
# Automation and Control Laboratory

[M-Z]

Prof. Alessio La Bella
DEIB – Politecnico di Milano

AY 2024/25 - II semester

### Teacher

Alessio La Bella
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### Tutors

Andres Felipe Cordoba Pacheco
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Mar Ibáñez Puchades
mar.puchades@polimi.it

### Office hours

By appointment (ask via e-mail)

### Course website

WeBeep Portal (https://webeep.polimi.it/)


P.za L. Da Vinci
prima di Via Ampere
Via Bassini prima
di Via Ponzio
Via Bonardi prima
di Via Ponzio
Via Edoardo Bonardi
Via Edoardo Bonardi
P.za L. Da Vinci Fronte
9 prima di Via Spinoza
CT1
10
2
2A
4
4A
8
Edificio 7
Carlo Erba
Piazza Leonardo da Vinci
Piazza Leonardo da Vinci
1
6
7
Via Giuseppe Ponzio
Via Giuseppe Ponzio
Piazza Leonardo da Vinci
Viale Dottor Architetto
3
5
9
9A
Via Giovanni Celoria
Via Giovanni Celoria

# Course info


033
032
003a
004
005a
005b
006
007a
008
009a
009c
003f
007b
019
020a
021
010c
011f
012d
012b
013
022
027
026a
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016d
026c
026e
014
012a
035
016f
015
016h
N

# Course info

## Course objective

Challenge the students in applying the theoretical skills acquired during the study program on a real apparatus

## Topics

Span the design and development of automated systems:

- system modeling and analysis
- controller synthesis and analysis of the closed-loop system
- implementation on a real apparatus
- validation of the model/controller performance

## Format

Numerical simulations and real experiments via a *team project work*

### Prerequisites

Students are expected to have previous knowledge about

- mechanical systems modeling and dynamics
- fundamentals of control theory
- electrical actuators and sensors
- system identification
- advanced and multivariable control techniques

## Laboratory material

In the laboratory there are different set-ups, each one simulating (on a small scale) a real system to be controlled

## Available control problems

- control of unstable systems
- control of critically stable systems
- control of underdamped systems

## Course organization

- students are asked to form teams of 4 people each
- each team will receive one laboratory set-up
- each team will work autonomously on the assigned set-up (with the support of a teacher/tutor)
- all team members are required to be in the lab

# Organization info



## Laboratory availability

Every Tuesday: 2:15 pm $\rightarrow$ 7:15 pm (5 hours)
(effective time: 2.30 pm - 7:00 pm)

Every Other Friday: 9:15 am $\rightarrow$ 1:15 pm (4 hours)
(effective time: 9.30 am - 1:00 pm)

## Shared set-ups

- 7 set-ups are available in the lab
- at most 14 teams will be formed
- some set-up may be shared among two teams
- access to shared set-up is scheduled in time slots (A/B)

## First weeks

| | W2 | W3 | W4 | W5 | |
|---|---|---|---|---|---|
| Tuesday | Feb 25 | Mar 04 | Mar 11 | Mar 18 | ⋯ |
| Friday | Feb 28 | Mar 07 | Mar 17 | Mar 21 | ⋯ |

□ Slot A □ Slot B □ No Lab

A complete schedule will be available on WeBeep

## Note

The team not using the set-up has still access to the lab to work and receive support on design/simulations activities

## Expected steps

- preliminaries
  - model of the set-up at hand
  - identification of those parameters that are difficult to measure (friction coefficient, spring stiffness, efficiencies, etc.)
  - model validation via time/frequency responses
  - open-loop analysis
- list of self-given specifications for the closed-loop system
- for each controller
  - design based on a linearized/nonlinear model
  - test of the controller on the model via simulation
  - controller validation via time/frequency responses
- critical analysis/comparison of all developed control strategies

