PID in Smart Buildings

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Abstract—This paper investigates a smart heat control system inside a household using a family of dynamic controllers called PID (Proportional Integrative Derivative), conducted with Wireless Sensor Networks (WSN). The laws of thermodynamics and other physical knowledge was used to model the effect that a heat exchanger has on the temperature of a room. Realistic simulations have been run to illustrate how a PID control system outperforms the traditional on-off approach, in terms of energy efficiency. Simulations shows that the PID controlled system is 28% more energy efficient than an on-off. This can make the future use of PIDs in home automation more common. Lastly a future extension to other systems is discussed.

I. INTRODUCTION

ENERGY efficiency is an increasingly centralized subject in today’s building sector, due to the expanding population and increasing energy consumption around the world. Buildings are responsible for approximately 40% of the world’s annual energy consumption [1]. United Nations Population Fund predicts that the number of megacities will increase by 13 (from 28 to 41) by 2030, which are expected to have more than 10 million inhabitants [2]. Then, construction companies are challenged to build more energy-efficient buildings. One way to reduce the energy consumption in these cities and others around the world is by means of smart buildings [3].

Smart building is as colloquial expression to refer to a building equipped with some advanced technologies allowing it to make its own decisions [4]. These technologies are called “home automation” systems and are usually divided into three generations [5]:

1. Wireless technology (First generation)
2. Artificial intelligence (Second generation)
3. Robot buddy (Third generation)

The so-called “home automation systems” can, for instance, regulate the heat flow or adjust the brightness of the lights inside a household depending on the needs of the residents. They are able to do this by using a wireless network. Home automation systems can also control washing machines or implement robotic systems for cleaning purposes. Research regarding smart building applications is being made constantly, and the number of energy-efficient oriented application keeps ascending.

A prior project regarding control systems for energy in smart buildings showed that it was possible to reduce the energy consumption by using a multi-agent control system with an intelligent optimizer [6]. These agents could control everything ranging from the energy flowing from the power grid to the smart building system to the temperature inside the household [6]. In this work, we propose to use a PID (Proportional Integrative and Derivative) control system, together with a WSN (Wireless Sensor Network), as a solution to home automation and energy efficiency.

PID controllers are one of the most common control systems implemented in industries. An investigation in Japan showed that more than 90% of the controllers used in their industries were PID controllers [7]. Its advantage over traditional static controllers is that it uses more information to design the control law applied to the controlled system. On the other hand, WSNs have become an important aspect in automation and especially in the field of Internet of Things (IoT) [8]. It has been shown that they provide an efficient way to reliably transmit data without incurring in a large distortion.

The objective of this thesis is to investigate the characteristics of building automation and control systems using Wireless Sensor Networks (WSNs). Particularly, temperature control inside a room will be studied. The heat will be controlled by a PID controller supported by a WSN. This system will be compared to an on-off controller in terms of energy-efficiency. The transmission problem that WSNs can introduce will also be studied, along with the robustness of the PID controller in terms of performance. These two aspects will be studied by simulating the closed-loop systems. Realistic scenarios will be implemented by modelling disturbances and the shortcomings of using WSNs.

The layout of this work is structured as follows. Section II states the problems, Section III designs the model, Section IV presents the PID controller, Section IV describes how the model of the control system was created, Section V studies the Wireless sensor network along with communication protocols, topologies, delays and packet losses, Section VI presents results and discussion, Section VII introduces a new application and Section VIII, is the conclusion of this paper.
II. PROBLEM STATEMENT

Consider a heat exchanger (radiator) inside a room, whose input-output relationship is defined by the unknown system $G$ as

$$y = G u,$$

where $u = \{u(t)\}_{t \geq 0}$ is the input signal, corresponding to the power flowing into the heat exchanger, and $y = \{y(t)\}_{t \geq 0}$ is the output signal, corresponding to the noiseless temperature in the room. Both of them are considered to be continuous-time signals.

