Department of Control Engineering
Faculty of Electrical Engineering
Czech Technical University in Prague

Controller Design For Heating System Of A Building

Graduate Diploma Thesis

Lukáš Ferkl

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V Praze dne ……………………….   ……………………………………….
                                                                              podpis

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Abstract:

This work brings a solution for a heating control in the church of St. Theresa from Lisieux in Prague 8 - Kobylisy. A 3 year operational data history is available. I performed an analysis of these data, gathered the available technical information about the existing system, made a system model and based upon the acquired knowledge, I have designed a cascade control, with a PD controller in the inner loop regulating the heating water temperature, and an equithermal control regulating the inside temperature in the church. I implemented the system on a PC as a C program, and tested in operation. There were no serious problems during the testing period and the system is fully operational.

In the scope of this work I have made an ARX modeling, robust control design using an H^∞ method, a control strategy based upon the outside temperature forecast and a 3-position incremental PID inner loop controller design for further upgrade of the system.

Anotace:

Tato práce přináší řešení regulace topení v kostele sv. Terezie z Lisieux v Praze – Kobylisích. K dispozici jsou 3 roky dosavadních provozních záznamů. Provedl jsem analýzu těchto dat, shromáždil dostupné technické informace o stávajícím systému, udělal jsem model systému a na základě získaných poznatků navrhl kaskádní řízení s PD regulátorem ve vnitřní smyčce, která řídí teplotu topné vody, a ekvitermním regulátorem ve vnější smyčce, která řídí teplotu uvnitř kostela. Systém jsem implementoval na PC jako program v jazyce C a vyzkoušen v provozu. Během zkoušek nedošlo k žádným vážným problémům a systém je zcela provozuschopný.

V této práci jsem provedl také ARX modelování, návrh robustního řízení metodou H^∞, návrh řídící strategie na základě předpovědi venkovní teploty a návrh 3-polohového inkrementálního PID regulátoru vnitřní smyčky pro možnost dalšího rozšiřování systému.

Contents

1 Introduction

1.1 History

I have begun to work on the heating control in the church of St. Theresa from Lisieux in spring 2003. One of my friends, Tomáš Kubalík, is a high school teacher (he teaches communication technology and microprocessors), and a regular of the Salesians (Societas Don Bosco, SDB) in their monastery in Prague 8, Kobylisy. The original chapel of this monastery, built in 1930's, had been reconstructed and extended to form the today church of St. Theresa from Lisieux. Within the reconstruction works, a new heating system was built in summer 2000. However, no control of the heating was established. This control has been put on my friend.

During the next year, the students of Tomáš Kubalík have designed and implemented a control system and programmed a simple control of the heating.

However, this program wasn't enough. There were some difficulties during the winter and after a major accident in January 2003, when the temperature of nearly 70 °C was reached in the floor heating, Tomáš Kubalík turned his eyes to me and asked me to design a simple control of the heating water temperature. With Zdeněk Hurák, an advisor to this work, we have decided to design a complex control of the entire church.

First, we have designed a very approximate PD controller to control the temperature of the heating water, without knowing any detailed information about the system, only to avoid any further accidents.

Then I had to gather all the information available about the original system. Unfortunately, many of the construction documentation has been precisely archived and, hence, probably lost. So the very first step was to measure all the unknown parameters.

Then the second stage came. Tomáš Kubalík has been collecting all the operational data history resulting in about 150 MB of unorganized data. I made the data preprocessing, sorted the data and converted them to MATLAB. Then I carefully observed all the data, so as to get familiar with them and to be able to obtain some useful information. At the same time, I tried to find as much information about the heating systems control as possible. Zdeněk Hurák was a great help for me in that time.

After the data analysis, I continued in designing the control. This seemed to be rather easy at first and I have proposed a cascade control of the system, with a 3-position incremental PID controller in the inner loop controlling the heating water temperature, and an equithermal control of the inside temperature.

The most complicated stage has been the implementation. I had to modify and extend the original program. I decided to not write a brand new source code, which turned out to be almost fatal. The original program had an improper data structure, however, I have discovered this fact too late.

So I continued in modifying the original program. My idea was to write the program at home, come to the monastery, put it there and watch it working. That was rather silly, I spent one entire weekend in the monastery debugging my source code. (It was an exciting experience to spend two days among the monks.) The first control was rather a "reality simulation", my program had to observe the system and calculate the equithermal control, but it didn't regulate the heating water temperatures.

The system appeared to work properly, so I unlocked the heating water temperature control and set my system on. I was very nervous, as I didn't trust it. I made some safety precautions, Tomáš Kubalík was getting up every two hours for the first two nights and controlling the operation of my system (even though he trusted the system much more than I did), I made my system to send me a SMS every four hours to inform me about any problems that would occur. The result was surprising – my system really worked. I had to make only a fine tuning of the control just before Christmas, so my heating control system was in fact a Christmas gift for the church of St. Theresa from Lisieux.

However, the system and its implementation are not ideal, some further upgrades are desirable. I will discuss them at the end of this work.

1.2 Contribution of this work

The control of the heating systems is rather non-trivial, mainly because of low-frequency (seasonal) and high-frequency (diurnal) climate changes coupled with non-linear characteristics in heating plants, as well as a variety of disturbances, noises and uncertainties. On the other hand, failure in the heating systems due to improper control seldom leads to catastrophic results, so the heating control is often treated as an art of past. This has sometimes led to surprisingly good results, but frequently to a failure to satisfy all the essential tenets of good heating control – to achieve good comfort at minimum energy use, operating cost and initial cost [1].

To satisfy these demands as much a possible, I have made the following:

- **Data analysis**
  As the first step, I had to get familiar with the operational history data, analyze them and prepare for the controller design.
- **System modeling**
  I made a mathematical model of the heated church building.
- **ARX model**
  Based upon the mathematical model, I tried to find an ARX model of the real system.
- **Control concept**
  I had to design an overall scheme of the control system. I have decided to use a cascade control.
- **Controller design**
  I have designed a PD controller for the inner loop (to control the heating water temperature) and an equithermal control for the outer loop (to control the inside temperature in the church).
- **System implementation**
  I have written a C source code for the control system.
- **System testing**
  I have designed a series of tests to ensure a proper operation.
- **Future plans**
  As a preparation for the future upgrades to the system, I have proposed several control strategies – a feedforward compensation control, a robust control using H^{∞} method and a control strategy based upon the outside temperature forecast

1.3 Overview of this work

1.3.1 Contents of the respective parts

- **Part 1 – Introduction**
  This part. Gives an introduction to the problem and to the work done.
- **Part 2 – System Overview**
  Describes the original control system in the church of St. Theresa from Lisieux and sets the requirement on the new system.
- **Part 3 – Data Analysis**
  This part contains a detailed analysis of the operational data history for the purpose of the new control system design.
- **Part 4 – System Modeling and Control Design Concept**
  Theoretical part containing the modeling of the heated church building, and a reflection of existing control strategies in heating systems.
- **Part 5 – Implementation**
  The PID controller for the inner loop and an equithermal control for the outer loop is designed in this part. Flowcharts of the control program are located here along with their description as well.
- **Part 6 – Experimental Results**
  After setting the new control system on, the results have been analyzed. They are contained in this part.
- **Part 7 – Future**
  This part contains ARX modeling, feedforward compensation control overview, robust control design using H^∞ method, and a control strategy using the outside temperature forecast.
- **Part 8 – Summary**
  In this part, I have made a summary of this work and proposed some future upgrades to my control system.

1.3.2 Attached CD

On the CD attached to this work, following data are stored:

- The sorted operational data history
- The MATLAB source codes for data preprocessing
- The C code of the program implemented along with the configuration files
- Experimental results data

2   System Overview

2.1 System description – general

Figure 2.1 - The church of St. Theresa from Lisieux from N, NW, W and S

The church of St. Theresa from Lisieux is located in Prague 8, Kobylisy, on Kobyliské náměstí in the monastery of Societas Don Bosco (so called Salesians). The entire monastery was built in 1936-37, the church was rebuilt in 1997-2000. During this reconstruction, a new heating system has been installed. However, the system has been installed without its control.

Circuit	Rooms
Circuit No. 1	Office room, flowers preparation room and parish hall
Circuit No. 2	Room for mothers with children, confession room and one adjacent radiator in the church, library, music studio
Circuit No. 3	Sacristy, parish office room, WC, three radiators inside the church (in the chapel), office in the 1st floor
Floor Circuit	Front of the nave in the church

Table 2.1 - Heating circuits
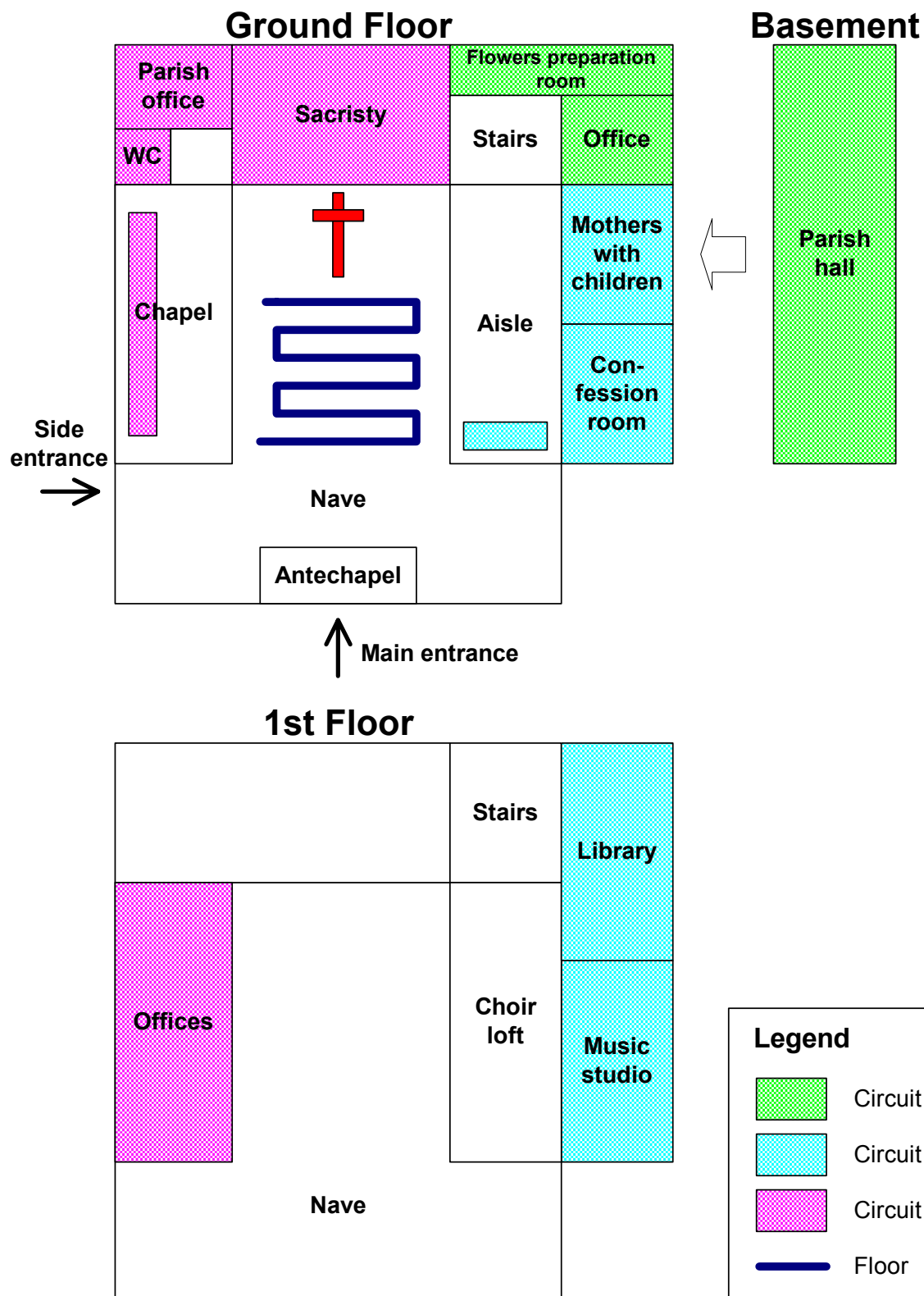
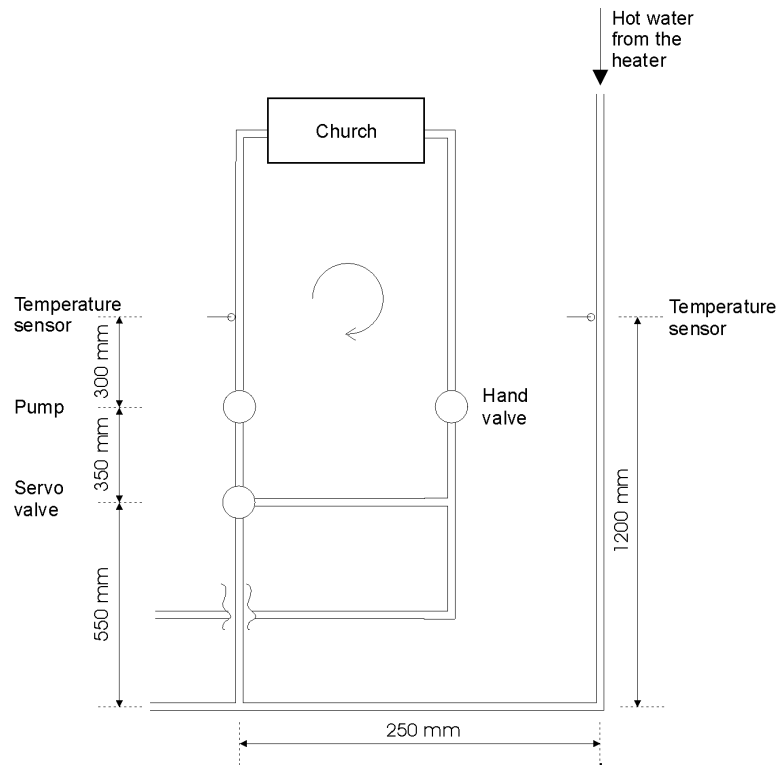**Figure 2.2** - The church of St. Theresa from Lisieux and the adjacent rooms
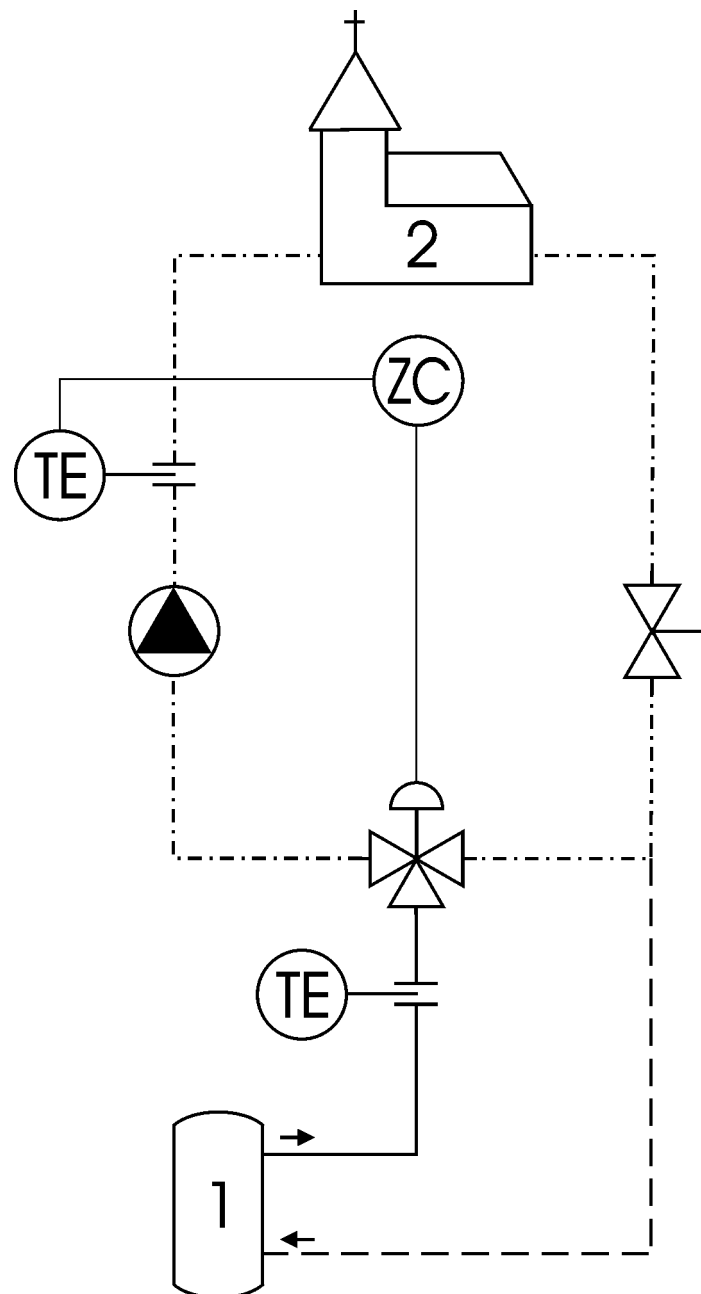
1   Heater
2   Church - the heated object

Hot inlet water   ———
Cold water   — — —
Heating water   — · — · —

Figure 2.3 - Heating circuit

Figure 2.4 - Heating circuit (approximate) dimensions

2.2 Actuators and sensors

The technical documentation of the actuators and sensors has been probably lost, the following data are taken from the technical data sheets found on the Internet sites of the respective manufacturers.

Temperature sensors

The temperature sensors are based on an intelligent Texas Instruments temperature sensor of an unknown type. The temperature is sent in a code and converted to Celsius degrees by the daemon ComIN (see 2.3 - Operating center and previous control).

The outside temperature sensor is located inside an arcade called "JABOK" in the monastery. It is placed away from direct sunlight, partially protected from the wind. The sensor faces south.

There are three inside temperature sensors. They are located inside the church, one in the nave in the height of 1,5 m on the central pillar, the other ones in the height of approx. 4 m on the choir loft on the right side and inside the wall on the left side.

