MATLAB EXPO

November 13–14, 2024 | Online

Leveraging Data-Driven and AI-Based Techniques for Control Algorithm Development

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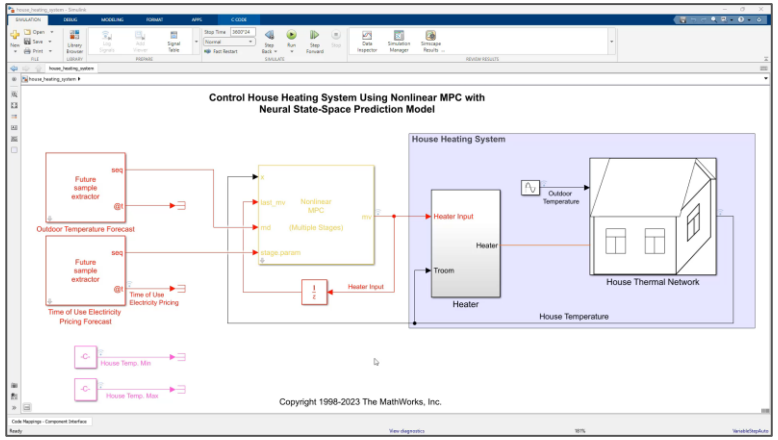
Key takeaways

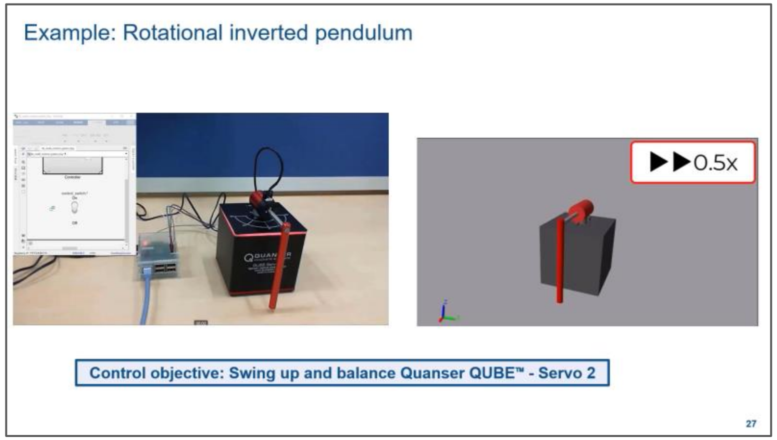
- Use **data-driven control algorithms** independently or along with model-based control algorithms to improve your control system performance

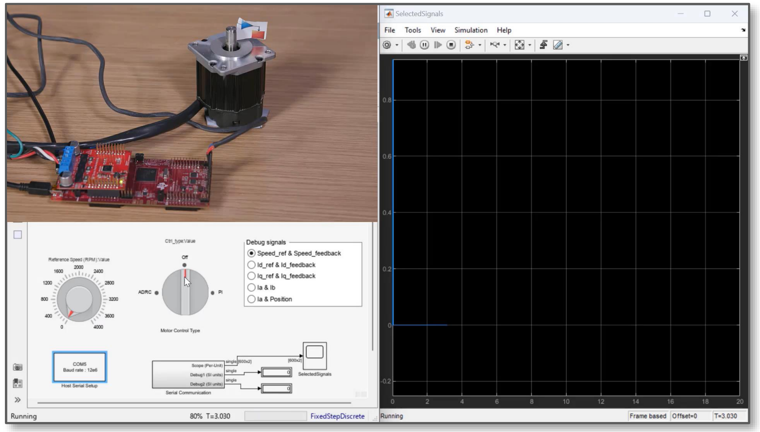
- Get started quickly with **pre-built Simulink blocks** and **reference examples** for designing and simulation-based testing of data-driven controllers

Agenda

- Introduction to Data-Driven Control
- Model predictive control (MPC) with system identification
- Reinforcement learning (RL)
- Active disturbance rejection control (ADRC)







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Sumitomo Heavy Industries speeds development of embedded Model Predictive Control (MPC) software for hydraulic excavators

Challenges

- **Lack of analytical engine model** for control design

Solution

Use Model Predictive Control Toolbox to develop an embedded MPC:

- **Estimate a model** from engine data
- Use the **identified model** as **internal prediction model** in an MPC
- **Auto-generate code and deploy** the designed controller with Embedded Coder

Results

- Fuel efficiency increased by 15%
- Engineering effort reduced by 50%
- Aggressive deadlines met

A Sumitomo hydraulic excavator.

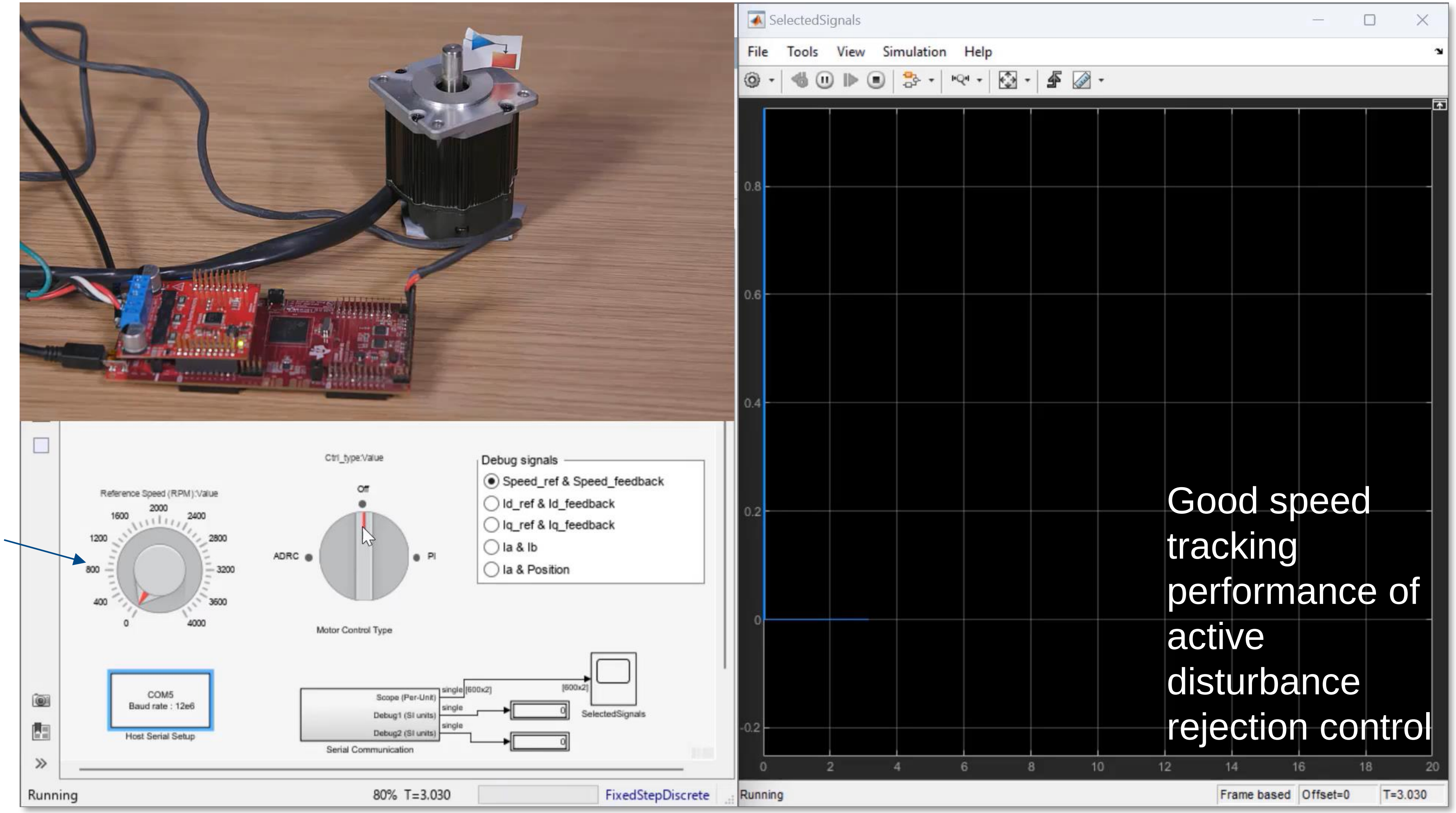
"Sumitomo Construction Machinery achieved a 15% reduction in fuel consumption without sacrificing the excavator's dynamic performance. The increase in efficiency was due, in part, to a 50% reduction in engine speed fluctuations made possible by Model Predictive Control Toolbox and our improved control design.