The temperature inside a room will be controlled by using traditional control architecture together with a network of sensors, communicating to each other wirelessly, as depicted in Fig. 1. Here, $r = \{r(t)\}_{t \geq 0}$ corresponds to the reference signal, representing the desired temperature in the room, and $e = \{e(t)\}_{t \geq 0}$ stands for the error between the desired temperature and the one in the room. System $F$ stands for the PID controller, whose output $u_c = \{u_c(t)\}_{t \geq 0}$ is known as the control signal. Signal $v = \{v(t)\}_{t \geq 0}$ is all the external disturbances on the control signal. Finally, the WSN block within the feedback defines a new system, probably introducing delays, packet loss and distortion.

The controller design is based on the physical knowledge of system $G$, condensed in a LTI (Linear and Time-Invariant) model. Then, the first task is to derive this model. After synthesizing $F$, the behavior of the control loop will be simulated on a realistic fashion to analyze the closed-loop performance and energy efficiency. For this purpose, it is necessary to model the disturbance $v$, and the problems that the WSN can introduce. In fact, the WSN must be chosen adequately to fit control performance requirements.

Summarizing, the problems we are solving are the following:

1. To derive a model for $G$ and to model the disturbance $v$.
2. To design an appropriate controller $F$.
3. To study a WSN, along with communication protocols and topologies, choosing the most suitable for this project.
4. To simulate the closed-loop system.

III. MODELING

The model of the system was constructed by analyzing a common bedroom in an apartment with the area of $75 \text{ m}^2$ see Fig. 2. Bedroom 1 consists of a window, a door, a heater, a...
\[ T(s) = \frac{1}{s + \frac{K}{W}} \]  \( s \) \[ (s) \]

\[ A. \text{ Solving } C \text{ and } D \]

C: The specific heat capacity of air in constant volume is approximately \( c_v = 0.718 \cdot 10^3 \frac{J}{kg \cdot K} \) \[ 10 \] at NTP (Normal Temperature and Pressure). Though the calculated value was in J/K therefore the mass of the air was needed and was calculated with the volume of the room. According to bedroom 1, the volume is 15 m\(^2\) \cdot 3 m = 45 m^3 and by multiplying it with the density of air which is approximately 1.2 [kg/m\(^3\)] \[ 10 \], the mass of the air was obtained as 54 kg. The sought-out heat capacity was derived by multiplying the specific heat capacity of the air with the mass, which gave

\[ C = 38772 \left[ \frac{1}{K} \right], \]  \( (4) \)

D: The heat-transport coefficient depends on many factors, such as the type of materials and area. Boverkets rules of construction \[ 11 \] showed a general demand of what the heat-transport coefficient should be regarding the materials used in the household, the following values were obtained in table I.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \gamma ) [W/m(^2)K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>0.18</td>
</tr>
<tr>
<td>Window</td>
<td>1.13</td>
</tr>
</tbody>
</table>

The heat-transport coefficient was derived by multiplying the heat resistant with the surface area of the exterior walls in bedroom 1 in Fig. 2 and the window \( \gamma \cdot A \), which gave the total value

\[ D = 7.88 \left[ \frac{W}{K} \right], \]  \( (5) \)

The calculated parameters (4) and (5) resulted with the following transfer function model of the temperature (6)

\[ T(s) = \frac{2.57 \cdot 10^{-5}}{s + 2.1 \cdot 10^{-4}} \left[ \frac{K}{W} \right] \]  \( (6) \)

The transfer function (6) is representing the model G mentioned in Section II, and is a first order equation.

B. Disturbances

In real time environment, a control system always gets affected by many sources of disturbances, taking them under consideration enables a better handling of the problems.

Sources of disturbances and the calculations are listed below. These disturbances were implemented into the simulation because they have an additive effect over the control signal.

1) Outdoor temperature

One of the most common disturbances in this type of system and according to equation (5), is the outside temperature which affects most of the temperature inside a room. The zero laws of thermodynamic say that the heat goes from warm to cold. In the northern part of the globe, the average temperature per year is below 25 °C which is the general temperature inside a common room, so there will be a heat-transfer out of the room in large part of the year. This was considered while simulating the heat inside a room.

The sum of the heat-transfer coefficient was calculated by considering the materials in table I for the exterior walls in bedroom 1, which gave

\[ DT_{out}(t) = 7.88 \cdot T_{out}(t), \]  \( [W] \)  \( (7) \)

the outside temperature varies depending on the time of the day.

