Thermal Regulator

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Contents

1 Introduction

The goal of this experiment is for the student to gain an understanding of the basic principles of regulator circuits by building a feedback control to regulate the temperature of a cooling element.

1.1 Open- vs closed-loop control

Loop controls are designed to put the system they are applied to into a specific state. The main difference between an open- and a closed-loop control system is the absence or presence of a feedback loop. In the absence of a feedback loop, the controller applies a single control effort to set the system to the desired state, then assumes that said state has been reached. In the presence of a feedback loop, as illustrated in Fig. 1 information about the state of the system is transmitted to the controller. The controller generates an error signal which then commands the magnitude and duration of the actuator's corrective efforts. This continues until the system reaches the desired state. Note that this setup also allows the controller to react to disturbances in the controlled systems.

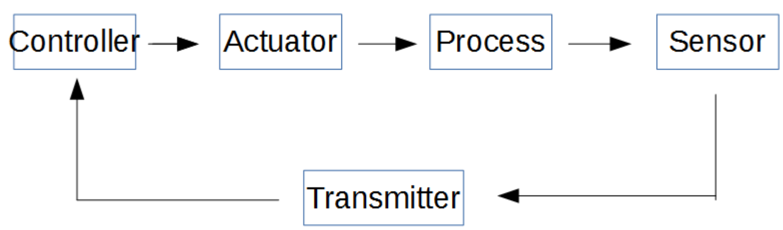

Figure 1: Illustration of a basic closed-loop control system.

1.2 Thermal regulator

The closed-loop controller used in this experiment is depicted in Fig. 2 The corresponding circuit schematic can be found in the appendix.

The control loop works as follows: an H bridge containing a PT100 resistance thermometer measures the temperature of the heat sink in the form of a potential difference. This potential difference corresponds to the *actual value* of the control loop, which is then compared with the *desired value* or *set point* of the loop. This comparison yields the error signal, which is fed into a PI controller, which in turn determines the instantaneous control effort of the loop. This control effort acts on the control element, which in this case consists of a transistor switch. The switch regulates how much power is dissipated by the heating resistor, which determines the temperature of the heat sink.

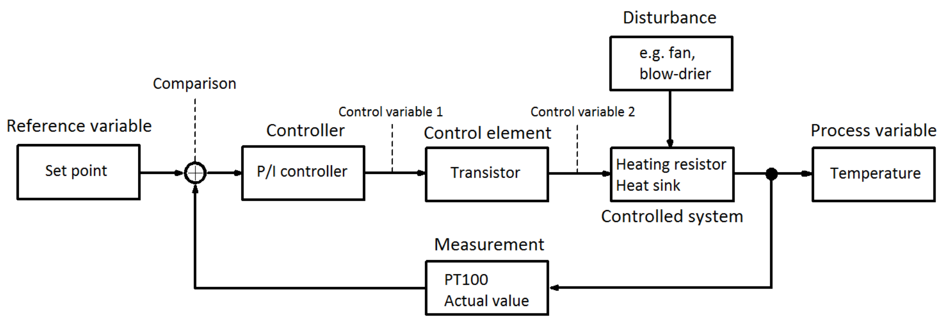

Figure 2: Illustration of the closed-loop control system used in this experiment.

1.3 Transistor

Transistors are nonlinear, active circuit elements which allow a power amplification of weak signals. There are many different types of transistors but their main characteristic is that they permit a small current (or voltage) at a low power to regulate and modulate a much larger current. For an 'npn' transistor, as used in this experiment, this small current flows from base to emitter, and the large current flows from collector to emitter. In this experiment, a transistor is used to switch on and off the supply current to the heating resistor to control the temperature of the heating unit.

1.4 Operational amplifier

Operational amplifiers are electronic voltage amplifiers with very high gains (10^5 - 10^6). The exact gain of any given op-amp is usually unknown, which is why op-amps are rarely used without additional circuitry (by themselves, op-amps are basically primitive comparators). However, when connected to an external feedback circuit, many useful applications are possible, including the differential amplifier, inverting amplifier, integrator, and Schmitt trigger, which are all used in this experiment.

An op-amp has five main connections: two input and one output connection, as well as two connections for the power supply. The op-amp amplifies the voltage difference between the inverting and the non-inverting input. The output carries the amplified difference, which can be fed back into its inverting or the non-inverting input, resulting in negative or positive feedback respectively. The device operates in the voltage range set by the power supply.

