Laboratory Manual

Automation System Control Laboratory

- Dual temperature control system
- Closed loop control of dual temperature control system
- Wind levitation system

UbiLAB

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ФАКУЛТЕТ ЗА ЕЛЕКТРОТЕХНИКА И ИНФОРМАЦИСКИ ТЕХНОЛОГИИ

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8 Automation System Control Laboratory

8.1 Introduction

The laboratory experiments are intended for students to learn basic and advanced feedback theory concepts. The exercises cover basic feedback design techniques with graphical tools and modern design approaches with more complex and sophisticated tools. All the experiments can be executed remotely over the web graphic user interface. The developed web interface based on HTML and JavaScript can be easily portable to the different MOOC platforms and used for distance learning.

This document describes the exercises on two different setups, where the goal is to design feedback control algorithms and perform activities remotely. The basis of both experiments is a connection bridge developed on the ARM32F7 controllers. The main board has two possible links to share the data over the network. The first link is based on serial communication, where the data is collected from the experiment and provided to the server, which ports the data to the web. A second connection is based on the LWIP stack, which enables a direct connection over the TCP/IP protocol. All data can be provided over both connection links and are managed to speed up the package transportation and multi-platform connection.

The main board of the experiment collects the data from the existing system and processes the data from the sensors. Safety and connectivity are ensured with a multilevel watchdog timer, which distinguishes between non-activity from the user and safety protocols to maintain the system's safe operation. If the system detects the user's absence of network activity, restart the connection and re-establish a new link to the other user. The safety protocols of the experiment activity maintain the proper functionality and avoid unwanted malfunctions in the system.

The exercises are divided into three subsections, where each previous experiments are starting point for the next practice. All the activities are closely related to the feedback control theory. Feedback control theory is a branch of engineering and mathematics that analyzes and designs systems governed by feedback loops. It provides a framework for understanding and manipulating the behaviour of dynamic systems to achieve desired objectives. Feedback control theory aims to design controllers that stabilize the system, reject disturbances, and achieve desired performance criteria such as stability, accuracy, speed, and robustness. The design process typically involves mathematical modelling of the system, analyzing its behaviour, and applying control techniques to achieve the desired objectives. Feedback control theory finds applications in various fields, including robotics, aerospace, automotive, process control, and electronics. It enables engineers to design control systems that can effectively control and optimize the behaviour of dynamic systems.

8.2 Laboratory experiment 1 - Dual Temperature Control System

The laboratory experiment is based on a dual heater system. A dual temperature control system comprises two power transistors and two temperature sensors. A dual temperature control system is a specific feedback control system that controls two different temperatures simultaneously. It is commonly employed in applications where maintaining two different temperatures is critical, such as in industrial processes, environmental control systems, or HVAC (Heating, Ventilation, and Air Conditioning) systems.

A dual temperature control system typically has two separate control loops, each responsible for regulating one temperature. Designing and tuning a dual temperature control system involves setting appropriate control parameters for each temperature loop to achieve stable and accurate temperature regulation. It also requires considering any interactions or cross-couplings between the two control loops to ensure proper coordination and prevent interference.

The dual temperature control system can provide precise and independent control over two different temperatures, allowing optimal operation and energy efficiency in applications where maintaining specific temperature conditions is crucial.

The essential components of the system include:

- **Sensors:** Two temperature sensors measure the temperatures of the two different zones or processes. These sensors provide feedback signals to the control system.
- **Controllers:** Two individual controllers are employed to process the feedback signals and generate the appropriate control actions for each temperature. Each controller compares the measured temperature with a desired setpoint and calculates the necessary control output.
- **Actuators:** Two actuators adjust the inputs to control each temperature separately. These actuators could be heating elements, cooling units, valves, or other devices that can manipulate the temperature.

8.2.1 Experimental setup

A dual temperature control system is developed as a small MIMO system, which is portable and easy to use. The system does not require additional laboratory equipment. For the heaters, two power transistors, TIP31 are used. The resistor does not limit the current to the base port of the transistor, and a larger current is provided through the collector and emitter, therefor the heat dissipation is increased. On each power transistor, the LM60 temperature sensor is attached. The sensor has an analogue output, and the temperature scaling is processed on the microcontroller board. The main three components of the system are:

- **Sensors:** Two analogue sensors LM60.
- **Controllers:** The controller is implemented in the main timer-interrupt routine with a time tap of 1 second.
- **Actuators:** Two power transistors TIP31 driven with the PWM signal from the microcontroller board.

