# Laboratory
# Control of an air duct

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Course: **ACA**

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**Abstract**

In this laboratory the temperature at the end of an air duct will be closed-loop controlled. The temperature can be influenced with a heating element (electrical resistor) or with a fan. Therefore 2 command signals are available to control the temperature.

In this laboratory only the heating element will be used. The fan is supplied with a predefined voltage.

The specialities of this laboratory are:

1. Delay: Because the heating element in the air duct is not located directly in front of the temperature sensor, there is a delay in the process. Delays pose a big challenge to the design of a controller, especially regarding the stability.
2. Model: It is very time-consuming to find a theoretical model of this process (for example compared to the control of the revolution speed of a DC motor). In practice this is quite often the case. Therefore, we do not try to obtain such a model here. Instead, a reasonable model structure will be obtained from the experimentally acquired data.

# 1 Introduction

A picture of the experiment can be seen in figure **??**.

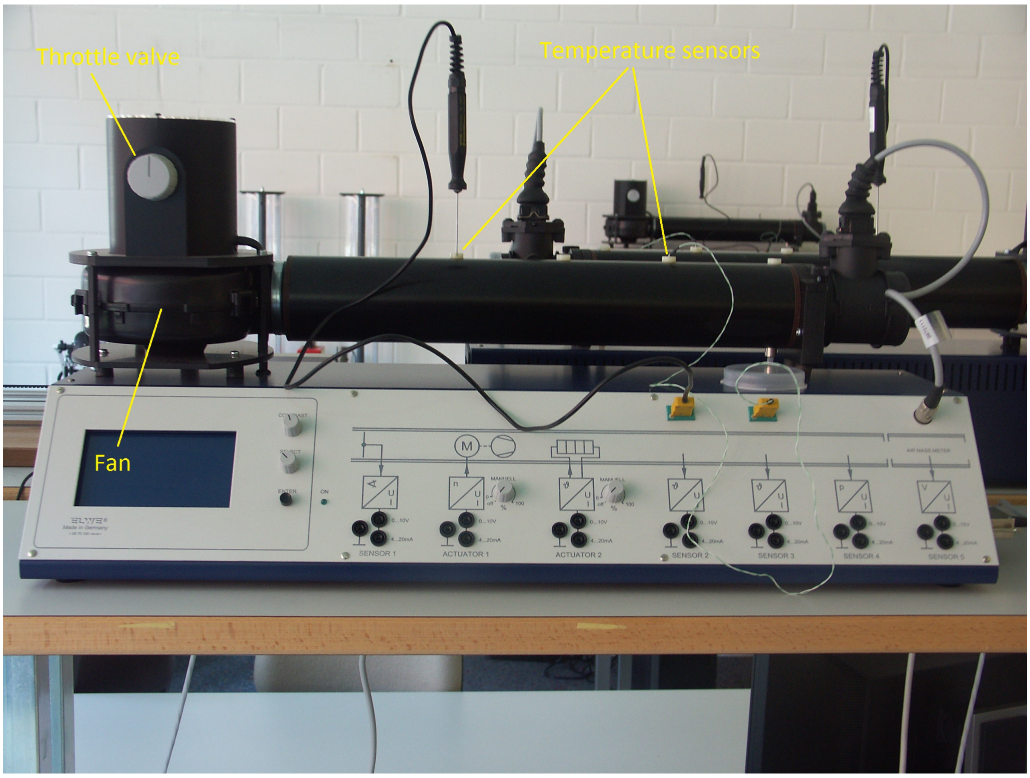


Figure 1: Picture of the air duct

The air duct experiment with two measurable outputs (pressure $P(t)$ respectively mass $M(t)$ and temperature $\vartheta_1(t)$ respectively $\vartheta_2(t)$) and two inputs (voltage $u_v(t)$ for the speed of the fan and voltage $u_h(t)$ for the heater) allows you to determine the properties of the process. With the control variables $\vartheta_1(t)$ respectively $\vartheta_2(t)$), $P(t)$ or $M(t)$ , it is also possible to analyse the performance of different controller structures. The angle $\varphi(t)$ of the manually adjustable throttle valve at the beginning of the air duct serves as a disturbance variable of the process.

A schematic diagram of the experiment can be seen in figure **??**.