- Eisuke Matsuzaki, Sumitomo Heavy Industries

Link to user story

Data-driven control can solve challenging nonlinear control problems that traditional techniques might struggle with

Different operating speeds



Good speed tracking performance of active disturbance rejection control

There are different approaches to control design

Model-Based Control

- PID control design
- Gain-scheduling
- Model predictive control (MPC)
- Linear quadratic regulator (LQR)
- Sliding Mode Control (SMC)…

Model-based control methods rely on a model for control design.

Data-Driven Control

- Active disturbance rejection control (ADRC)
- Extremum seeking control (ESC)
- Model reference adaptive control (MRAC)
- Reinforcement Learning (RL)
- Iterative Learning Control (ILC)

In data-driven control, the controller or the model is learned from measured data.

There are different approaches to control design. Today, we will focus on data-driven control methods

Model-Based Control

- PID control design
- Gain-scheduling
- Model predictive control (MPC)
- Linear quadratic regulator (LQR)
- Sliding Mode Control (SMC) …

Data-Driven Control

- Active disturbance rejection control (ADRC)
- Extremum seeking control (ESC)
- Model reference adaptive control (MRAC)
- Reinforcement Learning (RL)
- Iterative Learning Control (ILC) …

Modeling

First principles model

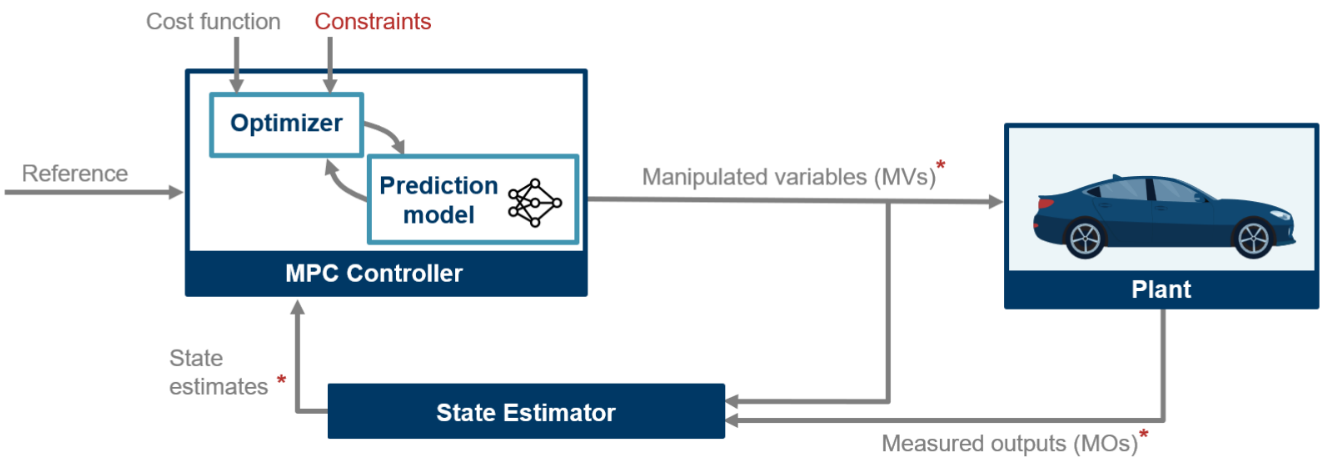
Data-driven model using system identification (e.g. data-driven MPC)

Model-based control methods rely on a model for control design.

In data-driven control, the controller or the model is learned from measured data.

Model Predictive Control (MPC) with System Identification

- Common applications of MPC
- What is MPC?
- Data-driven vs. first-principles prediction models
- Example
  - House heating system using nonlinear MPC with neural state-space prediction model
- Why use MathWorks tools for MPC with system identification?



Model predictive control is commonly used in automated driving, robotics, process control and energy management applications