Figure 2.5 – Inside temperature sensors location

Figure 2.6 – Inside temperature sensors location

The respective sensors location can be seen on Figure 2.5 and Figure 2.6. The temperature sensor located on the central pillar is hidden by the plaster, the other ones can be recognized as little black boxes.

Servo valves

The servo valves are of type Belimo AM 230. Their opening time is 100 seconds. They can be computer controlled. They have a possibility of a manual control as well. Their characteristics are stated in 3.2 - Valve Characteristics.

Pumps

The pumps are of type Grundfos UPS 25-60, Class H. Their maximum capacity is 10 m^3/h. They cannot be computer controlled, they can be switched on and off manually by a person responsible for the heating. The pumps of the first three heating circuits are usually switched on in the middle of October and switched off in the late April.

The floor circuit pump is being switched depending on the outside temperature. However, this is very confusing and rather unusual in the heating systems. In the future, it is suggested to switch all the four circuits together.

The Heater

The heater provides hot water to the heating system. There is a common heater for the entire monastery. It is a gas heater and it was built in 1970's. No further details about the heater are available as all the technical documentation is probably lost.

2.3 Operating center and previous control

The entire system is controlled from a PC with Red Hat Linux 7.3. The control program is written in ANSI C.

The control software has been developed by the Salesians and Střední průmyslová škola elektrotechnická (High School of Electrical Engineering), Panská, Praha 1, since spring 2001. Three different systems of data storing have been used. The last program controlling the heating was written by Jan Gilányi during the spring 2003 as a part of his high school graduation project.

The original program included following features:

- Communication with the actuators and sensors
  The communication is done by two daemons running under Linux – ComIN (enabling data acquisition from the sensors) and ComOUT (enabling sending messages to the actuators and sensors).
- Configuration of the actuators and sensors
  The original program included addresses and settings of the actuators and sensors.
- Valves control
  The valves have been controlled not by the temperature of the circulating water, but by the mere open ratio (e.g. "Open the valve 1 to 2/10"). There was a weekly timetable of how the valves should be open.

2.4 Requirements

The heating in a church has some specific requirements that have to be met. The space that has to be heated is very large, but it is used for the time of the service only. The timetable of the services in the church of St. Theresa from Lisieux is stated in Table 2.2.

Day	Hour	Attendance (approx.)
Mon – Sat	6:30	20
	18:30	50
Mon & Wed	17:00 (for children)	100
Sun & Fetes	7:30	100
	9:00	300
	10:30	200
	18:30	300

Table 2.2 - Timetable of services in the church of St. Theresa from Lisieux

The desired temperature in the church is required during the service only. However, the heating circuits for the church itself and for the adjacent rooms are not separated and, hence, the temperature in the church cannot be controlled separately. The specific requirements are as follows:

- Inside temperature 15°C
- Day and night mode with different heating characteristics
- File based control of the software
- Optional switching of the modes

3   Data Analysis

3.1 Data description

The data history from the church of St. Theresa from Lisieux comprises three systems. Before data analysis, I had to sort the data and export them to a "Matlab friendly" form. I achieved this by parsers written in ANSI C.

There are three different data file types:

- Inside temperatures, measured every 10 s – 5 min
- Heating water temperatures, measured every 5 – 30 s
- Outside temperatures, measured every 5 – 30 min

System No.	From	To
System 00	Dec 2001	Jan 2002
System 01	Jan 2002	Feb 2003
System 02	Mar 2003	Oct 2003

Table 3.1 - Different data sets

```
25.12.01   21:58:01     60.5    52.0    55.0    51.0    19.0
25.12.01   21:58:10     61.0    31.5    39.0    46.5    18.5
25.12.01   21:58:20     61.0    31.5    39.0    46.5    18.5
25.12.01   21:58:30     61.0    31.5    39.0    46.5    18.5
25.12.01   21:58:40     60.5    31.5    39.0    46.5    18.5
```

Figure 3.1 - System 00 data example; DATE TIME HEATER CIRC.1 CIRC.2 CIRC.3 FLOOR

```
01.03.02   00:00     17.85    2.60    15.50    14.95    14.50
01.03.02   00:10     18.00    2.55    15.50    14.55    14.50
01.03.02   00:20     17.70    2.50    15.50    14.50    14.50
01.03.02   00:30     17.95    2.50    15.50    14.50    14.50
01.03.02   00:40     17.55    2.50    15.50    14.50    14.50
```

Figure 3.2 - System 01 data example; DATE TIME FLOOR OUTSIDE INSIDE1 INSIDE2 INSIDE3

```
27.03.2003 22:48:53 – CT   KOSTEL1   18.5   KOSTEL2   19.0
KOSTEL3   19.0
27.03.2003 22:49:52 – CT   KOSTEL1   18.5   KOSTEL2   19.0
KOSTEL3   19.0
28.03.2003 00:14:48 – PA   KOSTEL1   18.5   KOSTEL2   19.0
KOSTEL3   19.0
```

Figure 3.3 - System 02 data example; DATE TIME – DAY INSIDE1 INSIDE2 INSIDE3

3.2 Valve characteristics

For better knowing the system, it would be useful to know the opening characteristics of the valves.

For control applications, control valves are used to regulate heat transfer thorough flow rather than to regulate flow itself. For both design and commissioning is to ensure that the valve achieves a linear response such that a proportional relationship exists between valve position and heat transfer at the plant [1].

With hot water heating a logarithmic relationship between heat emission and flow rate exists in heat transfer equipment. According to [1], hot water radiators are expected to follow the exponential characteristics

$$q \propto \left[\frac{(\theta_{wi} + \theta_{wo})}{2} - \theta_r \right]^{1.3} \tag{3.1}$$

   q .... heat emission
   θ_{wi} ..... inlet water temperature
   θ_{wo} ..... outlet water temperature
   θ_r .... room temperature.

The control valve needs to compensate for this non-linearity in its relationship between position and flow rate if linear control is to be achieved.

To be able to introduce a controller regulating the output temperature of a three-port valve, it is necessary to verify whether the valve characteristics are logarithmical or not.

However, this is not possible, as we have no sensor to measure the flow rate. But we can measure the temperature, which is proportional to the heat provided to the system:

$$\Delta\theta = \frac{q}{m.c} \tag{3.2}$$

So I performed the following experiment. For all three radiator circuits, I was gradually opening and closing the three-port valves. The output temperatures were measured every 10 seconds. The example of the resulted characteristics is illustrated on Figure 3.4.

In the same time, it was possible to measure the circulation time of the respective circuits. The water tubes have a diameter of 1" (25.4 mm), the overall length of the duct of each circuit is approx. 100 m, the volume of all the radiators of one circuit is approx. 500 l, the pump capacity was set to 7 m³/h. That gives an estimation of the circulation time about 6 minutes.

To verify the above estimation, I sent a pulse to the circuits and measured the approximate time constants of all three radiator circuits. These constants are stated in Table 3.2.

Circuit No.	Circulation time (approx.)
Circuit 1	8 minutes
Circuit 2	4 minutes
Circuit 3	4 minutes

Table 3.2 - Circulation times of the heating water.

For the floor circuit, I had opened the three-port valve to 40% for 3 minutes while monitoring the heating water temperature, but no temperature change occurred.
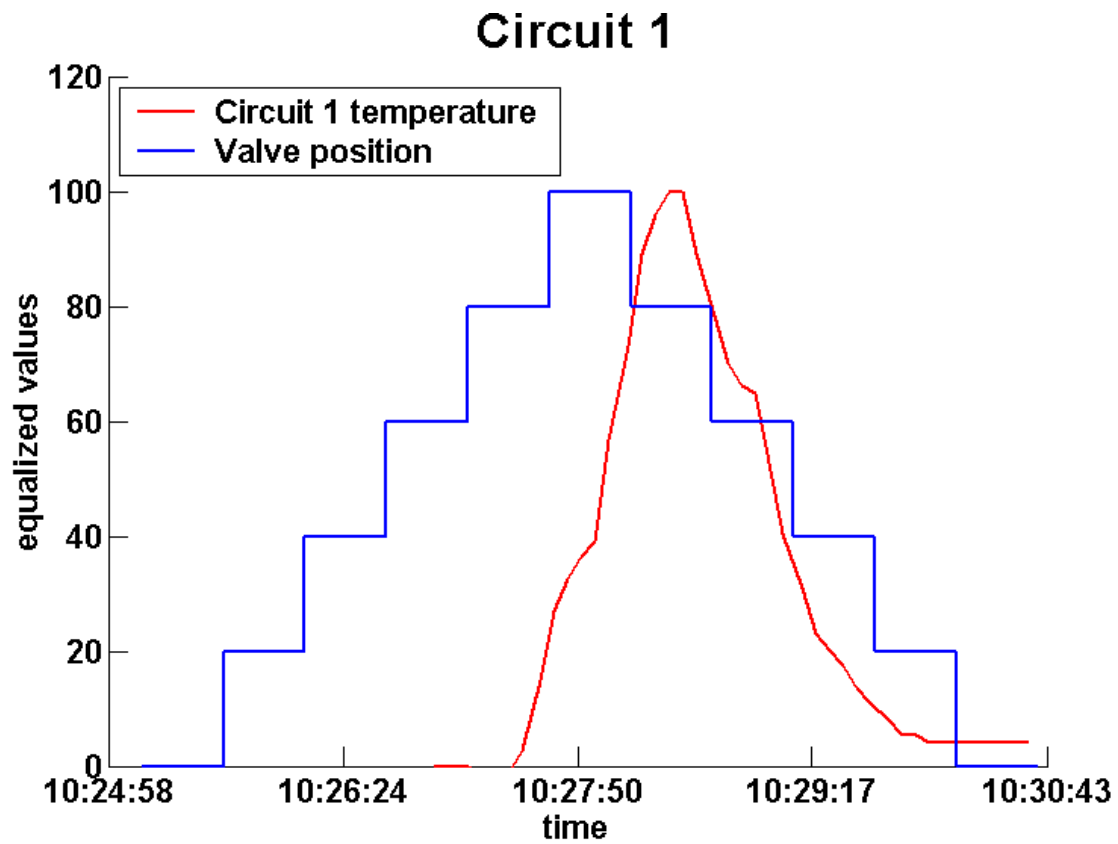

Figure 3.4 - Valve characteristics for Circuit 1 measured July 7, 2003

3.3 Church building characteristics

3.3.1 Time constants

The church of St. Theresa from Lisieux has several time constants that play role in the control being designed. The constants are stated in Table 3.3.

| Time Constant	Value (approx.)
Floor to Inside temperature	10-30 hours
Radiators to Inside temperature	1-2 hours
Heating water circulation time	4-8 minutes
Heating water temperature sensors	40 seconds

Table 3.3 - Time constants

The influence of the floor heating is very unclear. It probably has an influence only by its state (on-off), the value of the heating water temperature in the floor itself seems to play no role or a minor one. The reason for this can be seen on Figure 3.5. This figure depicts an anomaly from January 19-21, 2002, when the valve of the floor heating circuit was left fully open accidentally. The rise of 25 °C in the floor heating water temperature gave a 2 °C rise in the inside temperature. However, such an anomaly is strongly unwanted. The heating water temperature mustn't exceed 35 °C according to local standards and those skilled in the art recommend a temperature of about 20 - 25 °C. So we can say it is only the state of the floor heating, not its temperature, that has some influence on the inside temperature.
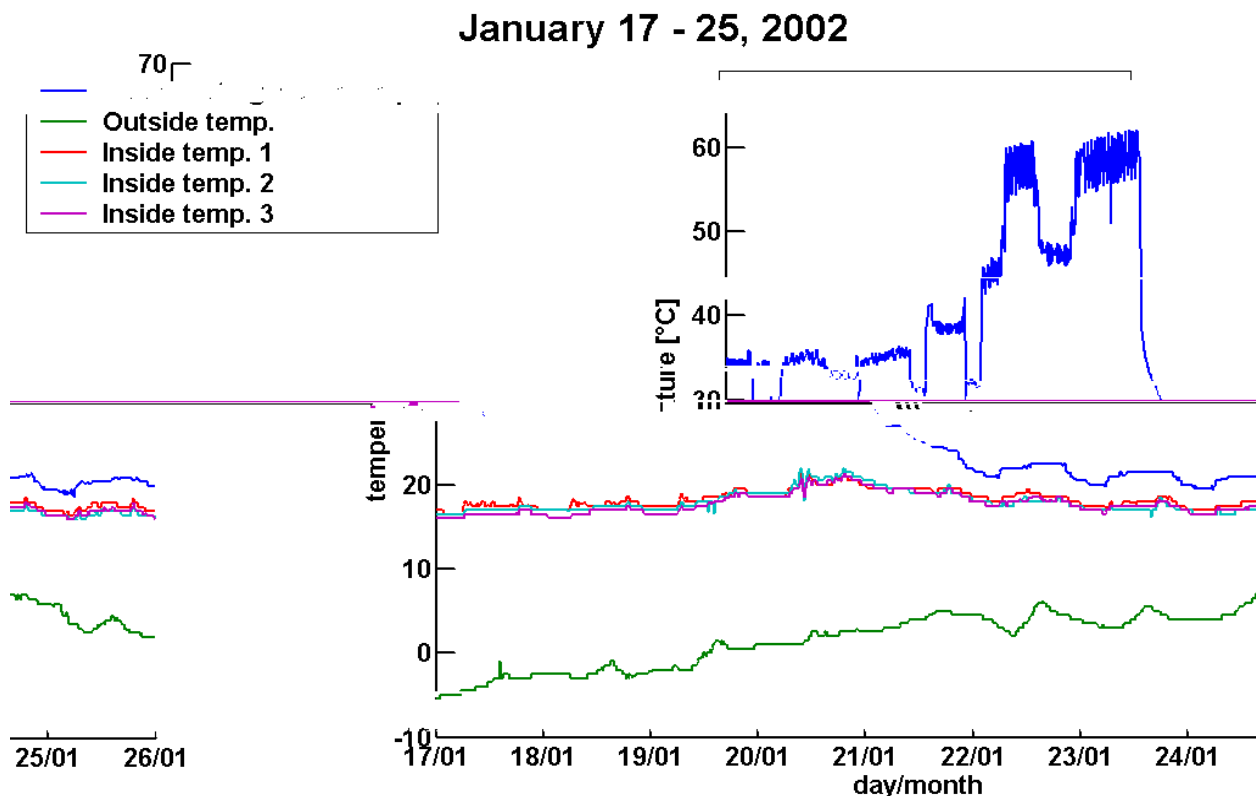
Figure 3.5 - Floor heating water anomaly in January 2002

The influence of the radiators is more significant. If we change the heating water temperature of the radiators by 20 °C, the inside temperature changes by 2 °C in 1-2 hours. This is a very rough estimation again. One identification experiment I proposed was done in October 2003 with the floor heating switched off. It seems like the inside temperature tends to increase further more, with a time constant of 15 hours or even more (see Figure 3.6).
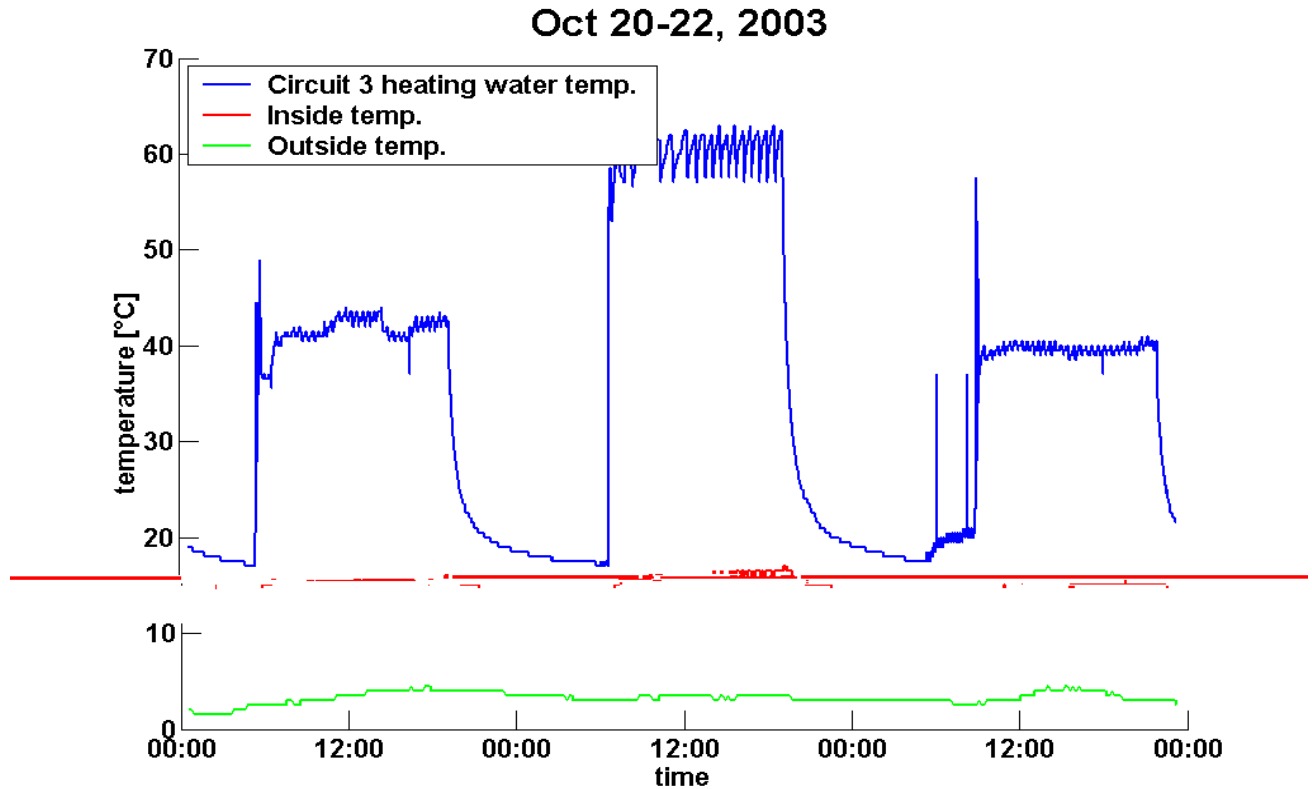
Figure 3.6 - Circuit 3 to inside temperature – an identification experiment

The other two important time constants – heating water circulation time and heating water temperature sensor delay – have been already discussed before (see 3.2 - Valve characteristics).