The experiment is presented in Figure 8-1, and the block schematic of the dual temperature control system is given in Figure 8-2.

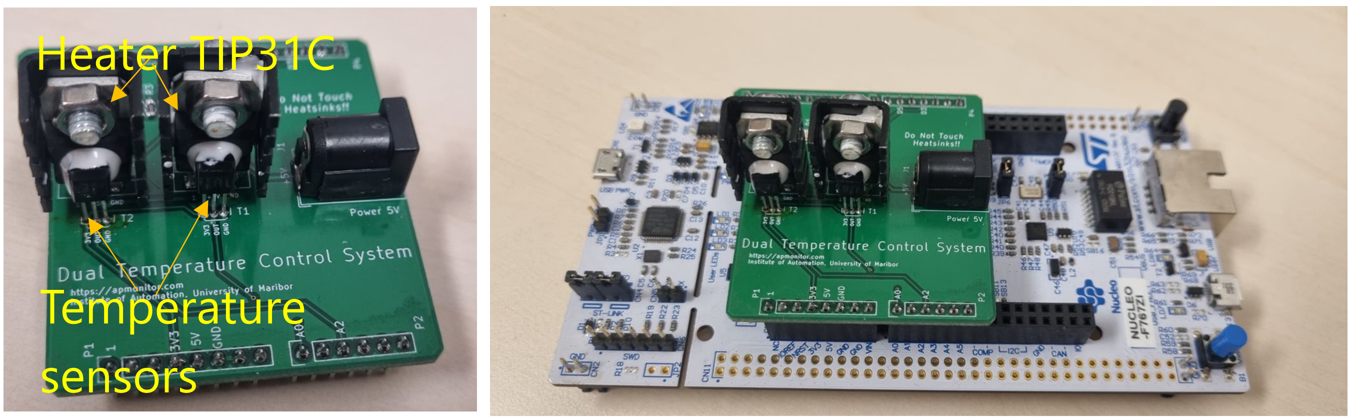
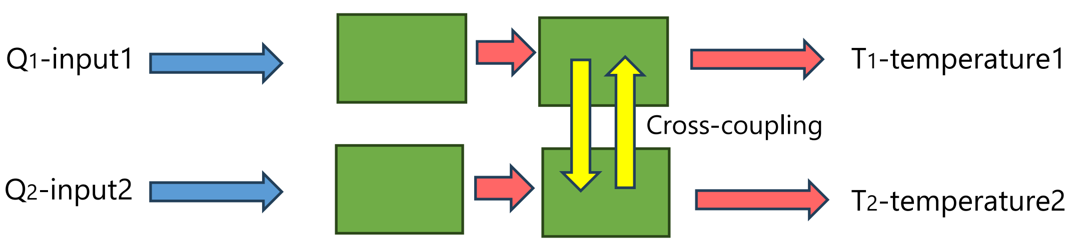


Figure 8-1. A dual temperature control system main board with microcontroller Nucleo F767ZI.



8.2.2 Goals of the experiment

Figure 8-2. Block schematic of a dual temperature control system.

Identify the parameters of the mathematical model. Identifying the parameters of the model is essential for the control design procedure. The mathematical modelling is based on the physics relation given below. The energy balance equation is given as:

$$m\,c_p\frac{dT}{dt} = \sum \dot{h}_{in} - \sum \dot{h}_{out} + Q$$

For the first input $Q_1 \rightarrow T_1$,

$$m\,c_p \frac{dT_1}{dt} = U\,A\,(T_\infty - T_1) + \epsilon\,\sigma\,A\,\left(T_\infty^4 - T_1^4\right) + Q_{C12} + Q_{R12} + \alpha_1 Q_1$$

with the coupling parameters

$$Q_{C12} + Q_{R12} + \alpha_1 Q_1$$

For the second input $Q_2 \rightarrow T_2$,

$$m\,c_p \frac{dT_2}{dt} = U\,A\,(T_\infty - T_2) + \epsilon\,\sigma\,A\,\left(T_\infty^4 - T_2^4\right) - Q_{C12} - Q_{R12} + \alpha_2 Q_2$$

with the coupling parameters

$$-\,Q_{C12} - Q_{R12} + \alpha_2 Q_2$$

The equations are complex, and most parameters are hard to determine. Most of the equation elements have a minor influence on the final temperature value and can be neglected. In this case, the approximation of the first-order transfer function is used.

$$H(s) = \frac{T_1(s)}{Q_1(s)} = \frac{k}{\tau s + 1}$$

Where τ and k are time constant and gain separately defined as,

$$\tau = t\left(0.63\,T_1(\infty)\right)$$

$$k = \frac{T_1(\infty)}{Q_1(\infty)}$$

As presented in Figure 8-3, both parameters can be assigned from the system step response.

