5ESD0: Control Systems
Laboratory Assignment 1

1 Introduction

The laboratory work within the Control Systems course is split in two parts. The first part deals with control of a *Mass-Spring-Damper-Mass* (MSDM) system and highlights the control challenges in high-performance positioning systems, automotive drivetrains, industrial machinery and other electromechanical systems.

Let us briefly examine the 2014 Porsche S E-Hybrid drivetrain shown in Figure 1. Our particular interest

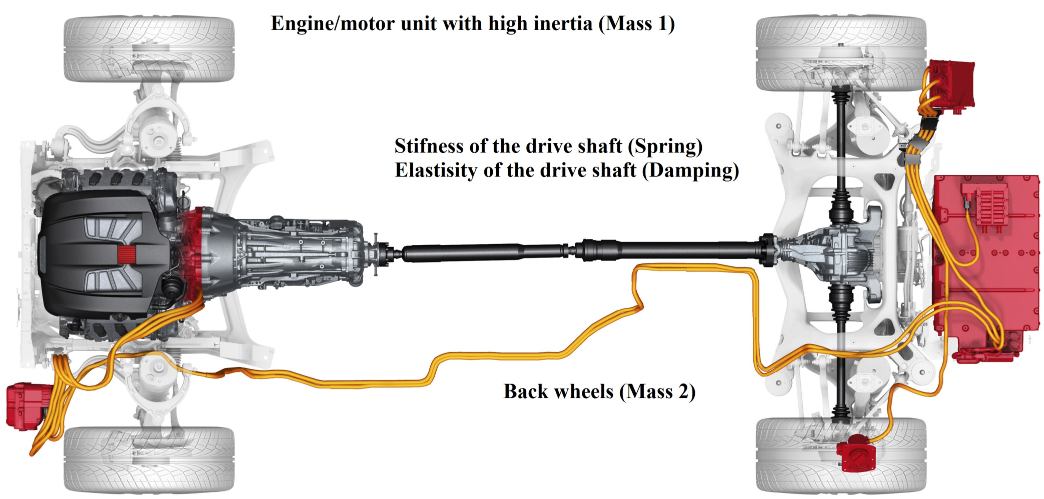

Figure 1: 2014 Porsche S E-Hybrid drivetrain.

is in the path from the propulsion unit containing the engine and the electric motor/generator to the rear wheels. The torque generated by the combustion and electro-magnetic forces in the propulsion unit is applied to the flywheel of the engine and the rotor of the electric motor. Both these parts have significant inertia and constitute the first *Mass* in the MSDM system. The drive shaft connecting the propulsion unit with the differential has limited stiffness and acts as a *Spring*. The elasticity of the drive shaft results in *Damping*, and the inertia of the differential and the rear wheels can be considered as the second *Mass* of the MSDM system.

Multiple control problems can be formulated for the drivetrain system, e.g., control the torque generated by the propulsion unit in order to maintain a predefined amount of torque on the rear wheels (this function is a part of the traction control system), transfer the propulsion unit torque to the rear wheels with minimal deformations in the drive shaft (minimizing the effects of the road surface and acceleration input on the drive shaft deformation), cruise control (maintaining a predefined speed of the rear wheels under varying external/internal disturbance levels), maintaining constant RPMs of the internal combustion engine to optimize its efficiency by controlling the torque of the electric motor and rejecting the external disturbances affecting the rear wheels. The Lab. Assignment 1 deals with the latter two control problems on a simplified version of the automotive drive train shown in Figure 2.