3.3.2 "Useful" data recognition

The floor heating has been switched on and off according to the outside temperature so far. This has been done by a decision of a person responsible for the heating. Unfortunately, there are no records of these switches. For further data analysis (esp. for the ARX modeling) I have to know, which data have the floor heating switched on.

To recognize the data with the floor heating switched off, I have used a procedure using daily variance.

$$Daily\ Variance = \frac{\sum_{i=1}^{n}(t_i - \bar{t})^2}{n-1} \tag{3.3}$$

n........ number of measurements during a single day

The idea is as follows.

There has been no heating water temperature control so far. Therefore, the heating water temperature has been varying according to the changes in the hot water temperature from the heater (see Figure 3.7). As for the radiator circuit depicted, the same dependence exists for the floor heating circuit. As the differences are low, it isn't apparent on a plot.
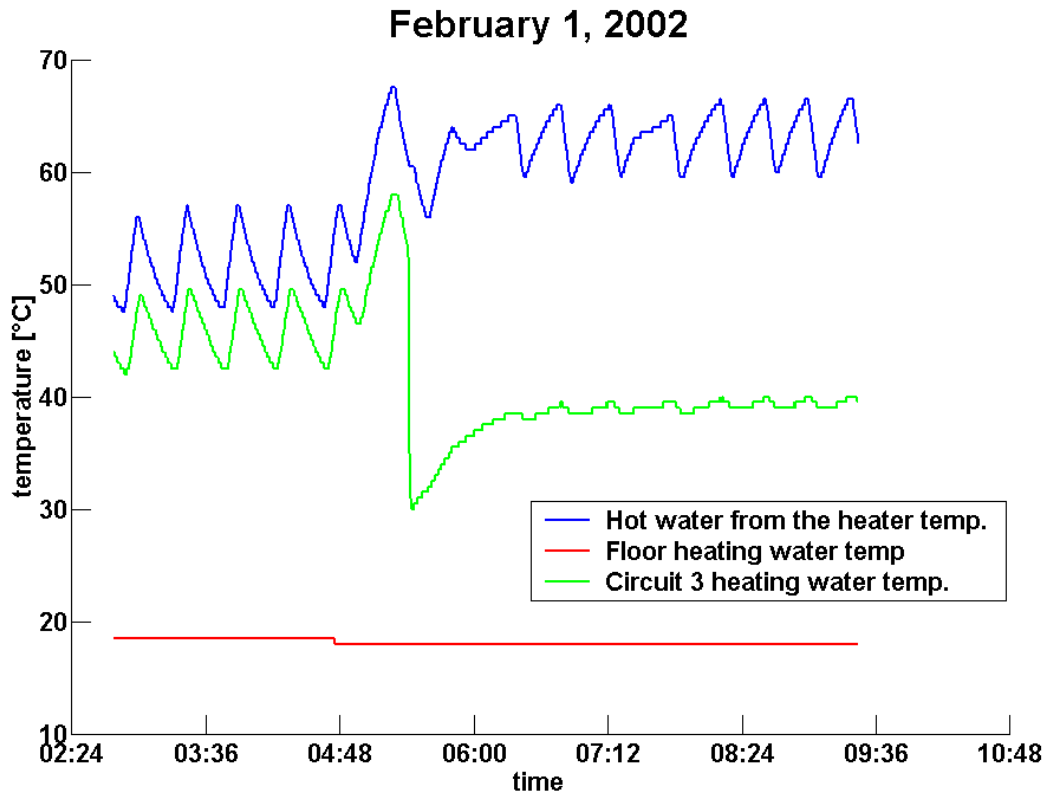

Figure 3.7 - Dependence of a heating water temperature on the hot water from the heater temperature

If we count the daily variances for the floor heating water temperature, fairly naturally, the data split into two groups. The limit is about 0.4 – when the daily variance is above 0.4, the floor heating circuit was probably on, otherwise off. We can set another condition – the period with the daily variance above 0.4 has to be "reasonably" long. (See Figure 3.8)

Using this procedure, the "useful" data with the floor heating on lie in the following periods:

- 4. - 24. 1. 2002
- 3. - 21. 2. 2002
- 6. - 14. 4. 2002
- 13. 12. 2002 - 17. 1. 2003
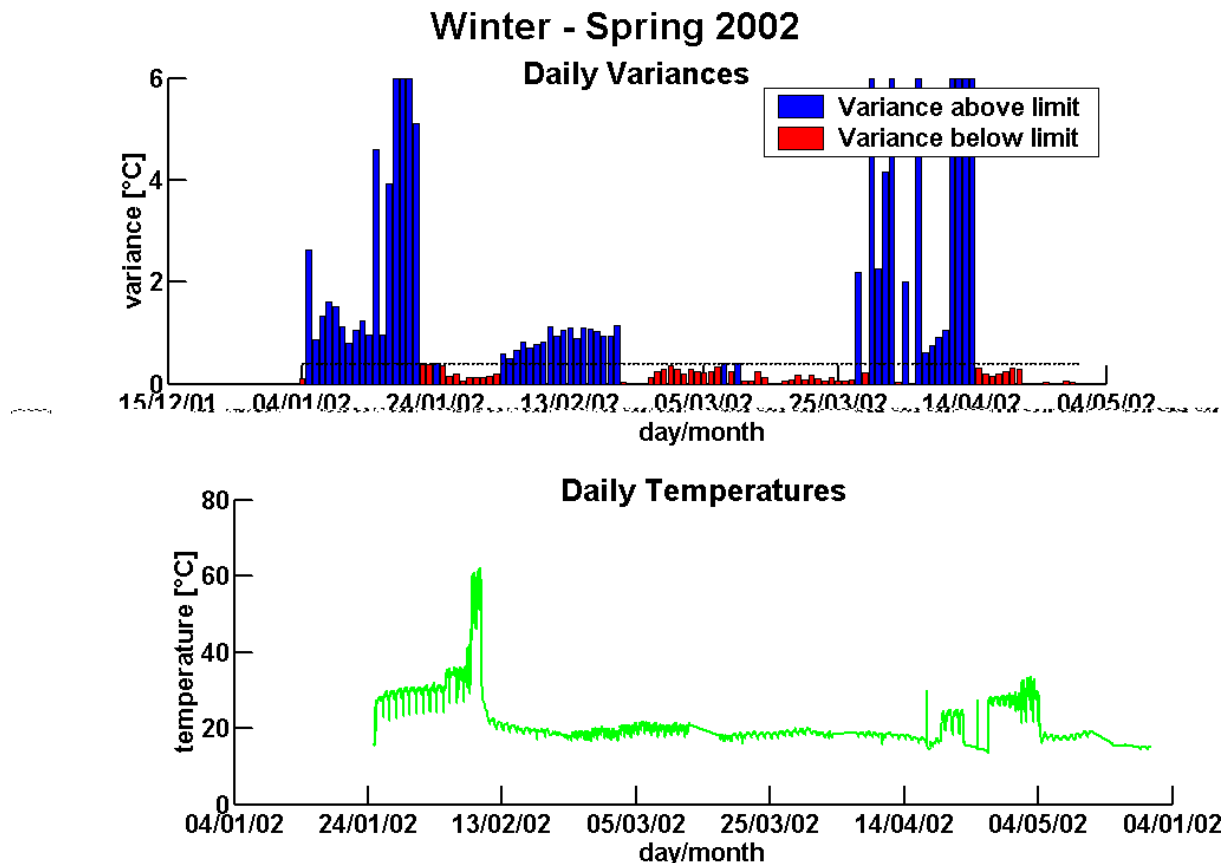
Figure 3.8 - Daily variances in floor heating water temperatures and said temperatures

3.3.3 Disturbances, noise and uncertainties

In general, the system and the communication is very sensitive to various kinds of disturbances, noises and uncertainties. There are several types of them.

Communication failures

The communication between the computer and the current net sometimes fails. The reason for this is rather unclear, it could be caused by an improper implementation of ComIN and ComOUT daemons (see 2.3 - Operating center and previous control) or by electrical disturbances on the net. It seldom happens individually, more often the communication fails for several minutes for all the sensors and actuators. This kind of failure happens once or twice a week.

Heating water temperature errors

The heating water temperature is sometimes unreliable. This can be caused by noise on the current net or bit inversions. This type of error occurs individually and it is quite rare.

Temperature oscillations

This is a common uncertainty of all digital sensors. If the temperature is close to a decision level of a sensor, the sensor magnifies the error. E.g. if the temperature ranges from 15.23 to 15.27 °C and the sensor accuracy is 0.5 °C, it will oscillate on 15.0 and 15.5 °C. This uncertainty is not important most of the time, it has to be treated somehow only on

the threshold of the equithermal control (i.e., if the control is to be switched off completely at 15.5 °C, the temperature oscillation can cause some problems).

"Open door"

If the main entrance door is left open for a longer period of time accidentally, the temperature drops significantly. Once they are closed, the temperature returns to a proper value quite quickly. This disturbance is very difficult to discover and cannot be distinguished from the previous disturbance for certain. See Figure 3.10.

Attendance

This is a major factor in the control design. With the large main time constant, it makes the feedback control of the inside temperature almost impossible.

The attendance in the church of St. Theresa from Lisieux is difficult to predict and it depends on the service held there. If there are 300 people inside the church each having a heat output of 150 W, it gives a total heat output 45 kW.

The problem is that we don't know the heat output of the heating system. To estimate it, we can use the following equation:

$$q = mc\Delta\theta \tag{3.4}$$

We don't know the temperature difference as we don't know the temperature of the heating water on the output of the heating pipelines exactly. There are only small analogue thermometers on this place. The temperature difference may be around 5 °C or less. The total volume of the water inside the church is about 500 l, i.e. 500 kg. The specific heat capacity c is approx. 4.2 $kJK^{-1}kg^{-1}$. So we have this equation:

$$q = 500 \times 4.2 \times 5 \cong 10.5\,\text{MJ} \tag{3.5}$$

This represents the upper estimation of the heat radiated into the church. This heat is transferred to the church in about 6 minutes, so the maximum heat output of the heating is

$$P = \frac{q}{t} = \frac{10.5}{360} = 30\,\text{kW} \tag{3.6}$$

We have to keep in mind this is the upper estimation. If there were only 300 l of heating water inside the church and the difference would be only 3 °C, the heat output would be only about 10 kW (compared to 45 kW of the people).

As a result, the influence of the heat output of the people will be comparable to the heat output of the heating system, moreover, it could be much more significant. The measurements show indeed that the people inside the church are the major source of the heat during the service (see Figure 3.9).

The people inside can give a 4 °C rise in the inside temperature. In addition, they keep the main entrance door open for a long time, so the inside temperature changes very fast.

Another problem arises during the data analysis – there are several fetes throughout the year (in addition to the Sundays) that have abnormally high attendance (e.g. Christmas, Easter, St. Wenceslas, etc.) (see Figure 3.10).

Tuesday, Feb 5, 2002

Sunday, Feb 17, 2002
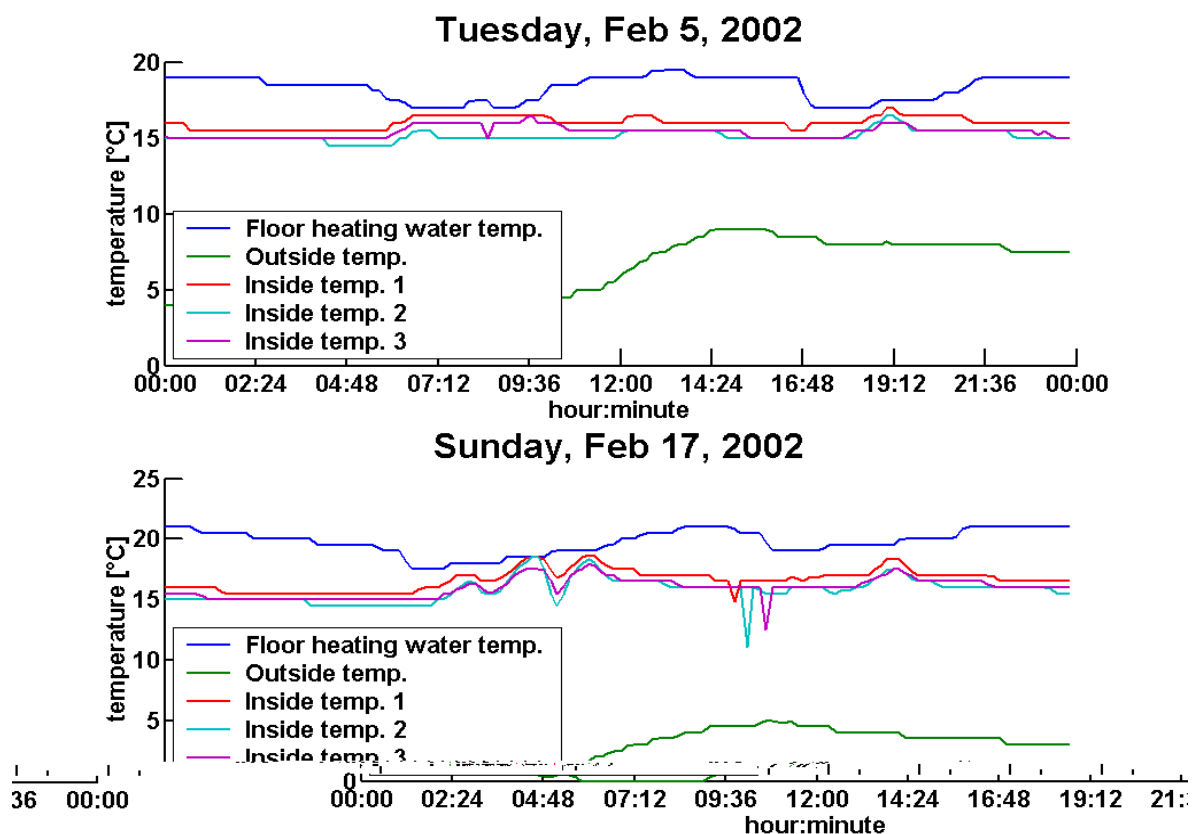
Figure 3.9 - Comparison of Sunday and weekday inside temperatures

Jan 24 - Feb 23, 2002
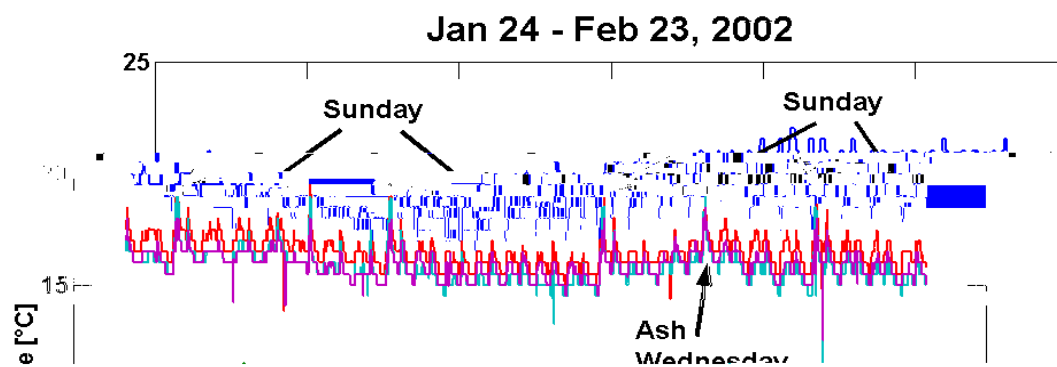
Figure 3.10 - "Open door" disturbance and uncertainties caused by fetes
(Sundays and Ash Wednesday)

4 System Modeling and Control Design Concept

4.1 System modeling

4.1.1 Simple room modeling

To have a rough idea of how the system works, it is very useful to make a mathematical model. Our system – a church – is very complex and no mathematical model can describe it precisely. However, it can provide us some important information about the variables in the system and serve as a platform for system identification and ARX modeling.

The detailed description of heating system modeling can be found in [1].

An energy balance for the room air is as follows:

$$C_r \frac{d\theta_r}{dt} = q_{plant} - \sum (AU_i)(\theta_r - \bar{\theta}_f) - \frac{n_v V_r}{3} \times (\theta_r - \theta_o) + q_{gain} \tag{4.1}$$

C_r .... room air thermal capacity [JK^{-1}]
θ_r .... room air temperature [°C]
q_{plant} .... energy input from plant [W]
θ_f .... the surface temperature of the room fabric [°C]
ΣAU_i .... area integrated fabric surface U-value (found in construction tables)
$n_v V_r/3$ .... ventilation coefficient [WK^{-1}], in which
n_v, V_r .... are the ventilation air change rate [h^{-1}] and room volume [m^3] respectively
θ_o .... external temperature [°C]
q_{gain} .... coincident room sensible heat gain [W].

In the following, we will express each term as deviation rather than as an absolute value, as usual in the control systems. Using

$$C_r = V_r \rho_a c_{pa} \tag{4.2}$$

V_r ...... room volume [m^3]
ρ_a ...... air density [kg.m^3]
c_{pa} ..... specific heat capacity of the air [J. kg^{-1}. K^{-1}]

we get

$$V_r \rho_a c_{pa} \frac{d}{dt}(\delta\theta_r) = \delta q_{plant} - \left(\sum (AU_i) + \frac{n_v V_r}{3} \right)\delta\theta_r \tag{4.3}$$

From here on, we will drop the δ notation for convenience.

After performing a Laplace transformation and further simplifying the equation, we get the room air capacity transfer function:

$$\frac{\theta_r(s)}{q_{plant}(s)} = \frac{K_r}{\tau_r s + 1} \tag{4.4}$$

$$\tau_r = \frac{V_r \rho_a c_{pa}}{\sum (AU_i) + n_v V_r / 3} \tag{4.5}$$

$$K_r = \frac{1}{\sum (A U_i) + n_v V_r / 3}$$ (4.6)

τ_r .... room temperature time constant to fluctuation in plant output
K_r ...... room temperature gain to fluctuations in plant output.

