Aalto University
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Distributed Computing as a Source of Heat:

The Design and Evaluation of a Computerized Heater

Master's Thesis
Espoo, May 24, 2015

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ABSTRACT OF
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Currently, ever growing amounts of electrical energy is consumed by computers and cooling systems in data centers around the world. This has led in to development of several concepts in which the heat output from the servers is extracted from the data centers and utilized as district heat. This raises the question: Could the computers be used in other ways to provide heat for households while performing useful calculations? For instance, could we use computers as replacement for electric heaters?

In this work we expand the idea of reusing the wasted heat from the computers and explore its use as source of direct heat. While the basis for this concept is sound and there are already some experiments ongoing regarding this topic, there are also many unanswered questions regarding the feasibility, reliability and practicality of such approach. To try and answer some of these is the goal of this work and this is approached through designing, developing and testing of a computerized heater prototype. This work also evaluates the results and different approaches that could be taken with these devices and technology.

Overall the results gained with the prototype are encouraging, showing us that computers can provide heat in controllable manner while at the same time performing useful calculations. The main issues with the computerized heaters were in the area of overall practicality and cost of these systems. Based on this several approaches that could improve both the practicality.

Keywords: Computers, Distributed computing, Heating, Electric heating, Energy efficiency, Computer heating

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Alati kasvava määrä sähköä kulutetaan tietokonekeskusten tietokoneiden ja näiden jäähdytysratkaisuijen toimesta ympäri maailmaa. Pyrkimys näiden konesalien energiatehokkuuden kasvattamiseen on johtanut ratkaisuihin joissa tietokoneiden ja servereiden tuottama lämpö otetaan hyötykäyttöön esimerkiksi kaukolämmön muodossa. Kysymys kuuluu voisiko tietokoneiden tuottamaa hukkalämpöä hyödyntää myös muilla tavoin lämmön tuottamisessa? Esimerkiksi, voisiko tietokoneita soveltaa tavallisten sähkölämmittimien korvaajina vaikkapa kotitalouksissa?

Tässä työssä tähän ajatukseen perehdytään tarkemmin tutkimalla tietokoneiden hukkalämmön hyödyntämistä ja sen käyttöä suoran lämmön lähteenä. Vaikkakin perusajatus on melko selkeä ja aiheesta on jo olemassa jonkin verran tutkimusta, sisältyy tähän lähestymistapaan silti paljon vastaamattomia kysymyksiä etenkin käyttökelpoisuuden ja käytännöllisyyden osalta. Tämä työ pyrkii vastaamaan näihin kysymyksiin tietokoneistetun lämmittimmen prototyypin suunnittelemisen, rakentamisen ja testaamisen kautta. Työssä myöskin arvioidaan prototyypistä saatujen kokemusten ja tulosten perusteella erilaisia lähestymistapoja tämän teknologian käyttöön ja jatkokehitykseen.

Yleisesti ottaen, prototyypistä saadut tulokset olivat lupaavia ja osoittavat että tietokoneita voidaan soveltaa suoran lämmön tuottamiseen hallitusti sekä samalla hyödyntää näistä saatava laskentateho. Suurimmat ongelmat näissä laskevissa lämmittimissä kohdistuvat toteutuksen yleiseen käytännöllisyyteen ja kustannuksiin. Tältä pohjalta esitetään työssä erilaisia lähestymistapoja jotka keskittyvät näiden osa-alueiden parantamiseen jatkossa.

Asiasanat: Tietokoneet, Hajautettu laskenta, Lämmitys, Sähkölämmitys, Energiatehokkuus, Tietokonelämmitys

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Johan Strandman

Abbreviations and Acronyms

HVAC	Heating, Ventilating, and Air Conditioning
CPU	Central Processing Unit
PUE	Power Usage Effectiveness
TDP	Thermal Design Power
FLOPS	Floating-point operations per second
GPIO	General-purpose Input/output
PWM	Pulse-width modulation
UDP	User Datagram Protocol
GPU	Graphics Processing Unit
AC	Alternating Current
DC	Direct Current

Contents

Chapter 1

Introduction

In this work we look in to the possibilities of wasted heat of computers as a source of heat and as means of improving the efficiency of electric space heating. At first this concept may seem somewhat foreign from traditional viewpoints of both heating and computer technology, especially if consider how far these two areas of technology are from one another. However if look closer into the areas of electric heating and computer hardware, along with their current trends, the concept and the benefits become more obvious. In terms of heating, efficiency is usually searched by changing into more efficient solutions of producing heat. In many cases this means changing into entirely different means of heating that provide better efficiency. An example of this would be move from locally generated heat to district heating where possible. However, if a more efficient solution is not viable or available, we still need to resort into technologies that are effective but not as efficient. Electric heating is one of these technologies, adopted due to its convenience, flexibility and wide availability of electricity. Also because of these reasons, electric heating has been one of the more popular solutions to heating in the past and still a valid choice in new buildings. However, there is an ever increasing drive to promote alternate heating solutions over conventional electrical heating, mainly due to the large amounts of energy it requires. And while the basic technology itself is efficient and clean, the means by which the used electricity is produced may not be. The problem is that while policy making can direct new buildings towards more viable heating solutions, we still have a large number of electrically heated households in existence. This is evident in Finland, for example, where there is a large base of electrically heated building especially in rural areas and while the amount of new buildings that choose electrical heating as their main heat source has been declining, it is still among the most popular choices of heating energy forms. Also interestingly, while some households in Finland have converted to other heat sources from the electric heating, some have converted into electric heating from other heat sources, primarily from use of heating oil. [31]

Considering the evidence indicating that the electric space heating is likely to be used for years to come, could we do something to improve the electric heating itself? This question has been partially answered by the heat pump technologies that have become more common in past decades and operate at energy efficiencies much higher that normal electric space heating. However, these devices are still intended to compliment the existing heating systems, especially if the outside temperatures can fall well below -15 degrees Celsius [8].

Interestingly, in the area of computer technology a problem that is almost the direct opposite of this exists. Computers, like all electronic devices, generate waste heat whenever operating and the disposal of this waste heat and reducing the power consumption which leads to the heat in the first place is among the priorities in computer design. This can be seen from the past and current commitments of major processor manufacturers AMD and Intel [23] [17]. Alongside the technology advancements, we also have several experiments and active ventures on utilizing the waste heat generated by computers to provide heating, but these are mostly restricted to large computer centres or larger buildings. The benefit from this kind of heating is that while providing heat, the computers also provide us with computational power. This in turn means that the efficiency of computers when used as heaters is higher than that of plain electric heaters. This approach also brings about potential of sharing or reducing energy costs, which especially attractive to data center operators [30]. The energy consumption of the data centers in US alone is in the range of 90 thousand gigawatt-hours [26] and at the same time electric heating in Canada used roughly 58 gigawatt-hours (218 petajoules) of electricity in 2012 [24]. If the heating of households could be done using computers and in association with data center operators, at least part of this energy could be saved and with a right business model, could also be financially beneficial for both parties.

Based on this knowledge, could it be possible to provide heat using computers on a small scale and in similar fashion to the current electric space heating? And if this indeed is possible, would this kind of devices be as capable and practical as the current electric space heaters? In this work, this idea is examined further and a small scale computerized heater that operates in similar fashion as a ordinary electric heater is designed, built, tested and finally evaluated based on the experiences and results gained. This work also tries to identify alternate ways of utilizing the wasted heat of computers and the possible issues or advantages related to these solutions. Finally, the work also explores on basic level possible business approaches and models that could accompany the technology of computerized heaters.

1.1 Motivation and goals

The main goal of this work is to examine the viability of ordinary computers as heaters and to identify the possible issues and problems related to use of computers in this manner. The viability consists of several factors including the technical restrictions and capabilities of computers, ability to control the heat output of computers, the hardware durability and so on. A prototype heater consisting of computers and control equipment is also produced as part of this work in order to test as many as possible of these factors. Finally we provide insights and concepts on how computers could be used in heating based on the results and experience gained from the prototype.

The motivation of this work is simple, to improve the efficiency of both heaters and computers through utilization of the wasted heat in meaningful manner. As the need for computing capacity will continue to increase and the electrical space heating is unlikely to disappear entirely from households, examining the possibilities of computerized heaters is not only meaningful in terms of improved efficiency, but also opens new possibilities for many operators in the areas of energy, heating or computing. In a small way, this work is also motivated by interest of possibly improving the lifespan of computers of older generations through reuse as heating units.

1.2 Overview of this work

This work is divided into chapters as follows. In Chapter 2 we cover the background of the technology and what has been accomplished so far through research and commercial projects. The chapter then continues to explain the heat as generated by normal electrical heaters & computers and aspects that need to be considered in case of computerized heat. The Chapter 3 covers the requirements and design of the prototype heater that is the core of this work. This explains the main system components and their functions as a part of the system in question. And finally the overall operation of the heater is explained.

The Chapter 4 covers the testing and development done using the testbed system and the prototype heater. These include the testing of various system components and functions and later on the performance and the capabilities of the prototype computerized heater. The Chapter 5 evaluates the results and experiences gained during the development and testing of the technology. This is followed by Chapter 6, where possible improvements and enhancements that could be made in light of the results are discussed further. This also covers many ideas which have been discussed during the course of the work as possible useful approaches to use the technology. The possible business approaches and potential is covered in the final section of this chapter. And finally the Chapter 7 presents the summary and conclusions of this work.

Chapter 2

Background

2.1 Electric space heating and other related heating technologies

The electric space heating is an old and relatively simple technology. Typically, a resistive wire is heated by running a current through and the resulting heat warms up the air. There are many variations of the heater design, but the core concept of resistive heating is used in all of them. The basic equations for electric power are presented in equations 2.1, 2.2 and 2.3. In the case of heating elements the power translates almost directly to heat with some possible losses, typically as radiative energy in form normal or infra-red light.

$$Voltage = Resistance \times Current \tag{2.1}$$

$$Power = Voltage \times Current \tag{2.2}$$

$$Power = Resistance \times Current^2 \tag{2.3}$$

As the resistive wire transforms a very large portion of the electric energy directly to heat, the heating power of these devices is simple to calculate as it corresponds in practical terms directly to electric energy consumption. This in turn means that the efficiency of these devices themselves is close to 100% and in heating terms, the devices have a Coefficient of Performance (CoP) of 1. This means, that for each 1 Watt of electric energy consumed results in 1 Watt of heat produced. When we take into account the manner how the electric energy is produced, the overall efficiency of the heaters tends to fall. This and the fact that the electric heating consumes large amounts of electricity, has resulted a search for better options in terms of alternate heat sources or alternate approaches of using electricity in heating. The former brings into picture competing heat sources, such as district heating, natural gas or burning of wood/pellets or oil. The latter technologies with higher CoP value such as heat pumps in their different forms, most commonly air source heat pumps.

Starting with the alternatives to electricity as source of heat, one of the primary options is the transfer to district heating, where available. As an old technology, electricity has been in use in areas that have nowadays become part of cities or larger communities, which also results in extension of the district heating network to the said area. District heat is usually hot water or steam generated in centralized facilities or power plants and delivered to households through district-wide insulated pipe network. The benefit of this is that the larger facilities can generate heat at higher efficiency than localized burners or many other heat sources. This efficiency can also increased further through combined electricity and district heat production. The problem with this option is that it requires access to the heating network and in many cases, it is not financially viable to expand the network to an area where there customer-base is small. The same problem is faced with the case of natural gas. While burning natural gas is an efficient way to provide heat, delivering the gas to households requires existing pipe network that is usually available only areas with sufficient population. In rural areas, more common alternatives are the use of local heating oil or biomass burners. While the use of heating oil has been in decline, burning of wood, wood pellets or other biomass solutions are still common and adopted. In all of these cases, the burner is used to heat water that is then used for central heating and as hot water. In many cases the benefit is relatively good energy efficiency at cost of dependency to the used fuel, which is one of the main reasons to the decline of heating oil.

In all of these different options, a major problem is the need of major renovation of the building to accommodate the new heat source. In case of electric central heating, the transition might be easier, but with electric space heaters installing all the necessary piping can require costly renovations or reconstruction.

As to the technology alternatives to electric space heaters, we again have several options that are based on the heat pump technology. The basic idea of heat pumps is to transfer heat from one medium to another. This can be done as long as there is some heat in the source medium, however the more heat there is in the source medium, the higher efficiency can be reached. The interesting part of this technology is that with right design, a heat pump can extract more heat energy than it consumes electricity. In other words their CoP value is higher than 1, usually close to 3 depending on the design. This means that if a heat pump that consumes 1 Watt of electricity can extract more than 1 Watts worth of heat from good source, making it far more efficient than normal electric space heating. Most of the different solutions using heat pump technology are only different in the selection of the source and heating medium [8]. Most common option today is air source heat pumps, that extract the ambient heat from outside air and transfer it to indoors or vice versa. The key selling point of these devices besides the obvious efficiency, is the simplicity of the devices which makes them possible to install into building that have not been designed with the technology in mind. While this makes the systems attractive to households with existing electric heating, it is also offset by the large initial investment. The problem with the air sources is the decrease of efficiency as outside temperature falls, which prevent the use of these devices as sole heat source in countries where the winter temperatures are too severe. If another heat source is required to act as a back-up system to such heat pump, end-users are again facing the dilemma of which technology or solution to choose. Other approaches of using the heat pumps include extracting heat from ground by circulating water through underground pipe network. Again, the approach is efficient, but requires more extensive modifications to existing building HVAC systems and structure. The benefits are that the operating costs are low and the system can provide heat throughout cold seasons and thus could act as a primary heating solution for households.

2.2 Energy efficiency of computers and data centers

Computers are a rapidly developing area of technology and each year we see more advances in performance, energy efficiency and size of computers or related equipment. However, from broader viewpoint computers are still electronic devices consisting of semiconductor components and as such, computer hardware is bound by common features shared by semiconductor devices.