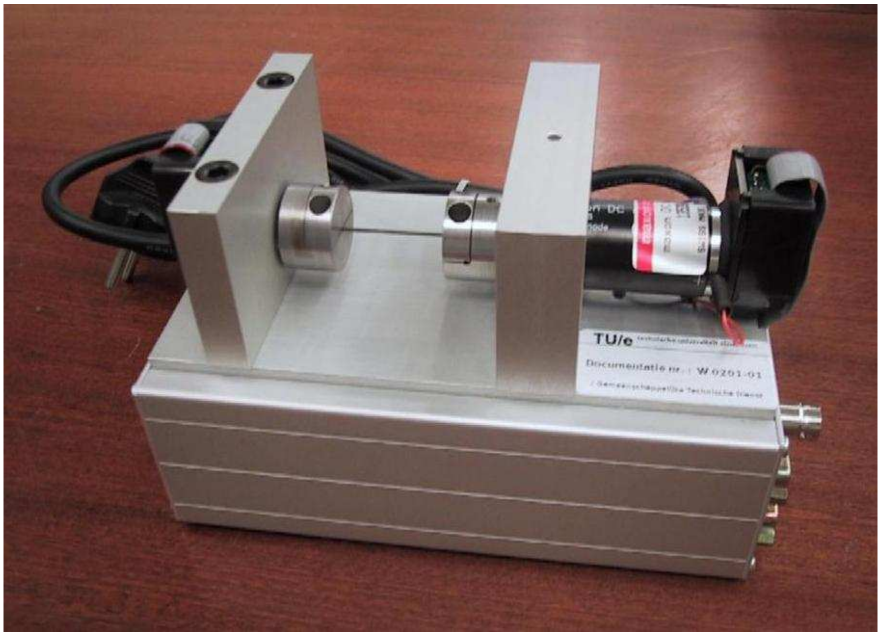

Figure 2: Electro-mechanical part of the MSDM system for the Lab. Assignment 1.

The MSDM system in Figure 2 contains two masses interconnected by a flexible shaft. One of the masses rotates freely whereas the other is directly connected to a DC motor. The set-point for the current running through the rotor of the DC motor is supplied from the control unit via a BNC connector. The positions of the masses are measured through quadrature encoders and provided to the control unit through two 9 pin D-sub connectors. The control unit is the myRIO device from National Instruments which features Zynq SoC (dual-core processor with FPGA fabric in the same package - see `http://www.ni.com/myrio/` for more details) and a multiple digital and analog input-output channels.

The available computational resources on the myRIO device can be programmed in LabView (RT/FPGA) or in C from the Eclipse integrated development environment. For the assignment, myRIO is preloaded with a personality that allows for communication with MATLAB. A library of MATLAB functions is provided with the assignment, which allows for sending reference waveforms, collecting measurements signals, and setting the controller parameters. The communication with the myRIO is done through TCP/IP. Therefore, students must have the Instrumentation Control Toolbox for MATLAB installed. For more information on how to setup the experimental hardware look into Appendix B.

1.1 Objectives

After the completion of this assignment, students will:

- be able to design classic control systems via loop shaping under specifications given in frequency domain and time-domain,
- obtain hands-on experience with controller operation on real systems.

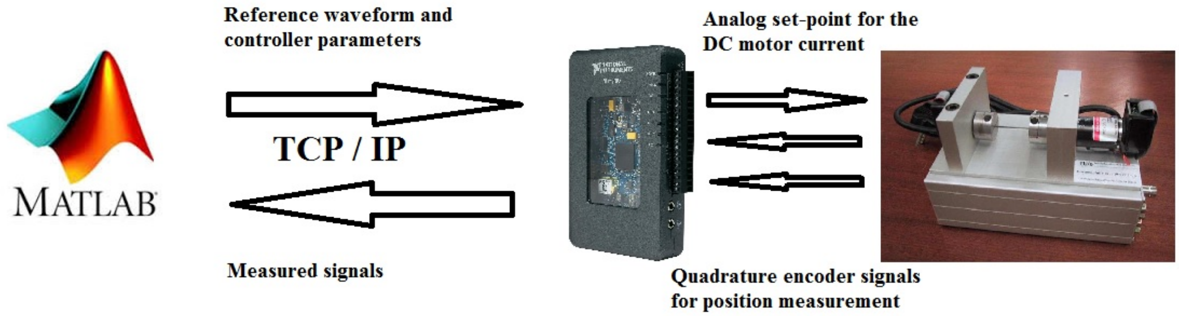

Figure 3: Overview of relevant signals and data flows within the experimental platform.