2) Humans inside the room

People are biological creature that needs a constant body temperature to maintain its functionality. By taking that in to consideration it was realized that the thermal radiations from people affect the household temperature. A person releases approximately 70 W when sleeping and 100 W when doing light work \[ 12 \]. This was considered while simulating this disturbance.

3) Sun

The solar radiation is another disturbance that can perturb the control of the temperature inside a room. The direct heat of the sun increases the temperature inside a household through illumination via windows. To be able to model it can be by deriving from the solar constant on the surface of the planet, which is approximately 684 \( \frac{W}{m^2} \) \[ 13 \]. Considering the clouds and windows reflecting some of the radiation with an approximation that 40% of the total incoming energy will penetrate to the room during 6 hours a day

\[ P_{sun} = 0.6 \cdot 684 \frac{W}{m^2} \cdot 3.75 m^2 \cdot \frac{6 \text{ hours}}{24 \text{ hours}} = 384.75 [W] \]

For the simulation, a stochastic model was used for the solar disturbance with the expected value of 384.75 W.

IV. PID CONTROLLER

PID controllers are today the most common controllers used in industries partly because their simplicity and operating conditions in wide range. The purpose of the controller is to regulate a desired output of a control system, which is in this case, the temperature in a room, by having a closed loop system, that takes the feedback loop and compares the output with the reference signal as an error signal which serves as the input to the controller.
The PID controller can be decoupled as a linear combination of these expectations whose weights $K_p$, $K_i$, $K_d$ parameterize the controller.

$$u_c(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$ \hspace{1cm} \text{(8)}

The first factor in equation (8) is the proportional factor, the second is the integral factor and the last is the derivative factor. Translated into Laplace domain [9] gives the following transfer function:

$$F(s) = K_p + K_i \frac{1}{s} + s \cdot K_d$$ \hspace{1cm} \text{(9)}

Each part of the PID controller has different functionalities taken on the error:

- **P.** The proportional factor observes the current error. The output is described as product of gain and error. Consequently with too high value of the weight $K_p$ results in oscillation. The Problem with only using a proportional gain with small error is that, it makes the output negligible, resulting with an error even when the proportional loop reaches steady state [14].

- **I.** The integral feedback observes how the error reacts. The integral factor is a summation of the errors. One of its function is to eliminate the steady-state error. A side effect of the integral factor is that it contributes with overshoot, with shorter integral time result in more aggressive work done by the integral [14].

- **D.** The derivative feedback works on the changes of the error, referring to foreseeing the change of the error. The derivative improves the stability but is sensitive for noises and it works on high frequencies with the error coming from minor disruptions [9].

### A. PID tuning

There exist different tuning methods, each method focus on different things, such as the rise time, overshoot and settling time. The parameters $K_p$, $K_i$ and $K_d$ defines a PID controller and are of big interest while tuning a PID control. One of the most common tuning methods is Ziegler-Nichols method and is known as the ultimate gain method [15]. The tuning methods that will be studied in this subsection are the auto tune method in Simulink and Ziegler-Nichols method.

#### Auto tune method:

The auto tune method is a tuning method embedded in Simulink, which is an add-on product in Matlab that provides graphical modeling, simulation and analyzes of dynamic systems [16].

The Auto tune method in Simulink tunes the controller by automatically computing a linear plant model from the Simulink model and designs an initial controller. The tuner computes PID parameters that robustly stabilize the system [17]. The only thing that is necessary to perform the tuning is a button press.

The parameters that was obtained after pressing the tuning button gave the following equation by using (9)

$$F_{Auto \ tuned} = 10.96 + 0.004625 \frac{1}{s} - 1573s$$ \hspace{1cm} \text{(10)}

#### Ziegler-Nichols method:

There exist two different versions of Z-N (Ziegler-Nichols) tuning: open loop and the closed loop methods. Only the closed loop method will be considered in this article.

This method is implemented by first increasing the proportional gain of the proportional factor until the system starts oscillating with constant amplitude. The values that are being sought are the critical gain $K_c$ and the period $P_c$. When the critical gain has been reached, the period can easily be determined from the step response by measuring the amount of time between two peaks [18].