One uniting feature of all semiconductor components is that they dissipate more or less power when operating, depending on the type and complexity of component. In simple integrated circuits, the power dissipation is usually in manageable range, but as we reach the complexity level of modern CPU technology with tens to hundreds of millions of integrated transistors on one chip the power dissipation becomes a major design point. While the current manufacturing techniques and better designs have managed to reduce the amount of power dissipation while at the same time improving the performance of the CPU's, the fact remains that these devices are still semiconductor-based and as such will always dissipate some power and thus require some form of cooling. [18]

The amount of power dissipation becomes more evident when we look at data centers and their power consumption. As a single computer will always consume power and the resulting wasted heat needs to moved from the computer components to another medium, in most cases air, in order to keep the components operating within their specified thermal limits. With a single computer, the increase of air temperature due to this transfer is usually not noticeable in typical room environment, but when we have hundreds of computers operating within a same hall, as we do in computer centers, the temperature increase is significant. The traditional approach to combat this problem is to have specialized HVAC systems installed in server rooms and data centers to remove the excess heat and to maintain suitable room temperature for computer hardware. This brings about an interesting factor about the power dissipation in computers: when used in large numbers, we not only waste energy in the computers, but in a sense we usually also waste energy by cooling the premises the computers are located in.

$$\textit{Power Usage Effictiveness} = \frac{\textit{Total energy consumption of the facility}}{\textit{Energy consumption of the IT equipment}} \tag{2.4}$$

Due to the need of cooling in data centers, the effectiveness of data center is usually measured in Power Usage Effectiveness (PUE) metric. This measures the ratio between all energy consumption of the facility and all energy consumed by the IT hardware 2.2. An ideal figure from facility standpoint would be 1, as this would mean that all the energy consumed in the facility is consumed by the computers and relevant IT equipment. However, this would still mean that the heat energy from the computers is still wasted in a sense, although no additional energy is spent on maintaining suitable temperature within the facility. An example of an approach coming close to this is the Google data center in Hamina, that uses sea water in cooling [7].

Apart from attempts to find new ways to improve the efficiency of data centers, there is also some work into improving the overall energy efficiency of computers used in households. In the technical report by Hlavacs et al[12] the shortcomings of the energy efficiency drive in computer hardware is also identified. Their finding is that even though the efficiency improves, the number of computers is also increasing, especially in households. As most of these computers do little useful work, the gains in efficiency are counteracted by inefficient resource use. Their suggested approach to minimize this energy consumption is by pooling the computing resources of each household into large distributed network. These pooled resources are then usable by each contributing household for their own workload as needed, allowing each household to utilize larger computing power than normally would be available to them. While doing this, the system also tries to maximize the resource usage through placing unneeded computing resources into hibernation, resulting an overall energy saving.

2.3 Computer heating experiments and existing work

The topic of harnessing the waste heat of the computers is not an entirely new, although actual research into the topic is somewhat scarce. As mentioned in the previous section, the computer hardware industry has approached the power dissipation and heat in computer components by trying to minimize its effects rather than directly trying to find a benefit from it, which is a natural approach as the heat is considered as an unwanted side product of electronics. As a result of this approach, the computer hardware industry is providing us more and more energy efficient designs that have relatively high performance-per-watt, but at the same time, almost no directly related research on how the heat of the computers could be utilized. There are, however attempts to improve cooling and energy efficiency of server hardware and data centers that are useful and could also be used to harness the wasted heat in a meaningful way. There are also few research projects that have tested different ways to directly benefit from the wasted heat and also energy efficiency projects with data centers that harness the wasted heat to improve the overall energy efficiency of the center. On smaller scale, there have been proposals on how computers could be used to heat buildings, but few of these have reached actual implementation phase. The few implementations that do exist have been created by small companies and there is very little actual scientific documentation related to their work.

On the data center and server side of research, we have the work conducted at the University of Helsinki by Pervilä et al [27] regarding the operating conditions of servers which included tests with servers located in open air with little to none actual air filtering or conditioning. These environment tests later evolved into experiment in which the hot exhaust air of these servers was vented directly into a small greenhouse to see if suitable conditions for growing plants could be maintained throughout the year by using this wasted heat. The experiment proved that although additional ventilation was needed during hot summer months, the growth conditions were maintained throughout the year in the cold environment of Finland.

In United States, we have another project performed at university of Notre Dame by Brenner et al [5] that involved providing heat for greenhouse using servers. This experiment involved a larger cluster of servers from which the hot exhaust air was directed into a large greenhouse. The difference here is not only the size of the experiment, but also that the Notre Dame system involved controlling the number of active tasks based on the temperature of the greenhouse. Their research also suggested the use of similar system in smaller scale to act as space heaters.

Both of these experiments show that computer generated waste heat can be utilized in clever ways to provide heat where needed and also that the amount of waste heat can be roughly controlled depending what the computers are set to perform.

Alongside these experiments regarding the subject, we also have several actual data centers operated by different companies that utilize the wasted heat from computers to improve the efficiency of the center and to provide heat in different forms to buildings. Among the first larger scale projects are the joint ventures of power company Helsingin Energia (nowadays Helen Ltd.) and data center operator Academica Ltd. which resulted in two specialized data centers built in Helsinki, Finland [28]. These data centers were directly connected to Helsinki district heating network to which the waste heat from the servers was extracted. Helsingin energia estimated that the data centers provided heat energy estimated to warm 2000 residences in Helsinki metropolitan area. As a result of utilizing the heat output of the facility, their PUE rating is estimated to be close to 1 or possibly even below that, depending what is taken into account in the calculation. These data centers have since be followed by similar projects that utilize the waste heat from servers or data centers to heat variety of buildings.

These experiments and projects validate the basic concepts of this work on larger scale, but the question still remains whether the same kind of results can be achieved on much smaller scale? So far there has been very little experimentation or corporate endeavours related to utilizing the wasted heat from small servers or small computer clusters. Such devices have been suggested by aforementioned study by Brenner et al [5] and by Liu et al [19] in more recent research paper on the topic of data furnaces . The concept presented by Liu et al is a installing servers or furnaces into households to provide cloud services to the residents and at the same time provide heat. A single data furnace would correspond to a small data center and consist from hundreds of CPUs.

The examples that can be found regarding the smaller scale heating using computers are Qarnot computing in France, Nerdalize in Netherlands and Cload&Heat in Germany. The concept behind the Qarnot computing

[29] is to generate computer based space heaters that should operate in similar fashion as the intended result of this work. As to date, Qarnot has not released solid specifications on the hardware of the heaters apart of the design illustrations in promotional brochures, which indicate that their solution consists of a cluster of computers that are passively cooled by a single large heat sink. The requirements of these heaters seem to be also similar to prototypes presented in this work, that is they require only a network connection and power in order to operate.

Another project to reach trial phases is the Nerdalize project in the Netherlands [25], that started testing their version of server-based space heaters in spring 2015. Their systems operate in collaboration with a local energy company Eneco.

The solution of German Cloud&Heat [6] is concentrated on providing central heating and warm water solution for residences through the use of water cooled small servers. The Cloud&Heat servers are installed next to the water reservoir of the central heating which is then used to cool the servers, thus transferring the heat to the water which can subsequently be used to either provide heating or warm tap water. Again the exact technical details of these servers and their cooling are not available thus we can only speculate on how complicated or viable their solution is. What seems to be clear is that their solution seems to be adopted by some residences which indicates that their approach is sufficiently developed to financially viable.

All these experiments and projects show that there is interest in utilizing the wasted heat from the computers, usually to improve the energy efficiency of the computing system or data center. These examples validate the basic ideas that this work is centered on, but also show that there is still little actual research done on the computer heaters, their design and the control of the heat output of the computers, especially on the level of small servers and computer clusters.

Chapter 3

Design

This chapter covers the requirements and design of the temperature control system and the prototypes in detail.

3.1 Requirements for computerized heaters

In the beginning of the actual design work on the computerized heating systems a set of requirements was established that the developed heater and control system would be evaluated against. These were:

1. The system must be able to accurately measure the current temperature in the room or space it is located in
2. Based on the measurements, the system should adjust the temperature within the said space until given target temperature is reached.
3. After the target temperature is reached, the system should maintain the temperature with reasonable accuracy
4. The system should not output unnecessary heat when the target temperature is exceeded
5. The temperature target is set by the user, but otherwise the system should operate reliably without user intervention
6. The above should be done using computers as heat source and the computers should perform useful calculations while providing heat
7. The end result should be practical and resemble a heater

3.2 Design overview

Based on the established requirements, a design consisting of sensors, a temperature control unit and computer cluster performing the heating was devised. In the design, illustrated in Figure 3.2, the temperature is measured from sensors connected to separate temperature control unit, which in turn sends appropriate commands to the attached computer cluster. Within the cluster, these commands are processed by the individual computers and the CPU utilization is adjusted accordingly. Based on the CPU power measurements Figure (4.3), the process control within the computers was approached through limiting the CPU amount of processor time available to the processes rather than simple starting and stopping of processes whenever needed. The idea in this limiting approach is that client computers would run processes that would normally use all available processor time whenever there is any available. By limiting such processes with suitable monitoring script, the power consumption of the computer should be theoretically controllable with relatively fine granularity. To achieve greater control and efficiency the control system should also control the number of active computers in the cluster by shutting down or starting these computers as needed, giving us control over the overhead power consumed by the computers. Combined, these two should give the system enough control over the power consumption and thus over temperature to meet the requirements set above.

The actual control system based on these requirements and the concept presented above was built around an Intel Galileo development board[16], which provided sufficient computing power, networking and general-purpose input/output (GPIO) connectors for reading the digital temperature sensors. The sensors to be attached to the system were DS18B20 high precision digital thermometers from Maxim Integrated[20], which utilize one-wire interface in their communication. These were chosen partly because they were readily available parts and partly because of the expandability and flexibility of the one-wire interface. However, early on it was discovered that the Intel Galileo GPIO ports were not able to reach the speed and microsecond-scale timings required by the one-wire interface. This was solved by creating a simple, custom add-on board to the Galileo utilizing a common Atmel ATmega 328PU programmable microcontroller[4] which acts as controllable interface for the one-wire sensor network. This hardware combination is then networked to the client computers via normal Ethernet connection without any specific requirements.

On the software side, the Galileo uses a Linux-operating system modified to meet the specialized hardware of the board whereas the other computer

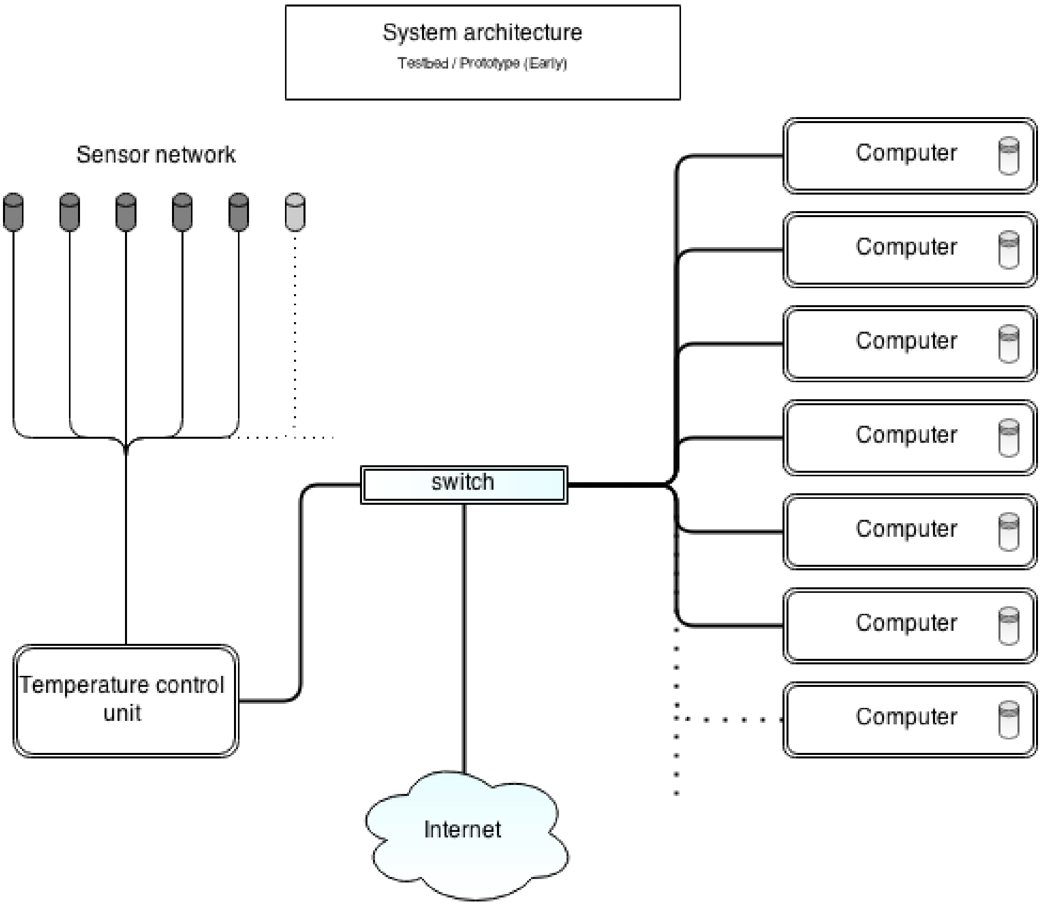

Figure 3.1: Architecture used in testbed and in early prototype. Temperature control unit performs measurements and based on them controls the computer units and their CPU utilization over the network. All the computers have their individual mass storage and operating systems.

units of the system are designed to run a normal Debian-based operating systems without any modifications. The server and client software running both on the Galileo board and the computer units respectively is written on Python programming language. Python was picked as it provides good interface for controlling the GPIO connections in the Galileo board and for its readily available support for network connections.

In an attempt to reduce the noise levels and improve the reliability through reduction of mechanical parts, the system was later modified to utilize USB memory sticks as mass memory from which the OS was booted. However while this was initially functional solution, it proved to be too failure prone due to constant read/write operations that wore the flash memory

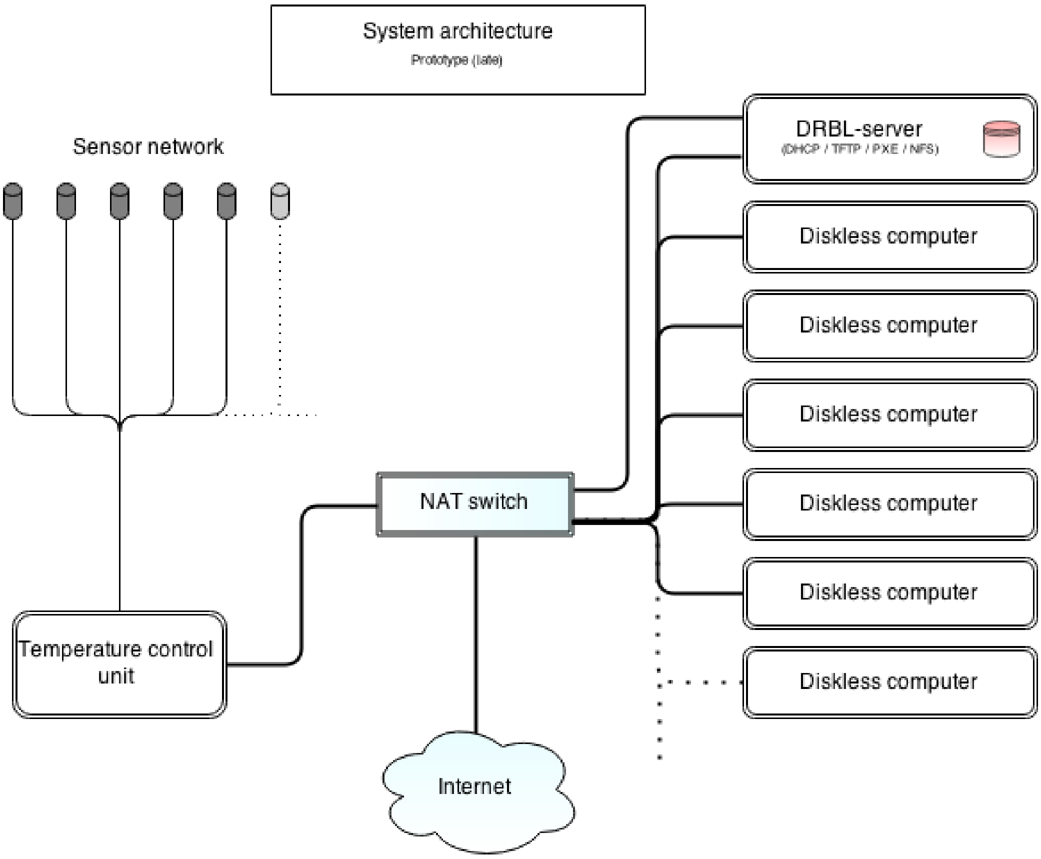

Figure 3.2: Architecture used in revised prototype. Each computer now longer has individual mass storage, instead a single DRBL-server provides mass storage and operating systems through the network.

out. In the final revision of the system, this problem was solved by including a network boot server to system, from which the clients fetch their operating systems. This eliminated the need for local storage for the clients and furthered the expandability of the system. The system structure in latest revision is illustrated in 3.2.