The secondary objective of the laboratory work is to gain experience in validating the real-life system behavior and comparing it to the simulation results, with the emphasis on non-ideal behavior such as measurement noise, plant-model mismatch, and control action saturation.

1.2 Prerequisites

The laboratory sessions are organized after the necessary course material is thought. However, some information from previously followed courses, such as the Systems course, can be instrumental to the successful completion of the assignment. Potentially useful topics contain, but are not limited to:

- Frequency response of first and second order linear systems, low-pass filter design.
- Computing transfer functions for interconnected systems.
- Final value theorem and system types.
- Time response of first and second order linear systems.

2 Organization

For further information on the organizational matters students must consult the Study Guide available on CANVAS. The summary of the guidelines follows.

- There are 8 hours of experimental work scheduled for the first assignment. The same amount of time is expected to be spent by students at home in preparation to the lab work and report writing.
- Lab work must be performed in groups of two students, which will submit a common report.
- **The report on the results of Lab. Assignment 1 must be submitted in PDF format by e-mail to `v.spinu@tue.nl` until November 1.**
- The report must be at most 8 pages and contain the main experimental results and elaborate on the key control design elements and choices.
- The assessment will be made based on the quality of the report and satisfaction of the performance specifications.

3 Assignment description

Let the schematic representation of the MSDM system be given in Figure 4 and the parameters given by the engineering department summarized in Table 1. In Figure 4, τ_m is the motor torque, i_m is the current

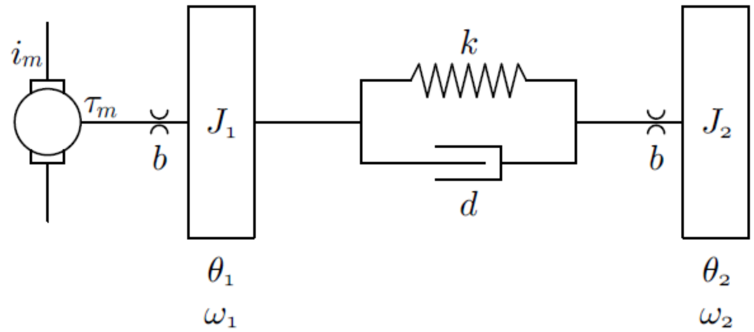

Figure 4: Schematic representation of the MSDM system.

Name	Description	Value
J_1	Moment of inertia of the first Mass	3.75e$-$6 [Kg m^2]
J_2	Moment of inertia of the second Mass	3.75e$-$6 [Kg m^2]
k	Torsional spring rate of the shaft	0.2656 [Nm/rad]
d	Torsional damping of the shaft	3.125e$-$5 [Nms/rad]
K_m	Motor constant ($\tau_m, = K_m i_m$)	4.4e$-$2 [Nm/A]
b	Viscous friction	$1e-5$ [Nms/rad]

Table 1: Summary of MSDM system parameters.

through the rotor windings, w_i and θ_i are the speed and position of the mass i, respectively. Bear in mind that the motor current saturates at ± 2 A, and that the parameters in Table 1 are nominal and can vary from setup to setup. Furthermore, the motor rotational speed is limited to about ± 500 rad/s.