## Controller design

- Frequency-Based (FB) techniques
  - compute the transfer function $G(s)$ of the linearized system
  - design the $R(s)$ such that $L(s)$ has desired properties
  - design via Bode diagrams (or root locus or Nyquist)
- State-Space (SS) techniques
  - compute the state-space representation of the linearized system
  - design state estimators (Luenberger observer & Kalman filter)
  - design Pole-Placement & Linear-Quadratic controllers
- Advance-Control (AC)[a] techniques
  - Model Predictive Control (MPC)
  - Sliding Mode
  - Feedback Linearization
  - Adaptive/Robust Control

[a] For top grades

# Evaluation info

## Time validation

- input impulse/step to $u(t)$ (or $y^{\circ}(t)$ in close loop)
- record output response $y(t)$ (and $u(t)$ in close loop)
- compare with model impulse/step response
  in terms of gain, settling time, . . .

## Frequency validation

- input sine waves to $u(t)$ (or $y^{\circ}(t)$ in close loop)
- record output (sine) responses $y(t)$ (and $u(t)$ in close loop)
- compare with model frequency response on a Bode diagram

### Expected timeline


### Suggestions

- use the time when you don't have access to the set-up
- plan activity for the next lab session
- have a backup plan

# Evaluation info

## Team duties

- final report (max 40 pages, 🇮🇹 / 🇬🇧 ) describing all the work done by the team on the assigned set-up
- final presentation (20+5 min, 🇬🇧 ) to the whole class describing the work done by the team

## Evaluation criteria

- participation to the team activity during laboratory hours
- content, clarity, and technical soundness of the final report
- content and clarity of the final presentation
- overall approach to the lab experience

## Mid-term review

Halfway through the semester there will be a 30 minutes private review meeting with each group

## Format

You will be asked to discuss (free format, / ) the result achieved so far and a planned schedule for the future work

## Outcome

The meeting is not graded: it is only meant to give you feedback about your progress

## Key dates

Feb 20: deadline for the “preference form” submission

Apr 8-9: review meetings (a schedule will follow)

May 27: end of the course

Jun 2: deadline for the final report submission

Jun XX: final presentations (during the exam period)

(tentative dates, you will be notified in case of changes)

## Note

Attendance of all students to all presentations is recommended

## Preference form

Each team has to provide (by email) the following information:

- team nickname
- ID (Codice Persona), Name, and Surname of each component
- a ranking of all available set-ups and alphabetical group, ordered by preference

The preference form can be downloaded from the WeBeep portal

## Available set-ups

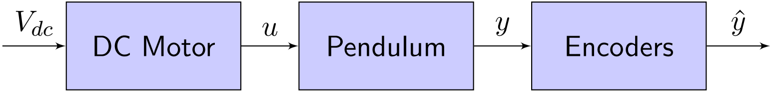
- inverted pendulum
- ball and beam
- rotating masses
- magnetic levitation
- helicopter
- rotary flexible joint
- CNC machine

# Rotary Inverted Pendulum

# Rotary Inverted Pendulum



## System




## Quantities

- $V_{dc}$ is the voltage applied to the motor
- $u$ is the resulting torque applied to the horizontal arm
- $y$ contains the angular position of the two arms
- $\hat{y}$ contains the *relative* angular position of the two arms

## Main challenge

Dynamical model and instability of the upright equilibrium position of the pendulum

## Control objectives

1. position control of the horizontal arm (FB)
2. stabilization of the vertical arm in the upright position (SS)
3. position control of the horizontal arm while keeping the vertical arm in the upright position (SS)
4. swing-up of the vertical arm (AC)

# Ball and Beam

# Ball and Beam

## System


## Quantities

- $V_{dc}$ is the voltage applied to the motor
- $u$ is the resulting torque applied to the gear of the lever arm
- $y$ contains the gear angular position and ball position
- $\hat{y}$ contains the gear *relative* angular position and the ball *absolute* position on the beam

## Main challenge

Marginal stability of equilibrium position of the ball on the beam and presence of state constraints