4.1.2 Accounting for fabric

Single layer

Let we have a thin, uniform layer of construction material, so thin that the temperature throughout its body can be assumed constant. Let us suppose it is a wall (though it could be any type of construction element) and is therefore bounded by room temperature (θ_r) on one side and an external temperature (θ_o) on the other side (Figure 4.1).
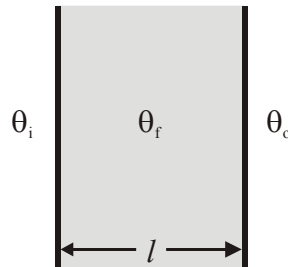
Figure 4.1 - Single layer building element

A transfer function representation for this can be built up as follows.

An energy balance for this element produces the following:

$$l \rho_l c_{pf} \frac{d\theta_f}{dt} = u_i (\theta_r - \theta_f) - u_0 (\theta_f - \theta_o)$$ (4.7)

ρ_f .... density of the material [kg.m^{-3}]
c_{pf} ...... specific heat of the material [J.kg^{-1}.K^{-1}]
u_i .... combined convection/radiation inside surface heat transfer coefficient [W.m^{-2}.K^{-1}]

Treating the variables as deviations and after the Laplace transformation, we obtain the following:

$$\theta_f (s) = \frac{K_{\theta_r}}{(\tau_f s + 1)} \theta_r (s) + \frac{K_{\theta_o}}{(\tau_f s + 1)} \theta_o (s)$$ (4.8)

The wall time constant:

$$\tau_f = \frac{l \rho_f c_{pf}}{(u_i + u_o)}$$ (4.9)

The wall/room temperature gain:

$$K_{\theta_r} = \frac{u_i}{(u_i + u_o)}$$ (4.10)

The wall/external temperature gain:

$$K_{\theta_o} = \frac{u_o}{(u_i + u_o)} \qquad (4.11)$$

If the external temperature is constant, the above reduces to a first order lag relating the wall temperature to the room temperature.

Multiple layers

Unfortunately, construction elements are not as thin as to treat them like uniform single layers. We can handle this by splitting out material layer up into a number of layers or slices of equal thickness l.

A two layer element is illustrated on
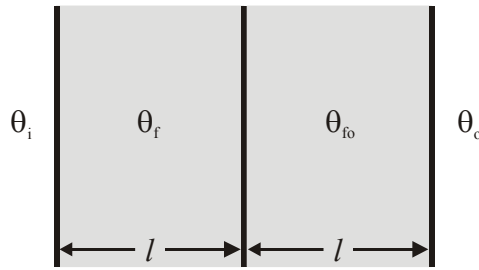
Figure 4.2 - Two-layer building component

An energy balance can be set as follows:

$$l\rho_l c_{pf} \frac{d\theta_f}{dt} = u_i(\theta_r - \theta_f) - u_f(\theta_f - \theta_{fo}) \qquad (4.12)$$

$$l\rho_l c_{pf} \frac{d\theta_{fo}}{dt} = u_f(\theta_f - \theta_{fo}) - u_o(\theta_{fo} - \theta_o) \qquad (4.13)$$

u_f ...... heat transfer coefficient due to the layer thermal conductivity [W.m^{-2}.K^{-1}].

Combining these two expressions and using Laplace transformation leads us to the following second order representation for a uniform building element which relates the two boundary temperatures to the inside surface layer temperature:

$$\theta_f(s) = \frac{As + B}{Cs^2 + Ds + E} \theta_r(s) + \frac{F}{Cs^2 + Ds + E} \theta_o(s) \qquad (4.14)$$

The respective constants (A, B, C…) are not interesting for our purpose and can be found in [1].

We can further assume that the external temperature deviation (and $\theta_o(s)$) is zero.

The higher order element descriptions can be obtained in a similar manner. However, they introduce a significant complication without bringing a description of the heat transfer dynamics that is more accurate, than the one of the second order.

Composite construction elements

Of course, only few buildings are made up of a single material construction layer. In practice, the construction elements (walls, floors, ceilings etc) are made of a combination of several layers of different materials and constructions. A composite construction element model therefore needs to be "chained" from individual element transfer functions in order to arrive at a composite construction representation. For a three layer composite, using second order element transfer functions and assuming exposure to an external temperature, Figure 4.3 gives us the resulting general model.
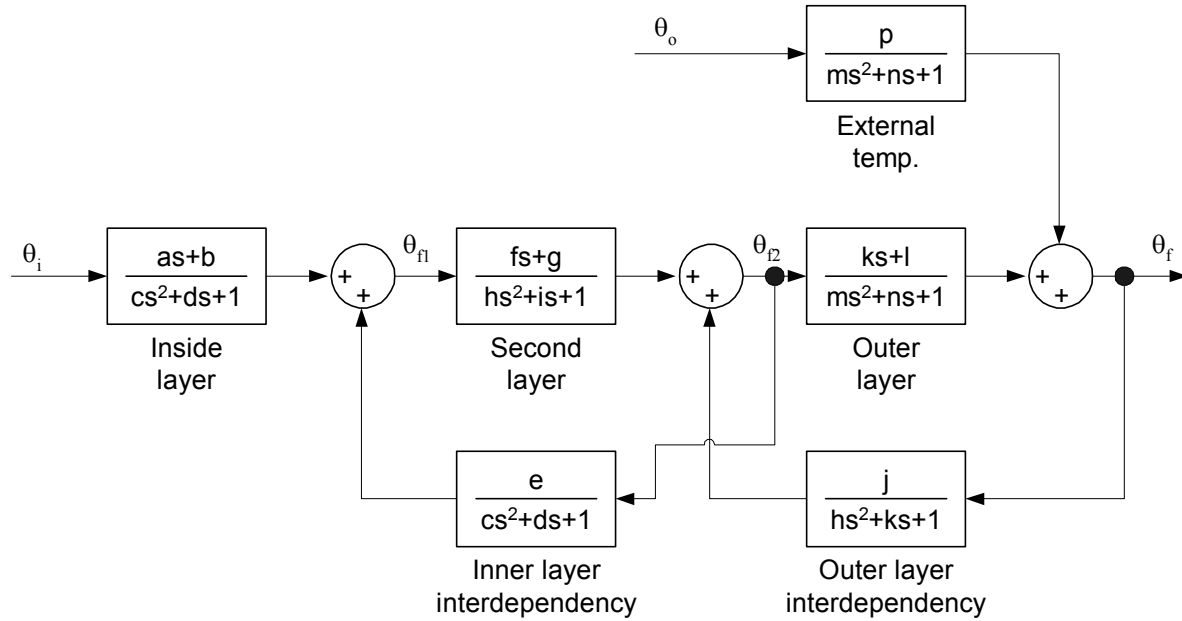
Figure 4.3 - Model of a three layer composite construction

4.1.3 Heat emitter model

The heat emitter is coupled to the room thermal environment through the room air temperature and (if the emission is in part radiant) the various room surface temperatures. We can express a general lumped capacity water based model as follows:

$$C_e \frac{d\theta_{wo}}{dt} = m_w c_{pw}(\theta_{wi} - \theta_{wo}) - E_c(\theta_{wo} - \theta_r)^{n_c} - E_r(\theta_{wo}^4 - \overline{\theta}_f^4) \qquad (4.15)$$

θ_w ...... water inlet and outlet temperature [K]
E .... emission constants for the radiant and convective portions
of the heat emission [WK^{-ne}]
n_e .... emission index
θ_r .... room air temperature [K]

and the heat emitter overall thermal capacity comprises a heat emitter material portion and an emitter water portion:

$$C_e = V_m c_{pm} \rho_m + V_w c_{pw} \rho_w \qquad (4.16)$$

The equation 3.15 is strongly non-linear. Neglecting second and higher order terms in

the Taylor series expansion of the respective portions of the general model and taking Laplace transformation, this will lead to the following linear expression:

$$\theta_{wo}(s) = \frac{K_{m_w}}{(\tau_e s + 1)} m_w(s) + \frac{K_{\theta_{wi}}}{(\tau_e s + 1)} \theta_i(s) + \frac{K_{\theta_r}}{(\tau_e s + 1)} \theta_r(s) + \frac{K_{\overline{\theta}_f}}{(\tau_e s + 1)} \overline{\theta}_f(s) \qquad (4.17)$$

where

$$\tau_e = \frac{C_e}{m_w c_{pw} + n_c E_c \left(\theta_{wo} - \theta_r\right)^{n_c - 1} + 4 E_r \overline{\theta}_{wo}^3} \qquad (4.18)$$

which represents a generalized *s*-domain model for a room heat emitter. Again, the respective gains are not interesting for our purposes and can be found in [1].

A coupled room and emitter model

Now we have some idea which variables influence the overall thermal system. The final step is to put them all together. Let us now repeat the main features of the church of St. Theresa from Lisieux now.

The church is heated by three radiators of Circuit 3 and one radiator of Circuit 1. These are common radiators, whose physical properties have been described beforehand. Further, there is a floor heating system. The composition of the outer walls and the roof is not known.

There are several stages to take:

- Derive the fabric model for the convective heating case.
- Derive the room transfer function for the convective heating case.
- Calculate the thermal capacity of the natural convector case and, hence, its transfer function.
- Form a block diagram model for the natural convector case.
- Modify the fabric model for the radiant effect of the floor heating case.
- Derive the room transfer function for the floor heating case.
- Calculate the thermal capacity of the floor heating and, hence, its transfer function.
- Form a block diagram model of this second case.
- Obtain and compare results.

We will not work these stages out as it is very complicated and we don't need this. The reasons will be described in the next chapter.

4.1.4 Conclusions from the system modeling

The purpose of this theoretical outline was to get an idea of how the system works. To make a proper model we don't have enough information. In addition, the church has a very complicated architecture. The building is attached to another building with unknown temperature, there are several artistic windows of difficult shapes, the inside space is very indented etc. Here such influences take effect, which we cannot cover by any means of mathematical modeling. However, we can get some idea about the system, about the linearities (e.g., the emitter model is strongly non-linear), the physical influences etc. The simplified models can be used as a basis for an ARX modeling, especially if we get at least some physical constants of the building. A very rough idea of this is shown in 7.1 - ARX.

4.2 Cascade control

As we don't have enough information about the system, the best thing to do is to design a cascade control of the system. The system with a cascade control is shown in Figure 4.4. The control variables are not determined yet, we will make decision of what to use for the control later. The existence of the feedback in the outer loop is still open as well.
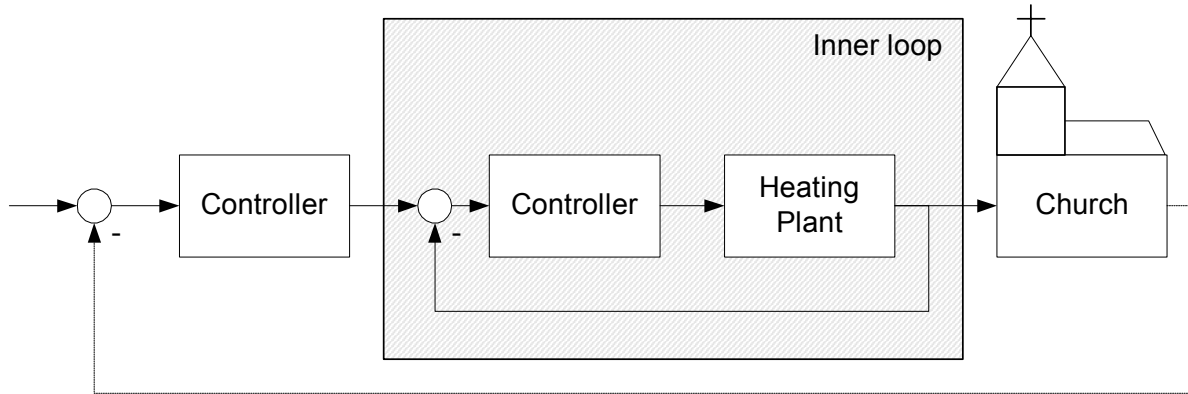

Figure 4.4 - Cascade control

The inner loop is a classical feedback controller. It regulates the heating water temperature supplied to the church. The reference is the required temperature of the heating water.

The outer loop controls the inside temperature in the church. There are two approaches to deal with the problem of heating up a building:

- Equithermal control (without a feedback)
- Feedback control ("Reference room control")

We will discuss these two approaches later. The main advantage of the cascade control is that the two loops can be designed, implemented and operated independently. It gives the possibility of a further upgrade to the system and provides the system an important feature – modularity.

4.3 Equithermal × feedback control

An equithermal control is the most common method of controlling the inside temperature of buildings. It comes out from long experience with the heating. A function is designed to express a relationship between the outside temperature θ_{out} and the heating water temperature θ_{water}.

$$\theta_{water} = f(\theta_{out}) \tag{4.19}$$

This function should keep the inside temperature constant at any outside temperature. A quadratic function is the most common case.

$$\theta_{water} = a\theta_{out}^2 + b\theta_{out} + c \tag{4.20}$$

The equithermal control has no feedback, hence, it is not sensible to short-term disturbances. E.g. if someone opens a window for a while, the control will not do anything. User-friendly equithermal controllers are available on the market that allow a user to set the heating function very easily. However, the equithermal control requires at least some idea about

the building characteristics and it takes some time to tune it, especially in new heating systems.

Considering the different modes used in the system (day and night), the inside temperature will change slowly, because the heating system (radiators and floor heating) maintains the same temperature for all the period the particular mode is active.

The equithermal control diagram is shown in Figure 4.5.
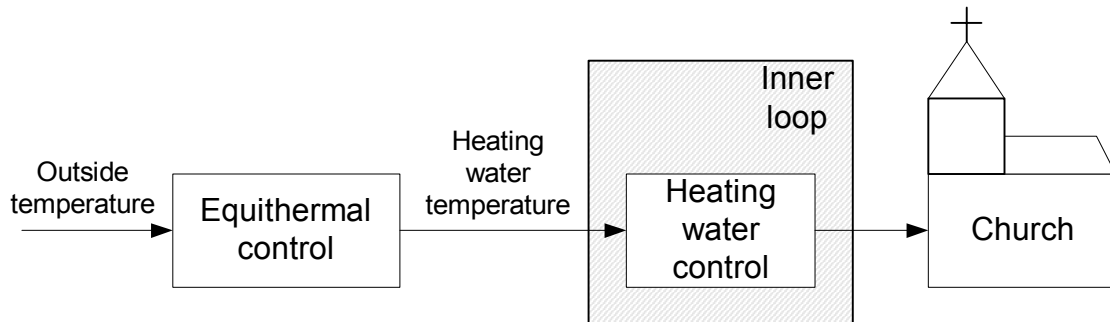
Figure 4.5 - Equithermal control of the church

Generally speaking, feedback control is the most common control. However, it doesn't have a wide spread application in heating systems. It is more sensible to short-term changes and a proper design is very complicated (if possible at all). Its advantage is a more robust behavior – even a badly tuned controller will maintain the desired temperature inside the building more or less reliably. It requires an experienced placement of the inside temperature sensors.

The inside temperature changes are faster, because the feedback has an ability to "overheat" or "overcool" the heating system and thus change the temperature more dynamically.

The feedback control diagram is shown in Figure 4.6.
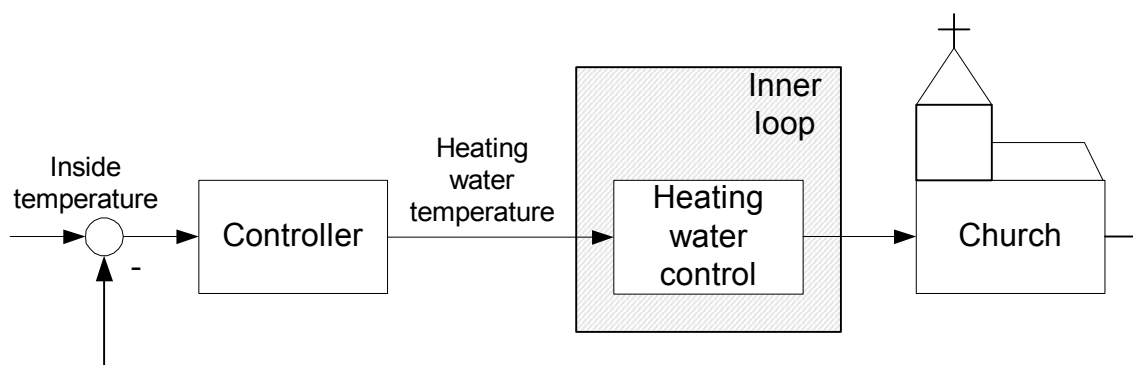
Figure 4.6 - Feedback control of the church

We can compare both heating control systems now. Table 4.1 illustrates the main advantages and disadvantages of the exuithermal and feedback control in relation to the church of St. Theresa from Lisieux.

Advantages	Disadvantages
Equithermal control	
+ Robustness against short term disturbances (open door, attendance to the service, …) + No need for inside temperature sensors + A large data set of operation history	- Only one outside temperature sensor available - Slow inside temperature changes
Feedback control	
+ Ability to maintain the desired temperature even if tuned very roughly + More dynamical control – it is possible to slow down or speed up the controller + A faster heating up and cooling down	- Risk of excessive heating temperature changes - Different rooms on four circuit and only one room temperature measured

Table 4.1 - Comparison of equithermal and feedback control

After considering all the advantages and disadvantages, I have decided, after a consultation with the contractor and the advisor to this work, to use the equithermal control as the outer loop control.

5   Implementation

5.1 Inner loop

5.1.1 Controller implementation

The inner loop has to control the three-port valves to regulate the heating water temperature. A servo valve is used to achieve this, as stated in 2.2 - Actuators and sensors.