Two golden rules of an op-amp: In order to better understand how an idealized op-amp behaves in circuits with external feedback, two rules are commonly applied:

1. The output voltage does whatever it can to keep the inputs at the same voltage level.
2. The input impedance is infinite. Thus, the op-amp draws no current from its input.

Knowing this, one can for example create a *virtual ground* by connecting one of the two inputs to ground level; the other input can then be treated as if it were connected to ground as well.

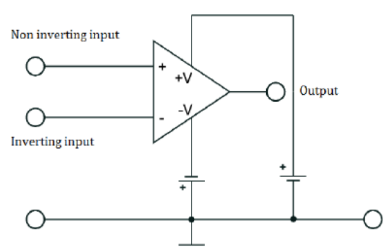

Figure 3: Connections of an operational amplifier.

Differential Amplifier The differential amplifier Fig. 4mplifies the difference between two input voltages, applied to the inverting and non-inverting input. The output voltage is given by

$$V_{out} = -V_1(\frac{R_3}{R_1}) + V_2(\frac{R_4}{R_2 + R_4})(\frac{R_1 + R_3}{R_1}) \,. \tag{1}$$

In the case of $R_1 = R_2, R_3 = R_4$, Eq. (1 simplifies to

$$V_{out} = \frac{R_3}{R_1}(V_2 - V_1)$$

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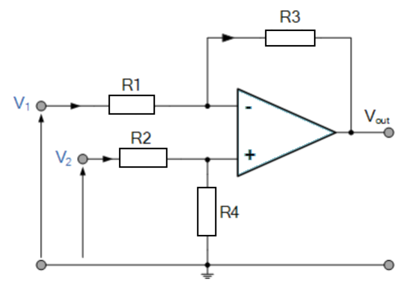


Figure 4: Schematic of the differential amplifier.

Inverting amplifier The inverting amplifier (Fig. 5 is a differential amplifier with the non-inverting input connected to ground.

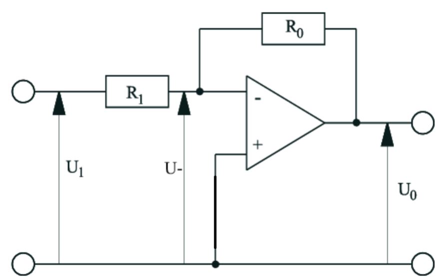


Figure 5: Schematic of the assembled inverting amplifier.

The gain of the inverting operational amplifier is given by

$$G = -R_0/R_1\,. \tag{2}$$

Integrator The integrator (Fig. 6 is assembled by replacing the resistance in the feedback loop of the inverting amplifier (R_0 in Fig. 5 with a capacitor.

The output voltage of the integrator is given by

$$U_0(t) = -\frac{1}{RC}\int_0^t U_{in}(\tau)d\tau + U_0(t=0)\,. \tag{3}$$

Comparator The comparator compares an input voltage to a given reference voltage and produces an output signal based on this comparison. The comparator has two output states. If the input voltage is larger than the reference, the output will be at the positive supply voltage. If the input

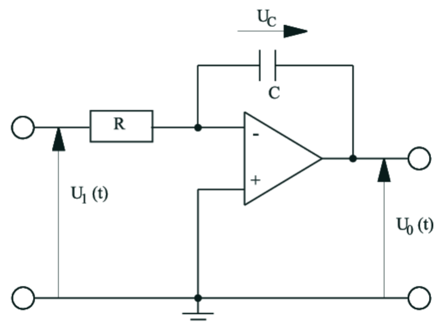


Figure 6: Schematic of the assembled integrator.

voltage happens to be smaller than the reference, the output will be at the negative supply voltage. An op-amp, with the input connected to the non-inverting port and reference connected to the inverting port, functions as a basic comparator (Fig. 7.

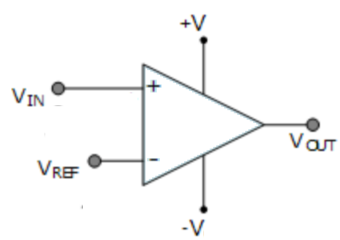


Figure 7: Schematic of the comparator.

