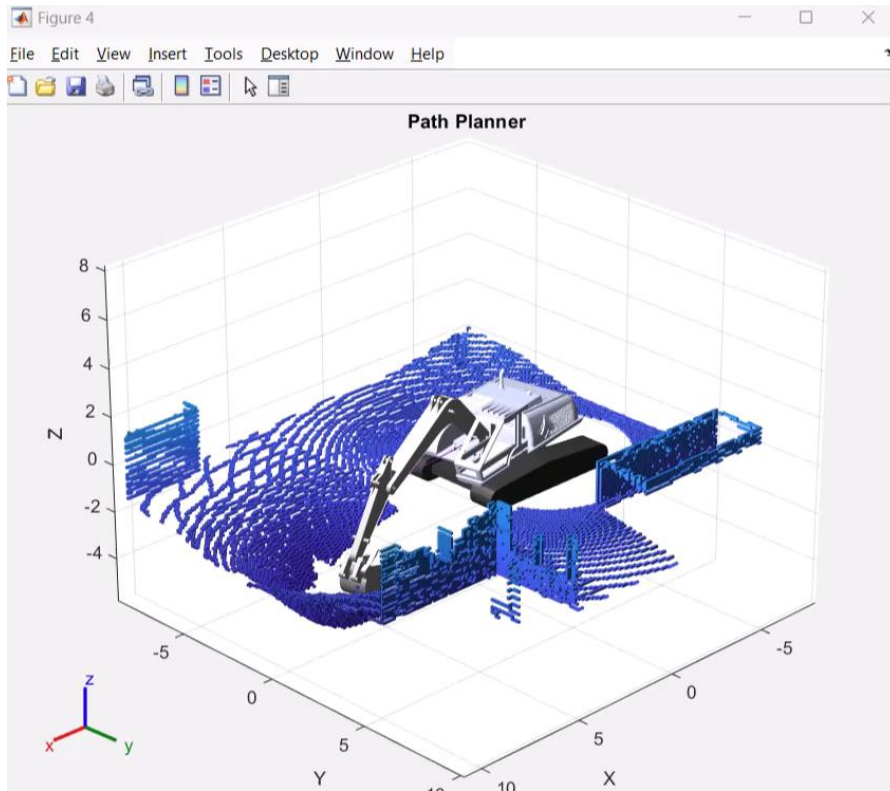




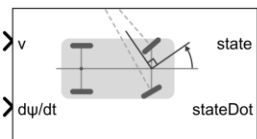
# Use different types of motion models for different tasks