## Control objectives

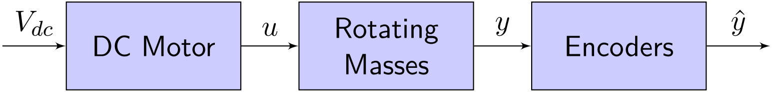
1. tilting control of the horizontal beam (FB)
2. ball position stabilization (FB+SS)
3. 1D ball trajectory tracking (SS+AC)

# Rotating Masses

# Rotating Masses



## System




## Quantities

- $V_{dc}$ is the voltage applied to the motor
- $u$ is the resulting torque applied to the gear shaft
- $y$ contains the masses angular position
- $\hat{y}$ contains the masses *relative* angular position

## Main challenge

Low damping of the system

## Control objectives

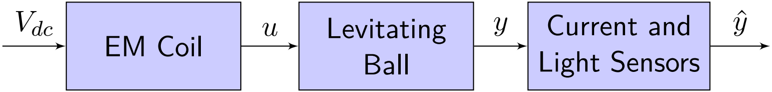
1. speed control of the first masses (FB)
2. position control of the first masses (FB+SS)
3. position control of the other two masses (SS+AC)

# Magnetic Levitation

# Magnetic Levitation

# Magnetic Levitation

## System




## Quantities

- $V_{dc}$ is the voltage applied to the electromagnet (EM)
- $u$ is the resulting induced magnetic field
- $y$ contains the coil current and the ball position
- $\hat{y}$ contains the measured current and *absolute* ball position

## Main challenge

Highly nonlinear system and instability of the ball position

## Control objectives

1. EM coil current control (FB)
2. ball position stabilization (FB+SS)
3. 1D ball trajectory tracking and lift up (SS+AC)

# Helicopter

# Helicopter



## System


## Quantities

- $V_{dc}$ is the voltage applied to the propellers' motors
- $u$ is the resulting thrust generated by the propellers
- $y$ contains the pitch and yaw angles
- $\hat{y}$ contains the pitch and yaw *relative* angles

## Main challenge

Coupled MIMO nonlinear system

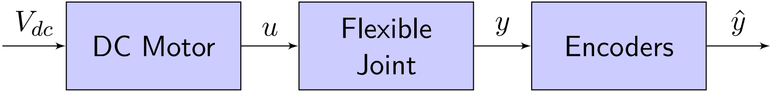
## Control objectives

1. pitch control with yaw rotation locked (FB)
2. fixed attitude control (FB+SS)
3. reference attitude tracking (SS+AC)

# Rotary Flexible Joint

# Rotary Flexible Joint

## System




## Quantities

- $V_{dc}$ is the voltage applied to the motor
- $u$ is the resulting torque applied to the top base
- $y$ contains top base and arm angular positions
- $\hat{y}$ contains the top base and arm *relative* angular position

## Main challenge

Low damping of the system and variable parameters

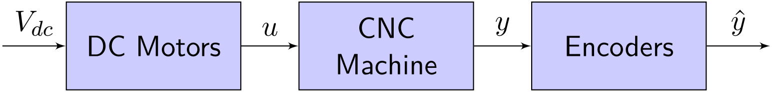
## Control objectives

1. position control of the top base (FB)
2. position control of the the arm tip (FB+SS)
3. position control of the the arm tip with uncertainty in the spring stiffness and arm moment of inertia (SS+AC)

# CNC Machine

# CNC Machine

## System




## Quantities

- $V_{dc}$ contains voltages applied to both motors
- $u$ contains the resulting torques acting on the chain
- $y$ contains the coordinates of the end effector
- $\hat{y}$ contains the motors' *relative* angular position

## Main challenge

Coupled MIMO nonlinear system

## Control objectives

1. motor position control (FB)
2. end effector 2D position control (FB+SS)
3. 2D trajectory tracking (SS+AC)