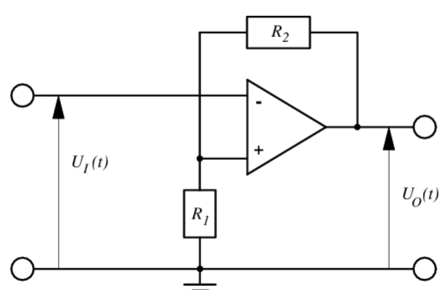


Figure 8: Schematic of the Schmitt Trigger.

Schmitt trigger The Schmitt Trigger (Fig. 8 is a special case of a comparator, with the reference dependent on the output voltage. It is an operational amplifier circuit which converts an analog input signal to a digital output signal. The circuit has an upper and a lower threshold,

$$U_{\pm} = \pm U_m \frac{R_1}{R_1 + R_2}.$$

If the amplitude of the input signal is in between these thresholds the output signal is constant at the upper or lower voltage limit of the operational amplifier $\pm U_m$. When the amplitude of the input signal crosses the thresholds, the sign of the output signal changes.

1.5 Proportional controller

The proportional controller is a control system whose control effort at time t is proportional to the current error value $e(t)$, i.e. the difference between the desired set point and the actual value of the process variable. When the error is large, the control effort is also large, and vice versa for small errors. However, this also means that the P controller will never be able to bring the error value to exactly zero. This leftover *steady-state error* can be reduced by increasing the gain K_P of the P controller, but only up to a certain point. If the gain is increased too much, the system becomes unstable. A P controller can be physically realized as an inverting amplifier, as shown in section 1.4nd Fig. 9

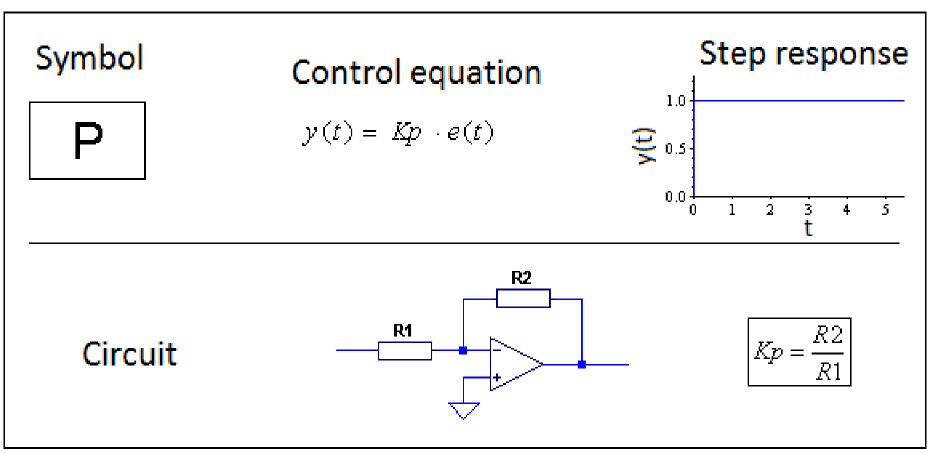


Figure 9: Overview of the P controller.

1.6 Integral controller

The control effort of the integral controller is proportional to the time integral of the error value $e(t)$. This means that the I controller is slower to react than the P controller, since the initial control effort is zero. However, since even small errors get accumulated over time, a substantial control effort emerges eventually. Thus, unlike the P controller, the I controller is able to push the actual value exactly to the set point. An I controller can be physically realized as an integrator, as shown in section 1.4nd Fig. 10

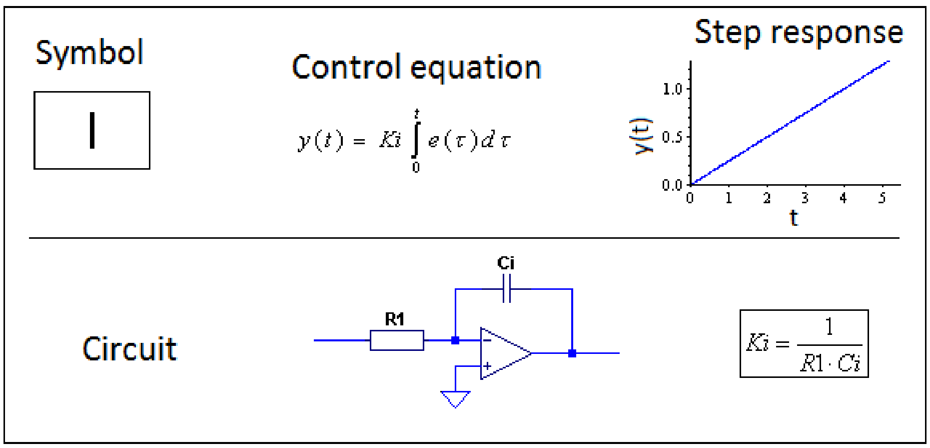


Figure 10: Overview of the I controller.