Automated driving

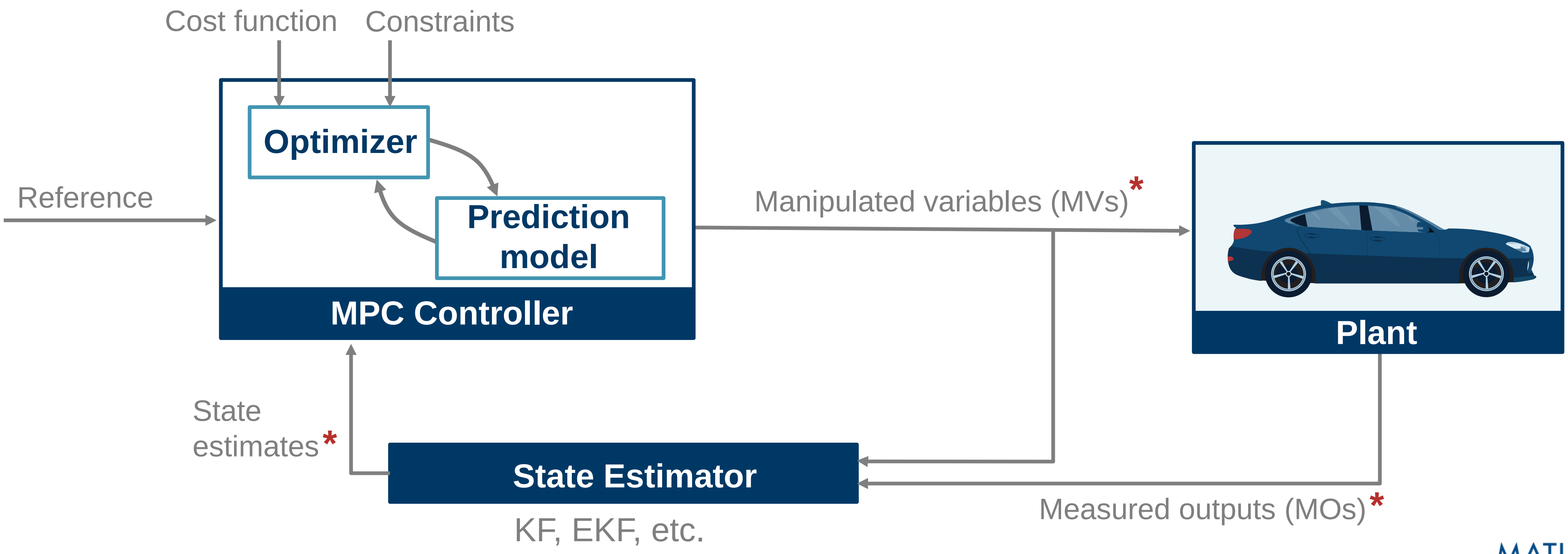
Robotics

Process control

Energy management

MPC: What is it?

- MIMO control technique that solves a constrained optimization problem in receding horizon fashion



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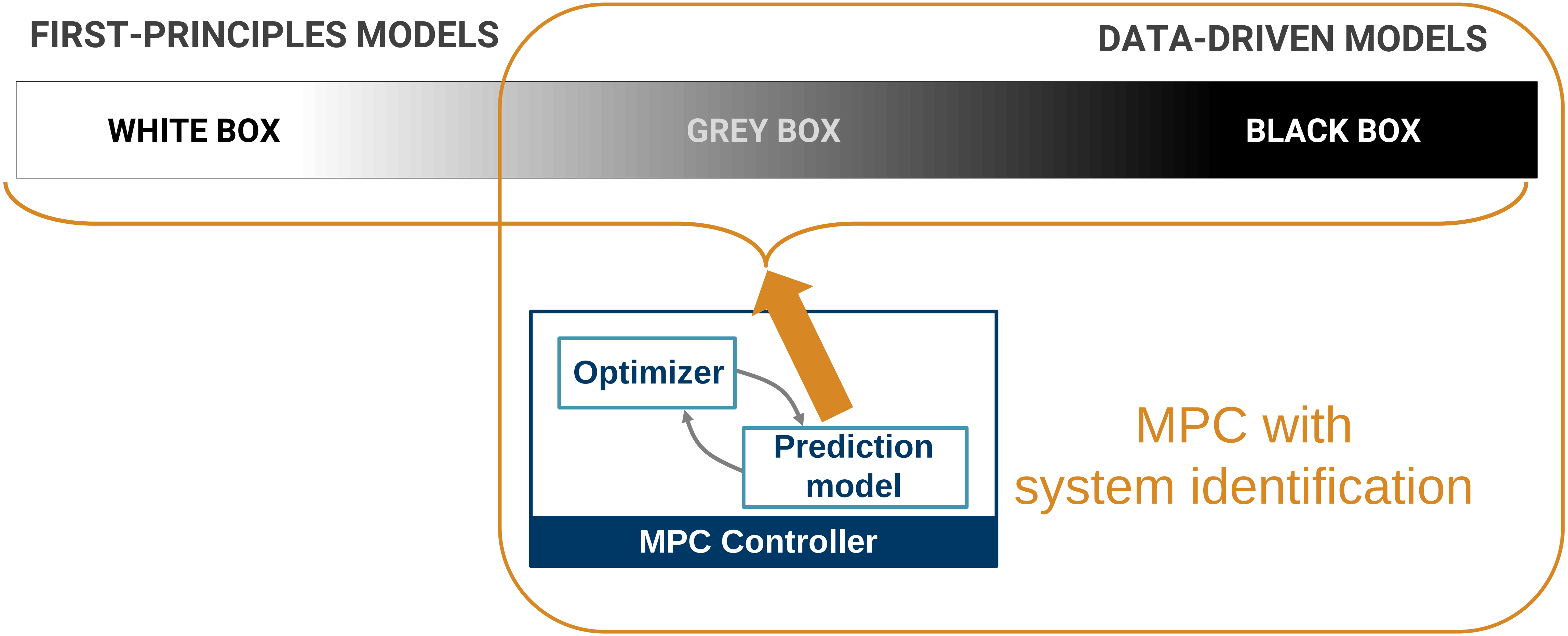
Data-driven vs. first-principles prediction models