## Kinematic Models Toolboxes for Robotics

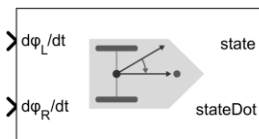
## Dynamic Models Simscape



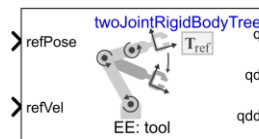
Guidance Model



Ackermann Kinematic Model



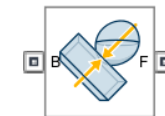
Differential Drive Kinematic Model



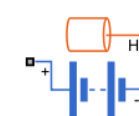
Task Space Motion Model



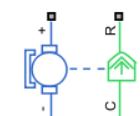
CAD



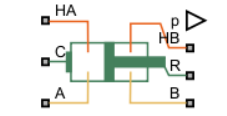
Contact Force



Battery

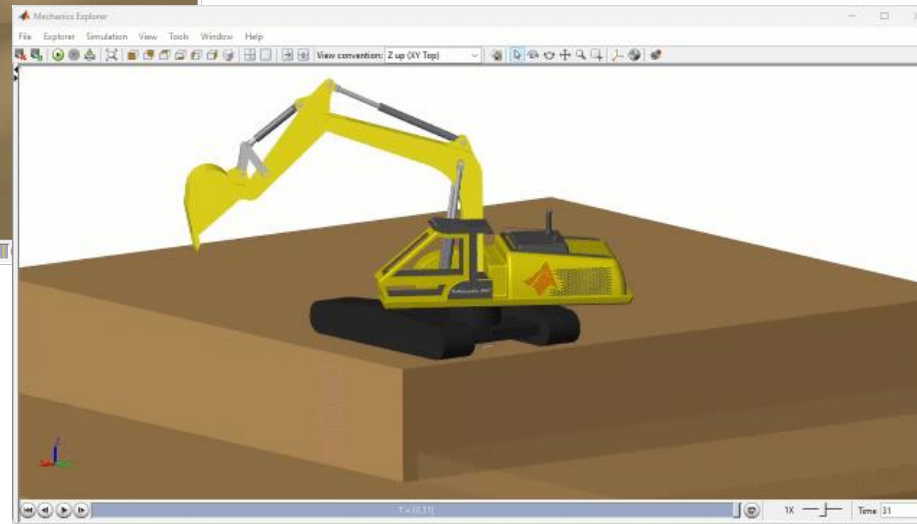
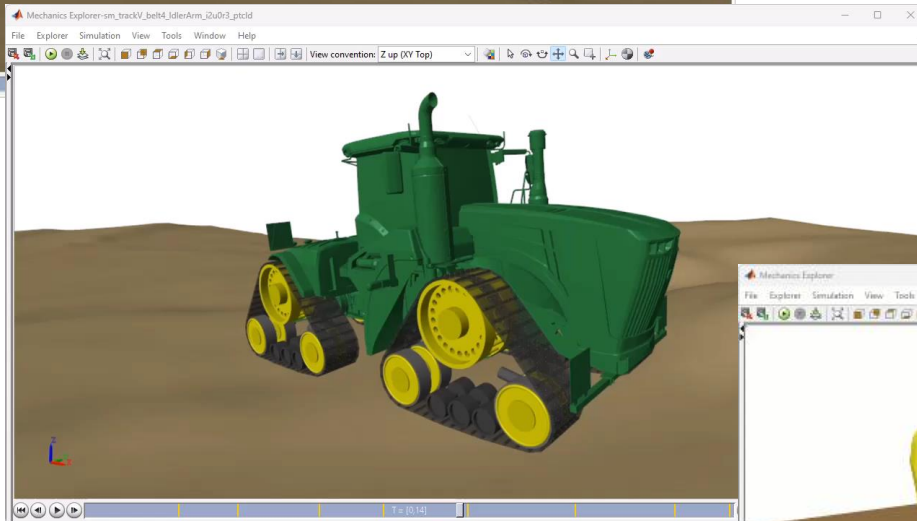
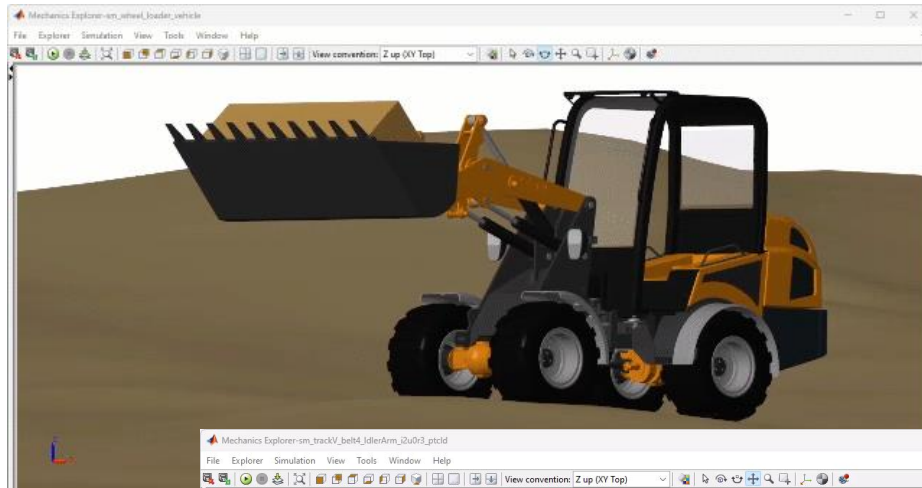