1.7 PI controller

In order to get rid of the steady-state error of the P controller, one can connect an I controller in parallel, resulting in a PI controller. The P controller is responsible for quickly pushing the actual value relatively close to the set point, and the I controller takes care of the steady-state error left by the P controller. It is possible to build the PI controller using only one op-amp (see Fig. 11, however, for the purposes of this experiment, it is better to use two separate op-amps.

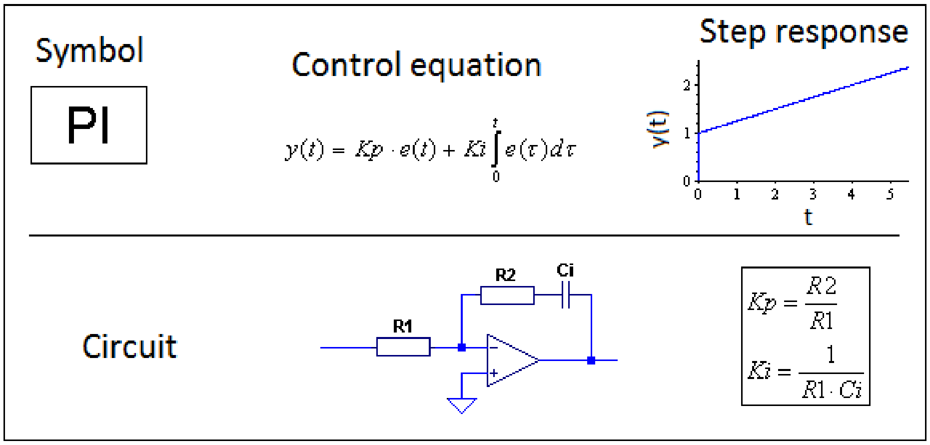


Figure 11: Overview of the PI controller.

2 Theory of operation

This section introduces step by step the principal components of the main control circuit as described in section 3 First, a simple heating unit is built without an automatic feedback loop. Then, two different types of switches are introduced, which act as control elements with minimal power loss. The second switch can regulate the temperature much more accurately due to the use of pulse-width modulation (PWM). Finally, the last subsection describes how an H bridge can be used by the control circuit to automatically measure the temperature of the heat sink.

Note: Electronic circuits can get quite complicated, so it is a good idea to adopt a tidy and structured approach. Assemble each circuit step by step and check regularly for possible errors. Use a consistent colour scheme for your wires and avoid long wiring paths. If something doesn't work and you have already checked the circuit and the settings, check for faulty components. Start with integrated circuits and then move on to passive elements. Finally, if there is too much noise in your circuit, you may be able to reduce it by connecting a small capacitance (100 nF) in parallel to the power supplies of your op-amps.

2.1 Simple heating unit

A simple heating unit can be built by attaching a heat sink to a heating resistor and running a current through it. The current through the resistor can be varied via a potentiometer. If a current I flows through a resistor with resistance R and potential U, the associated power dissipation is given by

$$P = UI = RI^2 \,. \tag{4}$$

Before getting started with the main experiment, it is a good idea to familiarise yourself with the simple heating unit. What is the maximum admissible power that can be dissipated by the potentiometer? Such information is often easily found on Distrelec, and for small potentiometers this is in the order of 1W. How does the temperature of the heating unit, when it thermalises with the surrounding environment, change as a function of the power? How long does it take to reach the saturation temperature?

The *thermal resistance* of an object measures the change in temperature (ΔT) for a given rate of heat flow ($\dot{Q}$):

$$R_{th} = \frac{\Delta T}{\dot{Q}} \,. \tag{5}$$

Task: Measure the thermal resistance of the heat sink by varying the dissipated power through the resistor and measuring the saturation temperature. You can check the data sheet for consistency. What relation between power and temperature would you expect? Is that what you see?