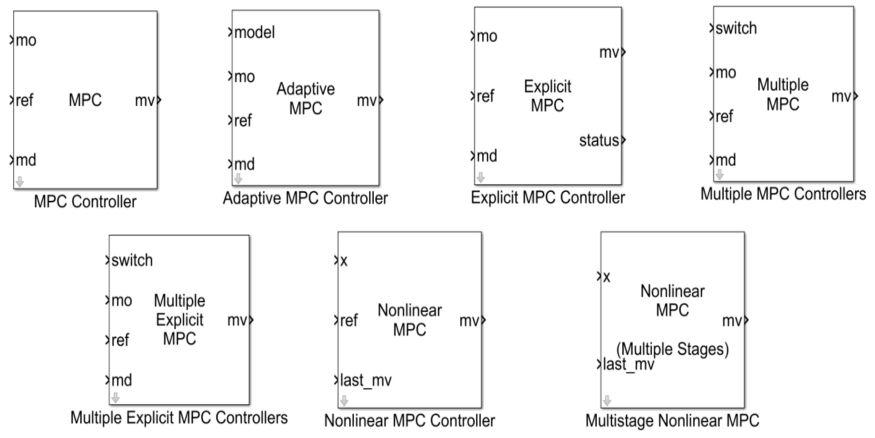


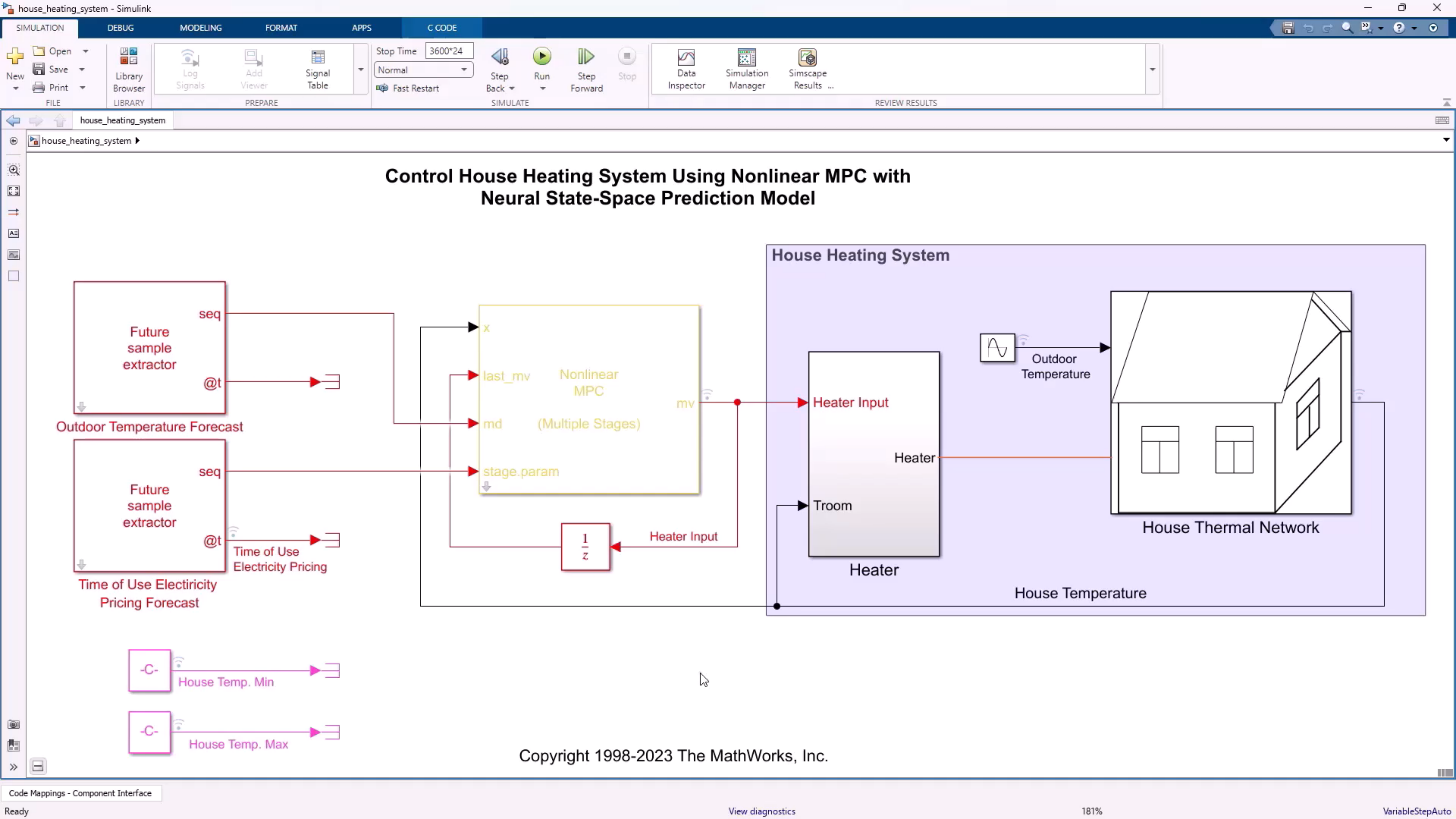
Why use MathWorks solution for MPC with system identification?

Model Predictive Control Toolbox lets you:

- Use pre-built Simulink **blocks**, **algorithms**, and **solvers** for designing and implementing different types of MPCs
- Easily define **data-driven prediction models** with **System Identification Toolbox** and **Deep Learning Toolbox**
- Generate Jacobians with **automatic differentiation** for faster computations
- Support for **automatic code generation**

Pre-built Simulink blocks

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Reinforcement Learning (RL)

- Common control applications of RL
- What is RL?
- Example
  - Inverted pendulum control using RL
- Why use MathWorks tools for RL?

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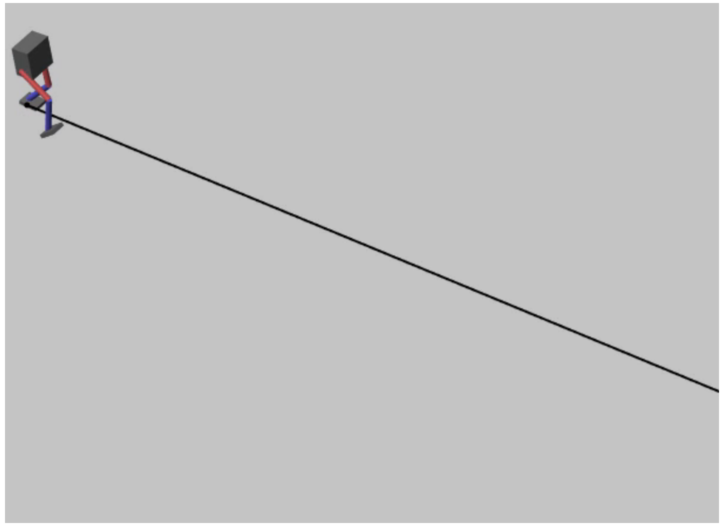
Common controls applications of reinforcement learning include automated driving and robotics