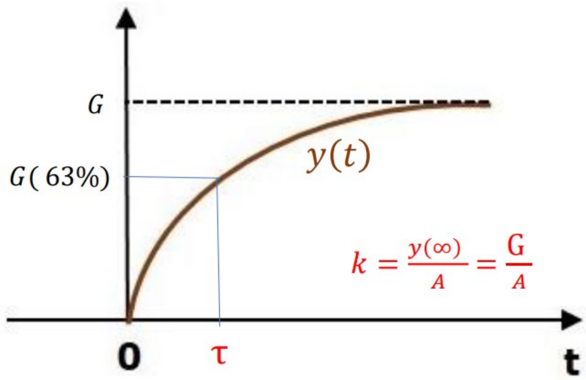


Figure 8-3. Step response of the system.

8.2.3 Experimental results

In the web-GUI (Figure 8-4), adjust the open loop slider to level 40 and read the step response of the system (given in Figure 8-5 for $Q_1 \rightarrow T_1$).

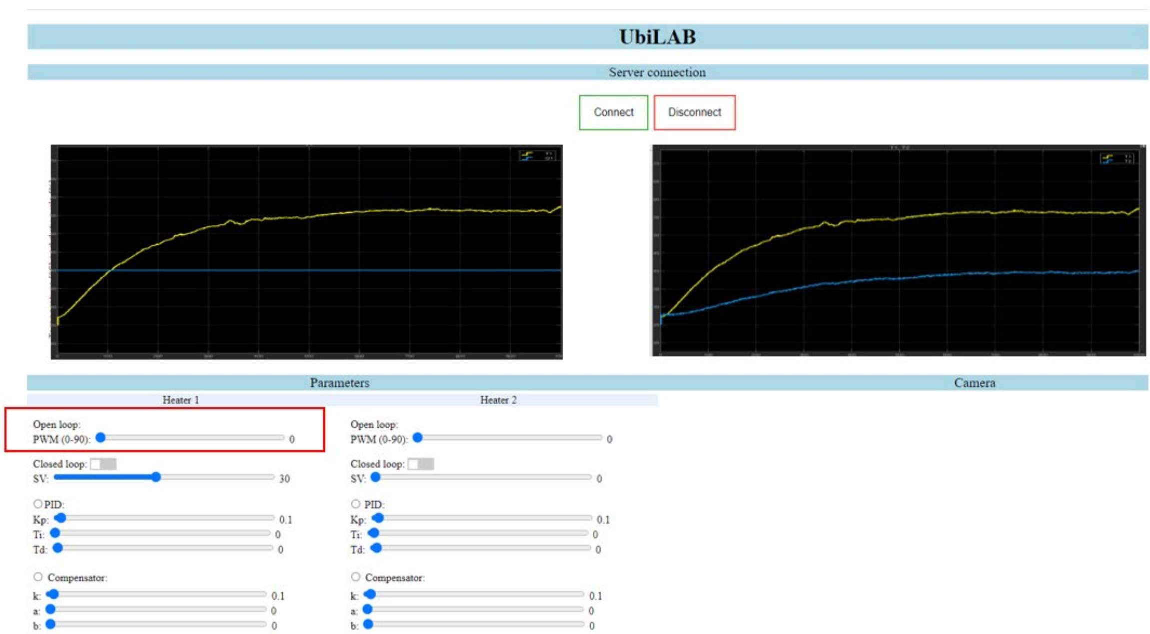


Figure 8-4. Web-GUI for Dual temperature control system.

Step response of the real system on channel one ($Q_1 \rightarrow T_1$) close view,

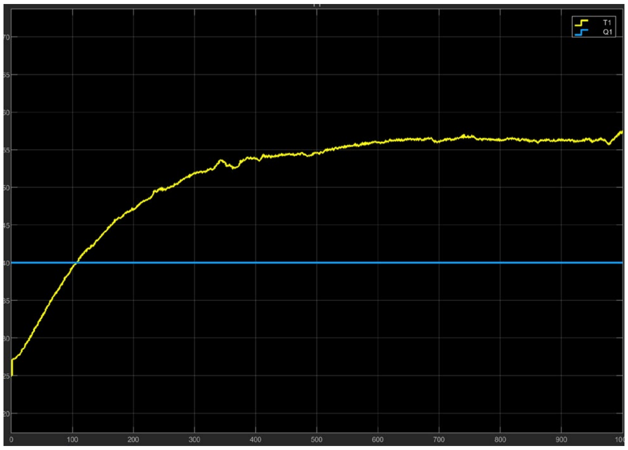


Figure 8-5. Step response of the system Q1->T1.