2.2 Heating without power loss

A big drawback of the simple heating unit is the fact that the control element itself (the potentiometer) also heats up significantly, thus wasting power. This can be avoided by using a switch as a control element. When the switch is on, its resistance is ideally zero and current can flow through the control element without dissipating power. Conversely, when the switch is off, no current flows and thus the dissipated power is zero. In order to obtain a specific rate of power dissipation through the heating resistor, the switch can be periodically turned on and off at a high frequency. The switch can be realised with a bimetallic strip or with a transistor controlled via pulse-width modulation (PWM).

2.2.1 Bimetallic switch

A primitive switch for the simple heating unit can be obtained by attaching a bimetallic strip (Fig. 12 to the heat sink and connecting it to the circuit as a circuit breaker. When the bimetal reaches a certain characteristic temperature, it expands rapidly and breaks the circuit. When the heat sink has cooled down low enough, the bimetal pops back into its previous state and closes the circuit. In both cases, an audible click sound is generated.

Task: Measure the temperature as a function of time and observe how the bimetallic strip regulates the temperature of the heat sink.

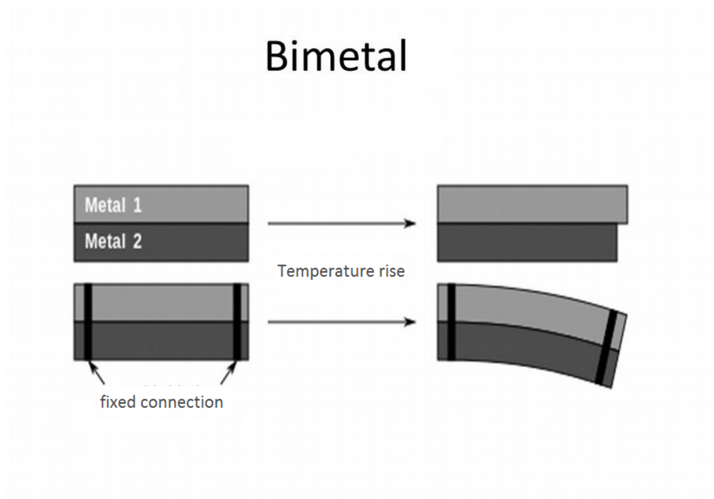


Figure 12: A bimetallic strip consists of two rigidly connected metals with different thermal expansion coefficients.

2.2.2 Darlington-transistor

A much more accurate switch can be obtained by using a transistor, which can be controlled with a pulse-width modulator (PWM). The PWM creates a periodic step function jumping between full voltage (on) and zero voltage (off). The ratio of "on" time to the full period is called the *duty cycle* of the PWM signal, expressed in percent.

For this experiment, a Darlington-transistor is used, which consists of two bipolar transistors connected in such a way that the current amplification is given approximately by the product of the amplification of the two individual transistors. Current is only allowed to flow through the transistor if the base-emitter voltage (controlled with the PWM) exceeds approximately 1.3 V.

Task As a first step, get a feeling for how the temperature changes as a function of the duty cycle by generating the PWM with a signal generator. To do this, connect the transistor to the heating circuit as indicated in the schematic in the appendix. *Always* include a protection diode (see the appendix) to prevent current flowing from emitter to base, and a resistor that limits the base-emitter current. Given the PWM voltages, the maximum current through the heating resistor and the gain of the transistor, what is the maximum value of this resistance? Why maximum? Record the PWM voltage and collector-emitter voltage. Comment on their shape.

The next section describes how op-amps can be used to build a self-made PWM.

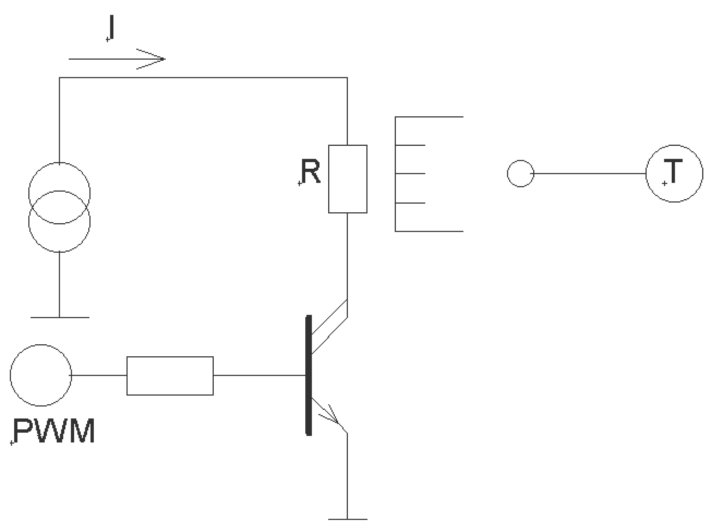


Figure 13: Heating resistor R connected to a Darlington-transistor controlled with PWM.