The parameters $K_p$, $K_i$, and $K_d$ can be determined by the formulas in Table II when $K_c$ and $P_c$ have been provided.

| **TABLE II** ZIEGLER-NICHOLS TUNING FORMULAS [18] |
|---|---|---|
| | $K_p$ | $K_i$ | $K_d$ |
| P | $0.5 \cdot K_c$ | | |
| PI | $0.45 \cdot K_c$ | $\frac{1}{P_c}$ | |
| PID | $0.6 \cdot K_c$ | $\frac{1}{0.5 \cdot P_c}$ | $P_c$ |

In the tuning of the controller, the critical gain was measured to be $K_c = 3060$ and the period was measured to be $P_c = 79.850$ s. The equations in Table II was then used to determine the parameters $K_p$, $K_i$ and $K_d$ and the following equation for the controller was gained:

$$F_{Z-N \ tuned} = 1836 + 0.0250 \frac{1}{s} + 9.981s$$ \hspace{1cm} \text{(11)}

#### B. Control Performance

The performance of a system depends on the PID controller, so when a controller is designed there are a few things to
consider if superior performance is wanted to be achieved. Some examples are settling time $T_s$, rise time $T_r$ and the overshoot $M$, that is described below:

Rise time, $T_r$: The rise time of a step response indicates how long time it takes for the system to increase from 10% to 90% of the unit step input (see Fig. 4) [9].

Overshoot: The overshoot indicates how much the signal exceeds the unit step input. The maximum overshoot $M$, is calculated by using $M = \frac{Y_{\text{max}} - Y_f}{Y_f}$, $Y_{\text{max}}$ is the maximum value on the $y$-axis, $Y_f$ is the unit step input (see Fig. 4) [9].

Settling Time, $T_s$: The settling time indicates the time taken before the output signal gets within $\pm 2\%$ or $\pm 5\%$ of the unit step response (see Fig. 4) [9].

A control system regulating the temperature in a room has reliable performance if the overshoot and settling time are as small as possible. The rise time is not of big interest in this case because the temperature wants to be regulated as precisely as possible. If the overshoot is too big, the temperature in the room will be too hot which is not desired.

![Figure 4. Plot of step response that shows settling time, rise time and overshoot](image)

V. WIRELESS SENSOR NETWORK

The aim of this section is to study the relationship between control synthesis and WSNs, choosing the most suitable topology and protocol from the ones existing. For this purpose, the shortcoming of using a wireless network is studied in terms of control performance. The following properties among different topologies and protocols are used to base the choice: power consumption, battery life, costs, data rate, transmission range, delay, and packet loss.

A. Wireless sensor topologies

Wireless Sensor Networks have different architectures, known as topologies, each of them have a unique structure defining how data flows in the wireless network. The different topologies that can be used depend on its physical layer app. [19, 20]. The topologies that will be studied in this subsection are the star, tree and mesh topology.

Star topology: The star topology consists of a base station (Actuator) and multiple end nodes as seen in Fig. 5 [19]. The base station coordinates the information that the nodes gather. The nodes communicates only with the base station and can only send or receive information, they are not able to send information to each other [21]. So, any packets/information must go through the coordinator. The advantage of this topology is that it is simple, and keeps the power consumption at minimum for the nodes. The disadvantage of this topology is that the network communication depends on the base station because all packets must go through it [19]. If the base station malfunctions all network communication will fall.

Tree topology: The tree topology is built as a tree and consists of a coordinator, several routers and end nodes as shown in Fig. 6 [19]. The coordinator is the root of the tree and the end nodes are called children. Both the coordinator and the routers can have children, but the end nodes cannot [19]. The children are only able to communicate with their parent, which makes communication between the end nodes more complex.

Mesh Topology: The mesh topology consists of a coordinator, several routers and end nodes as depicted in Fig. 7 [19]. If a node wants to send information to another node that is out of range, it can utilize other nodes to convey the message to the requested node, which is called multihop communication [21]. The advantages with Mesh network is that the range of the network can easily be extended by adding new nodes. If one node fails to convey the message, a remote node is still able to complete the work and forward the message to the desired node [21]. However Mesh networks fall into high power consumption because of the multihop communication [21], it
limits the battery life, which is not desired in a home automation system.