Assigned data from the step response in Figure 8-5:

$$k = 0.82$$

$$\tau = 165.2s$$

$$H(s) = \frac{T_1(s)}{Q_1(s)} = \frac{0.85}{165.2s + 1} = \frac{0.0049}{s + 0.0061}$$

Model validation is presented in Figure 8-6, close view.

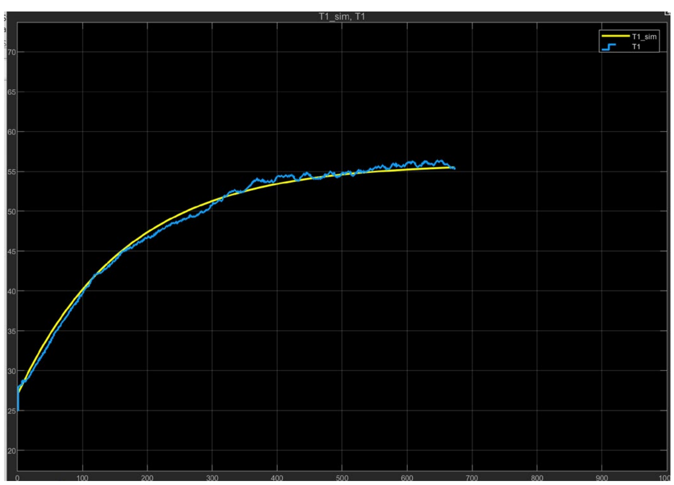


Figure 8-6. Model validation Q1->T1. Blue line: a real measurement, yellow line: simulated model.

8.3 Laboratory experiment 2 - Closed-loop Control

The laboratory experiment aims to design a feedback structure for the dual temperature heater system described in experiment 1.

8.3.1 Experimental setup

In experiment 2, the dual temperature system is used. In this case, the negative feedback (Figure 8-7) is employed.

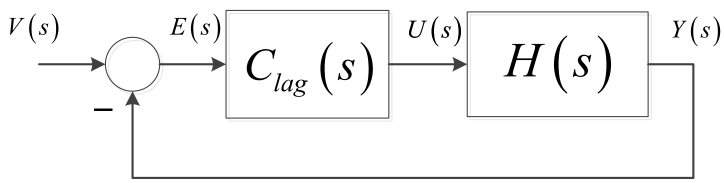


Figure 8-7. Closed-loop system.

8.3.2 Goals of the experiment

The experiment aims to design a feedback control loop with a lag compensator. A lag compensator is a feedback control system designed to improve the stability and performance of a system. It is often used to shape the frequency response of a system to achieve desired characteristics such as better transient response, reduced overshoot, and improved stability margins. The purpose of a lag compensator is to introduce additional phase lag to the system's open-loop transfer function, thereby reducing the system's gain at high frequencies while maintaining or increasing the gain at low frequencies. This helps to mitigate issues like instability or poor response time that may occur in the original system. The transfer function of the lag compensator is,

$$C_{lag}(s) = \frac{E(s)}{U(s)} = \frac{g(s+b)}{(s+a)} \qquad g, b, a > 0 \wedge b > a$$

Here g, b, a are compensator gain, zero, and pole, respectively. Designing a lag compensator involves analysing the system's open-loop transfer function and evaluating the desired stability and performance criteria.

8.3.3 Experimental results

The lag compensator regarding the system transfer (exercise 1) function is designed to compensate the pole of the system. The compensator pole located close to the origin achieves transient response behaviour and tracking capability.

The transfer function of the system,

$$H(s)=\frac{T_1(s)}{Q_1(s)}=\frac{0.85}{169.2s+1}$$

The root locus of the transfer function $H(s)$ is presented in Figure 8-8.