The dynamics of the MSDM system is summarized in the following set of differential equations:

$$
\begin{aligned}
\dot{\theta}_1 &= w_1, \\
\dot{\theta}_2 &= w_2, \\
\dot{w}_1 &= \frac{1}{J_1}(k(\theta_2 - \theta_1) - (d+b)w_1 + dw_2 + K_m i_m), \\
\dot{w}_2 &= \frac{1}{J_2}(k(\theta_1 - \theta_2) - (d+b)w_2 + dw_1).
\end{aligned}
$$

During this lab session the transfer from i_m to w_1 is of interest, which is characterized by the following transfer function:

$$
G(s) = \frac{K_m(J_2 s^2 + (b+d)s + k)}{J_1 J_2 s^3 + (J_1 + J_2)(d+b)s^2 + ((J_1 + J_2)k + b^2 + 2bd)s + 2bk}.
$$

The control unit implements the control architecture in Figure 5. The $G(s)$ block represents the real electromechanical system connected to the control unit. Transfer functions $H(s)$, $P(s)$, and $D(s)$ can be up to 5$^{\text{th}}$ order and are configurable by the user. $H(s)$ is the filter of the speed measurement of the first mass, which can be noisy particularly at low speed. $P(s)$ is a reference prefilter and can be used to prevent

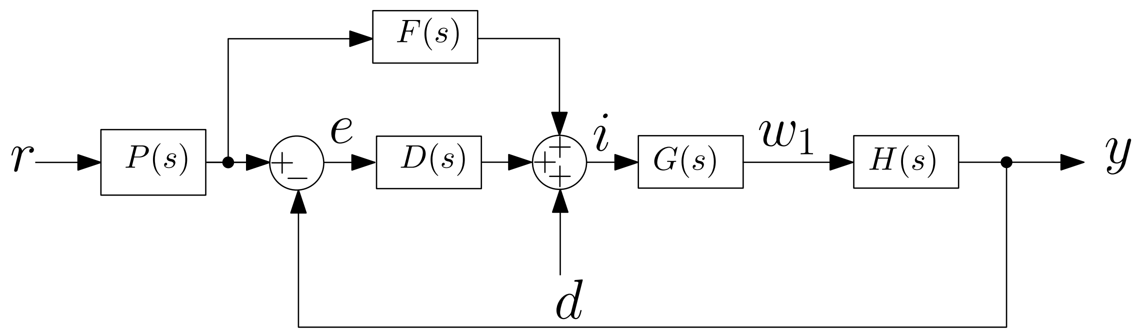

Figure 5: Control system architecture.

violent changes in the reference propagating to the closed-loop system. The block $D(s)$ is the compensator transfer function. The transfer function $F(s)$ is the feed-forward and can be used to perform open-loop measurements on the experimental platform. The external input disturbance is $d(t)$. In the context of the hybrid vehicle this disturbance may come from the internal combustion engine, and the electric motor must compensate for the slower dynamics of the engine while working in a so called *torque filling mode*.

3.1 Deliverables

Students must design the transfer functions $P(s)$, $H(s)$, and $D(s)$ such that the following set of specifications is satisfied:

- $H(s)$ is a low-pass filter which should efficiently filter the measurement noise and have the bandwidth of at least 100Hz, i.e., at low frequencies the magnitude should be as close as possible to 0 db, at 100Hz the filter magnitude should be larger than -3dB and the phase between $0° - 45°$.
- $D(s)$ and $H(s)$ must be designed such that the open-loop gain margin of at least 10dB and phase margin of at least $45°$ are ensured.
- The magnitude of the transfer from d to y must be lower than 20dB at the frequency of 1Hz. Validate the result via test T1 from Section 3.2.
- Closed-loop system must respond to a step in the reference with zero static error, and any constant disturbance must be fully rejected. Prove this item analytically in the report and via test T2 from Section 3.2.
- The step-response overshoot must be less than 5%. The overshoot is validated through test T3 in Section 3.2.

The main goal is to obtain a control system that obtains shortest settling time while satisfying the aforementioned conditions.