B. Communication Protocol

Communication protocols are used for transmitting data between electronic devices, such as computers [22]. The protocols mostly help the computers to understand how the data should be exchanged before a transmission can take place. With other words, protocols are called rules defining transmissions [23]. There are many different communication protocols and each have unique physical appearance and characteristics. There are several factors to be considered when choosing a protocol, such as power consumption, battery life, security, cost, data rate; depending on the environment it will be used.

![TABLE III

COMMUNICATION PROTOCOLS][24]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ZigBee</th>
<th>WirelessHART</th>
<th>ISA100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology</td>
<td>Star, Tree,</td>
<td>Mesh</td>
<td>Mesh,Star,</td>
</tr>
<tr>
<td></td>
<td>Mesh</td>
<td>Star-Mesh</td>
<td>Star-Mesh</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Low</td>
<td>&lt; Still low</td>
<td>&lt;= Still</td>
</tr>
<tr>
<td>Battery Life</td>
<td>Years</td>
<td>Years</td>
<td>Years</td>
</tr>
<tr>
<td>Range</td>
<td>50-100m</td>
<td>50 -100m</td>
<td>50 – 100m</td>
</tr>
<tr>
<td>Maximum Data Rate</td>
<td>250 Kbps</td>
<td>250 Kbps</td>
<td>250 Kbps</td>
</tr>
<tr>
<td>Frequency</td>
<td>868, 915 MHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td></td>
<td>2.4 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Security</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Application Context</td>
<td>Home Automation</td>
<td>Industries</td>
<td>Industries</td>
</tr>
</tbody>
</table>

**ZigBee:** ZigBee is a standard for wireless monitoring and control of equipment in homes, buildings, factories and other places [20]. ZigBee uses the radio standard IEEE 802.15.4 and operates at low-data rate and short range wireless networking. It operates in 868 MHz, 915 MHz and 2.4 GHz frequency bands and the maximum data rate is 250 K bits per second[20]. ZigBee is preferred for home automation systems because of the main characteristics of ZigBee and these are battery-powered applications with low data rate, low cost and long battery life, with other words low power consumption[20]. ZigBee is maintaining its low power consumption by using a sleep mode [20]. As a result of this the ZigBee is able to operate for many years.

C. Delay

The delay of a system can be caused by many factors, such as the type of communication protocol the Wireless Sensor Network uses, the distance between the sensors and the actuators or even the time it takes the heat to reach the thermostat [25], which is called real time delay. The number of sensors is also a factor that can affect the delay, more sensors means a bigger flow of packets and the processing of these packets introduces delay.

**Delay Calculation:** A simpler mathematicaly analyze of the time delay from a WSN, can be computed by using a summation of different time delays from the network. The Nyquist stability criterion [9] can show how much time delay a control system can endure before becoming unstable, which states that

$$n_c = n_p + n_z,$$  (12)

where $n_c$ is the sum of number of circles around $-1$ on the real-axis and depends on the direction of the curves, the clockwise direction counts as $+1$ and counterclockwise as $-1$. $n_p$ stands for the number of poles in the right side of the complex plane by the closed-loop. Last $n_z$ is the number of poles by the open-loop in the right side of the complex plane [9].

By using the Nyquist criteria, equation (12) can be analyzed if the open loop function does not have poles in the right side of the complex plane then the closed-loop is stable [9]. By evaluating the sample for different time delay values, the open system receives a higher or a lower magnitude and this shows if it corresponds to the criteria depending on the delay value.

D. Packet loss

If a transmitted packet fails to reach its destination then it is called a packet loss, this can happen for instance when a node fails [26]. When a packet loss occurs, a control law must know how to deal with it and must be notified when a packet of necessary information disappeared to continue the control process.