DC Motor



Hydraulic Cylinder

# Dynamic Modeling (Simscape) Reference Examples



## Heavy Equipment Design with Simscape

### Top 10 Use Cases

1. Refine linkage pin locations based on breakout force and load charts.
2. Assess exact working envelope by importing designs from CAD and FEM software
3. Integrate electric and hydraulic designs with models of mechanical linkages.
4. Explore the entire design space by running simulations in parallel.
5. Size powertrain components for both propulsion and power takeoff requirements.
6. Increase efficiency by simultaneously tuning design parameters in any system.
7. Investigate dangerous conditions in virtual tests including faulty components
8. Design and test control logic against all safety requirements.
9. Validate automated driving algorithms in virtual environments.
10. Test your embedded software against a virtual system using hardware-in-the-loop (HIL) simulation.

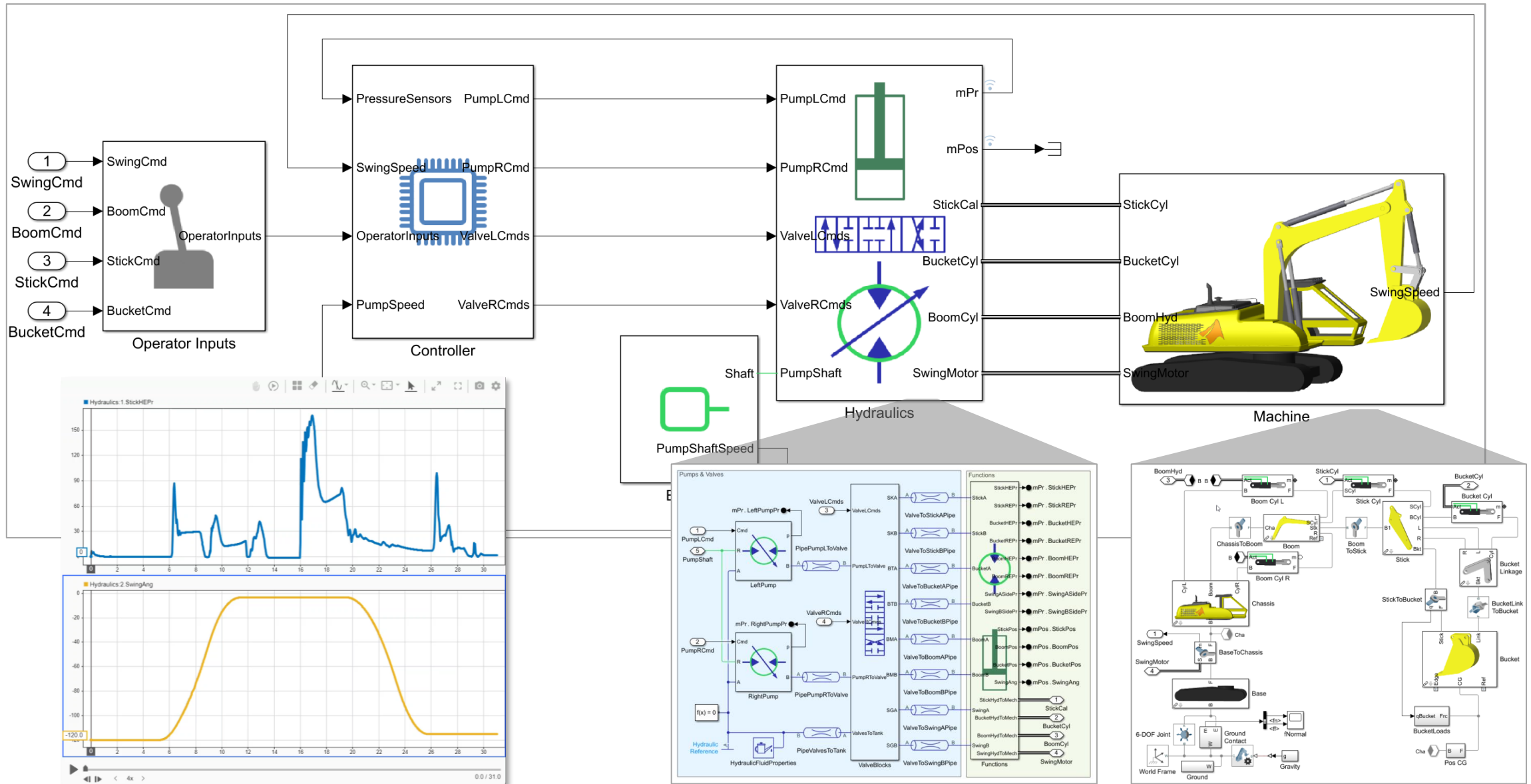


Excavator Design with Simscape



Wheel Loader Design with Simscape

# Test integrated hydraulic, mechanical, and electrical designs



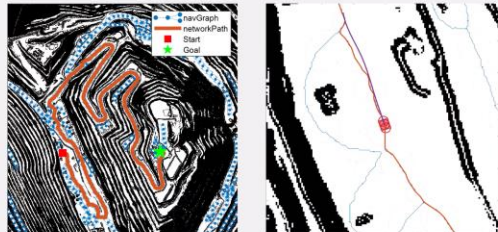
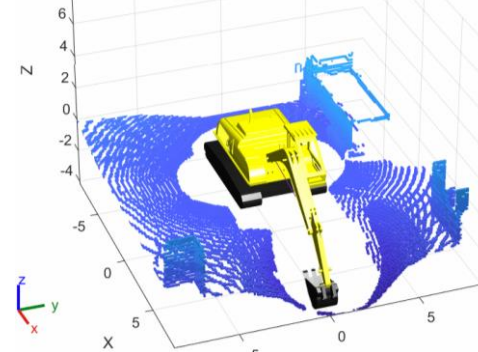


# Virtual Testing and Simulation play a key role in development and testing of autonomous offroad vehicle systems on all terrains

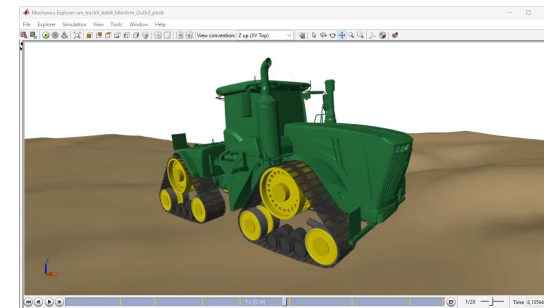
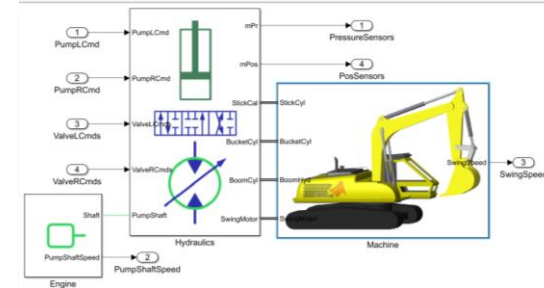
Test in Scenario Simulation