Students must summarize the control design decisions in a report with all necessary graphs. The report must contain bode characteristics of the following systems with nominal parameters:

1. Open-loop from e to y.
2. Closed-loop from r to y.
3. Closed-loop from d to y.
4. $H(s)$.

In case you believe that there is a large difference between the MSDM system behavior and the model, consider validating the model by comparing the open-loop response of the system to the model. To do this, apply custom input signals as described in Appendix A, while keeping $D(s) = 0$ and $F(s) = P(s) = 1$. If some of the necessary characteristics are not validated in practice due to model mismatch, attempt to modify the control system parameters until they do. Comment on differences between the nominal system and the real one.

3.2 Validation tests

The final closed-loop system must pass the following validation tests.

- T1 Consider a constant reference input of 100rad/s, and apply a sinusoidal disturbance $d(t) = 0.2\sin(2\pi t)$. Verify that the disturbance is attenuated with at least the specified amount.
- T2 Consider a constant reference of $r(t) = 200$rad/s and a constant disturbance of $d(t) = 0.1A$.
- T3 Consider $d(t) = 0$A and apply a sequence of steps of 200rad/s and -400rad/s on the reference. Verify the overshoot and the settling time.

Matlab functions that perform the tests are built in the *HW_LabAssignment1.m* object.

4 Grading

Students will receive the grade based on the Table 2.

Table 2: Grade construction.

Name	Grade %
Report quality and smooth system operation	30%
Satisfaction of the stability margins	10%
Sufficient bandwidth of $H(s)$	10%
Sufficient attenuation of d	10%
Zero static error	10%
Overshoot less than 5%	10%
Settling time to $\pm 1\%$	20%

The settling time dependent part of the grade is computed as follows:

$$x = \begin{cases} 10, & \text{if } t \leq 0.2 \\ 10\left(1 - \frac{(t-0.2)}{0.8}\right), & \text{if } 0.2 \leq t \leq 1 \\ 0, & \text{if any other specification is not satisfied} \end{cases}$$

We may decide to give bonus point if the settling time is lower than 0.2s in T3.

By smooth operation of the system is meant that there is no excessive noise (high-pitch, or grinding type of acoustic noise) present during the experiments. This can also be observed in the input signal waveform, i.e., the noise is considered high, if there is a high frequency component with an amplitude larger than 0.2 [A], and severe, if the amplitude exceeds 0.6 [A] peak-to-peak.

4.1 Notes

Questions regarding the assignment must be posted on the OASE forum or asked during the lab sessions.

Designing the feed-forward block for the closed-loop system is not compulsory, as feed-forward design is taught in Lecture 6 (after the time reserved for the LAB Assignment 1). This block can be used to investigate/measure the open-loop response of the system.

There is a chance o breaking the axle if the platform is overstressed. If this happens, students will have to replace the axle themselves. The spare axles and guidance will be provided by the instructors.

Appendix A: Summary of the Matlab functions

The interfacing with the experimental platform is provided by the class "HW_LabAssignment1", and its main methods and properties are explained in what follows. For student convenience "test.m" file is uploaded to CANVAS, which showcases the available interface functionality for the experimental platform.

Students must first create an instance of the object by calling

```
myobj = HW_LabAssignment1;
```

To setup the connection one must provide the IP address of the MyRIO device, '172.22.11.2' for the USB connection or '172.16.0.1' for the WiFi connection, and then call the 'createConnection' method:

```
myobj.ipaddress = '172.16.0.1'
myobj.createConnection;
```

Setting up the transfer function values is done by updating the corresponding properties of the object and calling the 'uploadSettings' method:

```
myobj.D = tf(0.001,1);
myobj.P = tf(1,1);
myobj.F = tf(0,1);
myobj.H = tf(1,1);
myobj.uploadSettings;
```

Bear in mind that the direction of the encoder may vary from platform to platform, which will result in a different sign of the $H(s)$ transfer function.