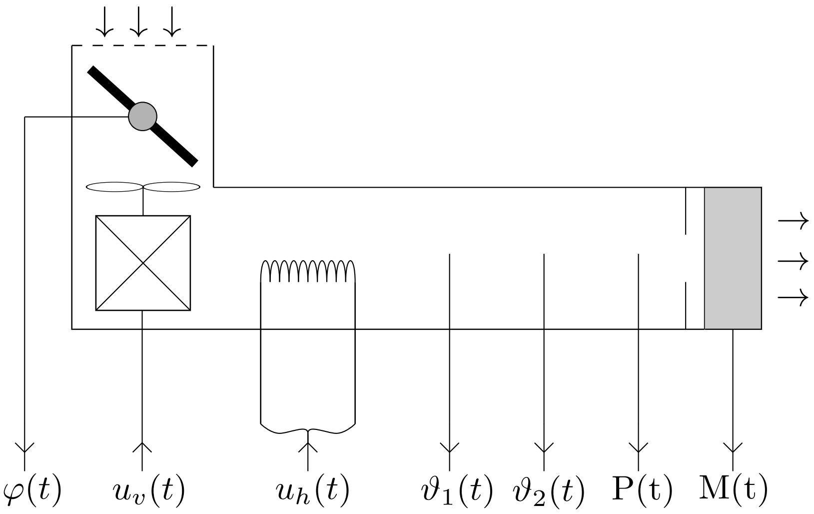


Figure 2: Schematic diagram of the air duct

# 2 Hardware

It is important to get familiar with the hardware of the experiment.

A Beckhoff PLC will be used to program the different controllers and test them experimentally. The following terminals will be used.

- EL4032: This terminal is used to control the fan and the heating element. It provides two analog output channels with a voltage range of -10 to +10V. Output channel 1 is connected to the fan ($u_v(t)$). Output channel 2 is connected to the heating element ($u_h(t)$).
- EL3004: This terminal is used to read the air mass, the two temperatures and the angle of the throttle valve. It provides four analog input channels with a voltage range of -10 to +10V. Input channel 1 is connected to the air mass sensor ($M(t)$). Input channel 2 is connected to the temperature 2 sensor ($\vartheta_2(t)$). Input channel 3 is connected to the temperature 1 sensor ($\vartheta_1(t)$). Input channel 4 is connected to the throttle valve angle sensor ($\varphi(t)$).

**Exercise 1:** *Terminal EL4032 takes an INT value and sets an output voltage according to it. How does the output voltage depend on the INT value?*

□

**Exercise 2:** *Check if you can operate the air duct manually (in free run mode) from TwinCAT system manager. For this you need to apply voltages to both the fan and the heating element. Read the values of the analog input signals. All necessary signals can be found in TwinCAT system manager.*

□

# 3 Model

The theoretical derivation of the model is quite complicated and is therefore omitted here.

We are searching for a transfer function to describe the process mathematically.

The transfer function $G_1(s)$ describes the relationship between the controlled signal $V_2(s)$ and the control signal $U_h(s)$, therefore:

$$\vartheta_2(t) \circ\!\!-\!\!\bullet V_2(s)$$
$$u_h(t) \circ\!\!-\!\!\bullet U_h(s)$$

It is assumed that $G_1(s)$ is a first order lag with delay:

$$G_1(s) = \frac{V_2(s)}{U_h(s)} = e^{-T_t s} \frac{K_f}{1 + \tau_f s}$$

# 4 Problem formulation

In this experiment the temperature $\vartheta_2(t)$ is controlled through the supply voltage $u_h(t)$ of the heating element. The pressure $P(t)$ is neglected. The voltage of the fan $u_v(t)$ is set to a predefined value of 5V and will not be changed. The goal is to design a robust controller that remains stable for the different states of the process. The various states of the process are realized through different positions of the throttle valve.

**Exercise 3:** *Draw the block diagram of the controlled process. The diagram should contain the process output, the command signal, the reference signal and the possible disturbances that exist in the process.*

□

# 5 Parameter identification

The parameters of the transfer function $G(s)$ will be determined for a half open throttle valve which corresponds to this setting **??**:

Figure 3: Setting of the throttle valve - Half open 45

The respective transfer function is defined as follows:

$$G(s) = \left.\frac{V_2(s)}{U_h(s)}\right|_{\text{half open}} = e^{-T_t s}\frac{K_f}{1+\tau_f s}$$

At first the process must be excited without the controller to determine the parameters $T_t$, $K_f$ and $\tau_f$. Therefore the process is excited with a step from $u_h(t) = 1$ [V] to $u_h(t) = 5$ [V]. The voltage of the fan is set to 5V.