Automated driving

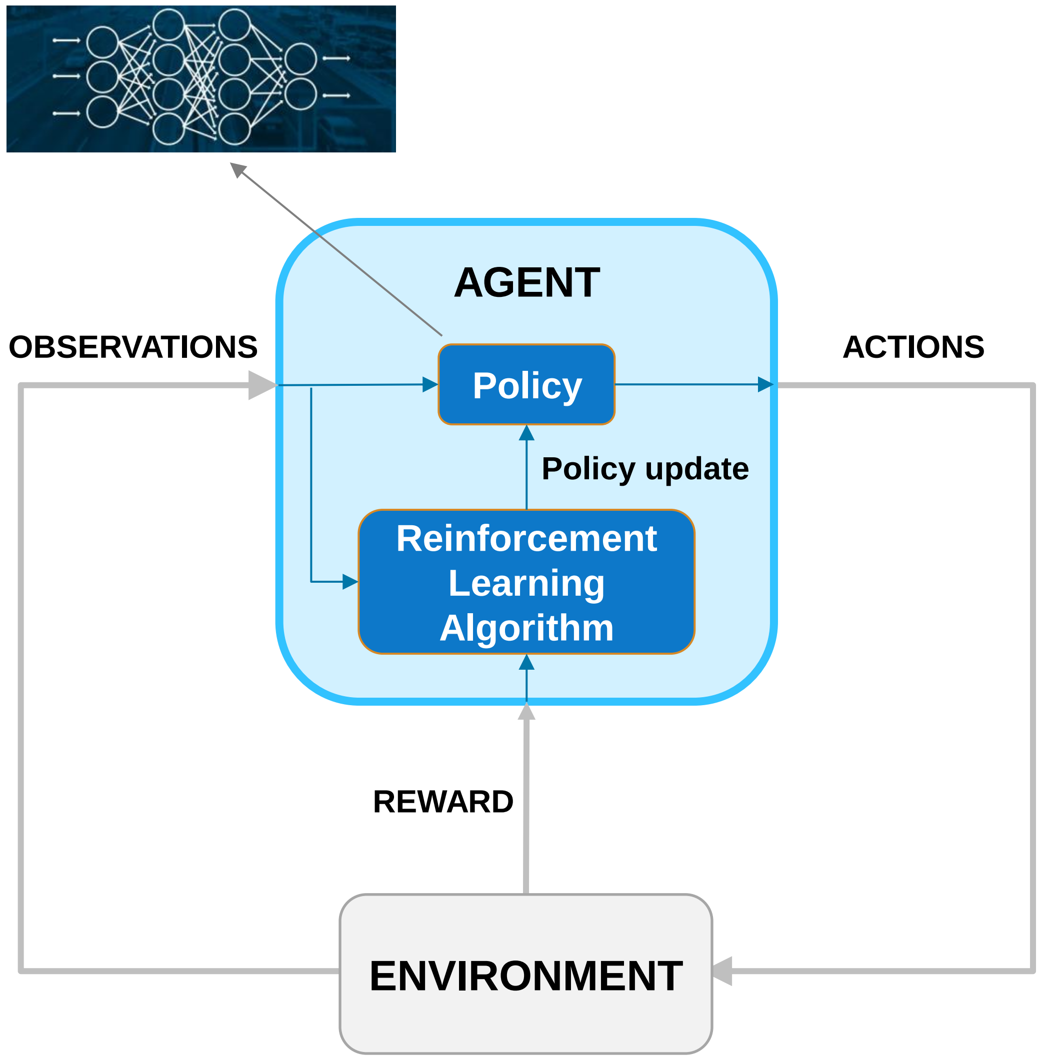


Robotics

RL: What is it?

- Type of machine learning technique that **trains an ‘agent’ through trial & error** interactions with an environment

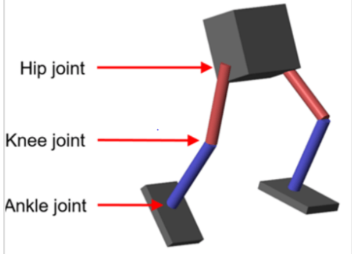
- Policy often represented as **neural network** in complex problems



Why use MathWorks solution for RL?

Reinforcement Learning Toolbox provides

- Built-in and custom reinforcement learning **algorithms**
- Integration with **Simulink**
- Visual interactive workflow with **Reinforcement Learning Designer**
- Support for **automatic code generation** of trained policies

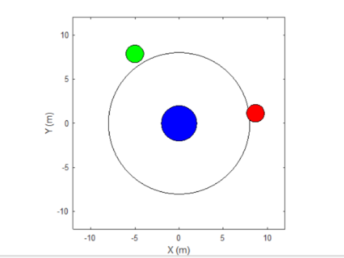


Train Biped Robot to Walk Using Reinforcement Learning Agents

Train a reinforcement learning agent to control a biped walking robot modeled in Simscape Multibody.

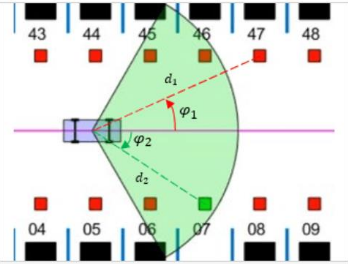
Automatic Parking Valet with Unreal Engine Simulation

Use a reinforcement learning agent with an MPC controller to perform a parking maneuver.



Train Multiple Agents to Perform Collaborative Task

Train two PPO agents to collaboratively move an object.



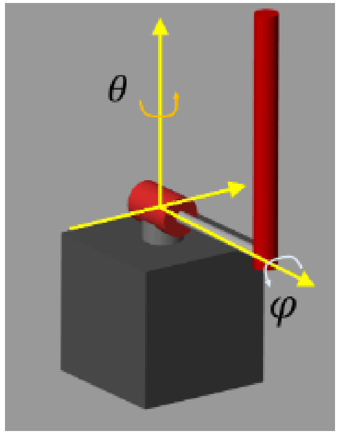
Train PPO Agent for Automatic Parking Valet

Train a reinforcement learning agent to park a car in an open parking space.

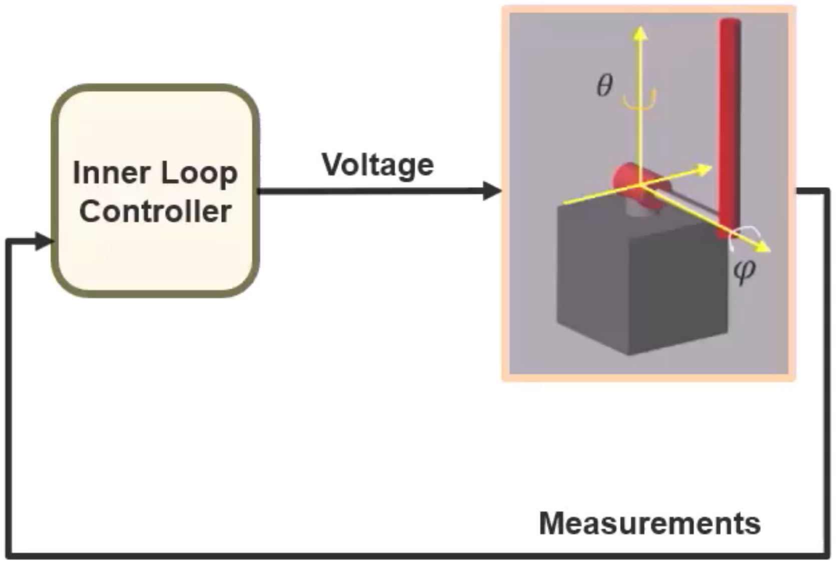
Example: Rotary inverted pendulum control using RL

Reinforcement learning workflow

Environment → Reward → Policy + Agent → Training → Testing → Deployment



Example: Rotational inverted pendulum



Vitesco Technologies Applies Deep Reinforcement Learning in Powertrain Control

Challenge

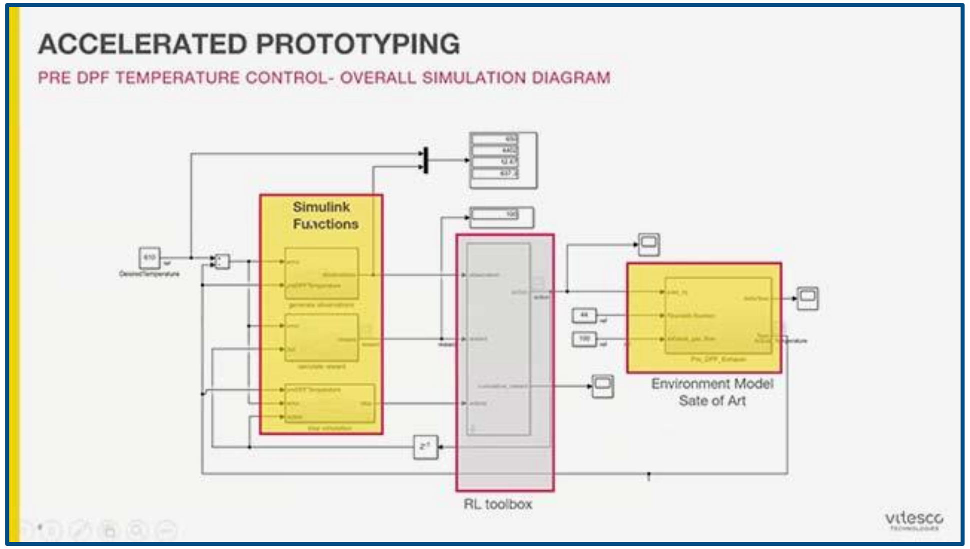
Accelerate development to meet climate goals and stricter emission laws.