![Figure 8. Gilbert Elliot model](image)

Easiest way to model a packet loss is via Bernoulli process. The Bernoulli process utilizes the mathematical theory of probability and statistic. Higher probability for transmission shows better status of the network. Considering a Bernoulli sequence of packet loss as a variable, which is independent and identical, and every variable has a probability of failure $p$ and probability of success $1 - p$ [27]. The Markov chain describes a good and a bad state of the packet. When a packet loss occurs, there is a probability that the next packet will be lost as well. Figure 8 shows the Gilbert Elliot model which shows that each
state got its limit and result. Markov process is characterized with the following probabilities:

\[ p_{gg} - \text{Probability to stay in the good state} \]
\[ p_{gb} - \text{Probability of going from good to bad state (failure rate).} \]
\[ p_{bb} - \text{Probability of staying in the bad state.} \]
\[ p_{bg} - \text{Probability of going from bad to good state (recovery rate).} \]

\[ p_{gg} = 1 - p_{gb}, \quad p_{bb} = 1 - p_{bg} \quad (13) \]

Equation (13) shows that a high value of \( p_{gb} \) and a small value of \( p_{bg} \) result with that the state of Markov process in probability is in a good state.

The packet loss problem will not be studied in the simulation, due to the fact that it is a relatively new solved problem.

The conclusions that can be drawn from this section is that ZigBee is the most suitable protocol among the protocols in Table III because of the low transmission rate, which means less power consumption. The most appropriate topology is the star topology because it is easy to implement and not as energy-consuming as the mesh or tree topology.

VI. RESULTS AND DISCUSSION

The temperature of bedroom 1 in Fig. 2 was simulated using Simulink. The model was simulated by using the control system on Fig. 9. The control system has a reference temperature input as 25°C and a PID controller. The system takes three disturbances into consideration and these are the outdoor temperature, the thermal radiation from a single person and the solar radiation. The block on the feedback loop is a transport delay caused by the WSN and the delay is set to 10 seconds.

A. Tuning Comparison

The auto tune method and Z-N tuning was compared with each other in terms of performance, the most suitable method was then implemented into the control system in Simulink. These simulations of the system were performed without any disturbances.

Figure 10 shows that the Auto tune method is much more stable than Z-N method on Fig. 11. The rise time, settling time and the overshoot is shown in Table IV. It shows that Z-N method is 99.35% faster than the auto tune method but this does not mean that Z-N method is better than the Auto tune method. Z-N method oscillates more than the Auto tune method as seen in Fig. 11 and 10, which means that the auto tune method is way more robust than Z-N method. Z-N method reaches up to 36°C before dropping down, this makes the temperature inside the room hot for an instance, which is not desired. The Auto tune method reaches only 27°C before steady state which is preferable compared to Z-N method. The Auto tune method is therefore used in the simulations.

<table>
<thead>
<tr>
<th>Tuning Methods and Performance Parameters</th>
<th>Auto tune</th>
<th>Ziegler-Nichols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise Time</td>
<td>44 min</td>
<td>17 s</td>
</tr>
<tr>
<td>Settling time</td>
<td>216 min</td>
<td>170 s</td>
</tr>
<tr>
<td>Overshoot</td>
<td>17.442 %</td>
<td>44.203 %</td>
</tr>
<tr>
<td>Max temperature</td>
<td>27°C</td>
<td>36°C</td>
</tr>
</tbody>
</table>
B. Disturbance Simulation

Fig. 12. The outside temperature $T_{out}(t)$

Fig. 12 shows the outside temperature. Implemented with a colored noise whose PSD (power spectral density) is a Dirac delta function at frequency $\frac{1}{24}$ [h$^{-1}$]. The plot shows an average temperature that varies during a day in the middle of spring, with the highest temperature at the middle of the day, lowest during the evening and at the morning. Multiplication of the heat-transfer coefficient (5) with $T_{out}$, gave the necessary input to the plant as power. For the disturbance of the sun, a similar model was used, but plotted with the expected value of 384.75 [W].

Fig. 13. Thermal radiation from a person

The simulation for Fig. 13 was done over 24 hours from the information in Section III-B and described for a single person inside the bedroom 1 with generating a step function. The person slept for 8 hours and released 70 W doing so. Later he studied for 6 hours which is showing with increase of power at 8 hour mark and then left the room. So he was just inside the room for 14 hours.

The simulation with the plant and all of the disturbances with the PID controller shows the output from the system in the plot below.