Develop and Simulate Autonomy



Design Physical Model



# We offer comprehensive tools for the development and testing of autonomous offroad vehicle systems



Toolbox

Test in Scenario Simulation

Develop and Simulate Autonomy

Design Physical Model

**Simulink 3D Animation**  
Simulate and visualize dynamic systems in a 3D environment

**Robotics System Toolbox**  
Design, simulate, test, and deploy robotics applications

**ROS Toolbox**  
Design, simulate, and deploy ROS-based applications

+

Many more

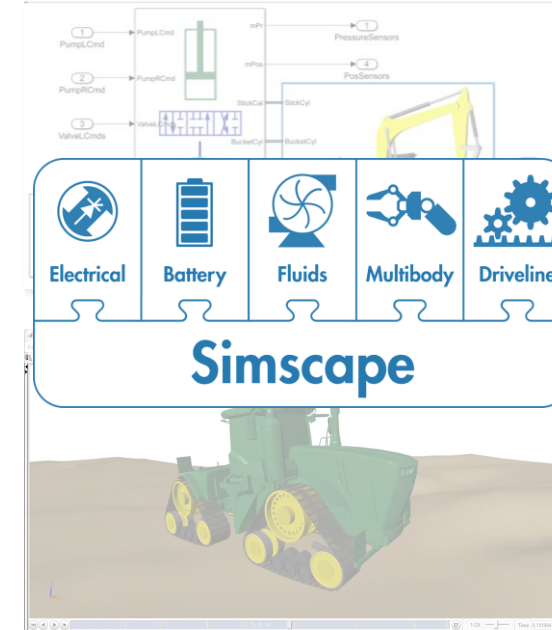
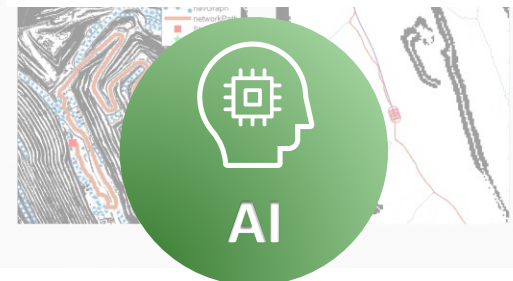


**Robotics System Toolbox**  
Design, simulate, test, and deploy robotics applications

**Navigation Toolbox**  
Design, simulate, and deploy algorithms for autonomous navigation


+

Many more



# Call to Action:

## Tell us about your applications & ask for a trial




### Seminar 1 Simulation & Control of A Construction Vehicle

Available in 3 vehicle options:

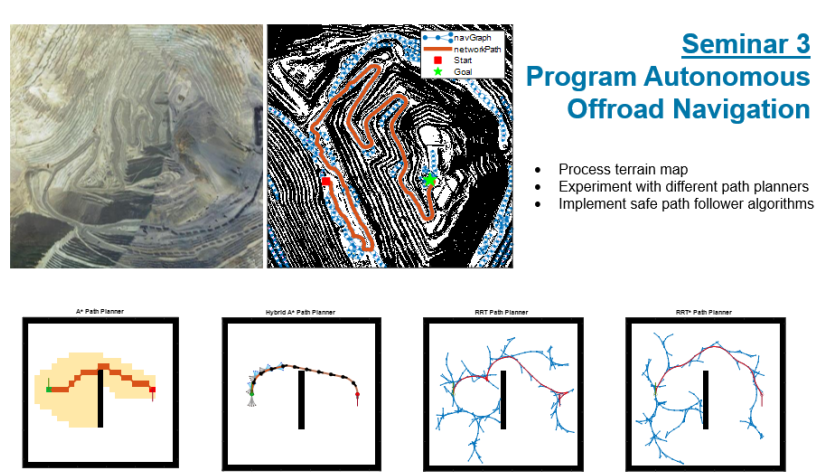
- Wheel Loader
- Excavator
- Tracked Vehicle

Simscape  
MATLAB Simulink



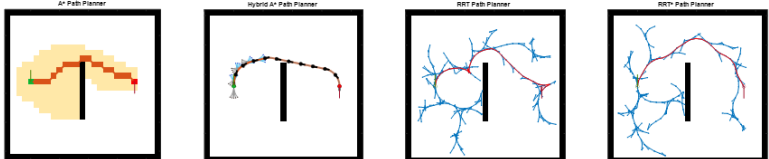
### Seminar 2 Setup Scenario Simulation to Test Control & Autonomy

- Put your vehicle model in a virtual scenario in Unreal Engine
- Generate synthetic sensor data including camera, lidar, IMU, and GPS data
- Use algorithms in MATLAB and Simulink to control the movement of the vehicle in Unreal Engine



### Seminar 3 Program Autonomous Offroad Navigation

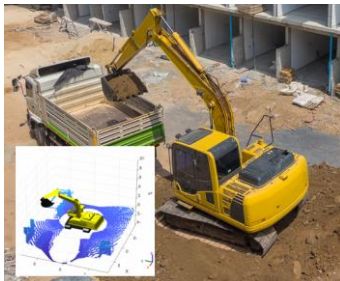
- Process terrain map
- Experiment with different path planners
- Implement safe path follower algorithms