3.3 Temperature control unit design

3.3.1 Components of the temperature control unit

Intel Galileo development board

Intel Galileo[16] is an Intel Quark System-on-Chip (SOC) -based Arduinocompatible development board. It can execute code in Arduino-mode or operate as a lightweight computer running a customized Linux system. As the board is intended for Arduino[3] and other embedded development, it features General-Purpose Input/Output (GPIO) pins and other interfaces for device interaction. As a miniature computer, the Galileo also provides USB connections and ethernet NIC. The GPIO pins are used in this project to interface with the ATmega microcontroller based one-wire interface and thus provide the system with the temperature date needed for load adjustment. In similar fashion the load adjustment commands are sent using the network interface to client computers.

The sensor network and one-wire controller

The sensor network used by the temperature control unit is based on one-wire protocol. One-wire is a line communication protocol in which numerous devices can populate and communicate through a single data line. The line is controlled by a master which issues commands to devices slaved to the data line. All one-wire devices have an unique identifier which allows the system to identify and send commands to specific devices connected to the data line. Devices can be added or removed from the data line without interrupting the operation of other devices, making the expansion and maintenance of the network very simple. These properties make one-wire a robust and scalable solution to build a sensor network upon, which is one of the core reasons it was chosen for this project.

DS18B20 One-Wire Digital Thermometer

The DS18B20 is a high precision digital thermometer with one-wire interface produced by Maxim Integrated Products [20]. When active, it actively measures the current temperature of the environment it is located in and stores this data on internal memory with accuracy of 0.0625 degrees Celsius. When receiving corresponding command through the one-wire interface, the device conducts a conversion of internal value based on parameters stored into the device. After conversion, the device signals the one-wire line of readiness after which the line master can read the temperature value from the device using separate read command. The rate at which the measurements can be taken is largely determined by the conversion operation, which in itself takes about 2-4 seconds to complete and the retrieval of the result far less time. Otherwise the speed is only limited by the number of the sensors in the network, as the result of the conversion has to be retrieved single sensor at the time. Overall, the speed of the system is more than adequate to be used in temperature control, allowing the system to collect a single reading in an about 5 seconds with five sensors. Each sensor is packaged in the same TO-220 package as many through-hole transistors used in electronics, that is, about the same size as an eraser at the end of an pencil. This should make installation of sensors into rooms where the measurements are taken much easier, contributing to the scalability and practicality of the measurement system.

ATmega 328PU based One-Wire interface board

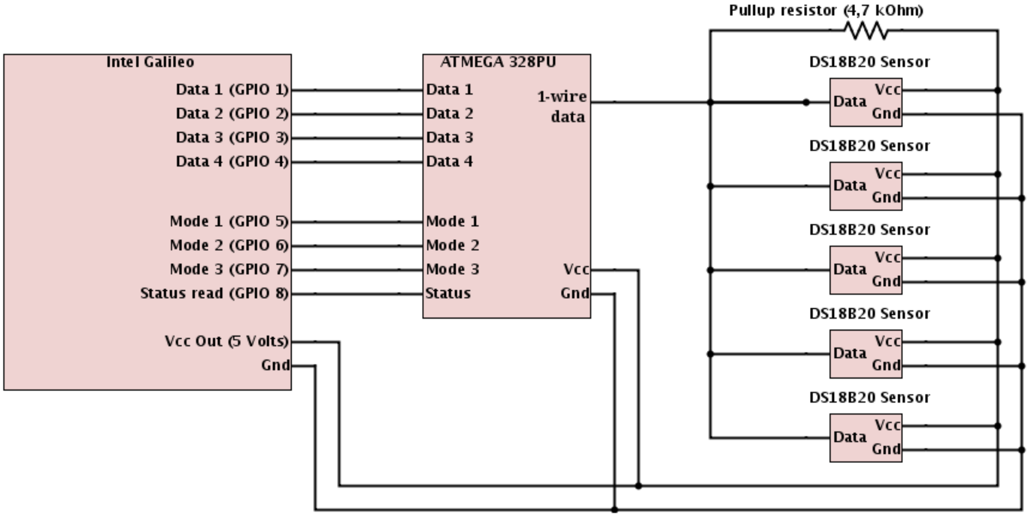

Figure 3.3: Circuit diagram for temperature controller and one-wire network

The custom one-wire interface board for Intel Galileo is built around a common ATmega 328PU microcontroller that provides the system with high accuracy timings required by the one-wire protocol and can be programmed to communicate with both the one-wire devices and the Intel Galileo. Manufactured by the Atmel Corporation, the ATmega 328PU microcontroller[4] provides 24 programmable digital input/output pins, 3 internal timers, PWM support in one compact microchip. It operates with clock speeds ranging from 1MHz to 8MHz which, combined with optimizations for efficient code execution and largely single instruction operations, makes the ATmega 328P microcontroller very good solution for timing critical systems. These features have made the Atmel ATmega-family a widely used solution in embedded systems.

The circuit design used in this project, as visualized in Figure 3.3.1, uses one digital pin to communicate with the one-wire line and 7 pins to communicate with the Intel Galileo. The Galileo communication pins are divided into 4-pin bi-directional data channel and 3 uni-directional mode selection pins, that allow the Galileo to control the operation of the microcontroller. Two of the mode pins are used by the Galileo to indicate data transfer or to select the mode of the device and the remaining pin is used by the ATmega to indicate its readiness to Galileo.

The commands and data are sent in 4-bit blocks through the data channel between the ATmega and Galileo. Communication is controlled by the Galileo, which checks the readiness of the microcontroller and then proceeds to read or to write data to the channel by signalling the data transfer mode pin. In case of sending a command to the ATmega microcontroller, the Galileo first sets the select mode pin high to indicate that command follows and then proceeds with data transfer. Received commands are then interpreted by the microcontroller and corresponding instructions are issued to one-wire network. As soon as the network devices have processed the given instructions, their responses are read back by the microcontroller and stored for retrieval. To indicate that the ATmega is again ready to respond, the chip signals Galileo through the ready-pin. To read data, the Galileo signals the microcontroller using the mode pins and then proceeds to read the channel. In this mode the microcontroller sends the first four bits of data to the data channel and continues to do so until signal is received from the microcontroller to switch to the next block of data. If the Galileo pulls the mode selection down at any point, the ATmega returns back to standby mode and waits for the next command.

This system allows the Galileo development board to send and receive data from the one-wire network, that would normally be beyond of the technical and timing capabilities of the development boards interfaces and hardware.

3.3.2 Operation

Serverside

The temperature control unit software consists of the C code running on the One-Wire interface and from the python script running on the Galileo. The ATmega microcontroller code functionality was largely covered in the previous section so the main focus here is on the server script operating on the Galileo. Before the script can be started it needs to know the MAC addresses and IP addresses of managed client machines in order to use both Wake-on-LAN commands and UDP-packets.

Upon startup, the script wakes up all connected machines and begins collecting data for temperature adjustment. The temperature data is collected from all available sensors connected to the one-wire interface chip and the polling is done at regular intervals. The received data for each sensor is converted to temperature reading and added to list of recent reading for that sensor. The list is used to give a short term average of the temperature readings of each sensor and is utilized in temperature adjustment decisions. After enough data is collected to form accurate short term temperature average, the adjustment function is performed. The temperature adjustment is managed using a simple software proportional-integral-derivative (PID) controller, which calculates new adjustment value based on previous readings, set temperature target and current temperature reading. Based on the result from the controller, the system then calculates the increase or reduction to target load and based on this, assesses the need to activate or deactivate client units.

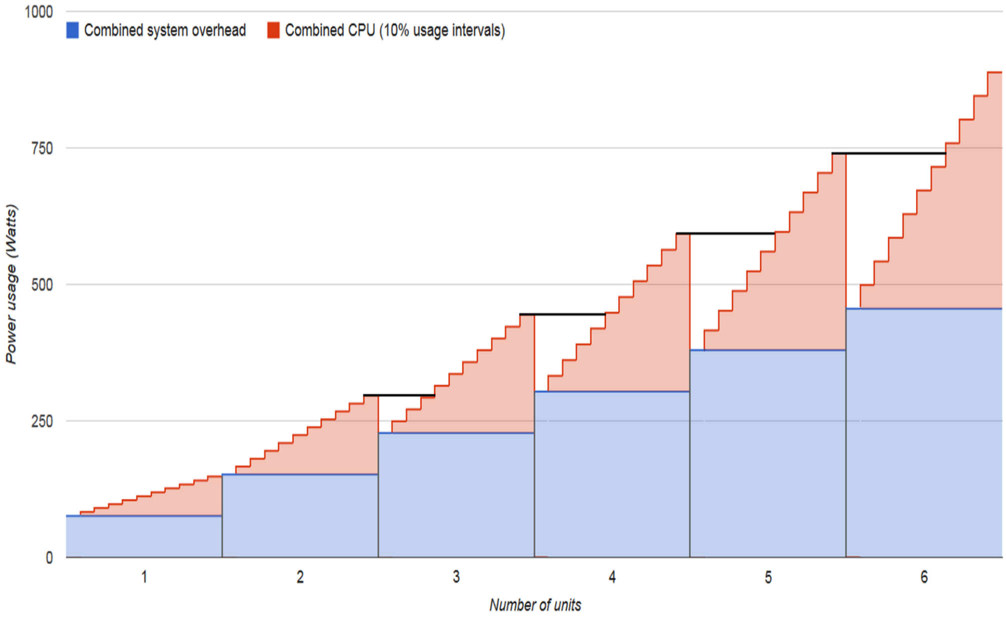

Figure 3.4: Prototype power consumption at different CPU usage levels and with varying number of active units. The black lines indicate change in CPU usage when activating/deactivating units

The change in number of active clients is done if the load target goes beyond the set load limits and the limits themselves are dependent on the number of currently active units. The idea behind this is maximize the usefulness of the attached clients, as each computer has overhead to their operation which will incur regardless whether the client actually processes any data or not. Based on tests, we verified that the maximum benefit from a client computer is reached when the CPU has full load, in which case the percentage of overhead from the total power consumed is smallest. Similarly, this percentage is highest when the CPU has little or no load at all. By measuring the energy consumption at different load levels, a simple solution was devised to improve the overall efficiency. Whenever the CPU utilization target reaches 100 percent and further increase is consecutively needed, an additional unit is activated and the combined CPU target is reduced to level that roughly matches the energy consumption before the change. In same fashion, whenever the CPU utilization target consecutively drops below the limit at which the same amount of energy would be consumed by one less unit at full power, an unit is deactivated and the CPU utilization target is increased close to maximum. This gearbox-like functionality, illustrated in Figure 3.4, helps the heater units maintain more reasonable energy/calculations ratio, especially in situations where a constant amount of heat is required.

The overall system operation and adjustment algorithm phases are illustrated in the Figure 3.5. In the figure, features that not close to the core functionality, such as user interactions (setting of temperature target, PID setting, etc.) and temperature logging, are not shown. In general, these are all performed either before the temperature measurement or while the system is waiting for the temperature conversion results from the one-wire controller.

Computer clients

Computer units attached to the heating system in the prototype run normal Debian/Ubuntu operating systems within which the client script and the processes providing the computational load are running. For the purposes of the prototype and testbed, BOINC [2] distributed computation projects were selected as the workload to be processed. One of the reasons is the availability of such projects and the distributed best-effort logic employed by the entire BOINC framework. Normally, the BOINC client utilizes the unused processor capacity in the computer it is installed on, depending on the preferences of the user, and calculates workloads of user-selected distributed projects. In terms of the heating, this is a perfect fit as a computational workload as it is not time-dependent and can be calculated at leisurely pace or even left unfinished. The primary project attached to the BOINC clients on the computer units was the CERN LHC@Home SixTrack -project along with several other European scientific projects.

The client itself is a python script that waits UDP-messages from the temperature controller server. Each message can contain one of the following commands for the client: a new CPU limit for the client, a shutdown command, burn-mode command for testing or a ping command. Whenever client receives a message it interprets the content and performs the corresponding action. The CPU limit and shutdown commands are used to control the CPU use of the client or to immediately shutdown the client. Burn mode command causes the client to replace the normal BOINC processes with CPUburn processes that can be used to test the system in more stable fashion. The CPUburn generates artificial loads that utilize the CPU and its cores fully. These are then limited to desired use level in same way as in normal operation.

The ping command is used by the server to check the client status and current client CPU use. When this message is received, the client checks the current overall CPU use of the system and reports this value back to the server. The client computers used in this work are wake-on-lan(WOL) capable and can be activated by the server using the WOL magic packet sent to the corresponding client. In the first revisions of the system, the clients would then start-up and load the operating system from an USB stick attached to the system. In later revisions the system fetches the operating system using network booting from a server and then proceeds to boot the system. The later revision was implemented as the wear-and-tear from the OS use proved to be significant on the USB memory sticks used and reverting to use of internal hard drives would be either costly and/or increase the sound levels of the system.