The disturbance and reference waveforms are sampled with 2ms interval and should be provided to the platform as vectors:

```
time = 0:0.002:5;
myobj.reference = 200+time*0;
myobj.reference(1)=0;
myobj.disturbance = 0.2*sin(2*pi*3*time);
myobj.disturbance(1)=0;
myobj.uploadDisturbance;
myobj.uploadReference;
```

Note that the first element of the disturbance and reference vector must be 0. This value is passed to the experimental platform outside the experiment time. If this value is not 0 the system can easily accelerate to the top velocity while in idle and possibly be damaged.

To run the experiment with the current settings one must call the method 'StartExperiment':

```
myobj.StartExperiment;
```

When the experiment is complete the message 'Experiment ended and the data are available' will appear in the command window. To retrieve the data from the experimental platform run

```
myobj.get_all_back;
```

Calling this function will transfer all the measurement waveforms into Matlab workspace from the local memory of MyRIO.

There are two options one can use to read the measurement data, either to get the complete dataset at once, i.e., the output of $P(s)$, $H(s)$, $F(s)$ and the combined $i(t)$, or to receive only the measured output $y(t)$. Let us first illustrate how the complete dataset can be retrieved.

```
close all
figure(1)
subplot(3,1,1:2)
plot(time,myobj.reference,time,myobj.measured_out,time,myobj.prefilter_out);
legend('ref','y','Pout')
subplot(3,1,3)
plot(time,myobj.disturbance,time,myobj.controller_out,time,myobj.ff_out,...
time,myobj.combined_out);
legend('dist','Dout','Fout','i')
xlabel('time (s)')
```

This command sequence will result in a similar plot as in Figure 6.

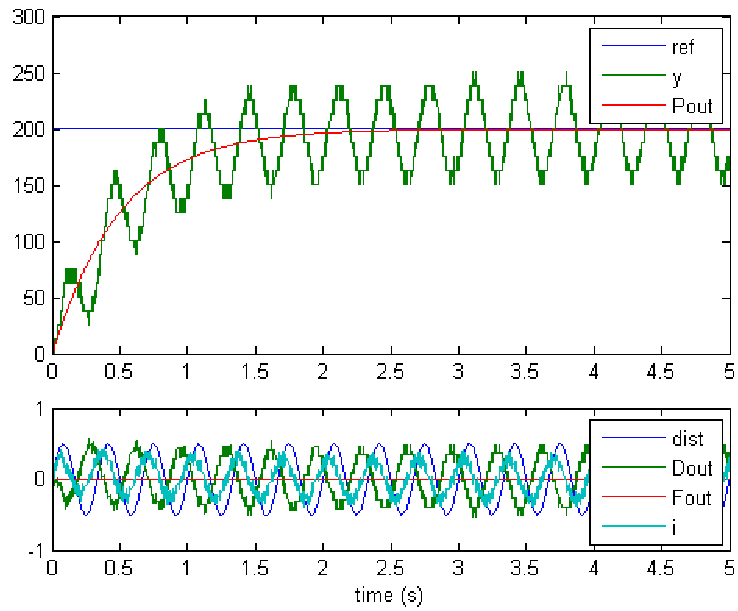

Figure 6: The figure resulting from running the commands in this section.

To update only the 'measured_out' property of the object use the method 'gety':

```
myobj.gety;
```

and to close the connection to the platform invoke:

```
myobj.CloseConnection;
```

Methods `myobj.T1`, `myobj.T3`, and `myobj.T3` implement the Test scenarios from Section 3.2.

To check the behavior of the functions from this section on your experimental platform, run the 'test.m' script available in the folder "5ESD0 Control systems /Files /Labs /LAB Assignment 1" on CANVAS website.

Appendix B: How to setup the environment for the lab session

This appendix summarizes the software requirements for successful completion of the laboratory sessions. Students must bring their own laptop to perform the experiments, and setup the software environment before coming to the lab session.