2.3 Self-made PWM

A PWM signal can be obtained by comparing a constant signal with a triangle wave (Fig. 14. An op-amp can be used as a basic comparator. Depending on which of the two input signals is greater, the op-amp will jump to either its maximum or minimum output voltage. The constant signal (and hence the duty cycle) can be adjusted via a potentiometer.

One way to generate the triangle wave is shown in Fig. 15 It consists of

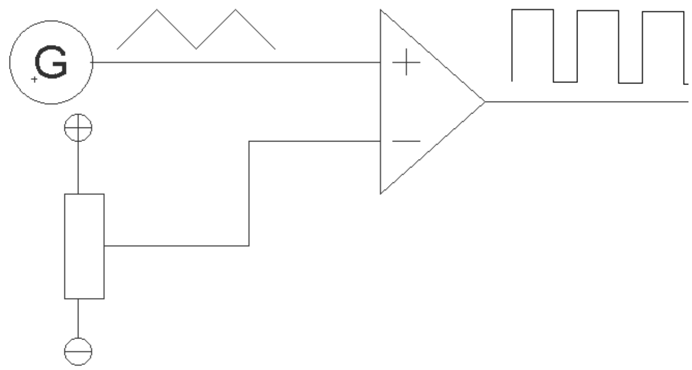


Figure 14: PWM generated by feeding a triangle wave and a constant signal into a comparator.

a Schmitt trigger and an integrator connected in series. The Schmitt trigger delivers a constant initial voltage that is integrated by the integrator and fed back into the Schmitt trigger. When the threshold voltage of the Schmitt trigger is reached, the voltage U_{R25} changes its sign, repeating the process in the other direction.

Task: Assemble the triangle wave generator and the PWM generator. Measure the saturation temperature as a function of the duty cycle.

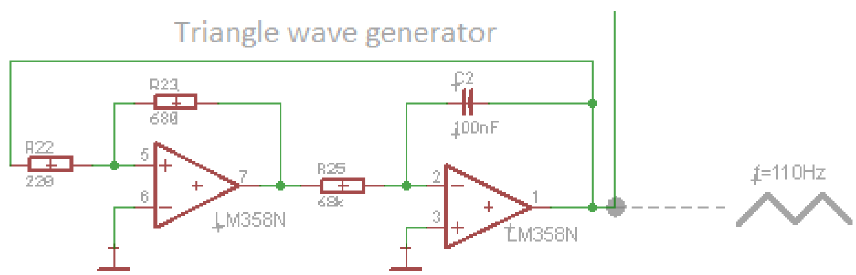


Figure 15

2.4 Temperature measurement and H bridge

The control system needs to be able to measure the temperature of the heat sink and use that information to adjust the PWM signal. This temperature measurement is done using an H bridge and a resistance thermometer.

Integrated on the heat sink is a PT100 resistance thermometer. The H bridge depicted in Fig. 16orks as follows: first, one needs to know how the resistance of the thermometer changes as a function of the temperature. Then, one can measure the potential difference ΔU between the thermometer and a known reference resistor. This ΔU then corresponds to a specific resistance of the thermometer, which in turns corresponds to a specific temperature of the heat sink. For the final control circuit, ΔU will be amplified and serve as the actual value of the control circuit.

Task: Measure the temperature-resistance characteristic of the PT100 thermometer and compare to a calibration curve from literature. Also compare to such curves for a Negative Temperature Coefficient (NTC, see e.g. this one) and a Positive Temperature Coefficient (PTC, see e.g. this one) thermometer, and argue why the PT100 is the best choice for this experiment.