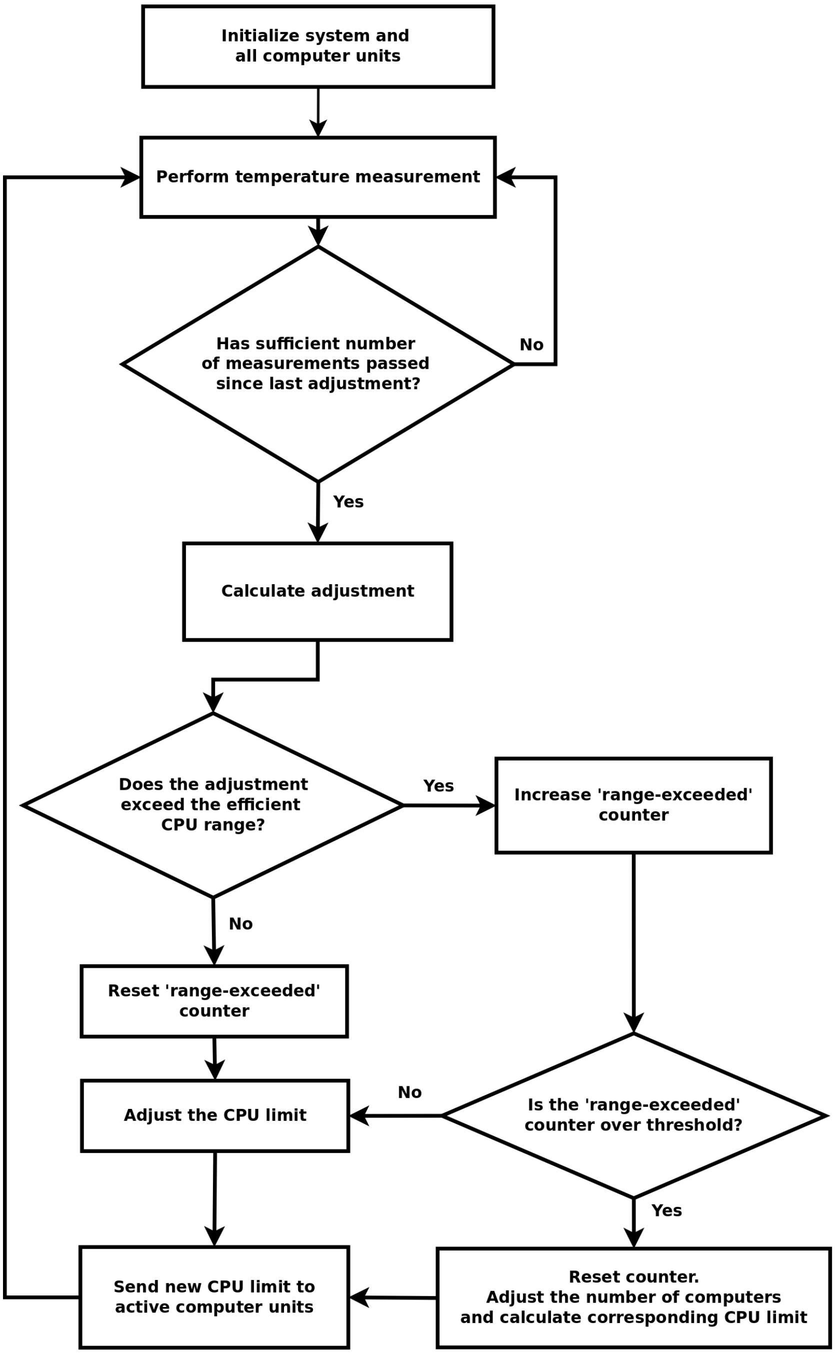

Figure 3.5: A flowchart depicting the main parts of the control system and adjustment algorithm

Chapter 4

Testing and measurements

The testing of the computer heaters and their components was done in two parts. The first part was the preliminary tests done at the beginning of the project to test the overall feasibility of the concept and later preliminary design of system components. The second set of tests concentrated on the operation of the computer heater as a whole. This included long term temperature control tests and further testing of system features and their improvements. During both testing periods, the reliability of the computers and other system components was monitored. In all temperature control tests, the temperature used for heater control was based on the average of two room sensors, to provide more error resilient readings.

4.1 Testbed prototype

The testbed prototype heater was a simple cluster of networked computers connected to the temperature control unit which was used in the early design phases of the system to develop, test and refine several of the concepts of the design. Most importantly it was used to create and test the process control in the clients and the temperature control unit design and software. The cluster hardware consisted of seven identical Dell desktop computers with Netburst architecture Pentium 4 HT single core processors. The machines were installed with normal Xubuntu-lightweight operating systems, BOINC clients and development tools. Several BOINC projects were also added to provide the computational load for the machines. The networked client computers were then connected to a small private network, which also contained the temperature control unit. The testbed was set up at the Otaniemi Recycling Center which was conveniently located in a 60 m^2 cellar room that had been formerly used as an archive of the local student union. The space was cool enough and offered enough protection from outside interference that it was deemed viable to run the first prototype there.

4.2 Preliminary testing

The preliminary tests were conducted from May till September 2014 at the Otaniemi Recycling Center permises. The test room was an old archive storage located in the cellar of a residental block. The building was built in the 1960's on Finnish building standards of the time, meaning that the building is relatively well insulated and built. The actual storage used for testing was partially underground and the walls that were above ground were on the side of the building that is in shade for most of the day. Based on this, the location was deemed sufficiently independent from outside environment that the effects of the test equipment to the room temperature would be measurable.

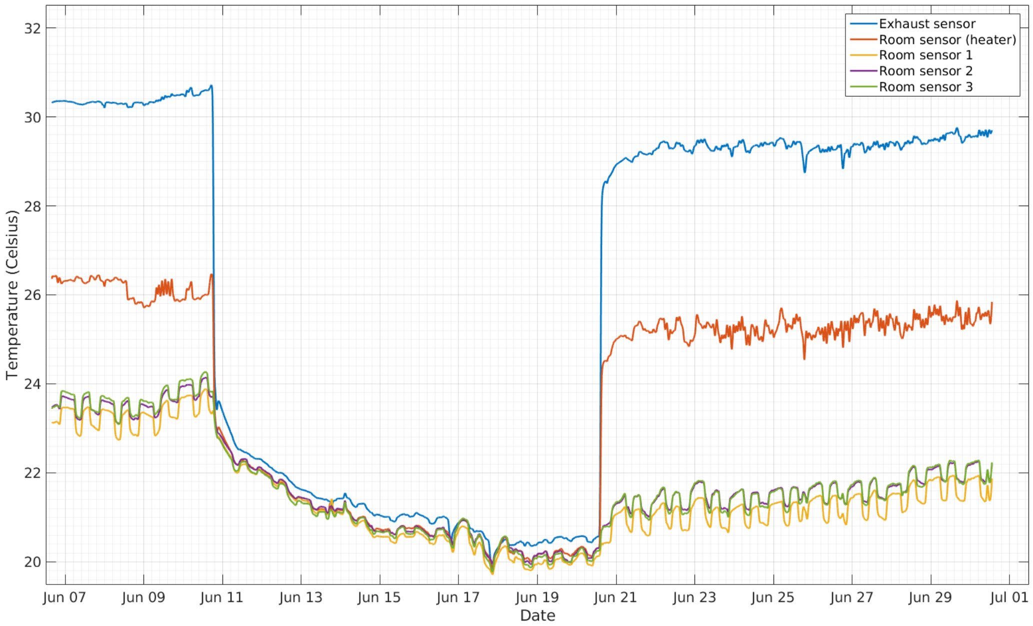

Figure 4.1: Temperature measurements from the June test period. Note the drop of temperatures after 11th of June.

The development and testing of the temperature controller was started in the end of May 2014 and began with construction of the sensor network and temperature measurement capabilities. After these were finished and tested to be functional, the testbed cluster was set up for the purpose of developing the control features and for performing initial heating tests within the test premises. One result of these tests can be seen in Figure 4.1, which illustrates the ability of the computers to affect the temperature of their environment, proving the basics of the computerized heating. In the beginning of the figure, the testbed has been operating at full processing power for roughly a week and we can see that the room temperature is rather steady at around 23.5 degrees. On the evening of 10th, all the cluster computers are shut down for a period of 9 days after which they are again started full processing is resumed. During this period, we can see a clear drop in the room temperatures of about 3 degrees. Following the restart of the computers, the temperature rebounds quickly to a level 1 degree higher than at the end of the cool period. This shows that computers can have detectable impact on the indoor environment they are located, provided that there is a sufficient number of computers available compared to the volume of the environment. In this case, the testbed consisting of 7 older Dell computers was enough to disturb the temperatures within the testing environment. The initial tests conducted also showed that the computers could handle the stresses involved in near continuous operation at full CPU utilization, which is something that might have been beyond their thermal design. Based on these findings, the development and tests with the testbed continued through the summer. The measurements done during this period were seriously hampered by the higher summer temperatures and were inconclusive in many ways regarding the overall performance of the system, but were still helpful in terms of prototyping several necessary features of the control mechanism.

The first proper testing of the temperature control systems was performed in September and for these, the original testbed was complemented with the more powerful dual-core computers of the prototype. The goal of this test period was to see if the new computers functioned as well as the older testbed computers and at the same time, test the ability of both the software and hardware to maintain steady temperature within the test environment. The measurements from this period can be seen in Figure 4.2.

These tests showed that while the outside environment and the building heating and air conditioning still had an effect on the tests, the system was visibly able to have a limited control over the room temperatures. Thus partially validating several goals of this work. The testing also showed that the control mechanism was heavily reliant on the availability of BOINC workload and the lack of work on several occasions caused the system to lose control over the temperature. This also clearly pointed out the need to have more controllable environment, as the impact of the computers could easily be negated by fluctuations of ambient temperature, especially if caused by other, more powerful HVAC systems.

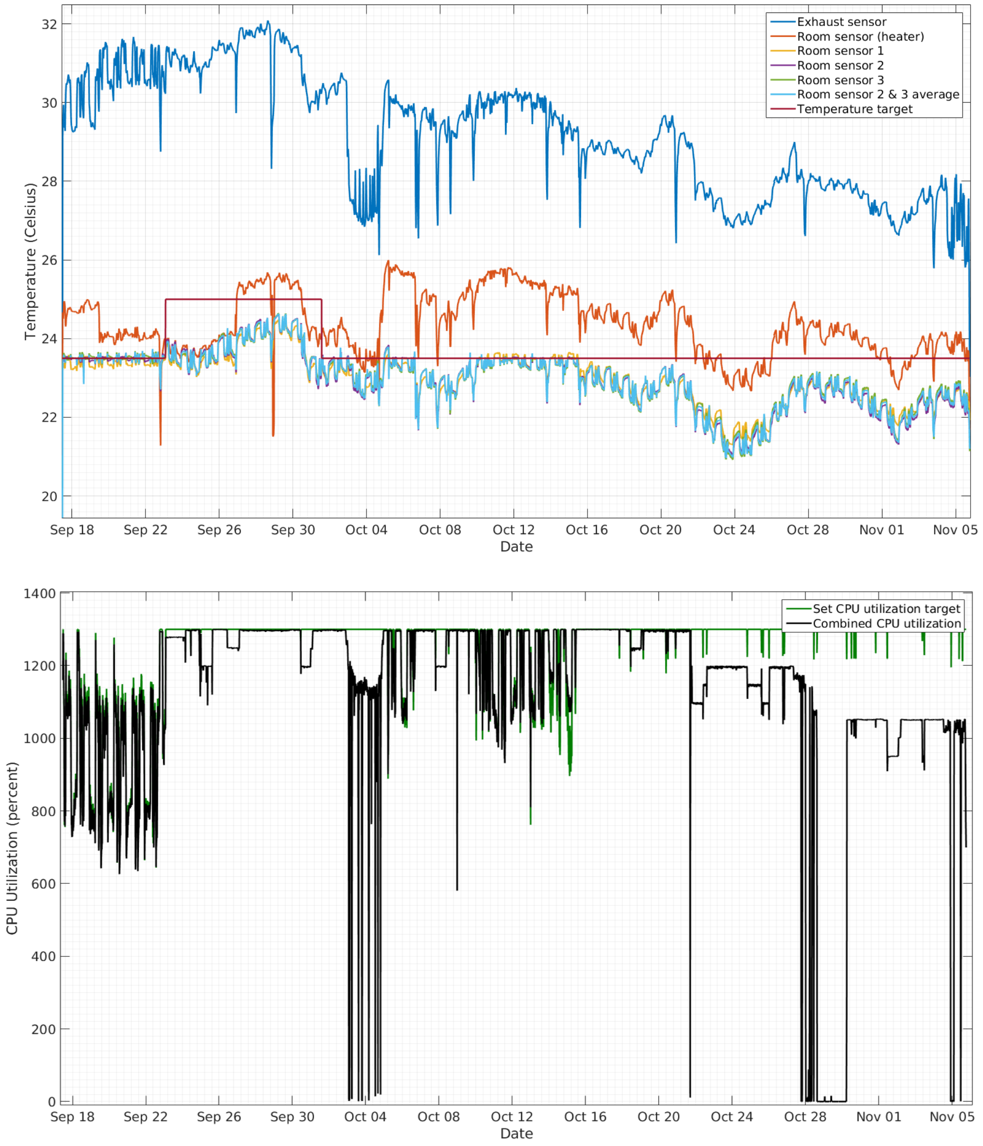

Figure 4.2: Temperature control test 1: September 18th-November 5th

4.3 Power consumption tests

In order to adjust the control mechanism that controls the activation and deactivation of units and also to verify the amount of power consumption of the computer units, a set of power measurements was conducted on the testbed cluster and the new prototype heater. These tests were also among the first to test the functionality of the new prototype and multi-core adjusted client scripts.

The testbed cluster consisted of older computers and had single core Intel Pentium 4 HT CPUs, combined with socket 478 motherboard and DDR memory. The newer computers in the prototype had Intel Pentium D dual core CPUs of the same architecture operating at same speed, combined with LGA 775 motherboard and DDR 2 memory. Both the testbed and the prototype ran Debian and Ubuntu operating system respectively and the measurements were done by running CPUburn stress testing software to provide comparable artificial load for the all the cores of the CPUs at 10 percent increments.