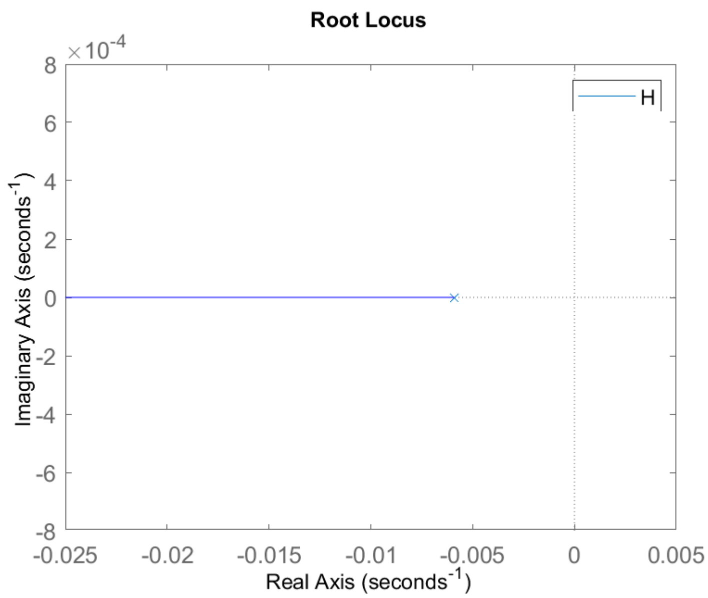


Figure 8-8. Root locus of the transfer function H(s).

Preselect compensator regarding latter design guidelines (Figure 8-9).

$$C_{lag}(s)=\frac{E(s)}{U(s)}=\frac{4.2\left(s+\frac{1}{169.2}\right)}{(s+0.001)}$$

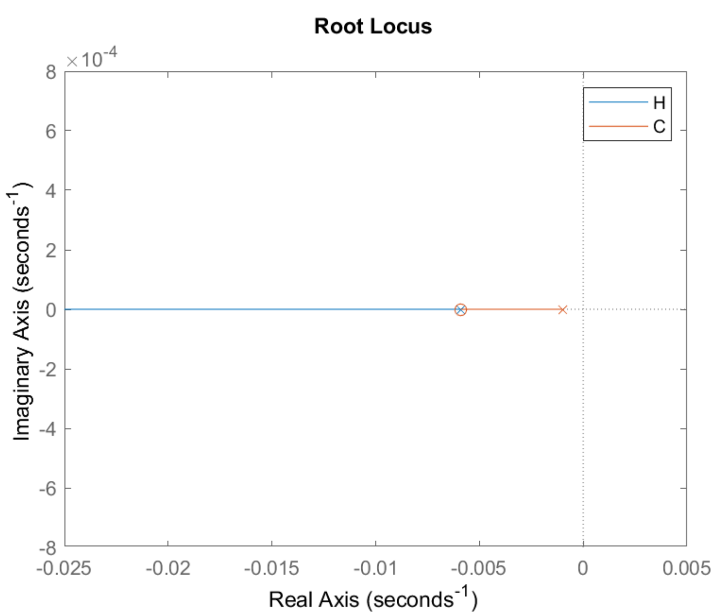


Figure 8-9. Root locus of the transfer function H(s) with lag compensator Clag(s).

Experimental results are given in Figure 8-10, for selected compensator and reference values.