**Exercise 4:** *In TwinCAT PLC Control (use the provided template project) and TwinCAT System Manager:*

- *connect the global variables (globInt...) in the template project with the hardware in- and outputs.*
- *in PROGRAM ReadInputs convert the value of global variable globIntTemperature2 from INT to celsius and save it in globCelsiusTemperature2. Use constants SCALE_CELSIUS_INT and OFFSET_CELSIUS_INT for the conversion.*
- *in PROGRAM WriteOutputs convert the values of global variables globVoltFan and globVoltHeater from volt to INT and save them in globIntFan and globIntHeater. Make sure the values do not exceed the INT value range! Use the constant SCALE_VOLT_INT for the conversions.*
- *use the provided visulization to control the heater voltage and create a step signal like described above. Use the TwinCAT scope to measure the step response and export the acquired data.*

□

**Exercise 5:** *In Matlab display the acquired data $u_h(t)$ and $\vartheta_2(t)$ in the same plot and determine $T_t$, $K_f$ and $\tau_f$ graphically. Simulate the previously carried out experiment with the determined parameters in Matlab. Draw in the same plot the acquired data and the simulation results. Verify if the experiment and simulation match well.*

*Useful Matlab functions:*

- *Use help <NAME_OF_FUNCTION> to get the description of a function.*
- *Use tf(...) to create transfer functions.*
- *Use lsim(...) to simulate the output of a transfer function to a given input signal.*

□

# 6 P Controller

In this section a P controller will be designed and experimentally tested. The controller design is normally done in three steps:

1. Create the specification (stability, stationary accuracy, rise time, oscillations)
2. Define the controller structure.
3. Calculate the parameters of the controller.

In this experiment we focus on points 2. and 3.

## 6.1 Controller structure

**Exercise 6:** *For a P controller derive first the closed loop transfer function.*

☐

**Exercise 7:** *Derive the reference tracking closed loop transfer function $T_r(s)$ of the controlled process.*

☐

**Exercise 8:** *Express the steady state error as a function of the controller gain $K_p$. Compute $K_p$ for the following cases:*

1. *Case 1: A steady state error of 40 % is required.*
2. *Case 2: A steady state error of 5 % is required.*

☐

**Exercise 9:** *In Matlab simulate the process output for a steady state error of 5 % and 40 % with the above computed $K_p$, when excited with a step:*

- *of the closed loop transfer function of the controlled process*
- *of the reference tracking closed loop transfer function of the process*

*Does the simulation behave as you expect? Are there any problems with the control signal $u_h(t)$?*

☐

## 6.2 Controller parameters

**Exercise 10:** *Program and test the developed controller (with* $K_p$ *for a steady state error of 40 %) experimentally and document the results (command signal, reference signal and process output). Test the controller with a reference value step to* $40\,^\circ\mathrm{C}$*. What will the steady state value of temperature* $\vartheta_2(t)$ *be? Test different positions of the throttle valve (between open and half open). Is the controller stable? Compare the simulation results with the experimental results. Document these results.*

$\square$

# 7 PI Controller

In this section a PI controller will be first analyzed and experimentally tested.

## 7.1 Controller analysis

**Exercise 11:** *What is the transfer function of the PI Controller?*

☐

**Exercise 12:** *Derive the closed loop transfer function for a PI Controller. How does this transfer function simplify if $T_i$ is chosen such that $T_i = \tau$?*

☐

**Exercise 13:** *Derive the reference tracking closed loop transfer function $T_r(s)$ of the controlled process for $Ti \neq \tau$. How does this transfer function simplify if $Ti = \tau$ and $T_t = 0$?*

☐

**Exercise 14:** *Prove that the steady state error is equal to zero for any value of $K_p$ and $T_i$.*

☐

## 7.2 PI controller parameters computation and experimental testing

**Exercise 15:** *Design a PI controller using the Kuhn approch.*

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**Exercise 16:** *Test this controller in simulation using Matlab/Simulink. Realistic boundaries on the control signal should be taken into account in this simulation. A realistic reference signal should be programmed as well (for example a step of a few $^\circ C$). Test the controller with and without the anti-reset windup activated in the PID block (set $K_D = 0$). Explain why it is important to have this option activated if an integral is present in the controller.*

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**Exercise 17:** *Test this controller experimentally using the PID function block provided by the teaching person.*

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