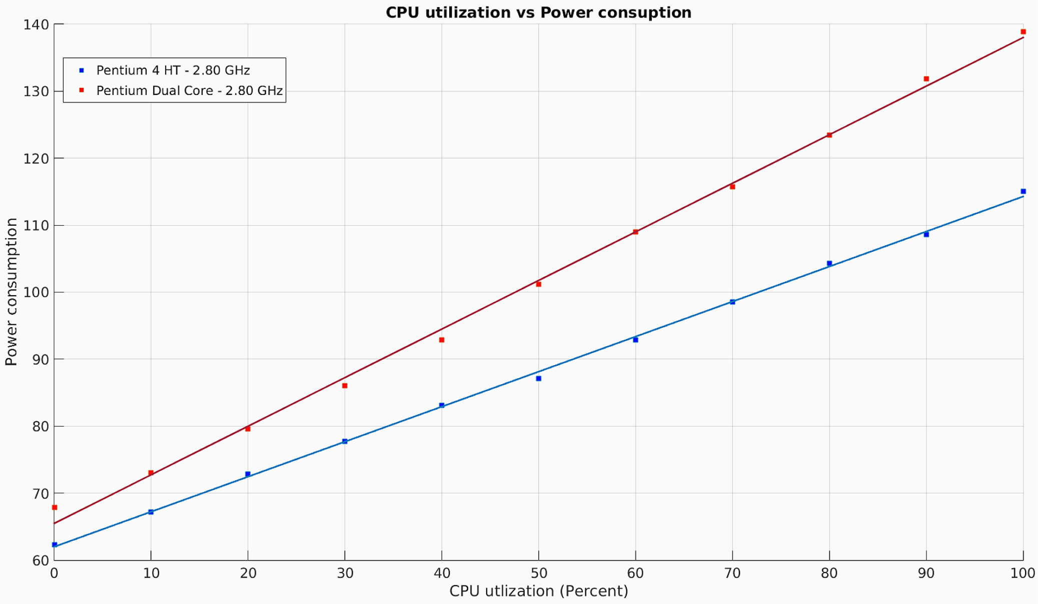

Figure 4.3: Power consumption at different CPU utilization levels. These are average single machine values from multi-machine clusters, each individual computer performing similar task (CPUburn) at given utilization level

Results of the simple tests can be seen in Figure 4.3 and as we can see, both systems consumed roughly 50% of the maximum system power consumption while idling at 0% CPU use. We can also see that the power consumption of the systems are directly proportional to the CPU use and that the change is more or less linear. This confirmed the validity of the CPU limiting temperature control mechanism that was already in place and allowed the fine tuning of the activation limits.

4.4 System testing

The system testing was conducted partially in the same premises as the preliminary testing and later moved to more dedicated location at the Aalto Energy Garage, the Aalto University's center for energy related projects and innovation [1]. After the move, a new test environment was set up to conduct the further tests with the new prototype. The new environment was a separated cubicle located within the Energy Garage main hall, constructed out of materials comparable to light interior walls. The size of the cubicle was measured to be roughly of a cube with 3 meter sides, with interior area and volume of 9 square meters and 27 cubic meters respectively. As the cubicle did not have a roof, a sheet of construction plastic was used to cover the cubicle and act as a primitive roof. The plastic used was similar to that used in construction of greenhouses and while it does not provide good insulation to the cubicle, it would prevent most the hot air from directly escaping from within the cubicle. The end result was an room within a much larger hall, that could be used in the experiments and testing. While the insulation of the room could only be considered poor, this would have little effect on the actual testing, as we were not looking for a truly realistic heating scenarios, but to test and prove that the prototype could and would maintain given temperatures for extended periods of time.

The first continuous testing period was started in the beginning of the December in 2014 and continued till beginning of 2015. This period, seen in Figure 4.4, consisted of initial test run at full power to find the capabilities of the heater in this new environment. As we can see in the figure, these tests proved that the heater can have a significant impact to the temperature of the room. The maximum impact the prototype based on these results seems to be 5 degrees Celsius over the ambient temperature within the hall. The end of this test was again riddled with lack of workload, as can be seen in the corresponding CPU utilization chart, but the result and the impact is still clearly visible. Following this test, the prototype was set to maintain a steady temperature of 23.2 degrees for an extended period of time. Apart from few occasions of insufficient workload and a peculiar drifting of room sensor readings near the new year, the system managed to maintain the set temperature admirably. For the most part, the temperature within the room was within 0.1 degrees Celsius of the set target while the environment temperature can be seen fluctuating on daily basis. We can also see from the controlled cooling period following the tests that even in situations where the computers failed to provide sufficient heat through the calculations, the control system still managed to limit the fall of the temperature by activating

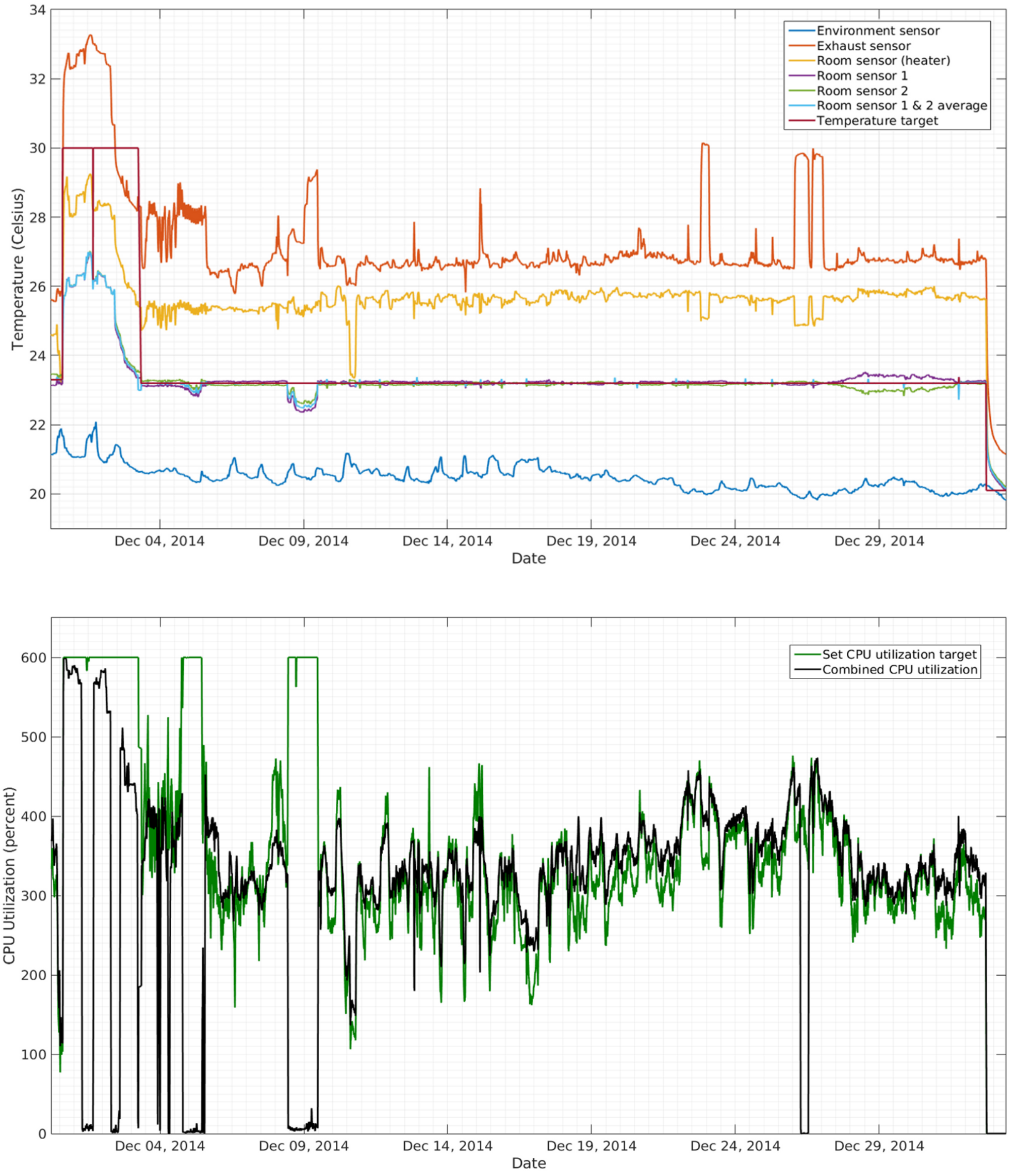

Figure 4.4: Temperature control test 2: December 3rd-January 7th. As we can see, the prototype can control the temperature in new environment very well, provided that suitable workload is available.

computer units and thus providing some of the heat that the system is capable of. Naturally, this is not an ideal situation as no useful computations were performed, but from the standpoint of providing heat, a correct functionality that could only be improved by performing useless calculations to reach full heat output. A feature that is not implemented on the prototype, but should be considered if the systems are deployed commercially.

To test the systems capability to respond temperature changes, a short experiment was arranged in which the target temperature would be raised in intervals until the system could not provide the required amount of heat. In Figure 4.5 we can see the results of this adaptivity experiment. As we can see, the prototype adjusts to the changes within 30 minutes to 1 hour, with the time increasing as the room temperature approaches the maximum temperature difference the prototype is capable of producing. This is especially visible in the second part of the experiment, in which the system is requested to heat the room from almost ambient temperature to the prototype maximum.

From mid February to the beginning of March, a third temperature test was conducted illustrated in Figure 4.6. While the results from this are not very different from the previous temperature test, the ability and failure tolerance of the temperature control system was put to the test by chance during this period. During the period, several BOINC client programs underwent an update, which caused the limiting client programs to lose track of these, causing the computers to operate partially unrestricted. As a result, the temperature control unit was unable to accurately control the heat output from the computers. Before this fault was noticed, the prototype had already operated under these conditions for almost the entire test period. Interestingly, this problem had little visible effect on the measured temperature as the temperature control system proceeded to control the temperature using the remaining CPU limiting capability and by simply by controlling the number of active computers. In fact, the system operated well enough that the problem was only noticed after observing a discrepancy between target and actual CPU utilization. As a result of this problem, the client programs were updated to search target processes in more more robust manner.

During the spring of 2015, the prototype was modified to perform energy measurements by attaching the previously used power measurement sensor to the DRBL-server and logging the readings along with the normal CPU utilization data. The idea here was to further explore how well the CPU utilization and power consumption would correlate during normal operation. This data could also be used to estimate how well the adjustment of the CPU utilization target values was done when the number of computers was changed. Initially, the changes also prevented the DRBL-server from shutting down as this would also cause the power measurements to cease, but as the day temperatures within the hall were causing the test environment to heat over the target temperature this was change to operation was reverted. This would mean that while the later measurements showed power measurement

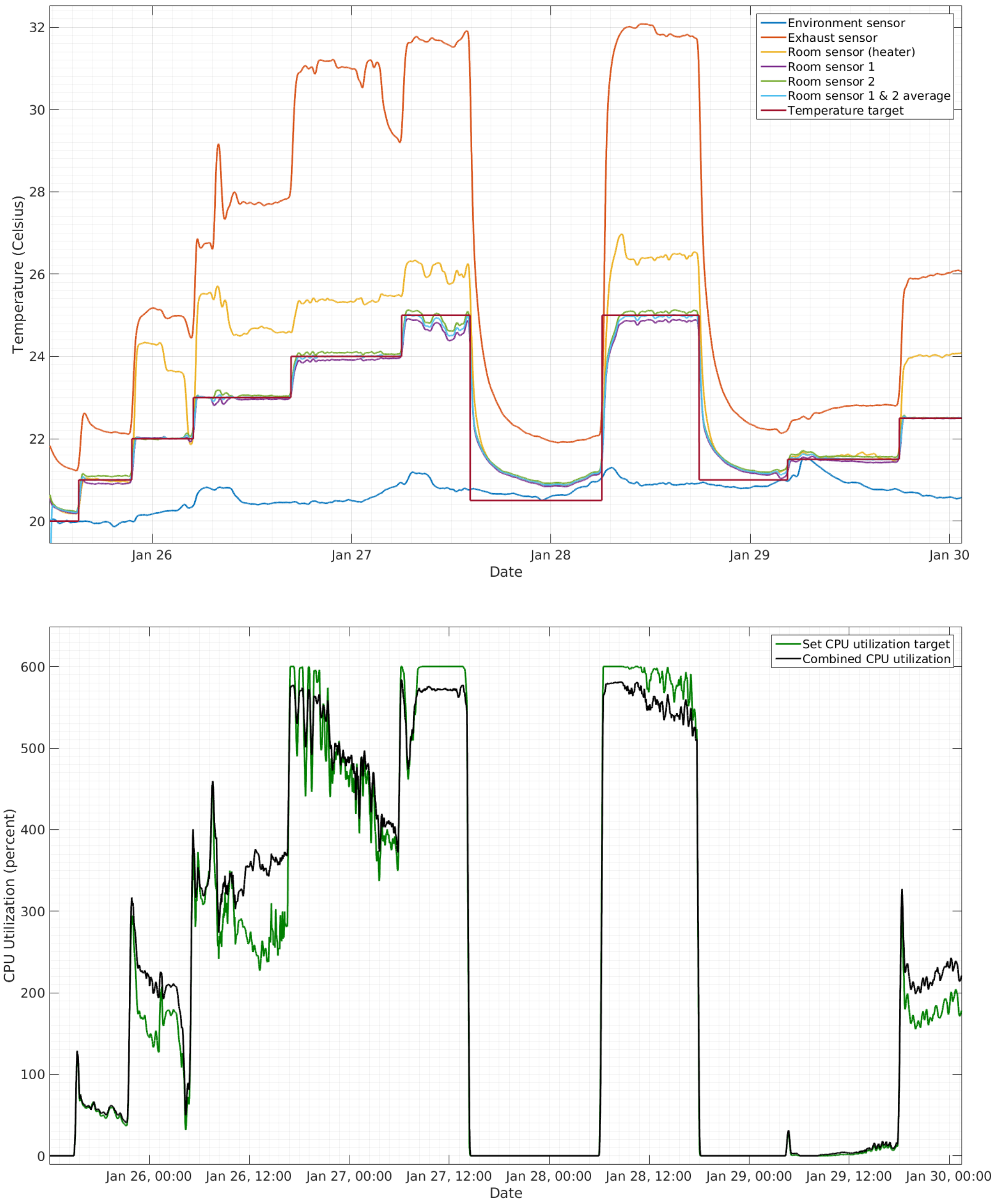

Figure 4.5: Adaptivity test

of 0 watts, the actual energy consumption of the system would still be in the range of some 5-10 watts which are used by the temperature control unit and the network switch.