The system to be controlled acts like an integrator. The angular velocity ω (i.e. the time the valve is being opened) is directly proportional to the opening angle ϕ (i.e. the mixing ratio of the cold and hot water generating the heating water) (Figure 5.1) [2].

$$\omega \longrightarrow \boxed{\dfrac{K_s}{s}} \longrightarrow \phi$$
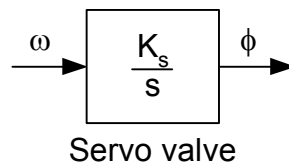
Servo valve

Figure 5.1 - A simple model of a servo valve

To control the servo valve, a PID controller will be satisfactory (Figure 5.2).

$$e \longrightarrow \begin{array}{c} \boxed{K} \\ \boxed{\dfrac{K}{sT_i}} \\ \boxed{sKT_d} \end{array} \longrightarrow \Sigma \longrightarrow u$$
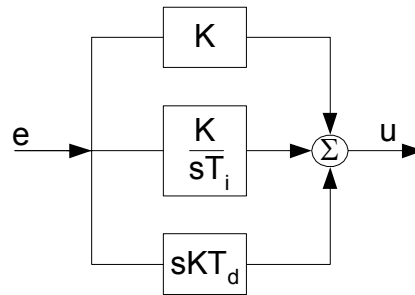
Figure 5.2 - A general PID controller

Because of a purely integration character of the servo valve, we can omit the integral section and use a simple PD controller.

This controller output has to be limited, as the maximum opening time during one actuating period is limited to 15 s (safety reasons). So the controller has to be extended by a limiting member.

The next thing is that we have to control the opening angle, not the angular velocity. The servo valve has no dynamics (we neglect the sensor dynamics), so the transfer function is linear.

As we control the angular velocity, we have to make a transfer from velocity to the temperature The temperature of the heating water θ is linear again and proportional to the opening angle ϕ - the valve is designed this way (see 3.2 - Valve characteristics).

Combination of the additional three aspects – the output limit, transfer from angular velocity to opening angle, transfer from opening angle to temperature – results in a ramp with limit between the controller and the system with a slope k that will be determined by experiment [8].
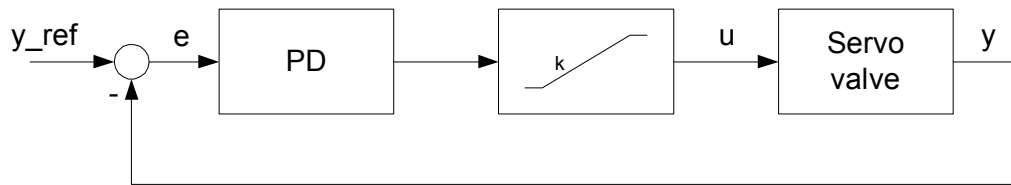
Figure 5.3 - The control loop of the servo valve

However, there is a problem with the temperature sensor delay. We can take the influence of the sensor into account and make a combined model of the servo valve and the temperature sensor together [1].

5.1.2 Controller tuning

I have proposed an experiment to estimate the combined model of the valve-sensor (Figure 5.4). For a proper identification, we have to eliminate the influence of the inlet hot water from the heater. In the experiment, the radiator circuits 1 and 3 temperatures unfortunately don't have the same amplitude as the inlet hot water and the information about the opening angle is not available. These data cannot be used, as they are not very reliable. Circuit 2 seems to be a little bit better and we will use it for identification.
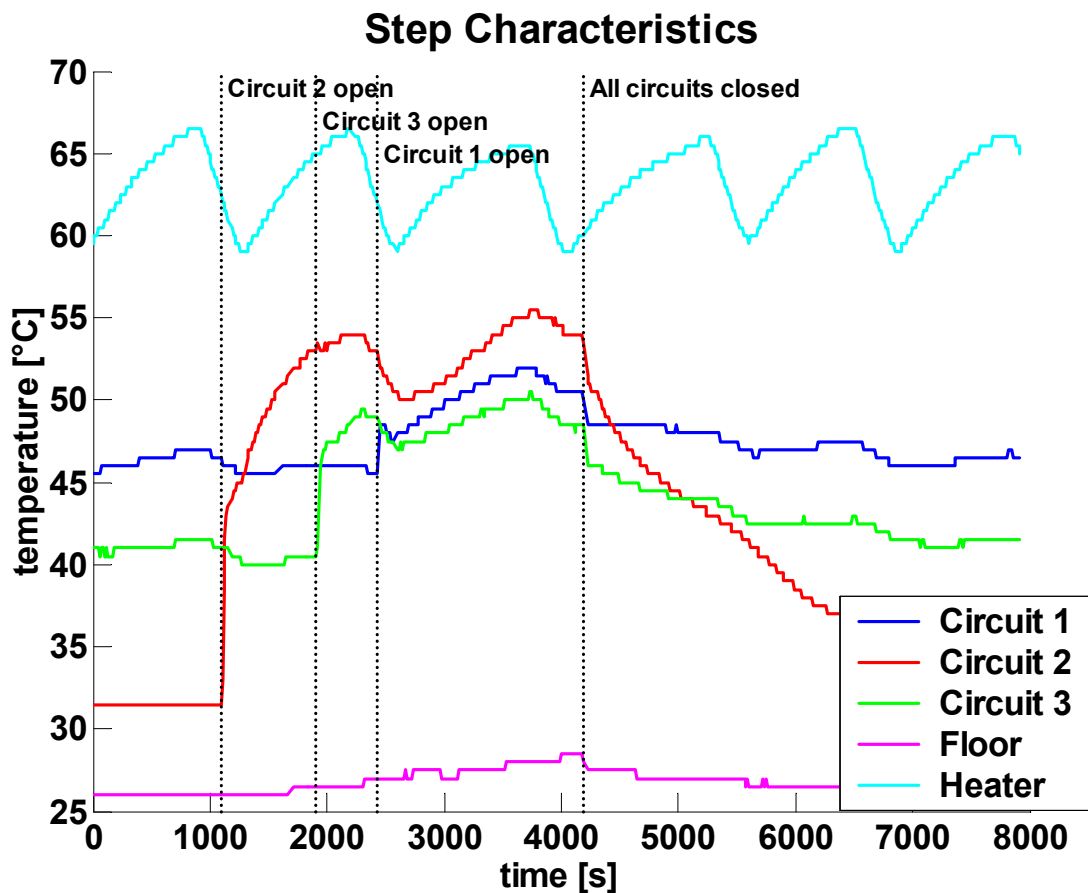
Figure 5.4 - Step characteristics of the respective valves - sensors

I subtracted the inlet hot water temperature from the circuit heating water and shifted the result to zero initial conditions (Figure 5.5).
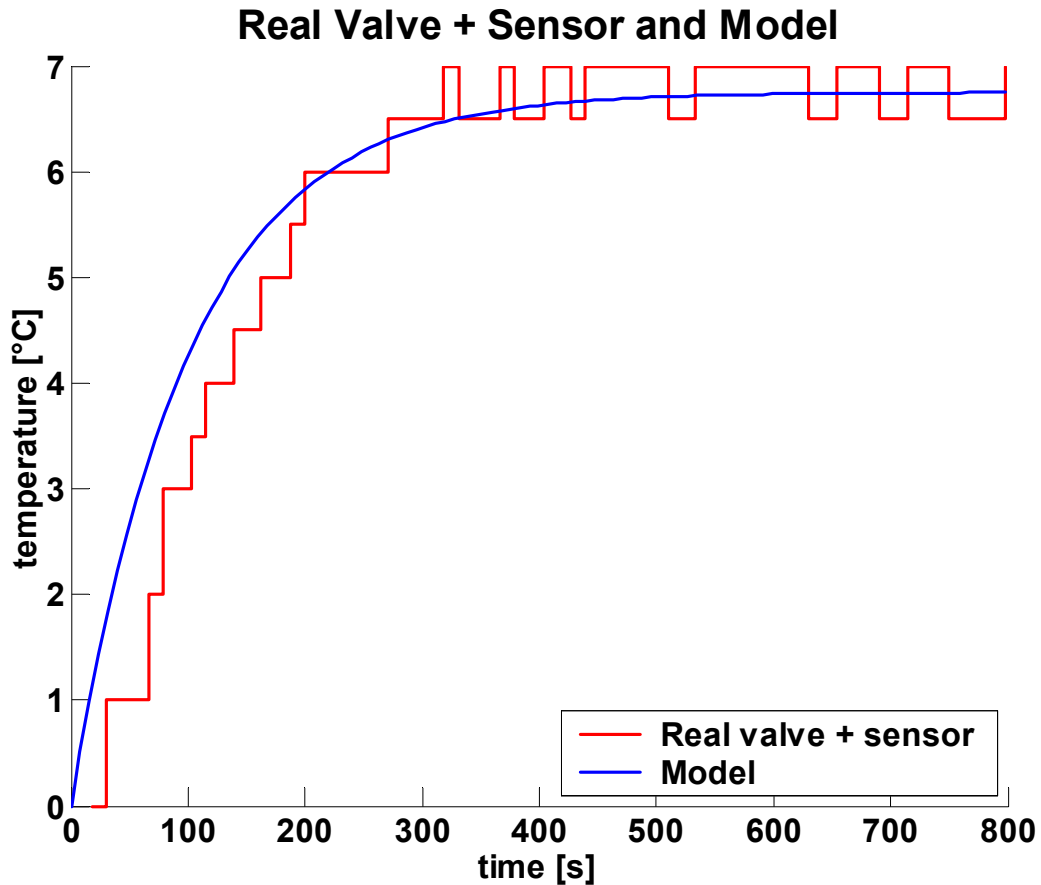
Figure 5.5 - The temperature sensor step characteristics on Circuit 2

The resulting step characteristics can be approximated by the following model:

$$P(s) = \frac{6.75}{100s + 1} \tag{5.1}$$

According to [8], the PD controller has been tuned and the following parameters have been found during the operation as the best ones:

- K = 15
- $T_d = 1$
- k = 2

According to the contractor's demand, we have introduced an additional insensitivity band. If the controlled temperature lies inside the insensitivity band, it is not controlled even if it differs from the desired temperature. This increases the lifetime of the servo valves.

The experimental results are shown in 6.1 - Inner loop.

5.1.3 Incremental 3-position PID controller

For a servo valve control, we can employ a three-position controller. Regarding the integration character of the system, we can even use a PID controller in an incremental form (Figure 5.6). With the previous PD controller we control the angular velocity of the servo valve, with the incremental PID controller we can control the opening angle directly [4].
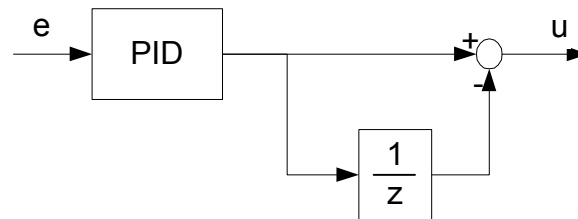
Figure 5.6 - An incremental PID controller

Further, we can use a weighted-input PID controller (Figure 5.7) as is usual in industrial controllers. According to the recommendations stated in [4] and [3], we set b = 1 and c = 0.
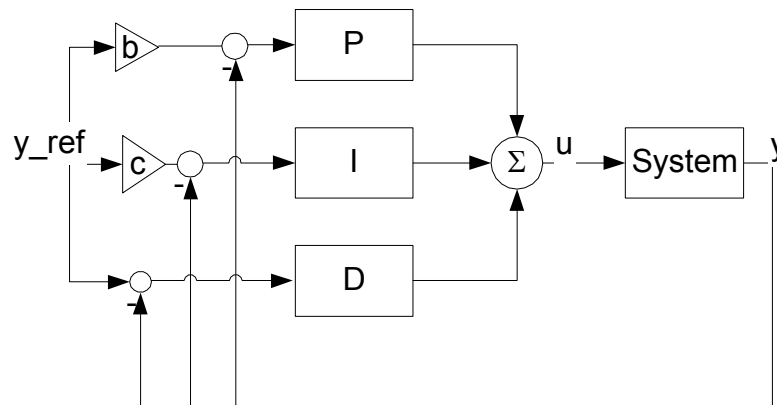

Figure 5.7 - Weighted-input PID controller

If we tried to use classical three-position control now, we would encounter serious problems. The minimal sampling period of the temperature sensors is 10 s, while the time required for the full opening of the valve is 100 s. The control precision would be 10 % and the controller would oscillate trying to set the exact value. Nevertheless, we can use a modification of the controller enabling more frequent actions, e.g. every 1 s.

A solution is given in [4] in the form of a controller extended by a buffer, where the value of the action is stored at some frequency and the controller works with this buffer at another frequency. The latter can be smaller then the first one. The overall scheme is illustrated in Figure 5.8.

The MATLAB source code implementation of this type of controller can be found in Appendix A.
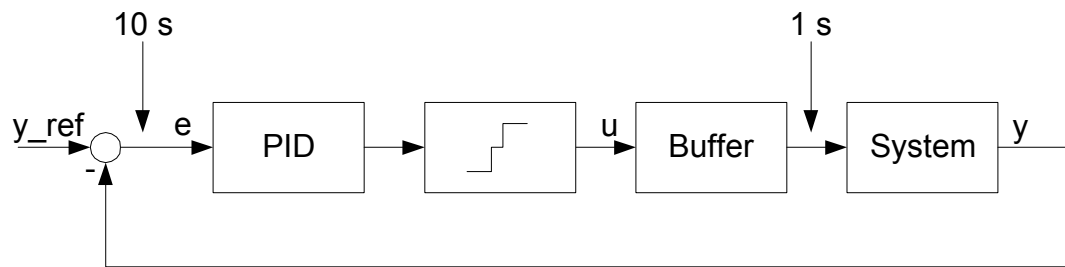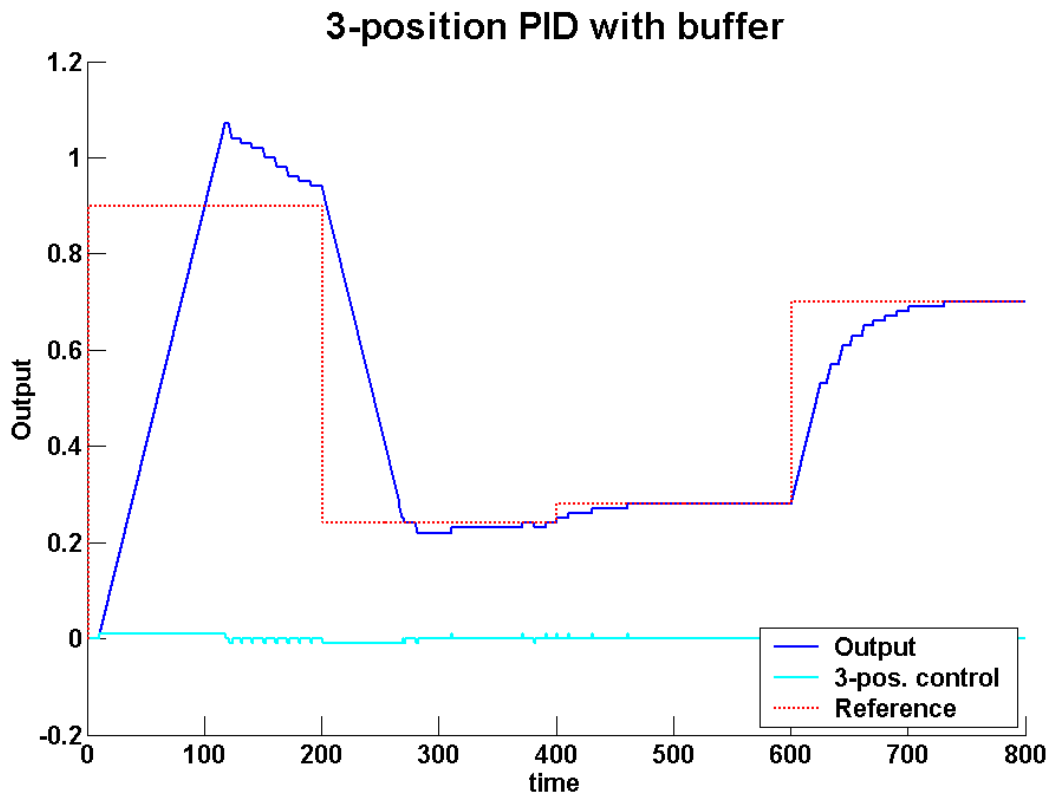
Figure 5.8 - A three-position PID controller modified by a buffer

For the implementation of the controller, I used the following constants ([3], [4]):

- $N = 10$ (derivative gain limitation)
- $h = 10$ (sampling period of the controller)
- $T_i = 10$
- $T_d = 100$
- $K = 0,18$

The results of my simulation are shown in Figure 5.9.

Figure 5.9 - Results of the three-position PID with buffer simulation

This controller gives very good results and its implementation is very reliable according to [4]. It hasn't been employed in the real system so far. The reason is a confusing original source code of the implementation and an extremely difficult debugging. It is scheduled to implement it after the optimization of the control program source code.

5.2 Outer loop

## 5.2.1 Equithermal control requirements

The detailed requirements for the outer loop are stated in 2.4 - Requirements. To fulfill them, I have decided to implement an equithermal control. Here is a brief summary of some major advantages of the equithermal control:

- Robustness
- No feedback – indifference against open door, large attendance etc.
- Design based upon existing experience with the system

5.2.2 Equithermal control design

For equithermal control design, we will advantageously make use of the large data set from past years. The idea of the design is to plot a graph of every temperature of the heating water in relation to its corresponding outside temperature. The same can be done with the inside temperatures.