Solution

Use Reinforcement Learning Toolbox for rapid prototyping, generation, and optimization of agents.

Key Outcomes

- Fast prototyping and reduced development time
- Simulink used for advanced plant modeling
- Quick start with Reinforcement Learning examples and documentation
- Swift issue resolution via expert support



Simulink model incorporating reinforcement learning agents.

"Reinforcement Learning Toolbox considerably reduced development time. The toolbox really helped in fast prototyping and generation of reinforcement learning agents."

- Vivek Venkobarao, Vitesco

 Link to case study

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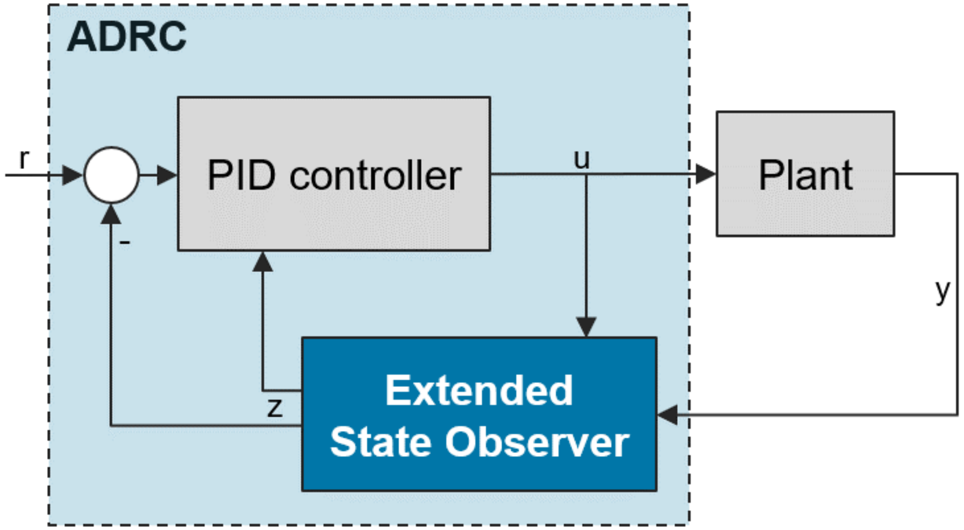
Active Disturbance Rejection Control (ADRC)

- Common applications of ADRC
- What is ADRC?
- Example
  - Permanent magnet synchronous motor control using ADRC
- Why use MathWorks tools for ADRC?



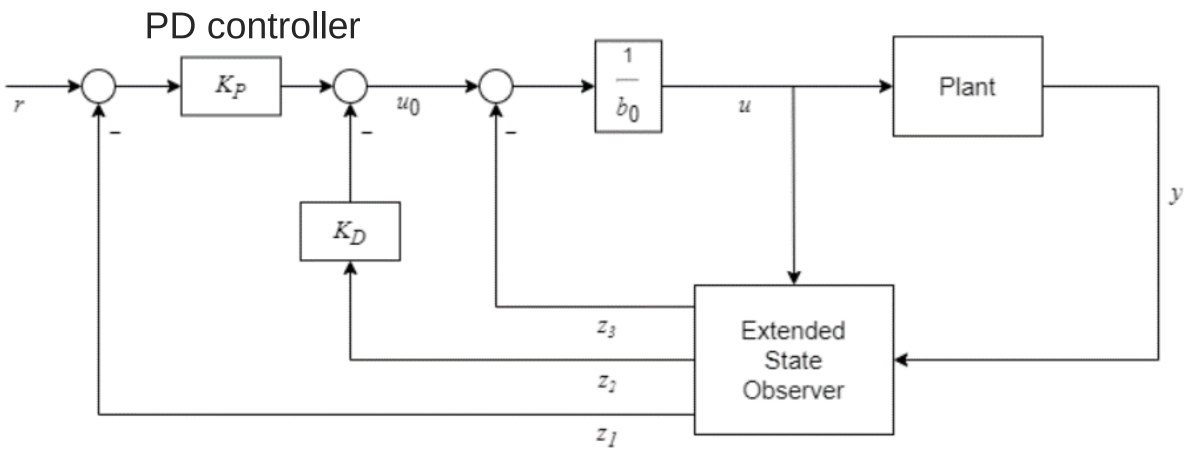
ADRC is a popular tool in power electronics and motor control

Power electronics

Motor control

ADRC: What is it?

- Model-free adaptive control technique that can be applied to **plants with unknown dynamics, internal and external disturbances**
- Powerful **extension to PID control**
- ADRC designs a nominal controller for a **simple model approximation**

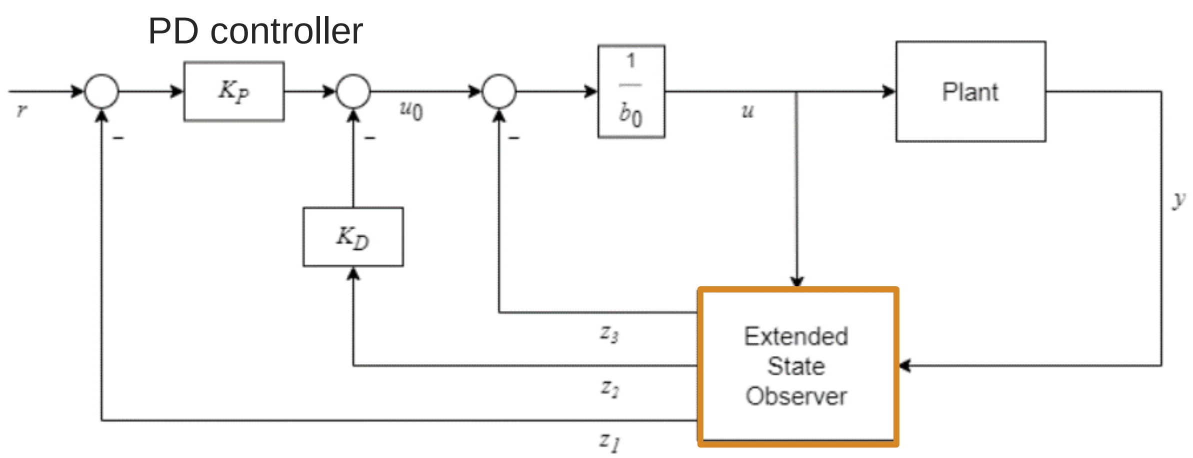


Controller structure based on a second-order plant model approximation $\ddot{y}(t) = b_0 u(t) + f(t)$

b_0: Critical gain
$f(t)$: Total disturbance that includes the unknown dynamics and other disturbances

ADRC: What is it?