The first short tests lasting for few days showed that the combined CPU utilization of all the computers in the prototype corresponded remarkable

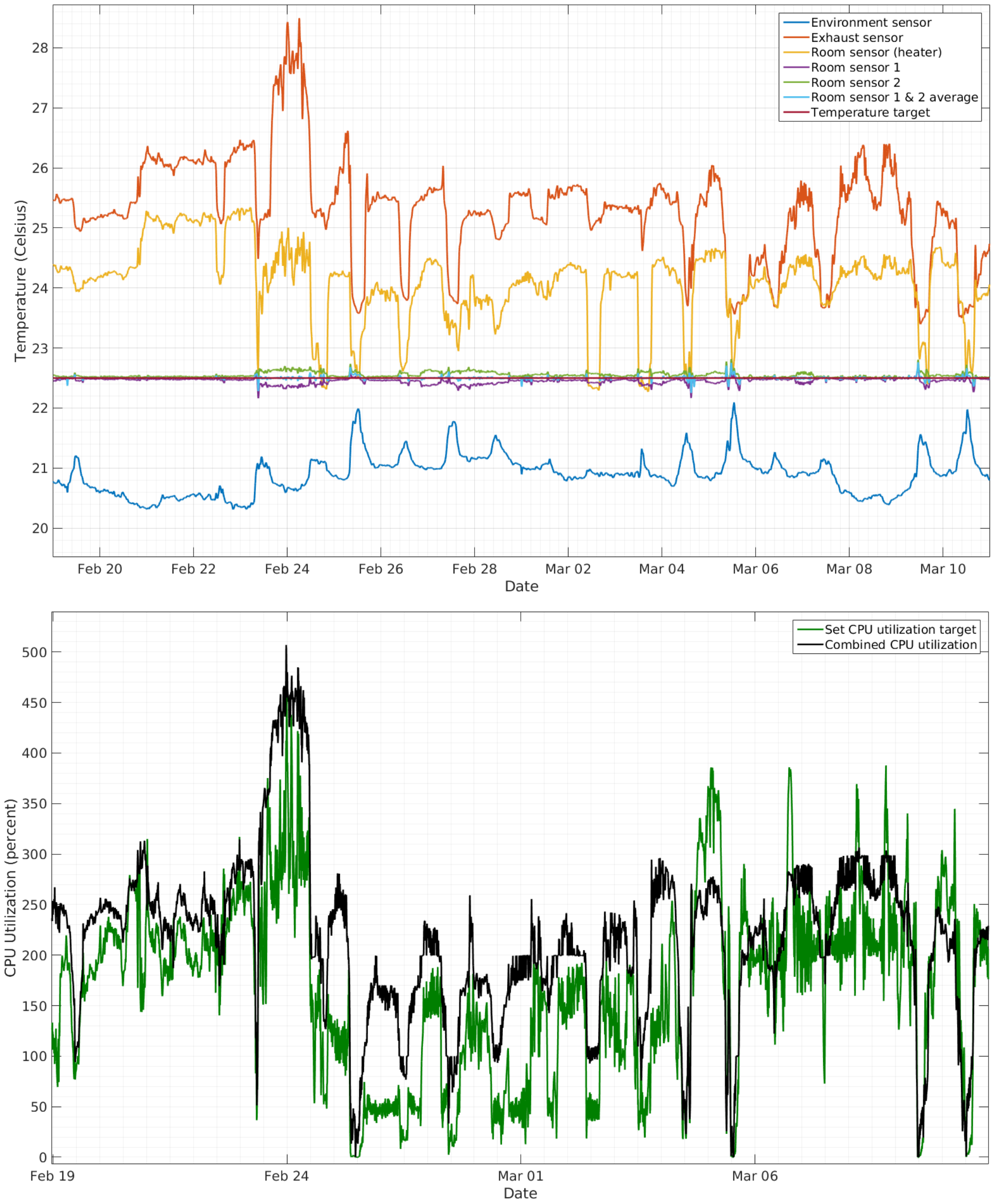

Figure 4.6: Temperature control test 3

well to the measured power consumption of the system. From the Figure 4.7 it is easy to see that the power consumption closely follows the CPU utilization, offset by the overhead generated by the active computers.

The preliminary tests were followed by a longer test run in April, shown in the Figure 4.8, which showed the same CPU-power behaviour during an

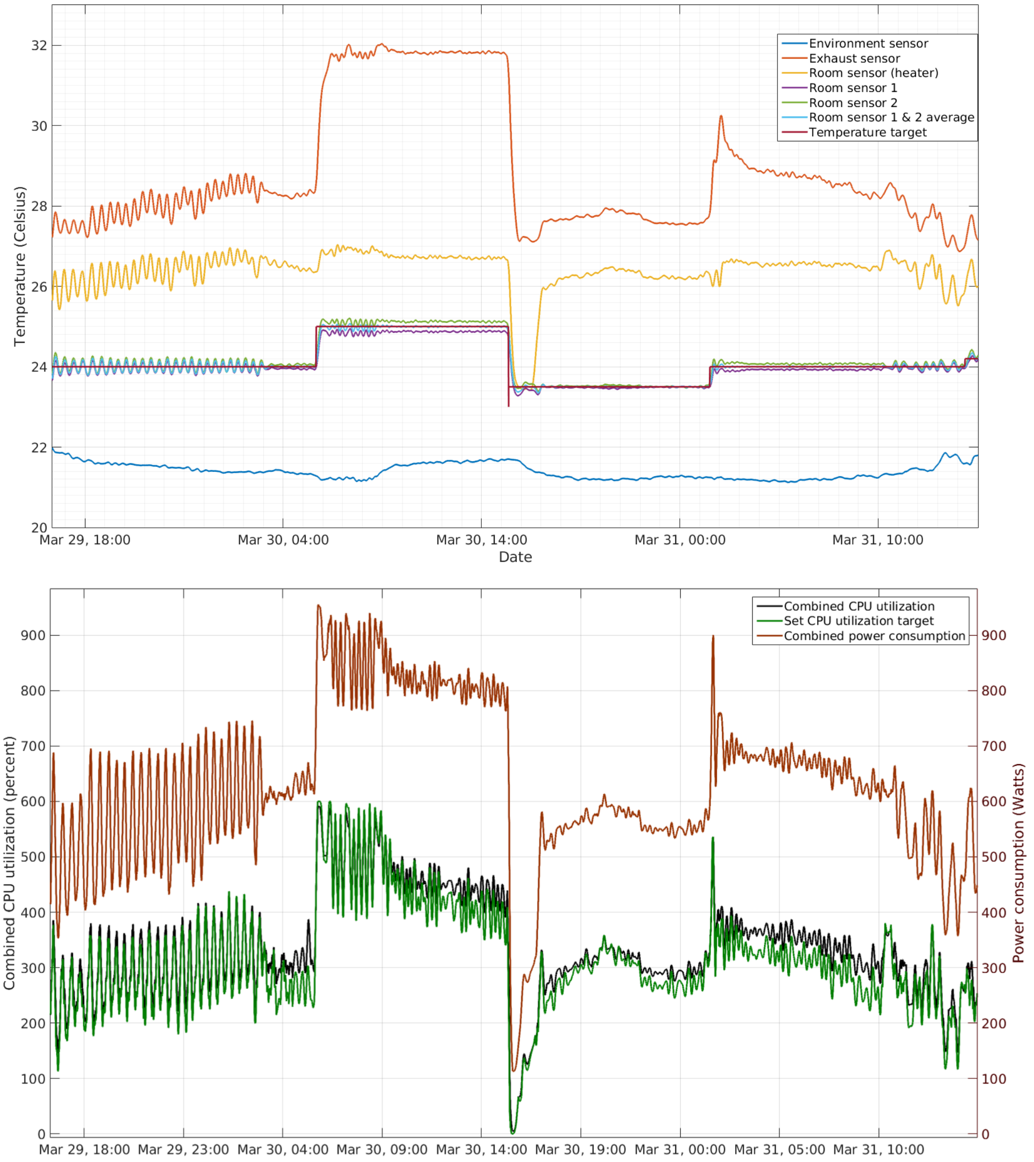

Figure 4.7: Power vs CPU utilization test 1: Note the close correlation between the CPU utilization and the power consumption.

extended test. In this later test we can also clearly see the environment temperature spiking during the daytime, in some cases causing the temperature in the test environment to rise above the given target. To counter this, the target temperature was changed to higher level several times to allow the system to continue functioning as a heater throughout the day. The large variance between the day- and night-time temperatures however allows us to clearly see the response of the heater to the changes in outside temperature and the resulting heating/cooling of the test environment. This is most visible in the exhaust temperature of the heater, which in many cases resembles the inverse of the temperature in outside environment.

For the final part of the test, the ability to shut down all the computers was restored to the control unit and we can see that the system could again have slightly better control over the environment as expected, however the impact of the normal fluctuations still exceed the limits of the heater causing the system to lose control over the temperature during daytime. However, this could be considered normal, considering that normal heating period in Finland is coming to a close.

4.5 Summary and statistics related to test results

The temperature control system and the prototype heater underwent several months worth of almost continuous testing of which the key highlight can be seen in Table 4.1. Based on the results related to temperature control, few basic statistics regarding the accuracy of the control are calculated in the Table 4.2. These include the mean target and measured temperatures and the calculated Root-Mean-Square error (RMSE) for these values. In case of the measurements done in December, the area for analysis was limited to remove the initial high temperature test which would have had a distorting effect on the result.

We can see that the accuracy of the system gradually improved and the peak values (lowest RMSE values) were visible in the third temperature control test and first power test conducted during the spring. The most interesting aspect is that the most accurate control was achieved during a test when the system was not functioning at full potential due to software error. The second power test most likely would have reached similar figures, but at this point the higher ambient temperatures caused deviations that the heater could not correct.

Another interesting aspect regarding the testing that has so far been largely disregarded is the computing performance of the prototype during this testing. Overall the prototype performed an estimated 300000 BOINC credits worth of calculations, which corresponds to roughly 1500 GFLOPS worth of processor operations. This figure is relatively small when compared to the performance of modern computers, but considering the age of the

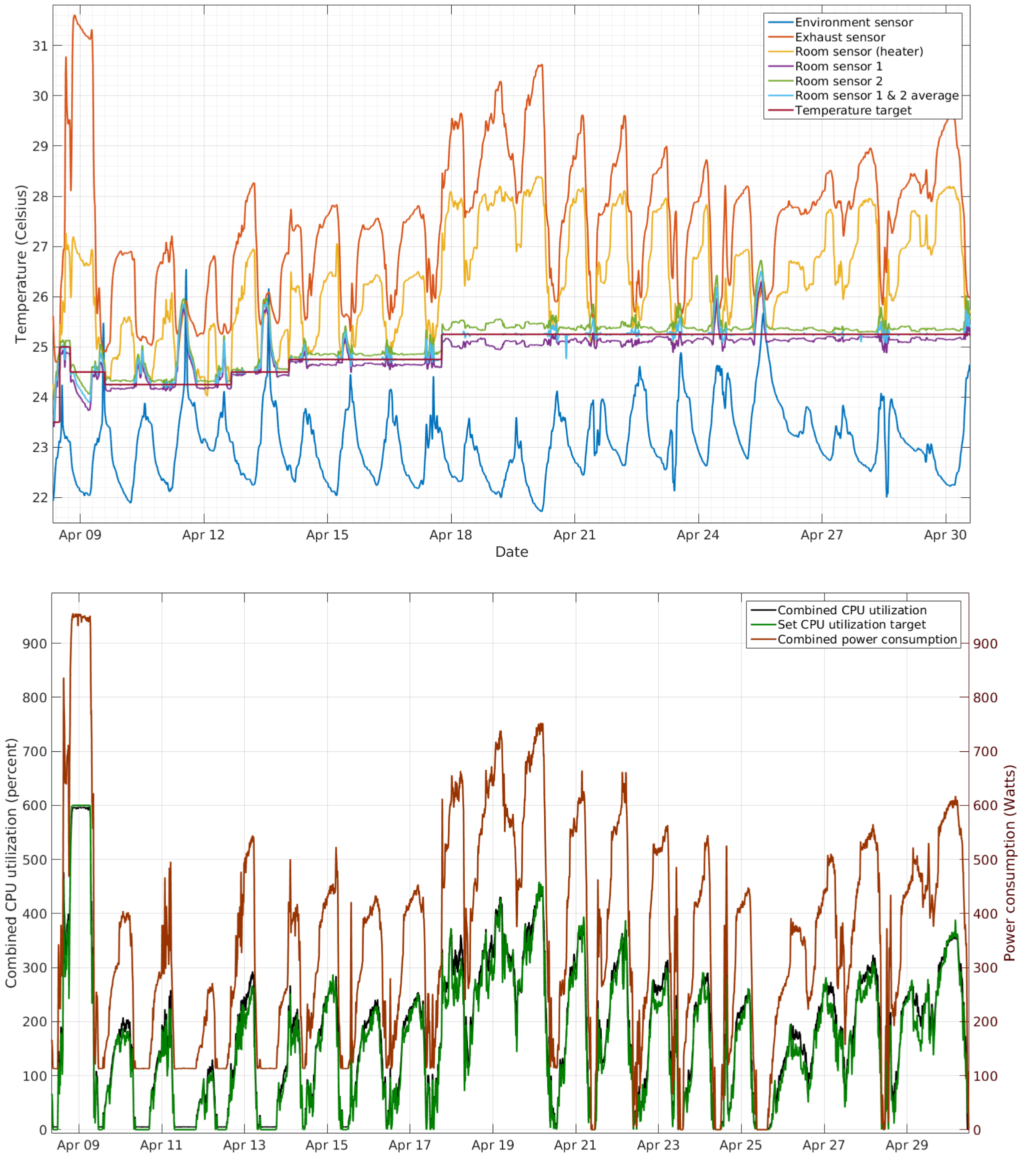

Figure 4.8: Power vs CPU utilization test 2. Again, we can see a close correlation between the CPU utilization and the power consumption. Also noteworthy is the system response to the differences between day/night temperatures.

hardware used the result is still respectable. By using CPU benchmark data provided by PassMark Software (`http://www.cpubenchmark.net/`), we can estimate the performance gain achieved by the more modern hardware. By upgrading the hardware in the prototype to Intel Core 2 -based processors

Test	Date	Significance
Heating test (Figure 4.1)	June 7th - July 1st	Shows the ability of the testbed to affect the temperature
Temp control 1 (Figure 4.2)	Sep 18th - Nov 5th	Limited temperature control, shows the need for more controlled environment.
Temp control 2 (Figure 4.4)	Dec 3rd - Jan 7th	Temperature control ability in controlled environment.
Adaptivity test (Figure 4.5)	Jan 26th - Jan 30th	Ability to respond to changing conditions.
Temp control 3 (Figure 4.6)	Feb 19th - Mar 11th	Temperature control under partial failure.
CPU utilization vs Power consumption (Figure 4.3)	November 2014	Correlation between power consumption and CPU use.
Power consumption vs CPU utilization 1 (Figure 4.7)	Mar 29th - Mar 31st	Correlation between power consumption and CPU use in practice.
Power consumption vs CPU utilization 2 (Figure 4.8)	Apr 9th to Apr 30th	Correlation between power consumption and CPU use in practice. Operation under varying conditions.

Table 4.1: Compilation of tests presented in this chapter

with similar power consumption, an estimate gain in performance would be about 3-5 times higher. With current generation Intel Core i7 processors, the gain could be 10 - 13 times higher while providing similar heat output.