Figure 14. The output affected by all described disturbances

What the simulation in Fig. 14 shows, is the regulation process of the temperature inside the room. By superposition of the disturbances shows a remarkably roughness. Especially regarding the heat from the person where it is visible comparing with Fig. 13, when the person wakes up and leaves the room. Though maximum temperature from Fig. 14 is 27.32 °C, the lowest is at 23.78 °C and the average temperature 24.74 °C concludes that the used PID controller handled the disturbances well.

C. Comparison of On-Off and PID controller

Simulation of two different controls was performed during this project, mainly because a comparison of energy efficiency wanted to be carried out for respective controls. One controller was the PID controller and the other one was an on-off controller implemented in Bedroom 1 in Figure 2. An on-off controller works so that it switches the heat on and off constantly depending in whether it has exceeded or gone underneath a reference value. The reference value was set to 25°C and all sort of disturbances were ignored except the outside temperature. It is possible to see how the two different controllers work on Figure 15. The On-Off controller oscillates between 28°C and 23°C meanwhile the PID controller gets a constant temperature at approximately 25°C.
The energy consumption was calculated by measuring the integral of the power flow into the plant by the time interval of 24 hours. The calculated energy consumption is shown in Table V and it is possible to see that the PID controller is 28% more energy efficient than the on-off controller. This means that a PID controller is more energy efficient than a common control method for radiators, which looks bright for future use of PID within home automation systems.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Energy consumption [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>5.06</td>
</tr>
<tr>
<td>On-Off</td>
<td>6.51</td>
</tr>
</tbody>
</table>

**D. Time Delay Calculation**

With the help of the theorem mentioned in Section V-C an approximation of the maximum delay of the system for bedroom 1 was evaluated.

The poles of the open-loop system are:

\[ s = -7.94 \cdot 10^{-4}, -2.1 \cdot 10^{-4}, 0. \]

Therefore, \( n_p = 0 \).

The closed loop system gives the poles:

\[ s = -0.00026 - 0.00024i, s = -0.00026 + 0.00024i, \]
\[ -0.0007 \text{ and } n_z = 0. \]

Therefore, the closed-loop system is stable.

Different time delay values \( \tau \) were tested, to determine the limit value before the system becomes unstable.

Figure 16 shows a plot of the Nyquist diagram of the system with the delay 3221 seconds. The curves encircle around \((-1,0)\) which is the red mark, resulting in instability.

In Figure 17 the curve does not encircle around \((-1,0)\) confirming our computations. Concluding with more time delay from the information sending throughout the wireless system shift the Nyquist curve much more to the left of \(-1\) indicating in more instability, and the critical time delay for the system in Fig. 9 is 3221 seconds.

**VII. NEW APPLICATION**

The development of a smart city requires continues innovation of applications that can help the all-day life for the citizens. The public transportation is one of the most central part in a city, which limits the time it takes to go to work or school. Something that affects many citizens nowadays is during rush-hour with many people going in the same direction on the subway. Escalators are a useful way to move up or down in a building, though it can become difficult during rush-hour to use the escalators, if for example everyone wants to get up to the station instead of going down to the trains. A solution that can be to help is sensors that are measuring the number of people that wants to get up and down. Usually there are not equal numbers of people that want to get up or down.

Take for instance that there are four escalators with two going up and two going down. Than some sensors will send information to a base station that also gathers information from other sensors that are located on another side. If the majority of the people on a train station wants to get up than one of the escalators that are going down will change direction and there will be three that are going up and just one that are going down.

A problem that can occur is when a person already is on an escalator when it is going to change direction. A Solution to this can be, to have a sign that tells people not to enter the escalator and blocks the entrance. A Controller that can receive information from sensors that checks if someone is on the escalator can be implemented. The change of direction can than occur when the escalator is empty. This automation system can facilitate the rush-hour and help people to gain some time for getting to work in time.
VIII. CONCLUSION

A PID control method was investigated in this article using a simulation. The results showed that a PID controller consumes about 5.06 kWh and a regular controller consumes 6.51 kWh for a heating system, which means that the PID is 28% more energy efficient. This can make the use of PIDs more common on the future inside households.

The simulation also showed that the PID can handle delays, which shows that a Wireless Sensor Network can be used within home automation systems.

The physical model that was designed to ensure the reality of the control system showed that it was an appropriate model for the heat regulating system.

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REFERENCES