There is some preprocessing to be done. To simplify the design, we will round the temperatures to the precision of 0.5 °C. The other thing is that we need to smooth the outside temperatures. The reason is that the outside temperature changes quite fast, but the reaction time of the inside temperature to the outside temperature is much longer – the building acts like a filter. So we needn't to care about the exact outside temperature, we can take the smoothed values instead. To smooth the temperatures, a moving average has been used (Figure 5.10).
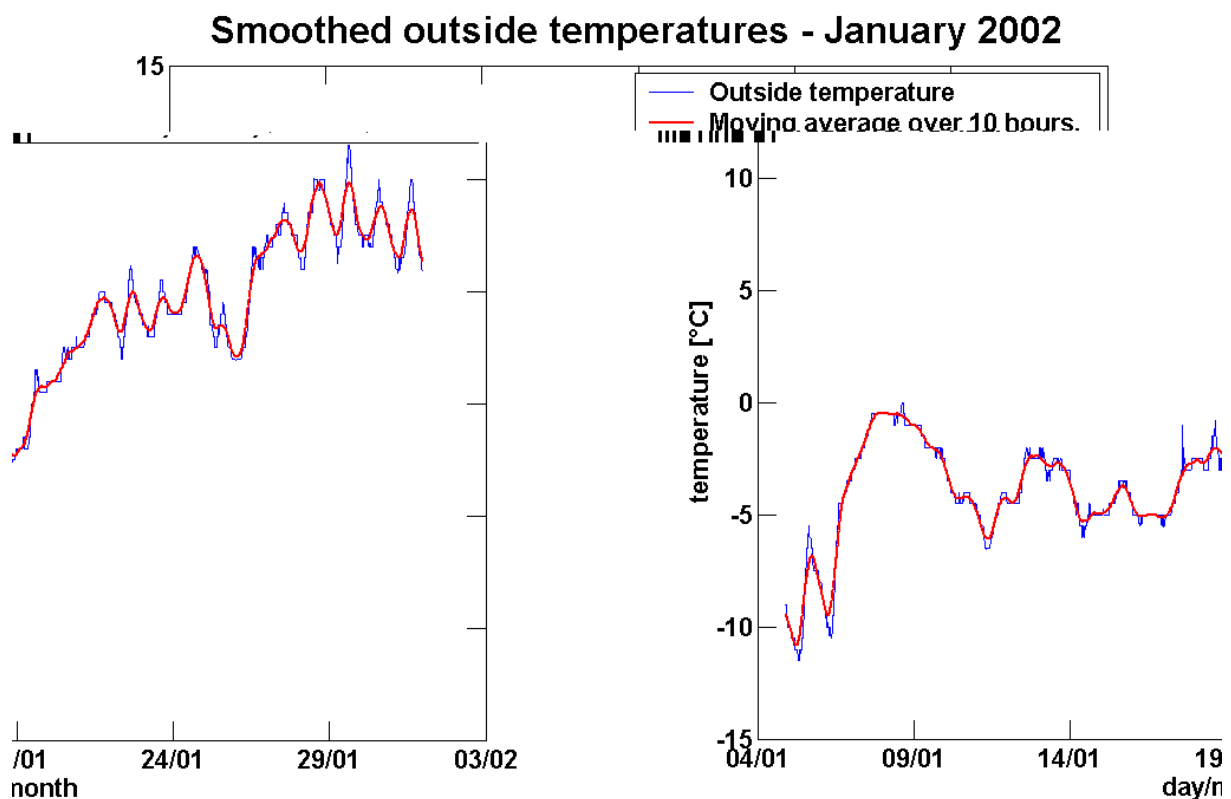
Figure 5.10 - Smoothed outside temperatures using moving average

Then we need to split the entire data set to night and day data sets enabling us to design a night equithermal curve and a day equithermal curve.

Referring now to Figure 5.11 and Figure 5.12, the meaning of the plots is as follows. The plots show the relationship between the outside temperature and a medium temperature (i.e. the inside temperature or the heating water temperature).

In **light blue**, there is a plot of the heating water temperatures from all the data available. The variance of the data is very broad. That is caused by the size of the data set. If we make an average for every 0.5 °C of the outside temperature (**dark blue**), we can see the data are concentrated around some kind of curve. If we look at the inside temperatures (**light green**), we can see the inside temperatures have a broad variance as well. That can have two interpretations – either the previous control is fairly bad or the disturbances are very high.

Now we can just interpolate the mean values of the heating water temperatures (**dark blue**) with an equithermal curve (**red)** according to equation 4.20.

The first values (from Dec. 2, 2003) were as follows:

Circuit No.	a	b	c	T_{lim}
Circuit 1	0.04	-2	55	15
Circuit 2	0.03	-1.5	45	15
Circuit 3	0.04	-2	55	15
Floor	0	0	20	10

Table 5.1 - Equithermal control day parameters from Dec. 2, 2003 to Dec. 23, 2003

The first values caused the inside temperature to be excessively high, so the values have been modified (Dec. 23, 2003):

Circuit No.	a	b	c	T_{lim}
Circuit 1	0.025	-1.2	45	15
Circuit 2	0.025	-1.3	41	15
Circuit 3	0.037	-1.3	42	15
Floor	0	-0.3	22	10

Table 5.2 - Equithermal control day parameters from Dec. 23, 2003

These parameters are the limits of the system. They cannot be further lowered, as the church itself isn't the only room heated by the heating system – other rooms are connected to the respective heating circuits as well. If we wanted to maintain an even lower temperature inside the church (less than 15 °C), the only solution would be to close partially the manual valves on the radiators.

In Figure 5.11 and Figure 5.12, the equithermal curves used since Dec. 23, 2003 are plotted.

Equithermal design - Night
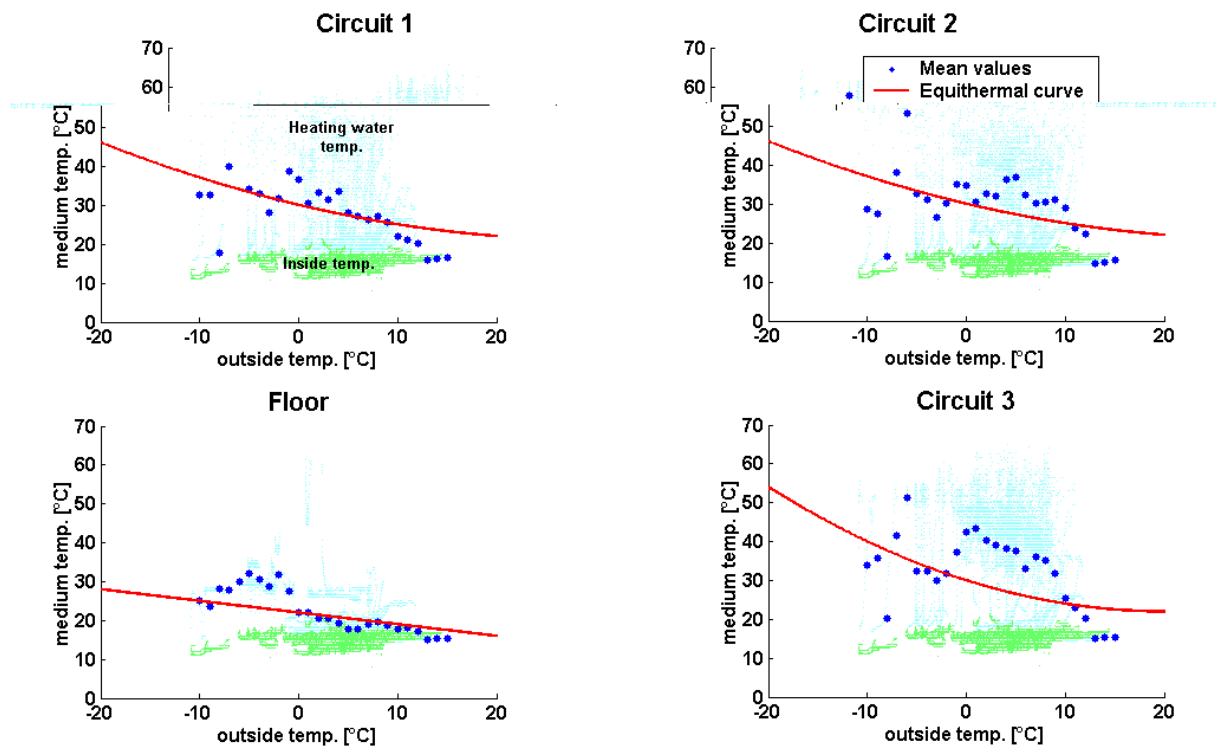

Figure 5.11 - Night data and the equithermal curve design
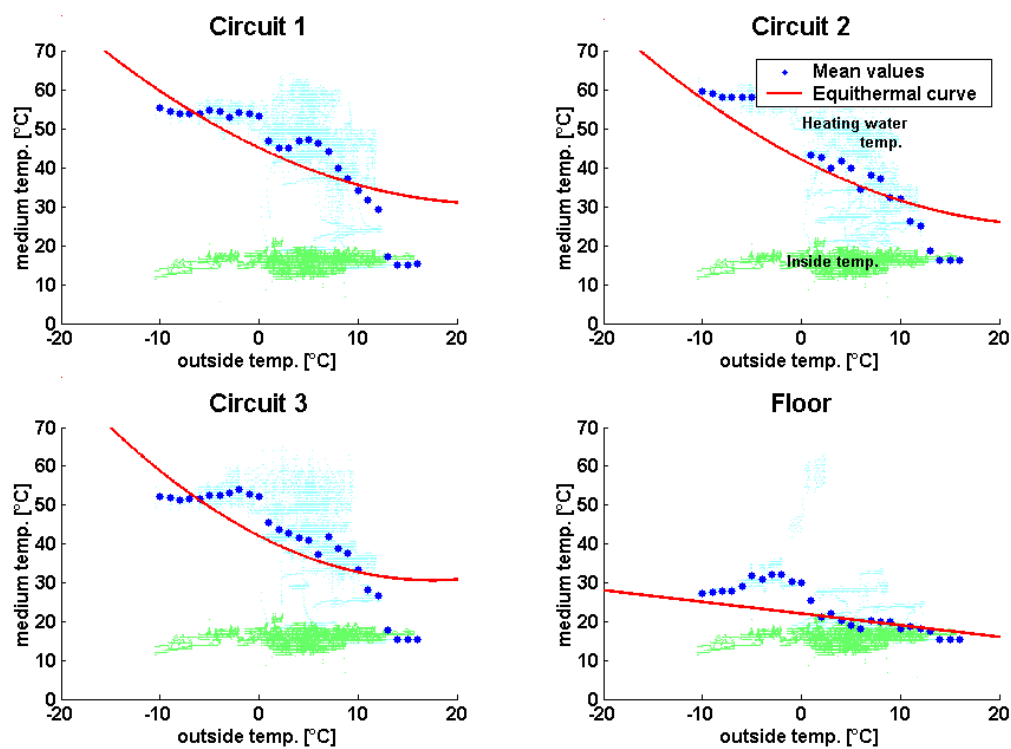
Equithermal design - Day

Figure 5.12 - Day data and the equithermal curve design

5.3 Software implementation

5.3.1 Safety requirements

Inside temperature sensors backup

There are three temperature sensors inside the church, so it was possible to employ a majority backup of the sensors:

- If one sensor gives a different temperature (it differs by 2 °C from the other two sensors), the temperature is treated as unreliable.
- If all three sensors give different temperatures, a random sensor is chosen.

Equithermal control switch off

The temperature control is switched off at some predetermined temperature. Because of the temperature oscillations (see 3.3.3 - Disturbances, noise and uncertainties), the control can be switching on and off for some period of time.

To avoid this, the program waits 30 minutes after the outside temperature limit has been reached. If the temperature remains above (below) this limit, the control is switched off (on), otherwise it remains on (off).

Communication failures

If a communication error occurs and no new temperatures are available, the program uses the last temperatures available.

This is not enough in the case of heating water temperatures – the controller would try on to regulate the temperature and the result would be a valve fully open or closed. If no new heating water temperature is available, no control can be done.

Other safety requirements

Other safety requirements must be regarded including file open failure treatment, dynamical variables treatment, safe start and termination of the program etc. These are general program safety requirements and will not be discussed here. For further details, see [7].

5.3.2 Previous software

The functions of the previous software have been described in 2.3 - Operating center and previous control.

Unfortunately, the source code of the original program was rather confusing. Even though it was commented, the orientation inside the source code was very difficult. The individual functionalities were not in separate procedures and it was very difficult to get the meaning of all of them.

The upgrade of the software was further complicated by the data structure. The entire program was based upon the global variables – all the structures were defined as global. This enabled the original authors to write the code quite quickly, however, the readability of the code has been decreased.

Considering these facts, the software upgrade couldn't fully follow the flowcharts present in 5.3.3 - Software upgrade. A major drawback was that the incremental PID controller couldn't be implemented for safety reasons, as the debugging of the controller was almost impossible.

5.3.3 Software upgrade

I made an upgrade to the previous software to meet the requirements and to implement the functions stated in previous chapters.

Flowcharts

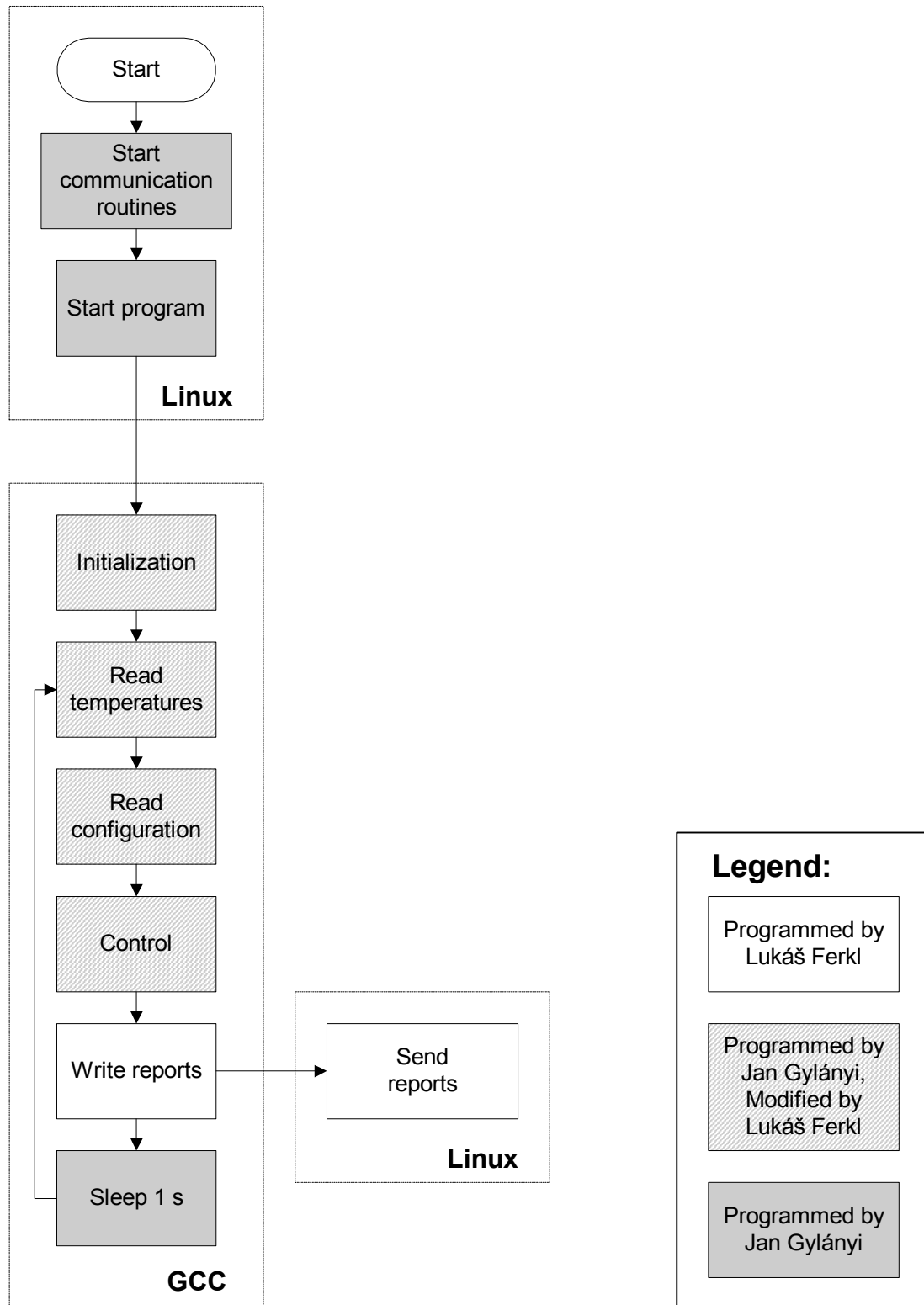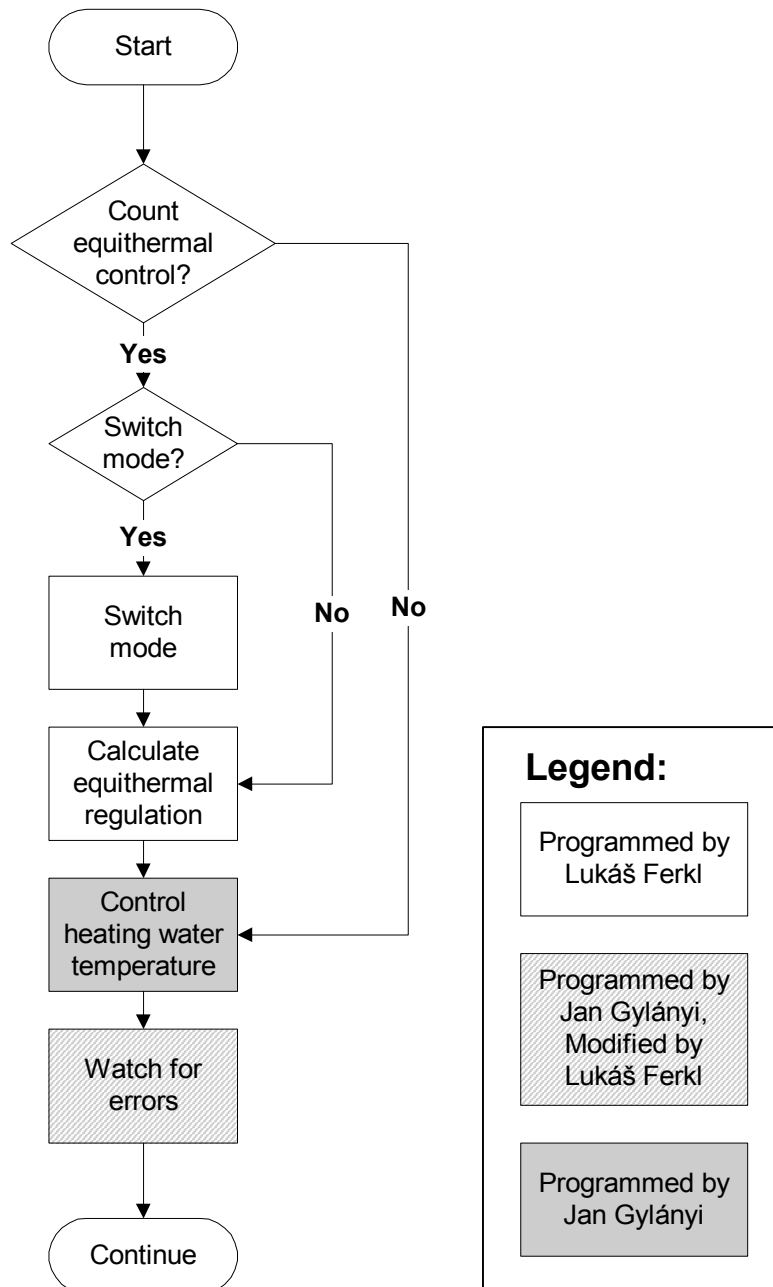The new software is described by following flowcharts illustrating the software operation.