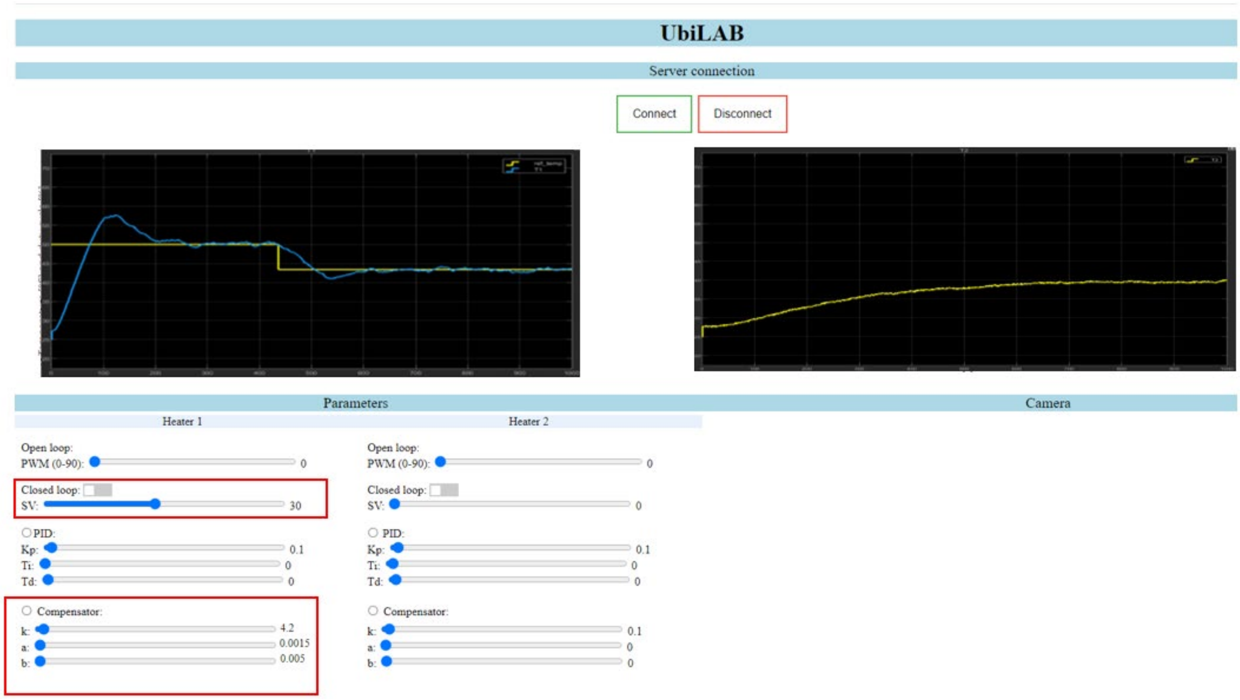


Figure 8-10. Real-time experiment with lag compensator, web-GUI.

8.4 Laboratory experiment 3 - Wind Levitation System

The aim of experiment 3 is t design the feedback structure that stabilizes the floater in the wind tube at a certain height. Height stabilization in the context of a wind tube typically refers to a device or mechanism designed to maintain stability and control the position of an object within the wind tunnel. In wind tunnel testing, a wind tube is used to simulate the effects of airflow on an object or model under controlled conditions. The object or model is typically placed within the wind tunnel, and the air is blown through the tunnel at various speeds to study the dynamic behaviour of the object. The specific design and implementation of a stabilizing floater in a wind tunnel can vary depending on the object being tested, the desired level of control, and the capabilities of the wind tunnel facility.

8.4.1 Experimental setup

The Wind levitation system experiment comprises the wind tube floater and the fan. The fan is placed under the wind tube with an attached sensor to measure the accurate height of the floater. Figure 8-11 presents the experiment system.

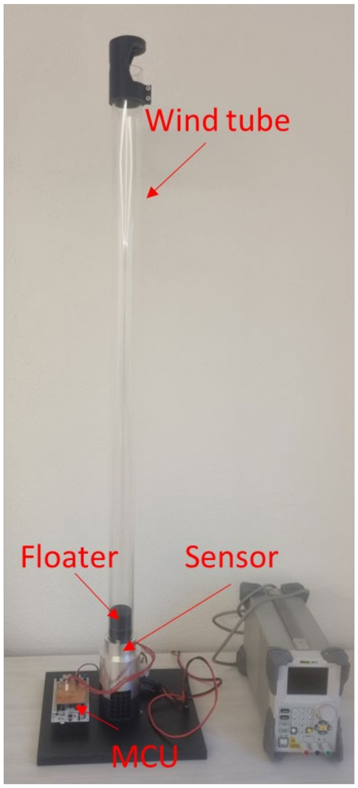


Figure 8-11. Wind levitation experiment system.

All the measurements, data processing, and communication task proceeded on board NUCLE767ZI. The communication protocol is the same as in the previous Dual temperature control system experiment. The main three components of the system are:

- **Sensors:** Time to Fligt (ToF) sensor VL53L0X.
- **Controllers:** The controller is implemented in the main timer-interrupt routine with a time tap of 1 second.
- **Actuators:** Fan EDF Ducated 70mm, 3000Kv brushless motor.

The hardware structure and connection between the system are presented in Figure 8-12.