Control of the experimental platform will be performed from Matlab. A Matlab class, called "HW_LabAssignment1" is provided in the folder "5ESD0 Control systems /Files /Labs /LAB Assignment 1" on CANVAS website. This class contains the necessary functionality to establish the connection with the experimental platform, set the control system parameters, set the reference and disturbance waveforms, and get the output data back after the experiment is completed. The methods in this class use TCP/IP connection from the "Instrumentation Control Toolbox", and to design the control system students should use SISO tool which is a pat of the "Control Systems Toolbox".

The functionality of the "HW_LabAssignment1" class was tested on the "Electrical Engineering" Matlab version from the university website: `https://intranet.tue.nl/universiteit/diensten/ict-services/hulp-en-ondersteuning/software-tue-werkplek/matlab/`.

The minimal Matlab installation should include

- Instrumentation Control Toolbox (for TCP/IP communication). To check whether this toolbox is installed type `help tcpip`.
- Control Systems Toolbox (for operations with transfer functions and SISO tool for control design). To check whether this toolbox is installed type `help tf`.

To check which toolboxes are installed in Matlab type `ver` in the command window. There are two options to connect with the experimental platform:

- Wired connection: MyRIO device has a build-in USB-LAN adapter. Therefore students must have a free USB port on their laptop. The drivers for the Microsoft Windows are provided in "5ESD0_Control_Systems/Lab 1 files/usblan driver.zip". Depending on your operating system, install "NiRio_USBLAN.msi" for 32bit OS, or install "NiRio_USBLAN64.msi" for 64bit OS. Wired connection is preferred as students can still use the WiFi for the Internet connection. The IP address of the MyRIO device in this configuration is '172.22.11.2'.
- WiFi connection: Students who use other operating systems than Windows (tested on Mac OS), must connect to the platform through WiFi, as the USB-LAN drivers are provided. Each MyRIO device will have a label attached to on the top with the WiFi network you have to connect to. Note that WiFi connection to MyRIO does not provide Internet. The IP address of the MyRIO device in this configuration is '172.16.0.1'.

Appendix C: Troubleshooting

A summary of possible problems and solutions follows:

- **Sending or receiving data to or from the MyRIO returns a timeout error in Matlab:** Here is the checklist to solve this issue:
  1. Check if the MyRIO is powered on: Power LED on and Status LED off. If the Status LED is glowing orange, wait until it turns off, it should take less than 10s. If the Power LED is off, check the power adapter, as it probably is disconnected.

2. To verify if the connection to the MyRIO device is available write the IP address in an Internet browser. The device configuration menu should appear (works only on Windows).
3. If the configuration menu appears, but timeout error is still returned, check the remaining LEDs on the MyRIO. LED1 must be on, if not restart the device by pressing the RESET button near the power connector. LED3 is on when the system is in idle and the data can be safely retrieved. When the experiment is in progress the LED3 is off. If LED3 is off for much longer than the requested length of the experiment, reset the system.
4. If the configuration menu does not appear, try to connect with the other remaining method WiFi or USB.
5. If you are using the USB connection, check whether the USB-LAN adapter was recognized properly in Device Manager. If not, unplug and plug back in the usb cable. Try to updated the driver (the USB-LAN driver must be installed on the PC before connecting the MyRIO device).
6. If you are using a cordless mouse (or other devices connected via Bluetooth or USB), the IP address of the MyRIO may change. In this case WiFi connection can be used or the USB connection can be re-initiated after the external devices are removed.

- **MyRIO sends/receives data, but the mechanical system does not move.** Check whether the he position of the switch 'motor' is 'off'. Move the switch to position 'on'.
- **System is unstable** Check if the sign of $H(s)$ is correct, i.e., the speed must be positive if i_m is positive. Change the sign of $H(s)$ if necessary. Check the stability margins of the control system. See if i_m saturates at ± 2A. In the later two cases modify the controller to remove instability and reduce saturation of i_m.

  If the system becomes unstable during the experiment, the mechanical system can be switched of by changing the position of the switch 'motor' to the position 'off'.

Shall you encounter any other problems please contact the instructors.