Figure 5.13 - General software flowchart

Figure 5.14 - Heating control

Figure 5.14 illustrates how the control is being done. The equithermal control is counted every 10 minutes. Every time the program is executed, the control procedure regulates the heating water temperature of all four circuits and watches for various errors – big difference between reference temperature and actual temperature, excessive temperatures etc.

The equithermal control can count a heating water temperature that is higher than the inlet hot water temperature from the heater. In this case, the temperature is set to ($\theta_{heater} - 5\ °C$) so as the PD controller in the inner loop is able to keep it. A warning message is produced as well.
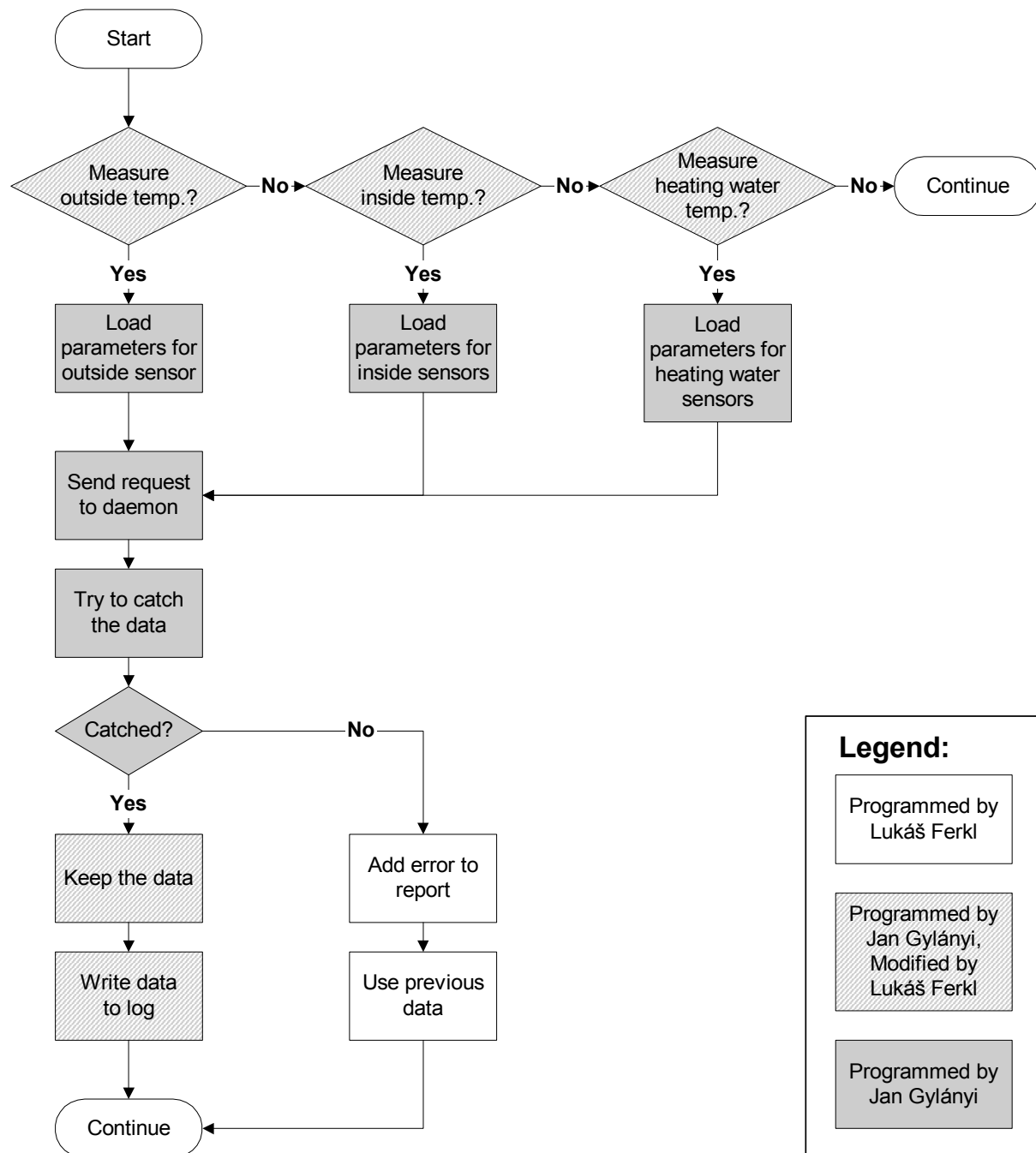
Figure 5.15 - Temperature measurement

Figure 5.15 illustrates the measurement procedure. The measuring system is not very reliable, the procedure has to be very safe and robust.

The measurement intervals can be set by a configuration file, the usual values are stated in Table 5.3. If some temperature cannot be measured, the previous value is used. If the system fails to provide a heating water temperature, no control action is carried out.

Temperature	Outside	Inside	Heating water
Interval	10 min.	5 min.	30 sec.

Table 5.3 - Measurement intervals
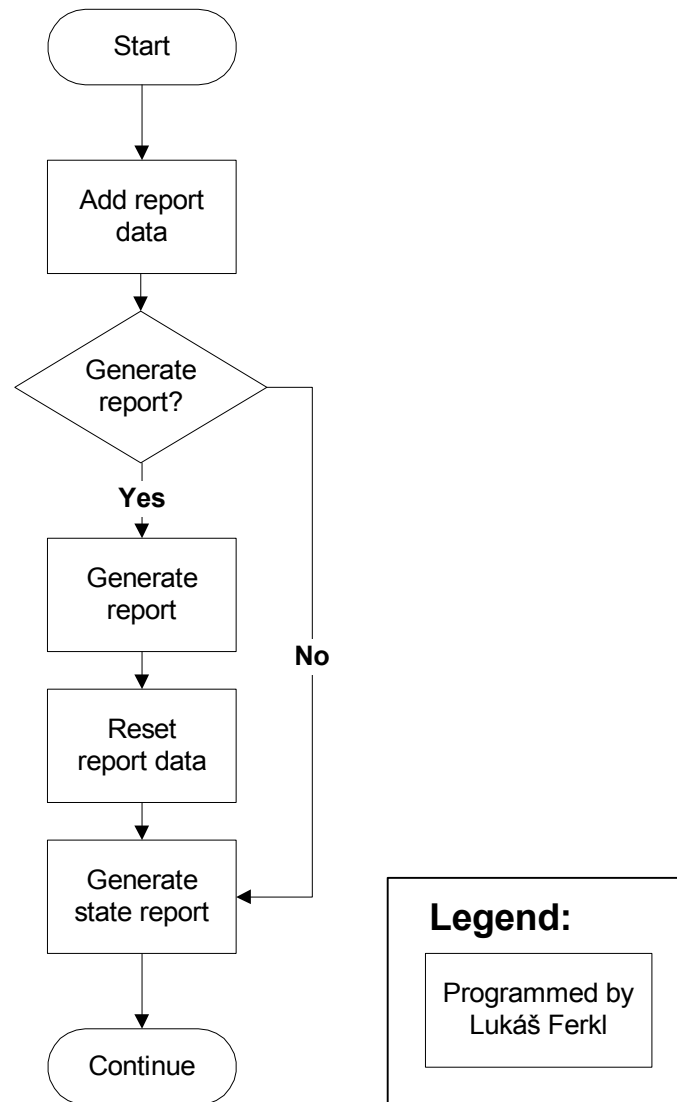
Figure 5.16 - Report generation

Figure 5.16 illustrates the report generation. A major report is generated every 8 hours, a state report is generated every 30 seconds.

A major report includes the information about the minimal, average and maximal temperatures on all the circuits, inside and outside, reports the errors and warnings and the times of switching the modes. I use this for sending the report via SMS (Appendix C).

A state report generates a file with all the actual information available. It can be used by some other program watching the state of the system and its control. It can be used for www presentation as well.
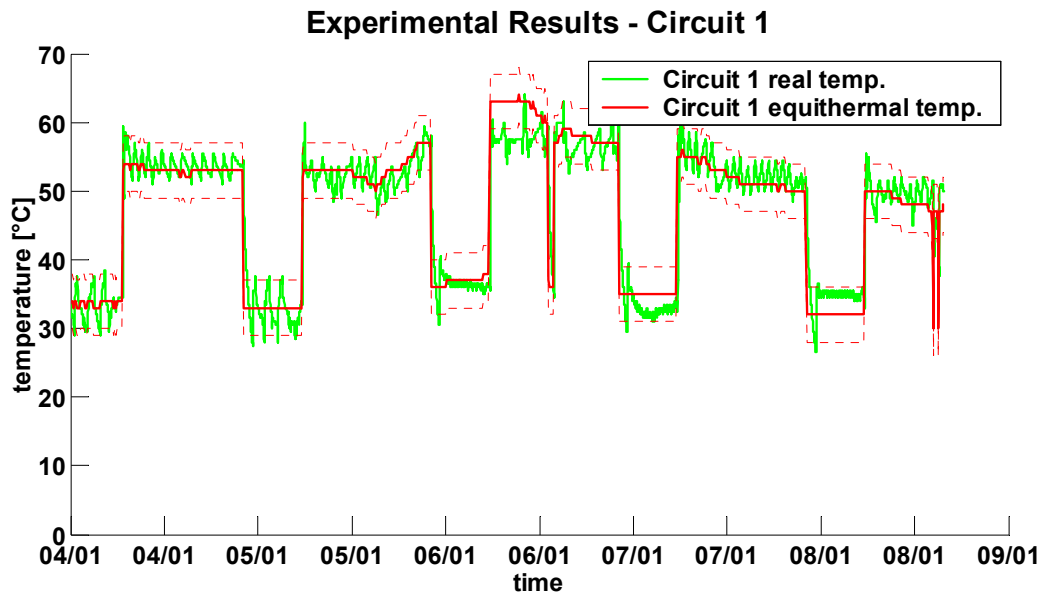
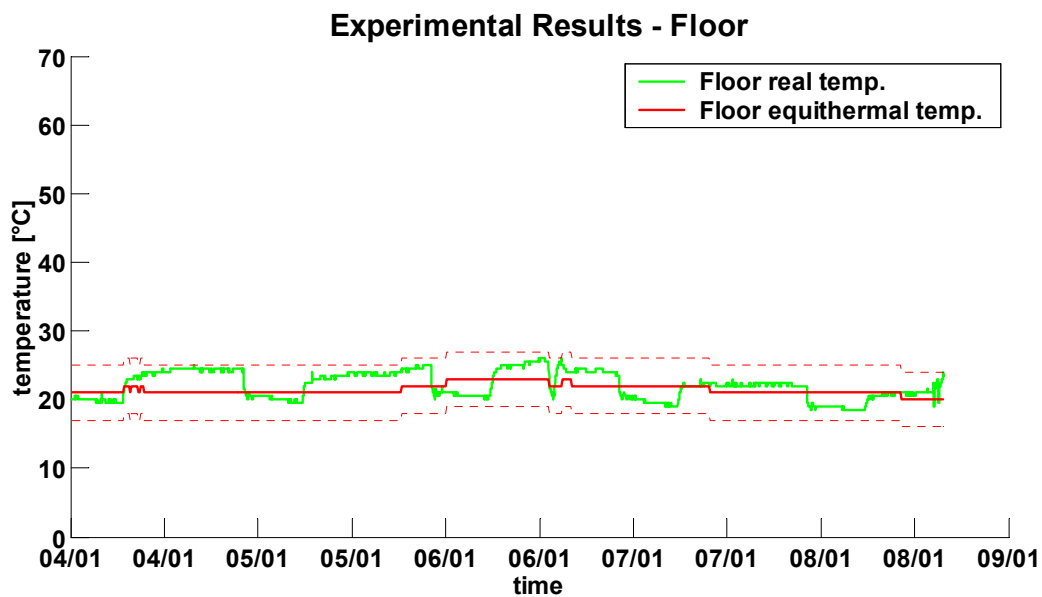The configuration files can be found in Appendix B.

6   Experimental Results

6.1   Inner loop

Experimental Results - Circuit 1

Figure 6.1 - Experimental results of the circuit 1 heating water temperature control
with the insensitivity band (January 2004)

Experimental Results - Floor

Figure 6.2 – Experimental results of the floor heating water temperature control
with the insensitivity band (January 2004)

The heating water temperature control looks very well (Figure 6.1). The insensitivity band has
been set to ± 4 °C according to contractor's demand.

However, this is not ideal in the case of the floor heating water temperature (Figure 6.2). In
this heating circuit, the temperature is required to be tight controlled. Therefore,
a modification to the insensitivity band is necessary.

6.2 Outer loop
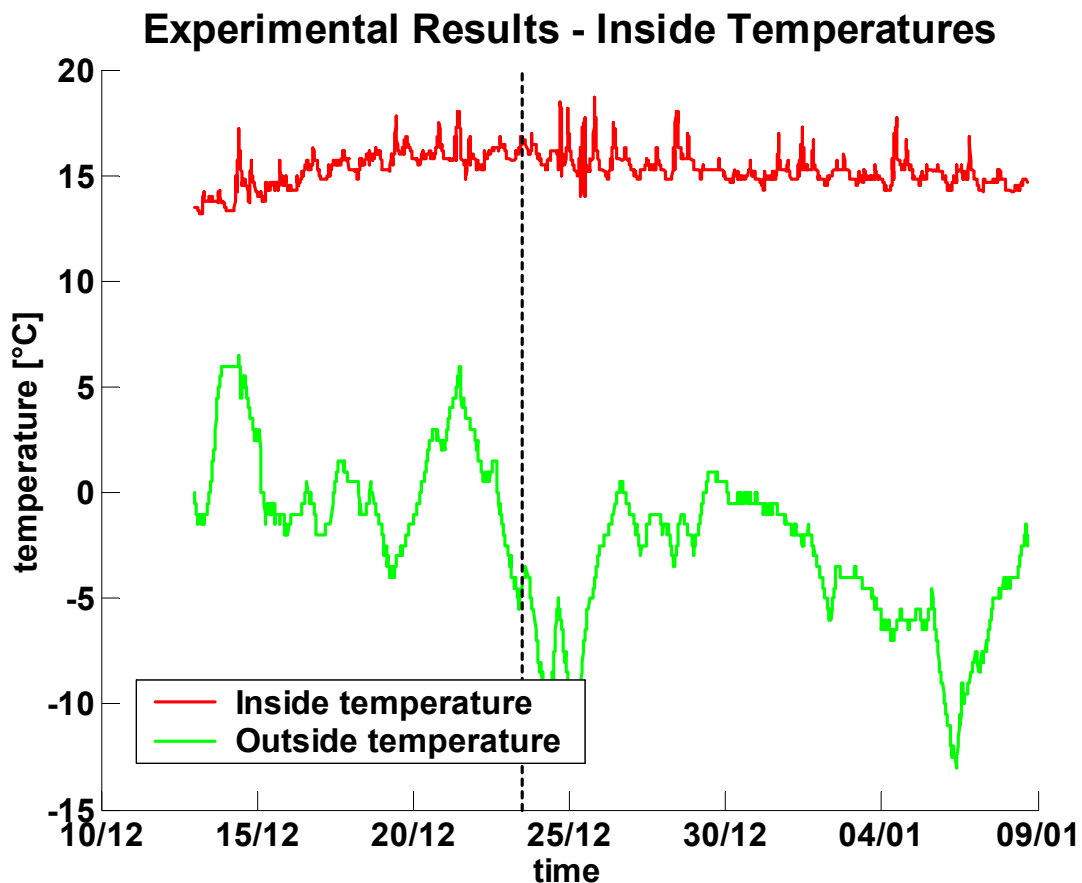
Figure 6.3 - The experimental results of the inside temperature. The black dashed line shows the time of equithermal parameters modification (Dec 2003 – Jan 2004)

The inside temperature exhibited a gradual rise to the average temperature of approx. 16.5 °C at first. I made a change to the equithermal parameters on December 23, 2003, so as to lower the inside temperature. This moment is indicated by a black dashed line on Figure 6.3.

Figure 6.4 and Figure 6.5 illustrate a comparison of inside and outside temperatures, as well as the heating water temperatures. (See 5.2.2 - Equithermal control design for a detailed explanation of the plots.) The day values are quite satisfactory. However, the night values show big differences from the counted values. There are two reasons for this – the insensitivity band again, and, in addition, the data processing function takes the temperatures from 22:00 to 7:00 as night temperatures, however, the night mode could have been set to a different period.

The insensitivity band has an effect on both circuits. On the other hand, it seems to have no influence on the inside temperature in the church of St. Theresa from Lisieux. Since it saves the lifetime of the servo valves, it has been suggested to keep it within the current values by the contractor. The insensitivity band leaves space for future improvements though.

Circuit 1
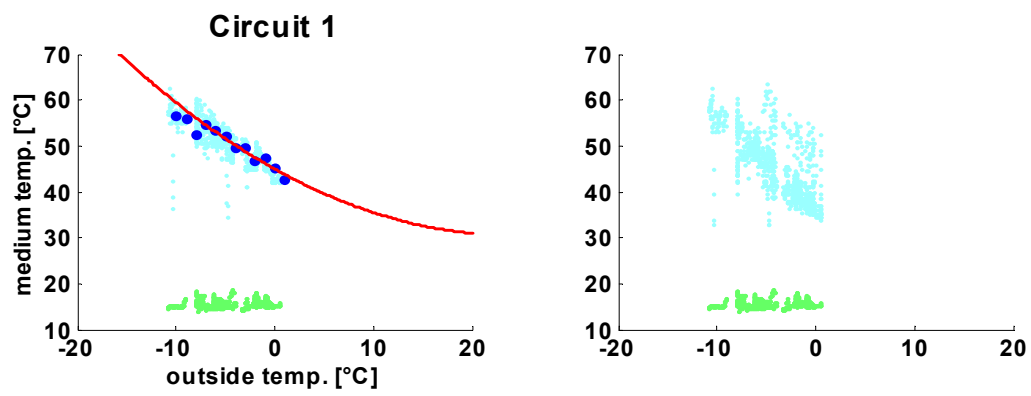
7   Future

7.1 ARX

From the ARX model, we can get some information about the system and we can use the model for a future feedback control of the outer loop of our system.