# Call to Action:

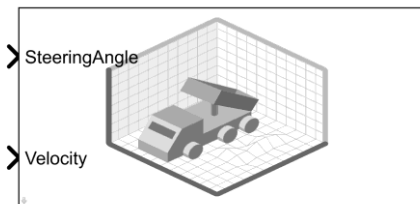
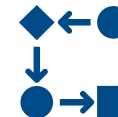
Try New Offroad Autonomy Library Support Package!



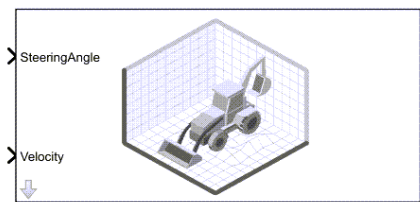
## Robotics System Toolbox Offroad Autonomy Library

by MathWorks Robotics and Autonomous Systems Team **STAFF**

Design, Simulate, and Test Autonomous Offroad Vehicle Applications

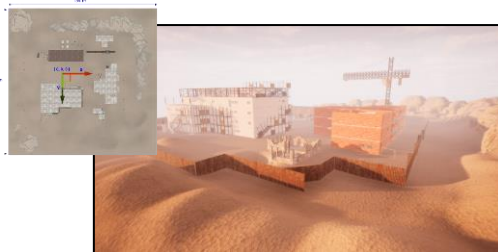


Simulation 3D Physics Dump Truck

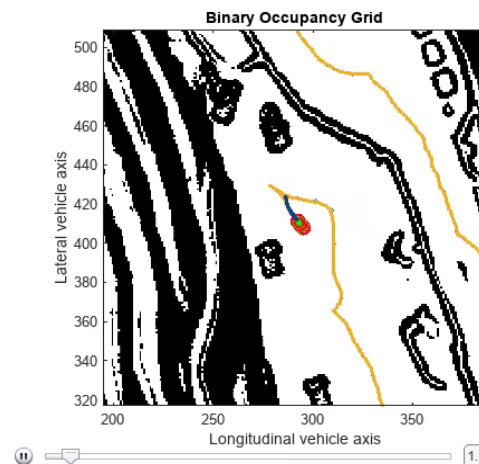


Simulation 3D Physics Backhoe

Physics Models



Scenes



Algorithms

<p>Simulate Earth Moving with Autonomous Excavator in Construction Site</p> <p>Simulate ground excavation to create a depression and move spoil to dump truck and further relocate it to another site.</p> <p>Since R2024b <a href="#">Open Live Script</a></p>	<p>Offroad Navigation for Autonomous Haul Trucks in Open Pit Mine</p> <p>Series shows how to create a set of planners to enable autonomous haul trucks in an Unreal Engine construction site scene.</p> <p>Since R2024a <a href="#">Open Live Script</a></p>	<p>Simulate Construction Vehicles in Unreal Engine for Material Handling</p> <p>Set up a simulation in which backhoe loads construction trucks into a dump truck in an Unreal Engine construction site scene.</p> <p>Since R2024b <a href="#">Open Live Script</a></p>
<p>Survey Pit Mining Site with RTK GPS and Point Clouds</p> <p>Create a digital elevation model (DEM) of a site using real-time kinematic (RTK) GPS and aerial lidar data.</p> <p>Since R2024b <a href="#">Open Live Script</a></p>	<p>Extract Scene From Lidar Data</p> <p>Create map of environment using point cloud data from lidar sensors mounted on an excavator.</p> <p>Since R2024e <a href="#">Open Live Script</a></p>	<p>Plan Collision-Free Path for Excavator Arm in MATLAB With Lidar Data</p> <p>Plan path for excavator arm in environment generated from lidar data.</p> <p>Since R2024e <a href="#">Open Live Script</a></p>

Examples



# MATLAB EXPO

## Thank You!



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