Test	Measuring interval	Temperature mean(°C)		RMSE
		Target	Room	
Temp control 1	Sep 18th to Nov 5th	23.77	22.96	1.023
Temp control 2	Dec 6th to Jan 4th	23.2	23.17	0.121
Adaptivity	Jan 26th to Jan 30th	22.67	22.75	0.442
Temp control 3	Feb 19th to Mar 11th	22.5	22.5	0.0415
Power consumption vs CPU utilization 1	Mar 29th to Mar 31st	24.13	24.12	0.097
Power consumption vs CPU utilization 2	Apr 9th to Apr 30th	24.94	25.00	0.245

Table 4.2: Basic statistics of target and measured temperature during the testing

Chapter 5

Evaluation of computerized heater

The evaluation of the heater prototype and the control system is covered in this chapter through the requirements and more detailed examinations of certain aspects of the results and prototype design. In later parts some aspects of the computers in general are considered and evaluated. Finally we consider improvements of the technology based on ideas and experiences gained during this work.

5.1 Comparison between requirements and prototype features & results

As a basis for evaluation of the computerized heater, a comparison should be made between the requirements established in the beginning of the design process and the prototype and it's performance.

1. The system must be able to accurately measure the current temperature in the room or space it is located in.
As is evident from the test results throughout the testing of testbed and prototype, the temperature control is capable of performing accurate measurements of the space it is located in. In fact, the system goes beyond that and would be capable of measuring temperatures in several different locations with the limiting factor being the sensor wire length and sensor count.

2. Based on the measurements, the system should adjust the temperature within the said space until given target temperature is reached.
While the initial testing conducted in Recycling center failed to conclusively confirm this, the testing done in Energy Garage showed that the prototype

and the control system was able to reached given temperature target. In other words, the system fulfils this requirement, provided that the size of location is reasonable compared to heat output of the prototype.

3. After the target temperature is reached, the system should maintain the temperature with reasonable accuracy
Again, during the testing in Energy Garage, the system was more than capable of maintaining the given temperature and to adjust to changes in ambient temperature, provided that there was a sufficient workload available. Whenever the availability of workload was poor, the system could fail at this requirement. It is worth noting that even in these cases, the system did not lose control completely, but was still able to provide some heat, through idling the computer units.

4. The system should not output unnecessary heat when the target temperature is exceeded
For the most part, the software revisions of the temperature control unit and client program were capable of meeting this requirement. The earlier versions had some issues with accurately limiting the BOINC processes the were used, that could lead into runaway heat output. The later revisions fixed all these issues and suffered only from rare OS/filesystem errors that might prevent a computer unit from responding to commands. During the testing in Energy Garage, the only instances the latest versions produced excess heat were during the energy measurements, when one computer unit was used to log the power data and was thus constantly on.

5. The temperature target is set by the user, but otherwise the system should operate reliably without user intervention
The temperature control system and computer units were capable of fulfilling this requirement very well, and required only minimal amount of user intervention at end of the test period, apart from temperature adjustments. Although the software parts of the system were not as problem-free as the hardware and most of the actual failures of the system were due to programming errors and bugs in the control elements. This was expected of from an experimental system and towards the end of the testing the quality of the software improved and the amount of these software failures at the end of the tests is minimal, occurring at rate of one failure per month or less. The severity of the problems also decreased and in latest revisions, majority of the issues with the system could be solved by restarting parts of the system. One of the issues still existing with the system is the inability of the control system to reset computers that have halted between BIOS and operating system or otherwise stopped responding to commands.

6. The above should be done using computers as heat source and the computers should perform useful calculations while providing heat
During the testing, the combined work done by the prototype computers was worth 300000 BOINC credits or 1500 GFLOPS. The temperature control system also included mechanisms that tried to maintain as high computing to overhead ratio as possible on the computer units, by activating/deactivating units.

7. The end result should be practical and resemble a heater
This might be the one area where the prototype falls short of the requirement. The while the system performed otherwise well as a heater, there are several aspects to its practicality some of which are improvement over normal electric heaters and some of which are clearly worse than in these. In general the practicality of the system is average. While the amount of maintenance is minimal, there are other aspects that affect the practicality of the system. Primarily, the current size of the heater is larger than an electric heater of similar performance. The operating noise of the normal electric heater is also lower when compared to the prototype. While the size of the prototype can be optimized through use of more compact computers, the noise generated by system fans and airflow through the computers remains an issue that is much harder to solve. It could be argued that the noise level of the prototype is not significant and through optimizing the operating logic, could be reduced, but this does not change the fact that the noise level is higher and even at low levels could be an annoyance to the user. The mechanical fans also pose problem by wearing out and failing, the former causing the noise level to increase and the latter posing a serious problem to stability of computer involved.

On the other hand, the actual maintenance of the prototype heater in case of failures is much easier than it is with normal electric heaters. Normally if an electric heater fails, the failure is in most cases terminal or if not, the repairs need to be performed by a qualified electrician. A hardware failure in case of the prototype is typically not terminal and affects a portion of the system and the repair can be done by anyone with knowledge of computer hardware. This is due to the modular design of the prototype, which consists of several independently operating computers, and the modular nature of these computers themselves. A failed computer can thus be either repaired by identifying and replacing the failed component or by replaced altogether with another unit. The only exception to this are the hardware components of the temperature control unit which are not as modular as the computers in the heater and the DRBL-server which differs somewhat in hardware from the other computer units.

There are also some factors that can be considered as a major benefit in practicality for the prototype system. With minimal modifications, it would be entirely possible to have very detailed temperature programs for all the controlled heaters which is something that can rarely be found at cheaper electric heaters. Another feature that increases the comfort of the system is the PID controller that is able to maintain very smooth temperature and can also be customized to perform as the user wishes. Both of these features make the system a very versatile heating solution in comparison to older electric heaters.

5.2 Prototype and control unit costs

As mentioned in the previous chapters covering the design of the prototypes, the systems involved were built using materials and equipment that was acquired at practically zero cost. The most of the incurred cost was from purchases of suitable mass memory for the computers, which was later found impractical. If we calculate the cost that were available to this project but would normally need to be purchased, we would arrive to figure that would be around 100 euros. Most of this would be spent on the Intel Galileo and other parts of the temperature control system and sensor network. It worthwhile to note that single temperature control unit is capable of controlling several heaters and the expansion of the sensor network is relatively cheap in comparison to the rest of the control system. The cost of building suitable casings for the heaters is more variable and depends on which materials are chosen. Using same materials as the prototype, the cost would be around 50-70 euros assuming that discarded obsolete computers are used. If new computers are purchased for the system, the costs would naturally be far higher and this would also increase other material costs as the casing would also need material and safety requirements of typical metal computer casings.

The operating costs of the prototypes, apart from electricity, were minimal and in normal situation, would only consist of the cost of the energy. The only hardware failures that did occur during the testing periods were the USB flash drives that failed due to excessive read/write operations of operating systems. Apart from these, there were no major hardware failures of any kind and the computers used have preformed admirably during the intensive use of the testing. These tests however cover only near-term effects of using computers in this manner and only long-term testing will reveal the true effects of the heating use to the computer hardware.

Chapter 6

Discussion

6.1 Computers as part of computerized heater

As mentioned in the background-chapter, from the broad physical aspect computers and electric heaters are identical as both devices during their normal operation convert electrical energy into heat. The actual physical processes are involved are naturally more complex in case of electronics and semiconductors, but the end result is indeed the same. The computer systems also contain numerous different parts and components that contribute to the heat output of the entire system whereas electric heaters have far less components that are providing the heat output. The components that produce the heat are naturally also more complex and built to perform completely different tasks than a simple resistive heating element found at typical electric space heater.

In the beginning of the design phase, an assumption was made that the CPU would be a major contributing factor in the power consumption of computers, based on the datasheet values of the processors that were used both in the prototype and in the testbed. However, the total power consumption is not directly indicated in the design documentation of many modern CPU's, instead the manufacturers give the TDP or Thermal Design Power of their products that indicates how many Watts of heat the CPU outputs in typical use case set by manufacturer. This results in a situation where different manufacturers tend to have different specification for calculating the TDP, none of which may be directly comparable. These still give a rough preliminary estimate of the power consumption of the CPU. In the case of the processors utilized in the actual prototype and testbed built during the process of this work, the TDP values ranged from 89 Watts [14] to 95 Watts [15] which can be assumed to be the power consumption in average use and around two thirds of power consumption under heavy load . Based on this, the control mechanism was centered on controlling the CPU utlilization and the number of computers, that proved to be remarkably good and accurate solution which is evident from the CPU vs Power consumption measurements done during the testing. As the rest of the power consumed by the computer systems could now be considered overhead, the question arises how this overhead could be reduced? Natural approach would to reduce the number of the other components used in the computers to bare minimum.

The rest of a computer system consists of hardware components that either exist to provide essential functions to support the CPU (motherboard, main memory), provide mass storage (hard disks, optical drives) or provide graphical capabilities (GPU's or graphics cards). In addition to these, there typically are different kind of fans to provide cooling to system components and the power supply that provides DC power to all system components. Out of these only CPU, memory, motherboard and the cooling mechanisms are absolutely necessary, and other parts can be either removed or in case of mass storage, replaced with network filesystems. Thus we can concentrate on these remaining components, out of which the motherboard and memory combined would consume power in range of 20 to 60 watts depending on multitude of variables. These include but are not limited to: the design of the motherboard, chipset used, number of memory modules used, number of the memory chips used per memory module and so on. However as these components are essential to the system and we have little control over their power consumption while the computer is operating, we can consider the power consumed by these components as overhead to the system operation. The same holds for the power supply, which consumes some power during the AC/DC conversion in efficiency losses.

Apart from these choices, the selection of computer hardware for heating use is relevant in other ways as well. In fact, majority of the design choices that have to be made with computerized heaters are eventually dependent on the computer hardware chosen and especially the efficiency of the said hardware. Basically, if we select too good a computer hardware as a base for the heater design, the heating power of the system will suffer due to more energy efficient designs, but the size of the computers may not decrease in same respect. In order to have sufficient heat output, we then need to increase the number of computers and thus the size of the heater or sacrifice some of the computing edge in favour of more inefficient CPU's. Sacrificing too much of the computing power however results something that is very close to normal electrical heater in a sense that it produces nothing else than heat. This three-way optimization dilemma is illustrated in figure 6.1. The size in this dilemma is seemingly pointless from physical point of view,

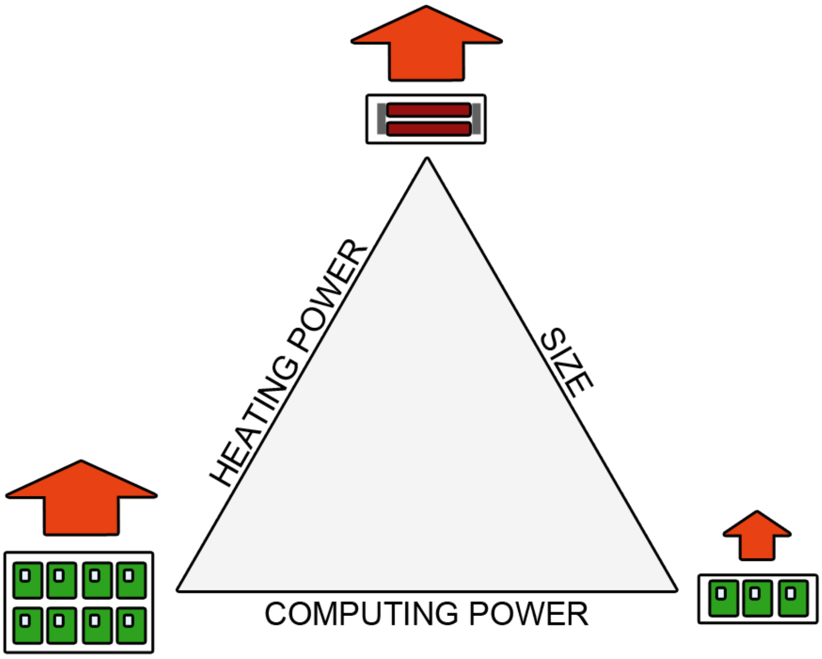

Figure 6.1: Heating power vs Computing power vs Size

but considering that these are devices that should be possible to practically install into households, it needs to be taken into consideration. The size also implies cost in a sense, as having more of highly efficient computers is going to increase the cost of the overall system if not directly in computer hardware then in the form of needed infrastructure and materials.

6.2 Comparisons between server hardware

When considering that computerized heaters could perform the tasks similar to those computed at servers, a comparison between the hardware differences becomes an interesting question. In general, the basic components (CPUs, Memory) used in servers are not very different from the hardware used in the desktop computers and in workstations. For instance, the Intel Xeon CPUs intended for server use correspond closely to the current processor technology used in common desktop computers. Typically, these contain some minor modifications that bring a slight advantage in heavy-duty computing, such as use of larger internal cache. While the processors and other basic components may be comparable, the server hardware usually emphasizes expandability, redundancy and easier maintenance of components. Another approach taken by the server hardware is to minimize the size of the hardware, at the cost of higher need for forced air flow and thus operating noise. The smaller size of servers allows for higher server densities in data centers. An good example of this minimization are the blade servers, which are more lightweight servers that are installed in specialized blade enclosures. Each enclosure contains several blade servers and provides each with power and other necessary connections.

Processor	Intel Pentium D 820 2.80GHz	Intel Xeon 2.80GHz (Dual Core)
Cores	2	2
Threads	2	4
Cache (L1 & L2)	32KB / 2048MB	32KB / 4096KB
TDP	95 Watts	135 Watts
Estimated performance (PassMark)	6̃00	665
Performance difference to Pentium D 820	1	1.108

	Dell Optiplex workstation (Heater)	HP ProLiant BL20p G3 - Blade server	HP ProLiant DL380 G4 - Server
Processor	Intel Pentium D 820	Intel Xeon (Dual Core)	Intel Xeon (Dual Core)
Number of processors	1	1-2	1-2
Total number of cores	2	2-4	2-4
Estimated Performance (PassMark)	600	665 - 1330	665 - 1330
Maximum memory	8 GB	8 GB	12 GB

	Heater Prototype	HP Bladesystem p-Class	HP ProLiant DL380 G4 - Server
Number of computers or blades	6	8	1
Total CPUs / Cores	6 / 12	8 - 16 / 16 - 32	1-2 / 2-4
Estimated total performance (PassMark)	3600	5320 - 10640	665 - 1330

Table 6.1: Comparison of desktop and server hardware. CPU performance values are derived from their CPU Benchmark scores provided by PassMark Software Pty Ltd (`http://www.cpubenchmark.net`).