For an ARX modeling with the MATLAB System Identification Toolbox, the data from January 2002 have been used as they are reliable and a large temperature fluctuation occurred in that time (see Figure 3.5 and 3.3.2 - "Useful" data recognition). The first half of the data was used as the validation data, the second half (containing the temperature anomaly) was used as working data. There were three inputs (outside temperature, floor heating water temperature and circuit 3 heating water temperature) and one output (inside temperature). From all the data, the means have been removed beforehand.

First the System Identification Toolbox was left to determine the optimum ARX parameters. Then the parameters were set according to the theoretical modeling done in 4.1 - System modeling. Assuming that the church behaves as a single-layer building, we would like to find a model in a form of

$$y(t) = \frac{b(d)}{a(d)} u(t) + e(t) \tag{7.1}$$

with the orders n_a=3 and n_b=2. As can be seen from Figure 7.1, the model based on the theoretical assumptions is a little worse than the best-fit model, on the other hand the difference is not significant. In general, the ARX modeling is rather disappointing.
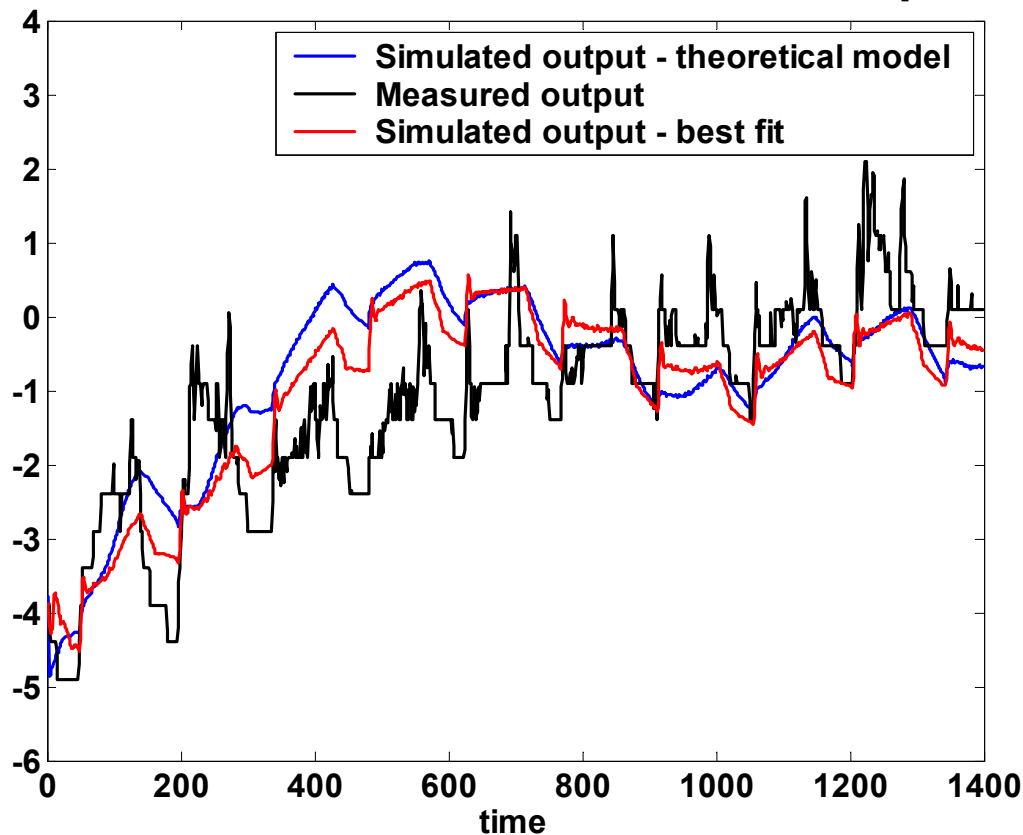

Figure 7.1 - ARX models

7.2 Feedforward compensation

A feedforward compensation provides means of taking the disturbances into account. This is very useful, especially when the disturbances can be measured. The feedforward compensation generally improves control by arresting the influence that disturbances have on a system as they happen [1].
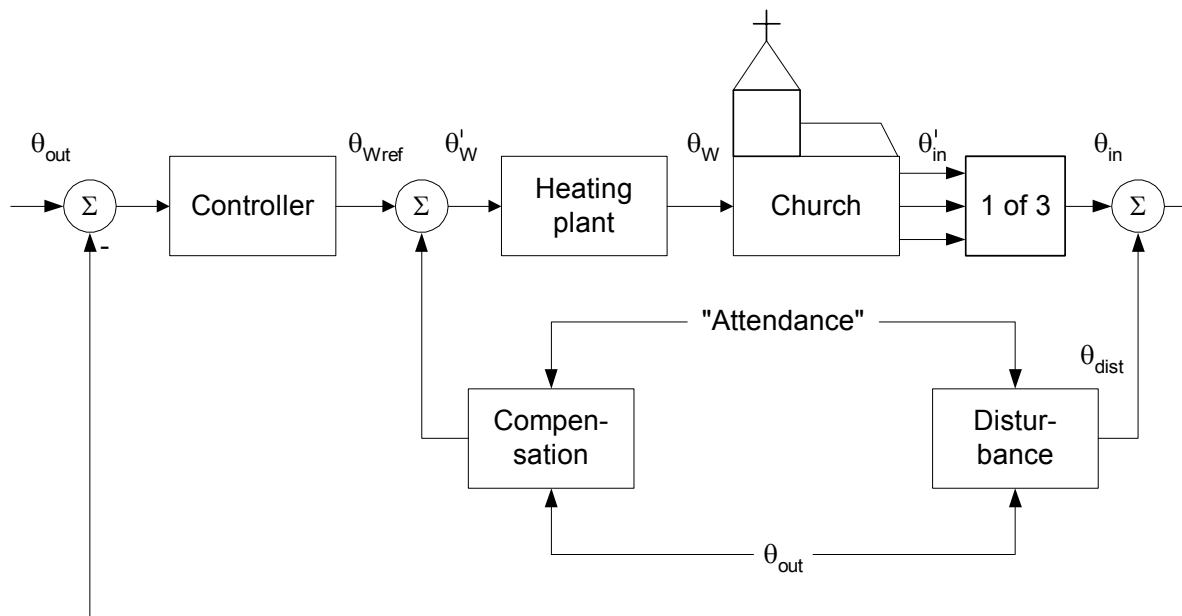
To design a feedforward compensation, we have to fulfill some basic conditions:

- The transfer function of the disturbance has to be known. This is not as easy as it seem to be considering our main time constants have values in the order of tens of hours.
- All the major disturbance variables have to be known.
- It must be possible to measure the disturbance. In our case, it is very difficult to measure the attendance to the church.

Because of these factors, it is strongly advisable to use the feedforward compensation with feedback control. There are two major disturbances on our system – the "attendance" to the services and the outside temperature θ_{out}. To design a feedforward compensation of our system, we have to know the transfer functions of the disturbances. The transfer function of the compensation is as follows:

$$compensation = \frac{disturbance}{plant} \tag{7.2}$$

We can measure the outside temperature, but the attendance would have to be "measured" statistically (e.g. suppose that the service on Sunday, 9:30 has always an attendance of 300 people). However, to design the feedforward compensation, various identification experiments would have to be performed.

Figure 7.2 - Control feedback with feedforward compensation

7.3 Robust control design using H$^\infty$ methods

The robust control "problem" is to find a controller, G_c, which is stabilizing when subject to a combination of disturbance, measurement noise and model uncertainty. One powerful method in robust control design is to minimize the H$^\infty$ norm of the plant. The theoretical background of this method can be found in [1].

For our model, we will use a simplified model obtained by ARX modeling (see 7.1 - ARX). Assuming that the floor heating water temperature and the outside temperatures are constant, we get a model transfer function with the Circuit 3 heating water temperature as input and the inside temperature as output. The transfer function is as follows:

$$G(s) \quad \frac{4.228 \ 10 \ (s-0.2701)(s-0.002346)(s+0.001027)}{(s+0.002745)(s+2.911 \ 10 \ )(s \ +0.00648s+3.791 \ 10 \ )}$$

7.4 Outside temperature forecasting

Generally speaking, there are "only" two factors that have an influence on the church of St. Theresa from Lisieux – the people and the weather.

Considering the people, something is predictable (the expected attendance on the service), something is not (whether someone will leave the entrance door open or not).

However, we can predict the weather as well. The daily temperatures are available on various web pages and it is not difficult to write a script (in Perl, Python etc.) to download the weather forecast every day (Figure 7.4). The major problem is to find a relation between the predicted temperature on weather forecast and the real outside temperature measured by our sensor, as well as the daily temperature progress (the weather forecast tells the maximum and minimum temperatures, but we have to know the temperature forecast for every day).

If we knew the temperature forecast for next few hours, we could eliminate the time lag of our system and heat "in advance". For details about this type of control, see [9].
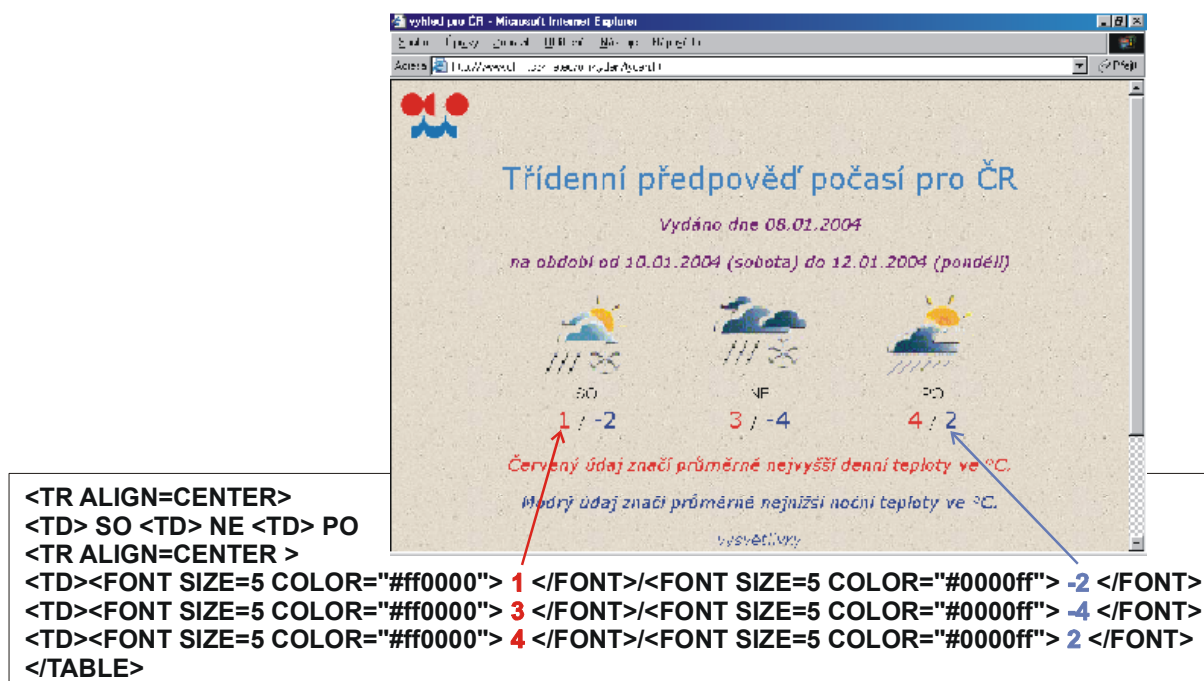
Figure 7.4 - Weather forecast on the web and the corresponding html
source code – html://www.chmi.cz

8   Conclusions

8.1 Summary

I have designed, implemented and successfully tested a heating control system for the church of St. Theresa from Lisieux. During the one-month testing period, no serious problems occurred and the system output fulfills the originally stated requirements.

After getting familiar with the 3-year data set available, it was feasible to design the system in complexity, with all the possible disturbances taken into account. However, the implementation of the system has been rather problematic and further upgrades are likely to be done, mainly the source code optimization. Part 7 - Future, proposes some further improvements including some modern control methods.

8.2 Next steps

Here is a proposed outline for the next steps that may be taken:

- **Code optimization**
  Includes data structure design, general flowchart design and an "easy-to-read" implementation. It is crucial for all the following steps.
- **Daemons debugging**
  There are some indices that the communication daemons don't work properly. This step may increase the system reliability.
- **Web presentation**
  Some people would find it useful to see the inside temperatures of the church of St. Theresa from Lisieux on the web.
- **3-position incremental PID control**
  This type of a controller can be used for the inner loop control.
- **Temperature forecast**
  Some statistically reliable system of the outside temperatures prediction can be found for an advanced "predictive" control strategy.
- **Equithermal design with the temperature forecast**
  It may be interesting to see if the forecast of the outside temperatures improves the behavior of the current system.
- **Feedback control of the outer loop with modern methods**
  The equithermal control does not allow some modern methods stated in 7 - Future.
- **GSM control**
  The system might be controlled by a GSM module.

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and last but not least

St. Theresa from Lisieux
for her church.

Appendix A
3-Position Incremental PID Controller MATLAB Source Code (Simplified)

```
% This m-file controls the servo valve and
% provides a 1 % accuracy.

if delta_u > 0,
    if valve_is_increasing,
        Buff_increase = Buff_increase + n;
    else
        Buff_decrease = Buff_decrease - n;
        if Buff_decrease < 0,
            Buff_increase = -Buff_decrease;
            Buff_decrease = 0;
            valve_is_decreasing = 0;
            valve_is_increasing = 1;
        end;
    end;

elseif delta_u < 0,
    if valve_is_decreasing,
        Buff_decrease = Buff_decrease + n;
    else
        Buff_increase = Buff_increase - n;
        if Buff_increase < 0,
            Buff_decrease = -Buff_increase;
            Buff_increase = 0;
            valve_is_increasing = 0;
            valve_is_decreasing = 1;
        end;
    end;
end;

if Buff_increase > 0,
    Output = 0.01;
    Buff_increase = Buff_increase - 1;
elseif Buff_decrease > 0,
    Output = -0.01;
    Buff_decrease = Buff_decrease - 1;
else
    Output = 0;
end;
```

Appendix B
Configuration Files

Modes Switching

```
#This is a comment
#Modes configuration file
#One day has the following structure:
#PO          starts Monday; every day starts in NIGHT mode
#  06:30 D   at 06:50 the system switches to DAY mode
#  09:00 N   at 09:00 the system switches to NIGHT mode
#  17:00 D   etc.
#  22:00 N
#/PO         ends Monday;

PO
  06:30 D
  22:00 N
/PO
UT
  06:30 D
  22:00 N
/UT
ST
  06:30 D
  22:00 N
/ST
CT
  06:30 D
  22:00 N
/CT
PA
  06:30 D
  20:00 N
/PA
SO
  06:30 D
  10:00 N
  16:00 D
  20:00 N
/SO
NE
  06:30 D
  12:00 N
  16:00 D
  22:00 N
/NE
```

Equithermal Parameters

```
#This is comment
#Equithermal parameters configuration file
#
#The active NIGHT and DAY modes are indicated by tag MODE
#MODE normal_day normal_night indicates
#the DAY mode uses normal_day settings and
#the NIGHT mode uses normal_night settings
#
#The lines include the constants of the respective circuits
#OKRUH1  0.025  -0.2  45  15
#The heating water temperature in Circuit 1 (OKRUH 1)
#will be calculated as follows:
#t1 = (0.025)*tout^2 + (-0.2)*tout + 45
#and the heating will be switched off at 15 C

MODE den noc

den
OKRUH1     0.025     -1.2      45        15
OKRUH2     0.025     -1.3      41        15
OKRUH3     0.037     -1.3      42        15
PODLAHA    0         -0.3      22        10

noc
OKRUH1     0.01      -0.6      30        15
OKRUH2     0.01      -0.6      30        15
OKRUH3     0.02      -0.8      30        15
PODLAHA    0         -0.3      22        10

#this mode will not be used (it is not on the MODE line)
studena_noc
OKRUH1     0.1       -1.5      50        20
OKRUH2     0.1       -1.5      50        20
OKRUH3     0.2       -2.2      60        20
PODLAHA    0         -0.3      22        10
```

Appendix C
SMS Report

This is an example of a report sent by SMS every 8 hours.

```
16:00:00                   //Time of report generation
Tout: 0.5 1.4 2.0          //Outside temp.
Tin: 15.7 16.1 16.5        //Inside temp.
C1: 39.5 43.6 46.5         //Circuit 1 heating water temps.
C2: 34.5 39.2 41.0         //Circuit 2
C3: 37.5 39.2 41.0         //Circuit 3
Fl: 22.0 22.3 23.0         //Floor
Al: 53                     //Number of alarms
F: MMMMMMMMMMD             //Alarm flags
M: OD08:10:00 N15:30:00    //Modes
```

The temperatures show the minimal, average and maximal values during the monitored period.

The alarm flags are generated at the rate 1 flag / 5 alarms. The characters have the following meaning:

M – (measurement error) one temperature sensor inside the church differ from the two others
D – (difference) the difference between the computed and real value of the heating water temperature is greater than 10 °C
C – (communication error) one temperature sensor sent no data

The meaning of the modes is as follows:
OD08:10:00 – the report started **O**riginally at 08:10:00 with the **D**ay mode
N15:30:00 – the mode has been switched to **N**ight at 15:30:00
Still another value can be displayed:
RESTARTN21:56:23 – the entire system was restarted at 21:56:23 with the **N**ight mode

SMS example in operation