- Model-free adaptive control technique that can be applied to **plants with unknown dynamics, internal and external disturbances**
- Powerful **extension to PID control**
- ADRC designs a nominal controller for a **simple model approximation**
- Uses an **extended state observer** to estimate and reject the total disturbance

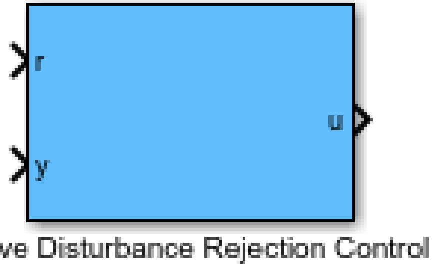


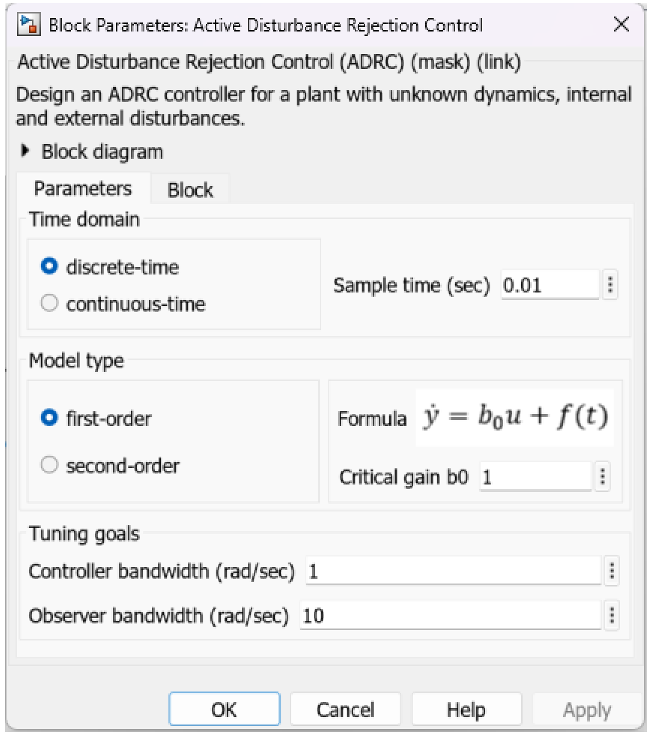
Controller structure based on a second-order plant model approximation $\ddot{y}(t) = b_0 u(t) + f(t)$

b_0: Critical gain
$f(t)$: Total disturbance that includes the unknown dynamics and other disturbances

Why use MathWorks solution for ADRC?