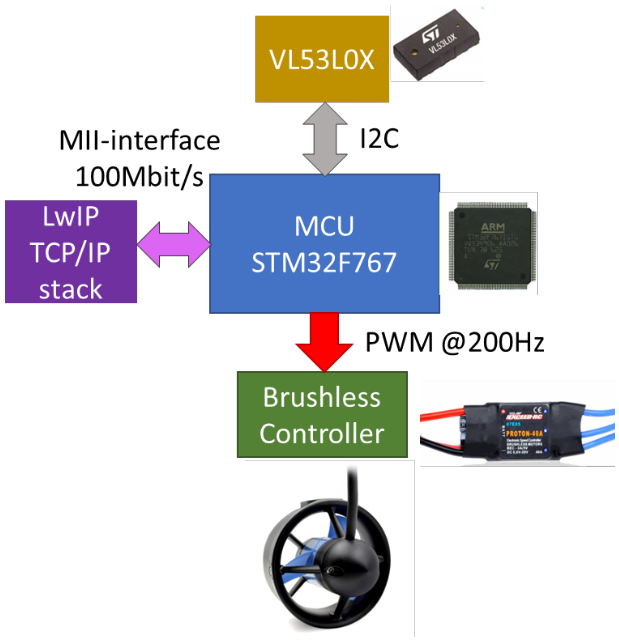
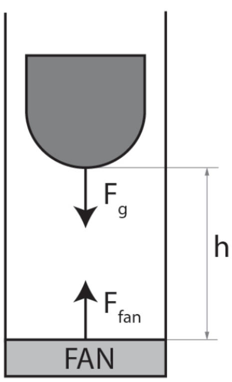


Figure 8-12. Hardware connection of the Wind levitation system.

8.4.2 Goals of the experiment

Design a PID controller for stabilizing the floater at desired height inside the wind tube. Use the following mathematical model.



Second Newton law of floater motion,

$$m\ddot{h} = -mg + F_{fan}$$

Second-order differential equation,

$$\ddot{h} = -g + \frac{1}{m}F_{fan}$$

The transfer function of the system is,

$$H(s) = -g + \frac{H_{height}(s)}{F_{fan}(s)} = -g + \frac{1}{ms^2},$$

$$\frac{H_{height}(s)}{F_{fan}(s)} = \frac{1}{ms^2}$$

The PID controller is designed for the transfer function $H_{height}(s) / F_{fan}(s)$. In the feedback structure presented in Figure 8-13, the gravity constant g can be compensated with additional input at the output of the PID controller.

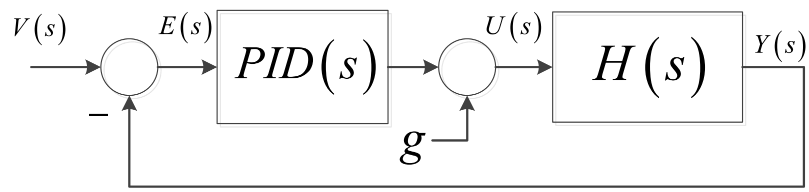


Figure 8-13. Wind levitation feedback structure.

The transfer function of the PID controller is:

$$PID(s) = K_p\left(1 + \frac{1}{T_i}\int e(t)\,dt + T_d\frac{de}{dt}\right),$$

where K_p, T_i, T_d are proportional gain, integrator, and derivative constant, respectively.

For the controller, the design uses a function 'pidtool' in Matlab software or a similar PID-tuner package (Python script, pidtuner.com, etc.). Tune the PID controller with the given closed-loop performance characteristics:

- Overshoot $\le 15\%$.
- Settling time $\le 32s$.
- Rise time $\le 25s$.
- Steady-state error $\le 2\%$.

8.4.3 Experimental results

The tuned controller parameters are,

$K_p = 1.59,$

$T_i = 11.2,$

$T_d = 0.25.$

The PID controller is:

$$PID(s) = 1.59\left(1 + \frac{1}{11.2}\int e(t)\,dt + 0.25\frac{de}{dt}\right).$$

The tuned controller is implemented over web-GUI for the Wind levitation system (Figure 8-14).