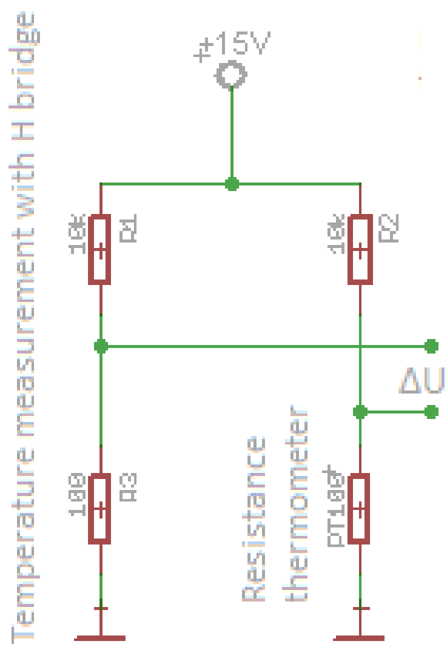


Figure 16: H Bridge with PT100 resistance thermometer and a 100 Ω reference resistor.

3 Control circuit

Now that the most important components of the experiment have been introduced, it is time to assemble the actual control circuit of the thermal regulator in its entirety. The functional principle of the thermal regulator is described in section 1.2 The schematic in the appendix depicts the corresponding circuit diagram in detail.

3.1 Measuring the process variable

A key element of any control system is the comparison between the actual value of the process variable and the desired set point. The actual value of this circuit is provided in the form of a potential difference as measured by the H bridge. However, as this difference is too small for the purposes of this circuit, it has to be amplified first.

Task: Attach a differential amplifier to the H bridge and measure the actual value as a function of the temperature. This knowledge will be used in the next section to define the set point of the control system. Also, in the next sections, use this knowledge to measure temperature by measuring the actual value, whenever possible.

Note: The electromagnetic fields that surround unshielded wires with currents can cause interference between wires that are close to each other. This is particularly true if the currents are large and they are modulated rapidly. Unfortunately, your heating resistor and your PT100 are close together. On the one hand, the resistor wires carry large and rapidly switching currents, and on the other hand the PT100 wires cary a voltage whose difference to another voltage is amplified very strongly to produce your error signal. Thus, also the noise is amplified very strongly. This can lead to a lot of noise on your error signals due to electrical pickup in the PT100 wires. To avoid this, twist the wire pair going to and from the resistor, and also the wire pair going to and from the PT100. Keep these wire pairs as far apart as you can. This reduces the pickup.

3.2 Defining the set point

In order to build a thermal regulator, one needs to define the temperature that the heat sink is supposed to be regulated to. Add the components for the setting of the desired value to the build as indicated in the circuit overview in the appendix. Think about how the set point is set using this set-up and what the purpose of the differential amplifier is.

Task: Verify that the output value of the differential amplifier in this module is zero in the case that the actual value equals the set point.

3.3 Level shifter

Add the level shifter to the circuit as indicated in the circuit overview.

Task: What is the purpose of the level shifter?
What is the purpose of the comparator?

3.4 PWM generator

Add the PWM generator built in section 2.3 to the circuit, as indicated in the appendix. Note that now the triangle signal is sent to the inverting input of the comparator, whereas in 2.3 it was sent to the non-inverting input.

Task: Test the PWM generator by applying a constant signal at the non inverting input of the comparator. How does the output behave if the constant input signal is changed?

3.5 Connect the proportional controller

Build and connect the proportional controller as indicated in circuit overview. Also include the inverting addition circuit after the P-controller, where you may set the leg that is normally connected to the output of the I-controller to ground. If you find that your 'Control variable 0' is not constant in time but looks noisy or shows signs of the PWM signal, you may try to reduce noise first by adding small (around 100 nF) capacitors between all the OpAmp supply voltages, right next to the OpAmps. If that doesn't help, reduce the gain of your P-controller.

Task: Use the potentiometer to set the level shifter so that the "Control variable 1" equals the minimum of the triangular signal in the case actual temperature=desired temperature.
Why is this step necessary?

3.6 Connect the cooling element

Task: Plot the saturation temperature of the cooling element as a function of the gain of the P-regulator. Compare to the set temperature. Up until which gain is the P controller stable? What is the cause of the instabilities, and what happens if it is unstable?