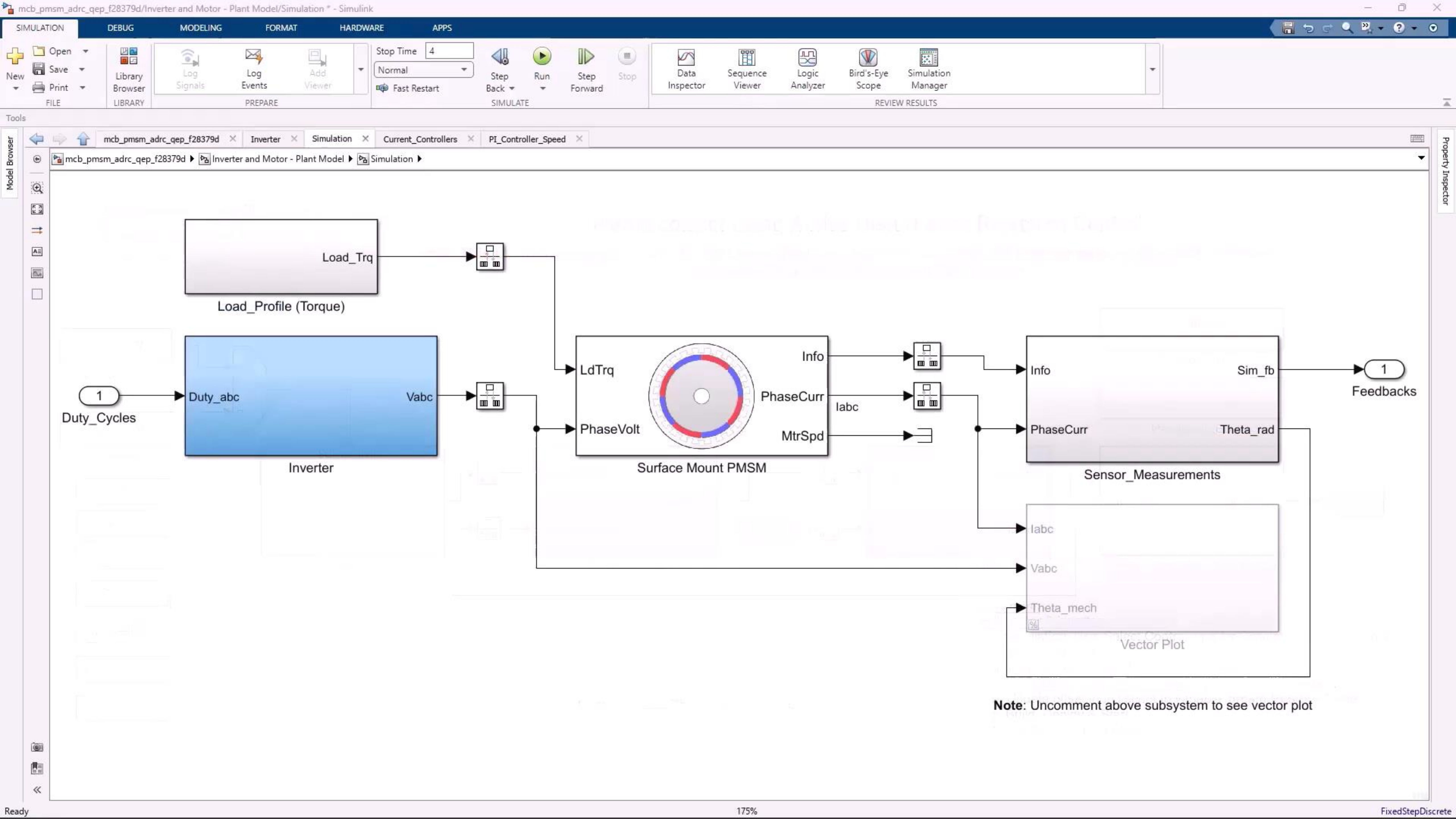
- Pre-built Simulink block





- Efficient code generation for resource-constrained hardware

ADRC is available with Simulink Control Design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Vector Plot
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Model Browser
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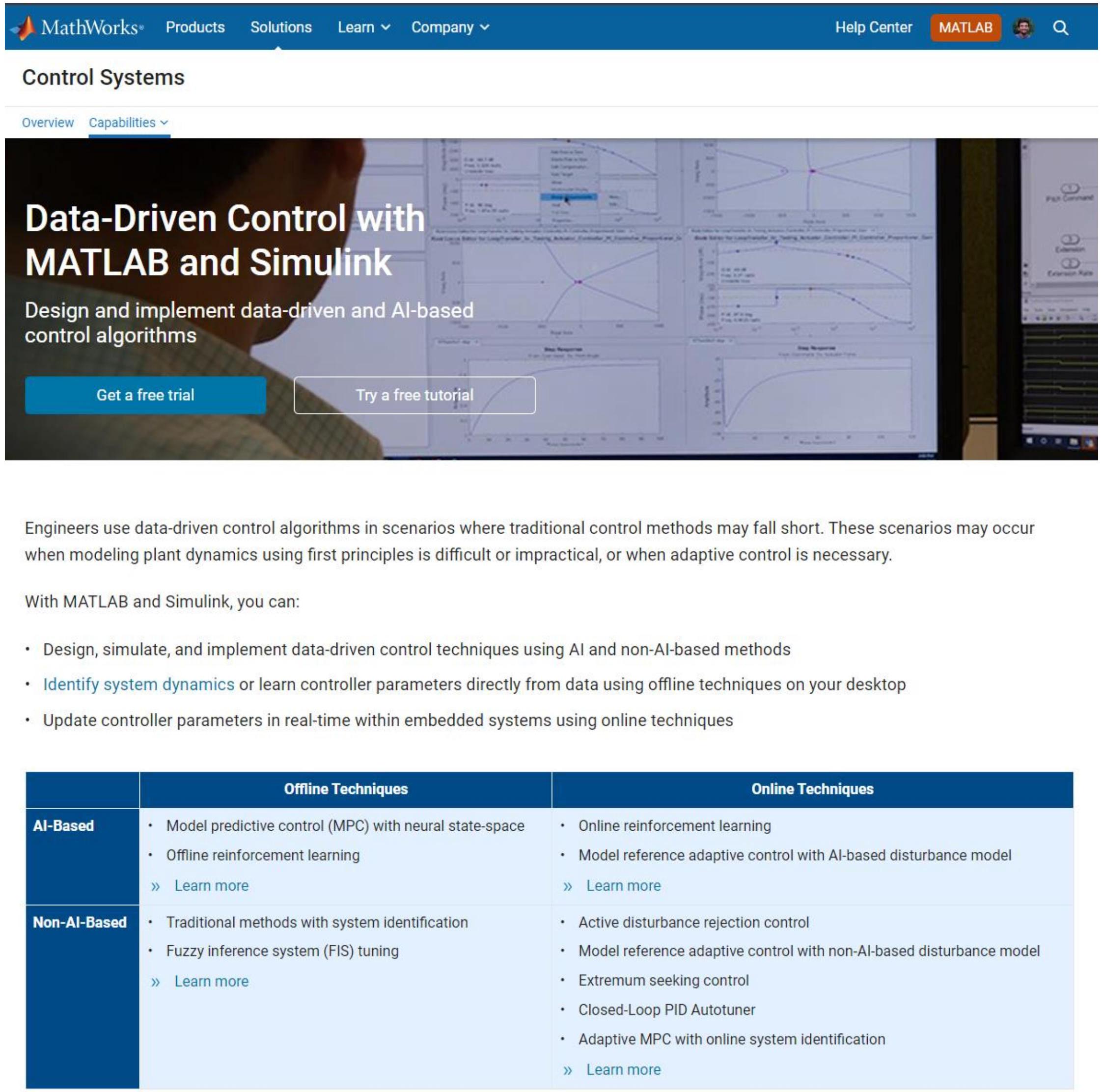
Key takeaways

- Use **data-driven control algorithms** independently or along with model-based control algorithms to improve your control system performance

- Get started quickly with **pre-built Simulink blocks** and **reference examples** for designing and simulation-based testing of data-driven controllers

Resources



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Control Systems

Overview Capabilities

Data-Driven Control with MATLAB and Simulink

Design and implement data-driven and AI-based control algorithms

Get a free trial | Try a free tutorial

Engineers use data-driven control algorithms in scenarios where traditional control methods may fall short. These scenarios may occur when modeling plant dynamics using first principles is difficult or impractical, or when adaptive control is necessary.

With MATLAB and Simulink, you can:

- Design, simulate, and implement data-driven control techniques using AI and non-AI-based methods
- Identify system dynamics or learn controller parameters directly from data using offline techniques on your desktop
- Update controller parameters in real-time within embedded systems using online techniques

	Offline Techniques	Online Techniques
AI-Based	• Model predictive control (MPC) with neural state-space • Offline reinforcement learning » Learn more	• Online reinforcement learning • Model reference adaptive control with AI-based disturbance model » Learn more
Non-AI-Based	• Traditional methods with system identification • Fuzzy inference system (FIS) tuning » Learn more	• Active disturbance rejection control • Model reference adaptive control with non-AI-based disturbance model • Extremum seeking control • Closed-Loop PID Autotuner • Adaptive MPC with online system identification » Learn more

[Data-driven control solution page]

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Resources

	ADRC	MPC with system identification	RL	PID control
What's the level of difficulty for getting started and getting good results? Easy — Difficult				
How does it perform handling nonlinear systems? Well — Poorly				
Is it a data-driven control method?	**Y**	**Y**	**Y**	N
Does it support use of neural networks?	N	**Y**	**Y**	N
Does it support state/output constraints explicitly?	N	**Y**	N	N
Does it support non-traditional signals (e.g. images, lidar)?	N	N	**Y**	N
Does it support discrete action space?	N	**Y**	**Y**	N
Does it run on resource-constrained hardware (e.g. TI C2000)?	**Y**	N	N*	**Y**
Can its performance be verified against standard metrics?	**Y**	N	N	**Y**
Can it be used for planning?	N	**Y**	**Y**	N

**Depends on the size of the policy.*

Slide information is based on the latest capabilities in MATLAB and Simulink.

Call-to-action

- Partner with us on your control design project!

Training

Guided Evaluations

Onsite Workshops

Consulting

Technical Support

- Download free trials for Simulink Control Design, Model Predictive Control Toolbox, System Identification Toolbox and Reinforcement Learning Toolbox

- Check out reference examples for adaptive control design, model predictive control, and reinforcement learning

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Thank you!

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