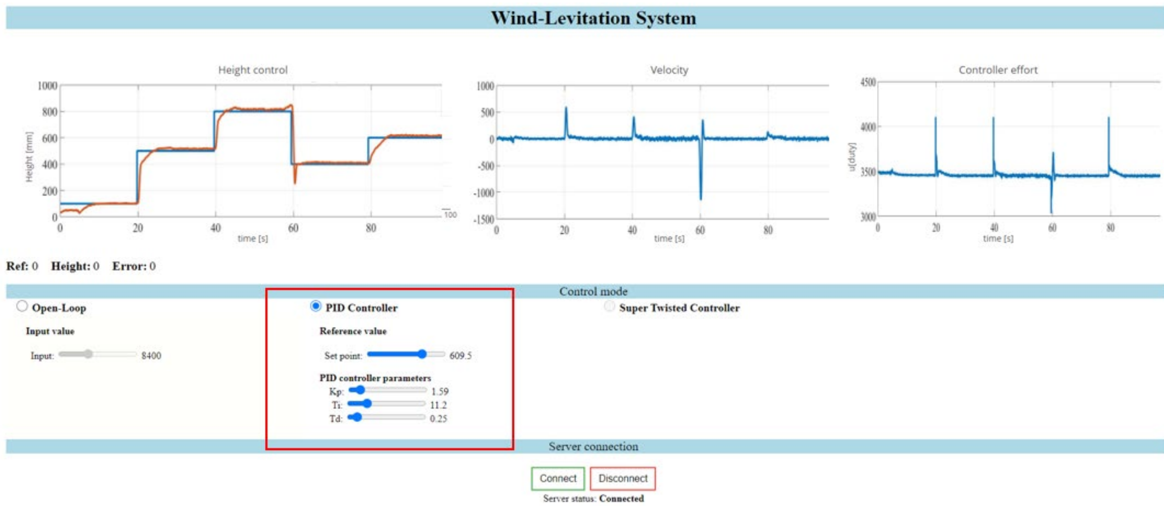


Figure 8-14. Real-time experiment of Wind levitation feedback control with web-GUI.

A close view of the experimental results is presented in Figure 8-15.

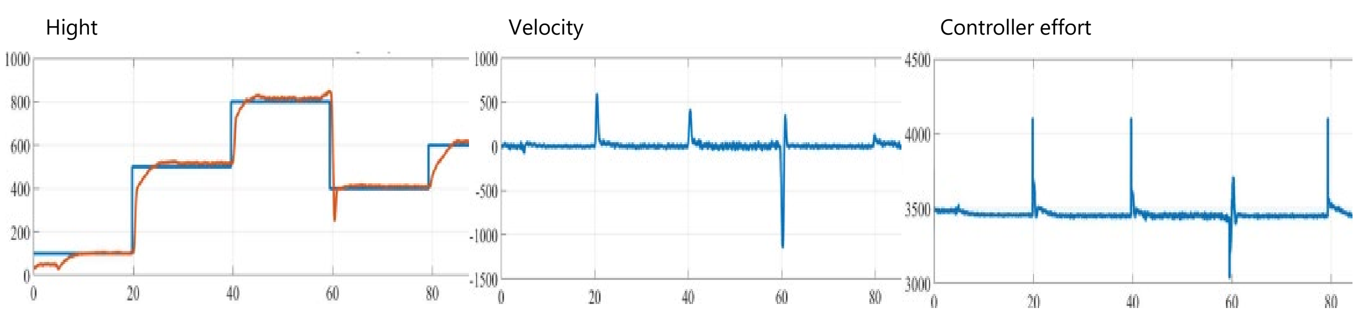


Figure 8-16. Real-time experiment of Wind levitation feedback structure with web-GUI.

8.5 Conclusion

The presented laboratory exercise presents the capability of the developed system. All the practices can be executed remotely, and the data are accessible to the student in real time. Such a system can be ported into vast platforms and web pages. The platform can be used online or offline. All the presented exercises are pilot examples for students with basic knowledge of the control theory and system or first level of study. The exercises are developed gradually.

The first exercise is an example of how to determine the transfer function directly from the measurement. Many industrial control applications (temperature, pressure, flow systems) can be described with first or second order differential equations. With the given exercises, the student can learn how to deal with the transfer function coefficient efficiently before starting with the controller design without a complex modelling procedure and analytical approaches. The second exercise is related to the first. The derived model from the first exercise is used as the plant for the feedback system design with the lag compensator. The lag compensator is designed to improve the tracking capability of the heater system. The design procedure uses the root-locus approach, where the dominant pole of the system is compensated with zero of the lag compensator. The compensator pole is placed close to the origin, which lowers the steady state error and improves the feedback system's tracking capability. The third exercise involves the design of the feedback system for unstable systems. The stability issue is essential in the design procedure, whereby the performance criteria must be met. The design introduced a non-classical feedback structure with direct compensation of the gravity constant. The Wind levitation system is an example of the many practical systems such as hovering drones, helicopter height stabilization, air pressure stabilization in the air piping, air suspension etc.

For further development, the exercises can be developed for students with advanced knowledge and researchers. With the capability of remote execution, there is no need for additional hardware or laboratory equipment. For the advanced exercises, the model predictive control (MPC) can be introduced for the Dual temperature control system or nonlinear controllers such as Sliding mode control (SMC) or Backstepping design for the Wind levitation system.