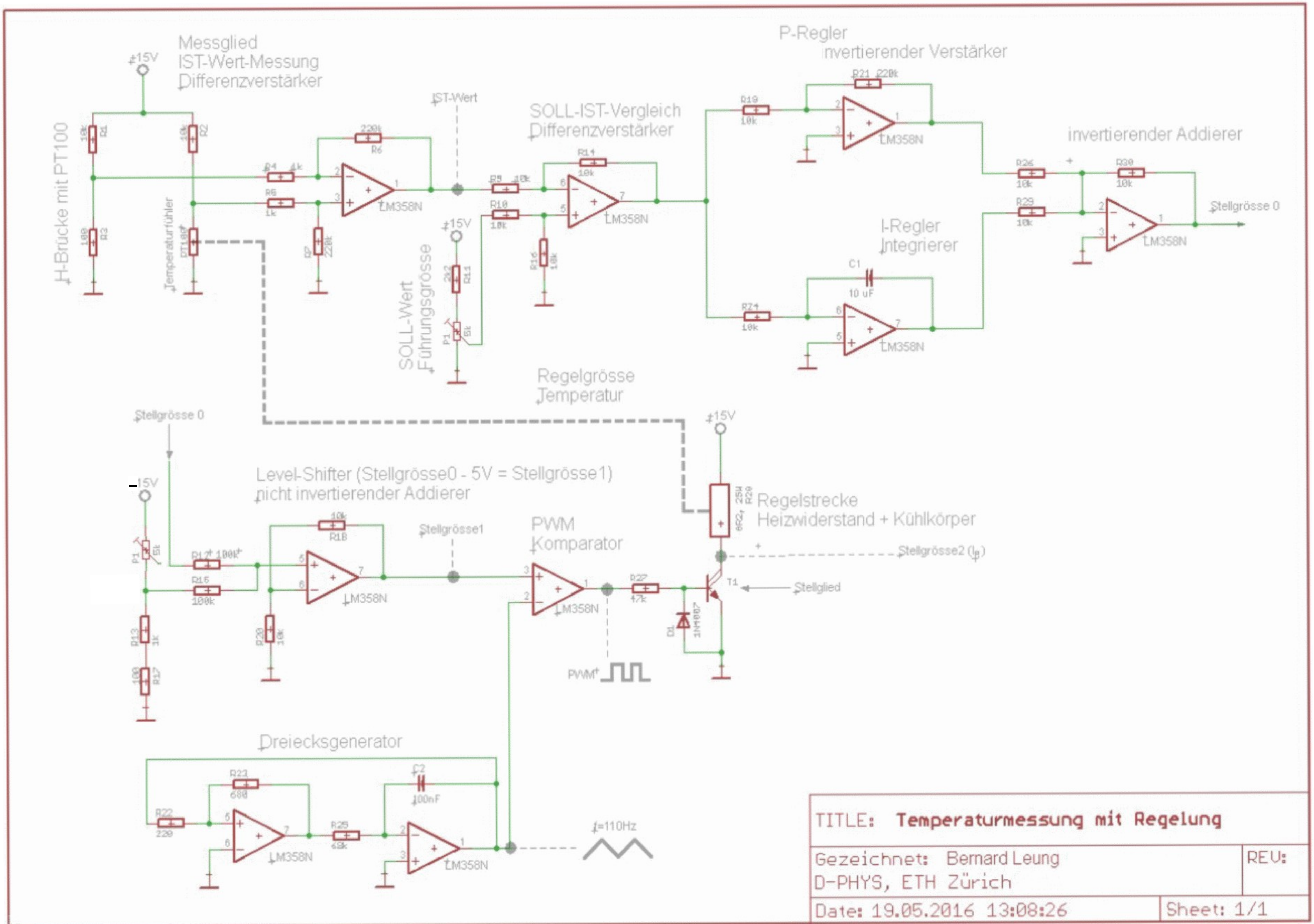
3.7 Connect the integral controller

Task: Connect the I controller into the build. Compare the circuits with just proportional and with also the integral controller. What are the respective disadvantages and benefits? Try out different values of the capacitor in the integral controller and describe the effect.

3.8 Behaviour of the control circuit

Pick a value for the P-gain and the I-gain for which you have a stable controller. Let your circuit stabilize at the set temperature and then apply an external disturbance to the system and describe the observed behaviour. You can use a fan to cool down the heat sink or isolate it by wrapping a piece of cloth around it. Record both duty cycle and temparature. Note that the system might respond very fast, so you could use a slow-motion video to record the temperature and duty cycle on the oscilloscope while you apply the disturbance. Also, it is better to not drive the controller into saturation (to its maximum or minimum heating current), because then it cannot regulate effectively and data is difficult to interpret. So do not put the fan to close, for example.

4 Appendix



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5 Literature

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