# Laboratory environment

MATLAB + SIMULINK

## Note

We will use R2019b: be careful to avoid compatibility issues

PC $\Longleftrightarrow$


$\Updownarrow$

Set-up $\Longleftrightarrow$

### Material provided

For each set-up there is a zip file (`NameOfTheSetup.zip`) on WeBeep containing the following files:

- datasheet for the data acquisition board (DAQ)
- datasheet for the power amplifier (PA)
- datasheet for the DC motor and the gearbox
- datasheet for the specific set-up
- simulink template file containing appropriate input/output blocks to start experimenting right away

### Note

Some experiments connect to the PC directly via USB and the zip file contains one datasheet only and the simulink template

# Quick-start guide

## Example

In the following assume a group received the *inverted pendulum* and the time slots marked with A

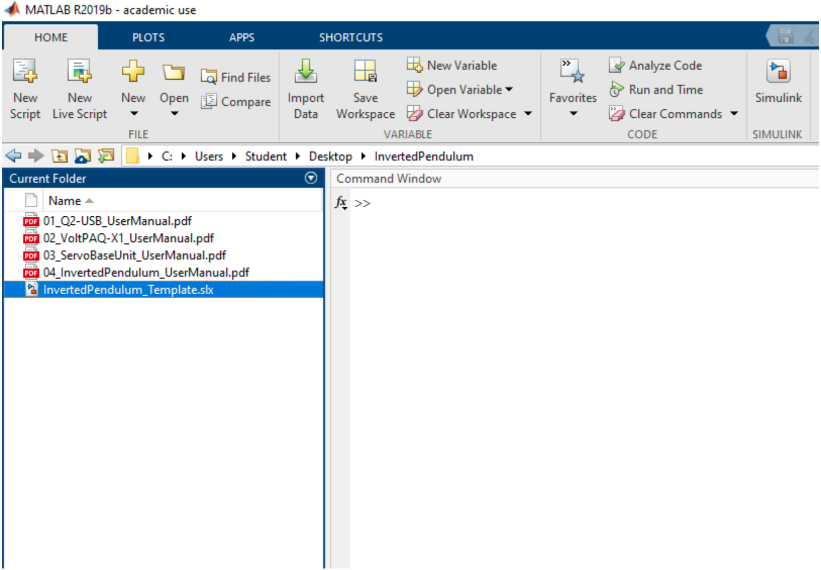
## Beginning of the lecture

- connect the DAQ board to a USB3 socket
- connect PA to the nearest AC plug and turn it on
- turn on the lab PC (use the "Student" account)

# Quick-start guide

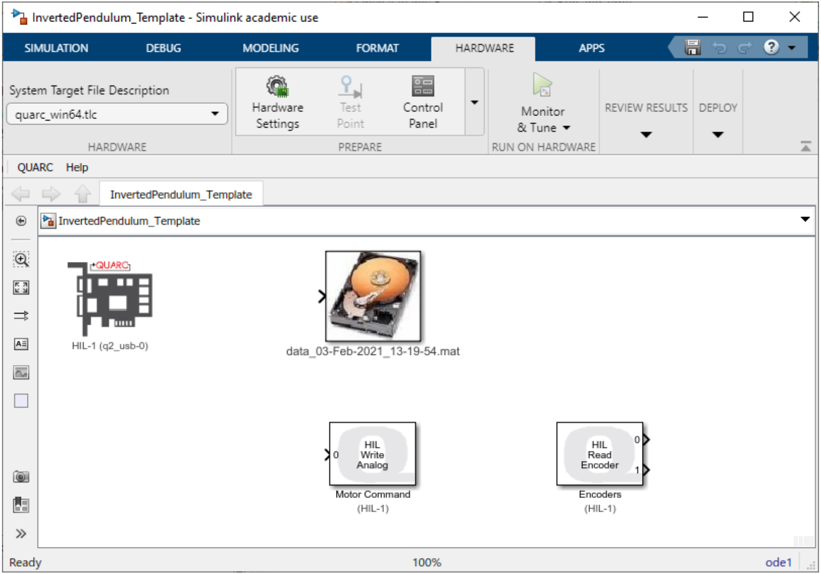
## First steps for using the set-up

- open the browser and go to the WeBeep portal
- login with your credentials, download `InvertedPendulum.zip`
- drag the folder inside the zip and drop it onto the desktop
- open MATLAB R2019a
- click on the icon  in the top-left part of the screen and navigate to the `InvertedPendulum` folder

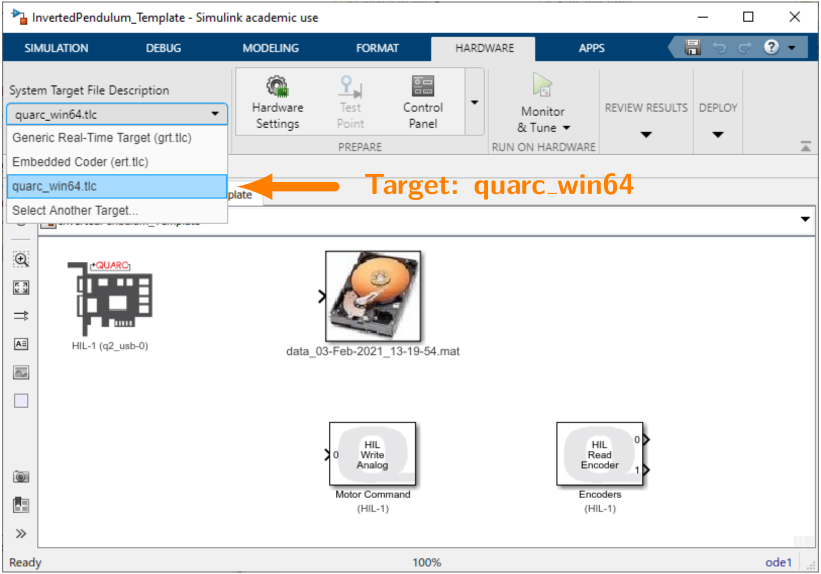


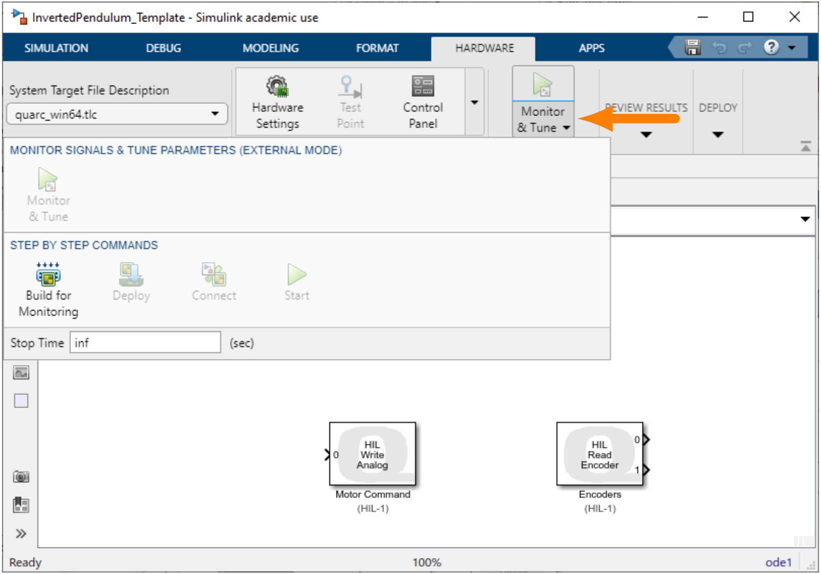
MATLAB R2019b - academic use
HOME
PLOTS
APPS
SHORTCUTS
New Script
New Live Script
New
Open
Find Files
Compare
FILE
Import Data
Save Workspace
New Variable
Open Variable
Clear Workspace
VARIABLE
Favorites
Analyze Code
Run and Time
Clear Commands
CODE
Simulink
SIMULINK
C: Users Student Desktop InvertedPendulum
Current Folder
Name
01_Q2-USB_UserManual.pdf
02_VoltPAQ-X1_UserManual.pdf
03_ServoBaseUnit_UserManual.pdf
04_InvertedPendulum_UserManual.pdf
InvertedPendulum_Template.slx
Command Window
fx >>

# Quick-start guide

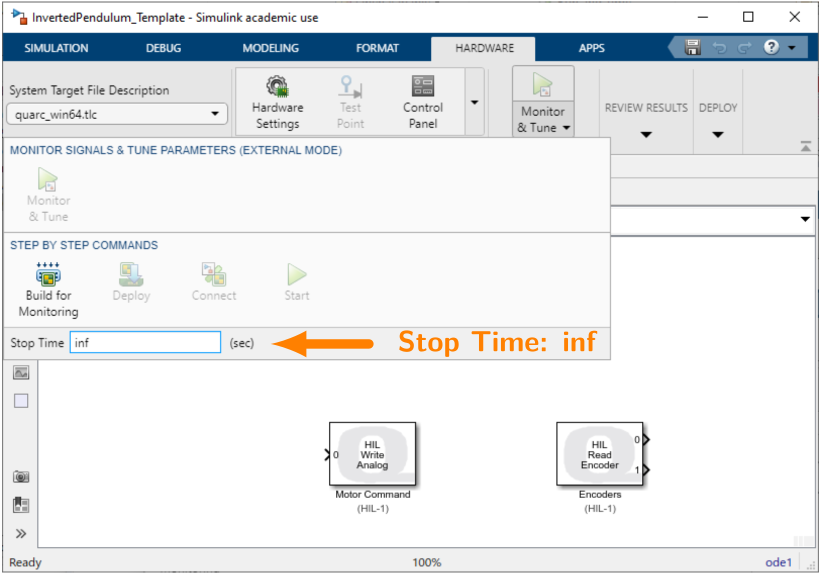


# Quick-start guide





InvertedPendulum_Template - Simulink academic use
SIMULATION
DEBUG
MODELING
FORMAT
HARDWARE
APPS
System Target File Description
quarc_win64.tlc
Hardware Settings
Test Point
Control Panel
Monitor & Tune
REVIEW RESULTS
DEPLOY
MONITOR SIGNALS & TUNE PARAMETERS (EXTERNAL MODE)
Monitor & Tune
STEP BY STEP COMMANDS
Build for Monitoring
Deploy
Connect
Start
Stop Time
inf
(sec)
HIL Write Analog
Motor Command (HIL-1)
HIL Read Encoder
Encoders (HIL-1)
Ready
100%
ode1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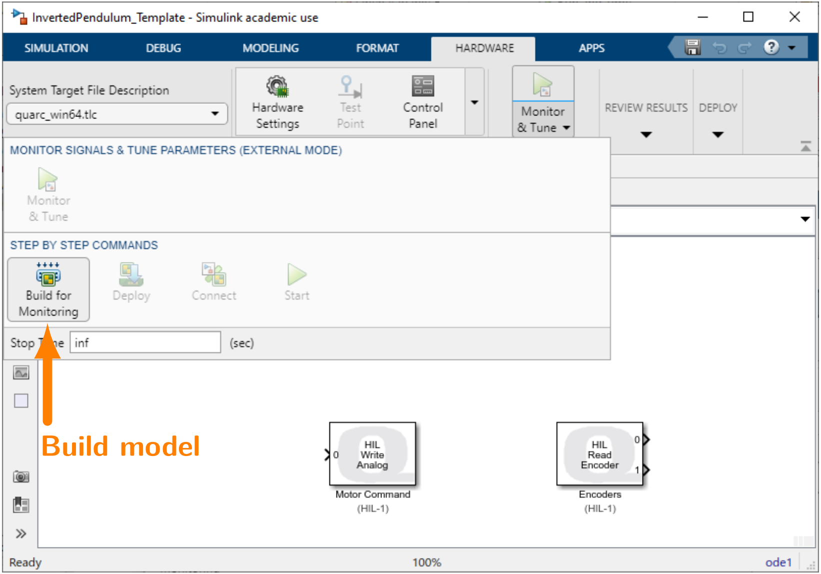
Start
Stop Time
inf
(sec)
Stop Time: inf
HIL Write Analog
Motor Command (HIL-1)
HIL Read Encoder
Encoders (HIL-1)
Ready
100%
ode1



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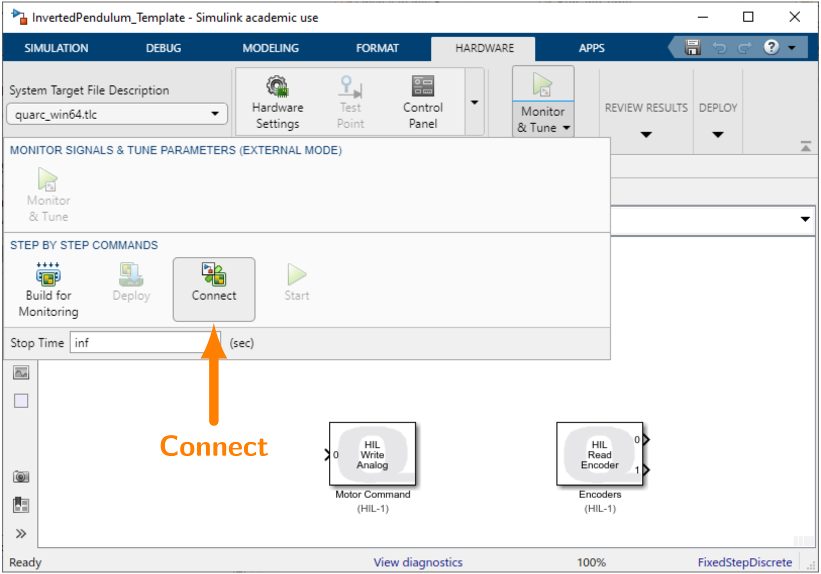
Monitor & Tune
STEP BY STEP COMMANDS
Build for Monitoring
Deploy
Connect
Start
Stop Time
inf
(sec)
Build model
HIL Write Analog
Motor Command (HIL-1)
HIL Read Encoder
Encoders (HIL-1)
Ready
100%
ode1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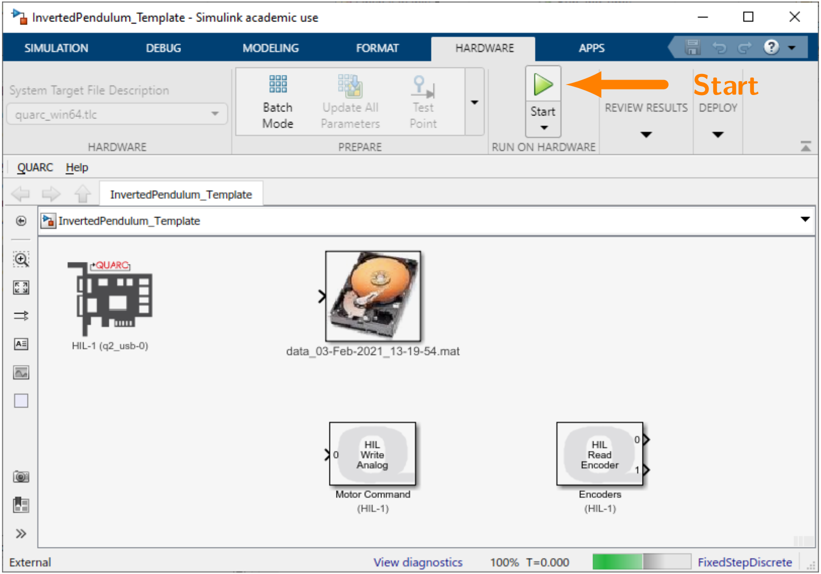
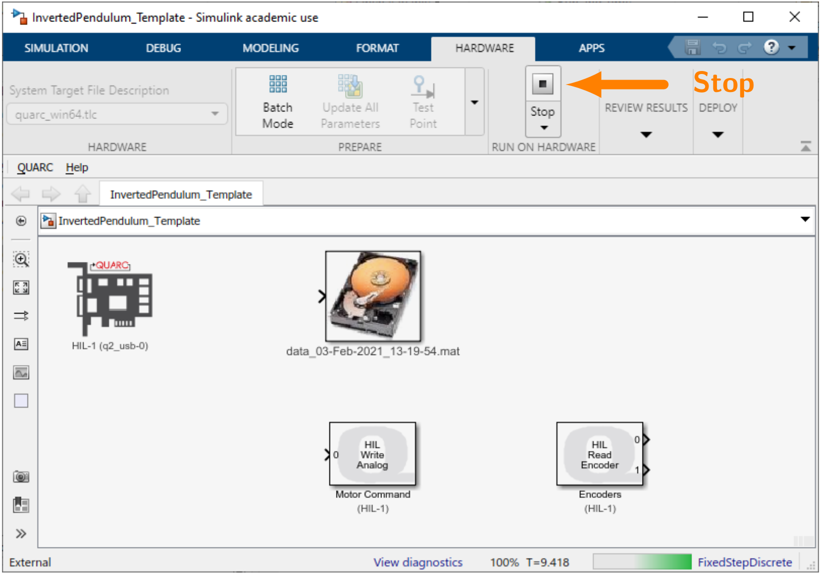
MONITOR SIGNALS & TUNE PARAMETERS (EXTERNAL MODE)
Monitor & Tune
STEP BY STEP COMMANDS
Build for Monitoring
Deploy
Connect
Start
Stop Time
inf
(sec)
Connect
HIL Write Analog
Motor Command (HIL-1)
HIL Read Encoder
Encoders (HIL-1)
Ready
View diagnostics
100%
FixedStepDiscrete

# Quick-start guide





InvertedPendulum_Template - Simulink academic use
SIMULATION
DEBUG
MODELING
FORMAT
HARDWARE
APPS
System Target File Description
quarc_win64.tlc
HARDWARE
Batch Mode
Update All Parameters
Test Point
PREPARE
Stop
RUN ON HARDWARE
REVIEW RESULTS
DEPLOY
Stop
QUARC
Help
InvertedPendulum_Template
QUARC
HIL-1 (q2_usb-0)
data_03-Feb-2021_13-19-54.mat
HIL Write Analog
Motor Command (HIL-1)
HIL Read Encoder
Encoders (HIL-1)
External
View diagnostics
100%
T=9.418
FixedStepDiscrete

## Note

While the Simulink model is running you can change constant values, amplitude/frequency of some signals, values of gains, etc.

## Other blocks

There are other blocks in the QUARC library and you can refer to their documentation for additional information
https://docs.quanser.com/quarc/documentation/index.html

## Asking for help

- if you need quick technical assistance call the tutor first
- if you have a conceptual doubt or you are lost call me

## Warnings

- the first time, ask the teacher before running the Simulink model on the real set-up
- keep away from all moving parts when experiment is running
- remember that set-ups are real, please be careful when you are performing tests

## End of the lecture

- make sure you stop all running Simulink models
- close Matlab
- zip all of your files
- transfer them to a personal device (thumb-drive or OneDrive)
- delete all files on the lab PC
- shut down the lab PC
- switch off the PA and remove the AC plug
- disconnect the DAQ from the PC
- collect all cables under the side table housing the set-up

**Enjoy the course! =)**