In Table 6.1 we can see a comparison between the Intel Pentium D 820 processor[15] used in the computers of the prototype heater and a Dual-Core Intel Xeon 2.80GHz processor[13] intended for server use. The figure also compares the Dell workstation computers used in the prototype against similar Hewlett-Packard ProLiant BL20p[9, 10] blade server and ProLiant DL380[11] server solution. From the figure we can see that the processors, which are both based on the Intel Netburst-architecture, are closely comparable. The Intel Xeon processor offers a larger cache and a support of execution of several threads per core. The estimated Passmark benchmark values for the similar Pentium D processors are also comparable although lower, probably due to the benefit given by the larger cache. The server hardware of the comparable era is also very similar to the basic hardware in the Dell Workstations, with the difference of the capability to support several processors in a single server. The overall performance differences between the complete blade system and the prototype heater are mainly caused by differences in processor capabilities, higher number of processors and higher number of total blade units. The normal HP ProLiant server would have similar capability as the Blade system, provided that several of these servers would be used. This higher server density is the most obvious benefit from the server hardware, resulting in higher number of processors and computers in relatively small space. For example a single rack could contain around 48 Blade servers in their enclosures and with their power units, total number of CPUs could then be between 48 to 96 depending on configuration. Similar amount of computing power could roughly be achieved by 8 to 16 prototype heaters. Improving this number may be difficult due to the forced airflow used in the servers, which is undesirable in heaters in household use.

All in all, the workstations and server hardware are not very different from basic hardware viewpoint. However the differences in hardware durability is a question still left unanswered. The redundancy and design principles should make the server hardware more durable and failure resistant, but based on the testing done with the prototype nothing conclusive can yet be said about the durability of the workstations. So far, the workstations have performed without problems and may continue to do so for a long time, but only further testing would tell the true failure rates of these machines.

6.3 Performance and energy efficiency of computerized heaters

The performance of the computer heaters is twofold: their performance can be measured both as computers and as heaters. The heater performance can be can be considered as the devices ability to output heat and the rate at which this heat is moved to surrounding air. For computer the heat output is basically identical with the output of ordinary electric heaters, but the rate at which the heat is moved to air outside the computer may be slower depending on the casing of the computer in question. This rate is significant in a sense that it affects the response time of the heater, which in turn needs to be taken into account when designing and tuning the control for the heater. Slower response time would also mean that the heat output is less likely to fluctuate.

The computing performance on the other hand is measured as the system's ability to perform computational operations. In terms of scientific calculations, this is usually measured as floating-point operations per second (FLOPS). The number of FLOPS the system is capable of depends on the clock speed of the processor, architecture of the processor and the capabilities of the underlying system. In general, current generation CPUs typically perform more operations per each clock cycle. Due to this, the clock speeds of current generation processors have decreased somewhat, leading to better energy efficiency as clock speed is one of the factors that has significant impact on energy consumption.

In terms of efficiency, the space electric heaters are a simple case as the energy is transformed with very little losses to heat and as a result of this, their efficiency is close to 100%. The computers are more complex case, as their energy efficiency is measured as performance per energy consumed or FLOPS per Watt. As the performance of the computers varies depending on the hardware, the energy efficiency needs to be measured separately for each different hardware configuration. Another issue complicating the estimation of energy efficiency of computers is that the CPUs perform differently on different tasks depending on the instructions the tasks require.

With computerized heaters, we have the combined performance and efficiency elements of both computers and heaters. Based on the performance and efficiency these, we can estimate the efficiency of the combined device. As the performance and efficiency of energy conversion is similar on both heaters and computers, we can assume that the energy efficiency on this part is also similar. As for the computational part, if the design of the computerized heater does not change the actual computer hardware in any way, the efficiency and performance of it should remain the same. Unfortunately, it is difficult to combine the factors of these two devices into one meaningful indicator of performance or efficiency, thus the computerized heaters have to be evaluated both as a computers and heaters. In short, higher heat output at faster rate would make the combined system a good heater and at the same time, high performance per every watt consumed would be considered good computing performance.

6.4 Comparisons with electrical heaters

As mentioned earlier, the computerized heaters have similar heating performance as their electric counterparts and thus a similar CoP ratio, if we ignore the computations made. However there are other aspects should be compared as well, most importantly the cost and lifetime of both systems. The cost structure in both systems is in ideal situation the same as both approaches consume electricity at same rate and provide same amount of heat. The main differences in cost come from other operating costs, such as replacement parts, and from the initial cost of the computerized heater. The initial cost of electrical space heater is very small compared to other heating technologies [22] due to the simple nature of the technology. This makes competition in this area difficult, especially if new computer hardware is used in construction of the computerized heater. If the computers are recycled, this cost can be reduced but at the same time some computational power is most likely sacrificed. Even in this situation, the larger frame of the computational heater may result in somewhat higher assembly cost. As the calculations performed during operation might counteract this higher initial cost overtime, the price difference between the two technologies might be acceptable. However, possibly even larger source of costs is shorter lifespan of computerized heaters and computer components.

The problem arises from the more complicated nature of computers, the computations themselves and the software used. The hardware used in the computers is not specifically designed to last for decades as the advances in technology will make most computers obsolete in many ways within 5 to 10 years. Although the components in the computers are designed to be modular and replaceable, finding suitable spare parts may prove challenging after 3-5 years. Naturally, an easy solution to this is to upgrade the computer hardware as it fails or becomes obsolete but this basically means incurring the initial cost of the system again every 5-15 years, depending on the performance requirements and hardware failure rates. This emphasises the need to use very high performance hardware that provides value for longer time or very low cost equipment that can be cheaply replaced if need be. In both cases, a modular approach in design is recommended to allow easy replacement of computer units. In comparison, quality electrical space heaters are very reliable and require very little maintenance. If used correctly, electrical space heaters can operate for decades making their lifespan very long in comparison to computers.

6.5 Improvements and alternate applications

Although the space heater and related control systems proved to be sensible providers of controllable heat, there are still aspects that could be improved in the system. During the course of this work, several additional ideas were also presented on how to utilize the waste heat of computers. In this chapter we go through some of the ideas that could improve the operation of the computer space heater as well of some of the ideas on how to use the wasted heat in different ways.

The design and architecture of the final revision of the heater prototype has significant flexibility that allows the system to be used in various ways. Few of the earliest ideas of utilizing the accuracy and distributed nature of the design was to disperse the heating computers into different parts of the room and by accurate measurement through number of sensors, individually control the computers to maintain very stable temperatures at all areas of the room. This approach might reduce the noise levels of the overall heating and offer a reduction in needed space. The final revision of the heater prototype is designed to be like an ordinary electric space heater and with similar amount of heating power. As such, the six computers combined to it take sizeable amount of space in comparison to normal heaters. By separating the computers from this set up would allow more free positioning within the room and thus opens a possibility to save space.

Another benefit from the modular and scalable architecture of the prototype is that it would allow us to create heating systems for the entire building it is located in. As the one-wire connection used by the system should be able to operate significant number of sensors over distance of hundred meters or more, the sensors can cover a normal sized house. As the sensor coverage is sufficient and the temperature control unit can be easily modified to manage temperature at several locations at once, providing centralized temperature control over different areas of a house is just a matter of placing computers at monitored areas and programming the system accordingly. When considering that the final revision of the heater prototype included a centralized server to provide the clients with necessary operating systems and shared network drives, the proposed set up is more than viable. In fact transforming the independent computer heaters into several centrally controlled heaters offers the benefit that we can separate the server providing the operating systems for the clients into a location where it can scaled up without the noise generated by the hard disks and cooling fans being a problem. As a result, the computer heating system covering the entire building bears a close resemblance to central heating systems existing now. Naturally, this kind of set up could be taken one step further into the level of district heating, in which case a district data center would provide the clients or the servers located at each house with the tasks to be processed. However, at this point it is hard to say what kind of tasks these could exactly be to make this financially viable. Nevertheless, even in the current form, the idea of having building heated by computerized heaters that controlled by a system that can control the temperatures accurately, manage different kind of temperature setting for different times of day and can provide all these features and temperature statistics remotely, is something that should be a promising concept especially from the point of view of building automation.

As for the technical improvement of the heaters themselves, there are two of the key issues or restrictions that we can think of with the computerized heaters. These are the transfer of heat from the hot components and noise generated by components and air moving fans in the system. At the core of both of these issues is air, which has a relatively poor heat capacitance (1.005 kJ/kg.K) which makes it more difficult to transfer heat from hot components into the air which also translates into greater need of airflow. A solution to this would be to replace the air with more efficient cooling medium and obvious choices would be the existing water cooling solutions, which utilize specialized water cooling blocks installed on the hot components. The problem with this approach is that some airflow has to maintained through the system as these cooling blocks can only cover the major components, such as the CPU or Graphics card. Another approach to improve the noise levels of the computerized heaters would be to use completely passive cooling of the system components through massive heat sinks. This would be similar to the approach apparently taken by the Qarnot computing in their heater solution. The design would not be without challenges, as the heat from computer system originates from several sources, many of which are hard to connect into the large heat sink. In short, the completely passive approach has some of the same issues as the liquid cooling. Although it should be possible to design specialized motherboards that would reduce the need of airflow through the components, the cost of designing and manufacturing such specialized motherboards could be prohibitive from the financial point of view. In similar fashion, altering existing motherboards that are designed to have some amount of airflow through their components, to be completely passive could also prove to be financially non-viable solution.

More radical approach to reducing the noise and improving the transfer of heat from the system would be to immerse the computer system in a suitable non-conductive fluid with higher heat capacity and thus replace the air altogether. The liquid would remove the heat from all the components more effectively and only the cooling for the liquid itself would need to be arranged. The added benefit with this method is that all the fans and heat sinks continue to operate normally even when immersed in oil, meaning that the system requires no significant modifications in order to be used with oil instead of air. This method of computer cooling using liquids such as mineral oil is not an entirely new approach in computers and server, even less so in the world of electronics and electrical systems. In the electrical systems, different kinds of oils have been used for over hundred years to cool high voltage transformers. This approach has also been taken in some of electric space heaters, where the oil is used as a heat transfer and storage medium. In the computer world, there have been enthusiast experiments with oil cooling since the early 2000s and more recently, Intel performed testing with oil based server cooling at their computer center. As the heat stored in the oil can be moved more flexibly than heat in air, the oil cooling also opens more possibilities on what we could actually do with the heat from the computers. For example, by circulating the oil through a radiator we can create a computerized version of oil filled electric space heaters. It might also be possible circulate the oil through existing central heat systems or modify such systems so that we could transfer the heat from the oil into the existing liquid circulated by the central heating.

One of the other intriguing options for utilizing the heat from computers would be hot water boilers which, contrary to the space heaters, are in most parts of northern hemisphere throughout the year. They also have the added benefit of being highly regular in their heat requirements, making the availability of computing power from the heating computers usable in larger number of applications. The regular heat requirements derive from the cyclic nature utilized in many water heaters; during the night time, the stored water is heated and kept warm by efficient insulation throughout the day. This means that the time when the computers are active is cyclic and based on use history, the amount of actual computations provided when the heat is needed can also be predicted. The water heating however has some basic problems that complicate adaptation of computers for this purpose. First off there is the issue of transferring the heat from the computers to the water within the tank. This could be approached through either direct or indirect heat transfer and neither of these approaches is entirely problem-free. In direct approaches the heat from the CPU and other hot components is dissipated almost directly into the hot water using heat pipes connected to heat transferrer in the tank. This approach should be simple to implement using few computers, but the number of computers needed to heat a tank full of water starts to limit the implementation. There is also the fact that even though there are tested technologies, such as heat pipes, that could be used to directly cool the components to the water, these technologies would still need adaptation to current hardware. This would translate most likely translate into custom components customized for this purpose, which would mean higher manufacturing costs.

Indirect approach would entail transferring the heat from the computers using a separate liquid cooling circuit that is attached into heat exchanger within the water tank. This solution allows more flexible placement of computers and allows the use of normal after market cooling blocks available for most CPU's. There is still need for the specialized heat exchanger, but this might be cheaper to manufacture overall than entirely customized cooling solution in the direct approach. This system however suffers from the risks regarding leaks in the system at both computer and water tank side. In both cases the leak causes loss of cooling for the computers and if the leaked water comes into contact with any of the electrical components, also permanent system damage.

There is another aspect that makes heating of water more problematic than other options, and this is the health aspects involved with water boilers. The hot water used as tap water in households needs to be heated to certain temperature in order to prevent harmful colonies of bacteria forming into the system. In the EU, The European Working Group for Legionella Infections (EWGLI) has set the minimum required temperature to prevent *legionella* bacteria growth in hot water systems to be over 60 degrees while temperature of 65 degrees is strongly recommended [21]. In order to reach these temperatures the CPU's and components of the computers used to provide the heat need to reach temperatures higher than 65 degrees for extended periods of time. While this is possible, such temperatures are closing on the limit of the temperature envelope of the processors which may cause instability and other hardware issues.

6.6 Business and financial possibilities of computerized heaters

A question that was raised early on during the course of this work was could this technology be used commercially and if so, what would be the most logical business approaches to utilize the technology in such manner? In this chapter this idea is considered and possible approaches to the commercial use of the heaters is presented.

Based on the development of the prototype, three different main approaches to which the technology could be taken can be identified, each presenting us with different possible commercial opportunities. These directions are as follows:

- Improving the technology to utilize the latest in processor and computer technology to provide high performance in computations. The system cost is higher, but the computational gains that could be monetized are also larger. (Computing first -approach)
- Using the technology more or less as-is and concentrating instead on minimizing the system cost by maximizing the hardware compatibility and case design. In this approach, any computer could be considered suitable, as long as the cost and practicality are reasonable. (Heating first -approach)
- Applying the technology to area different from space heating, that could permit easier monetization of computing power and/or the generated heat.

The first approach considers computerized heaters as sources of computations. Maximum performance and state of the art. Benefit from computing capacity that can be sold as a service, the gains exceeding the cost invested into the hardware. Design refined and provided in standardized form, guaranteeing capabilities and reducing the cost somewhat through common components. This approach is most valid for companies already operating data centers as the heaters solve the problem of cooling data centers by distributing the computers to places where the heat is not an issue but a benefit. At the same time the distribution of the computers from a centralized locations removes the need and the cost for maintaining large electrical infrastructure, instead benefiting from already existing infrastructure to households. This combined with the existing technology of automatic meter reading which allows remote reading of power consumption, it would be simple to reimburse the costs of heating electricity to the end-users of the heaters.

The second approach considers the computers mainly as a hardware and as a true source of heat. As such the computations done in these devices are a benefit that improves the system efficiency but in themselves provide little direct monetary gain. Thus a business would be formed around design and manufacture of computerized heaters at a cost that could compete with existing heater technology. If this can be achieved, then the computations performed are truly little to no consequence to the manufacturer and are left to the control of the end-user or another companies or entities. The direct benefit from removing the computation aspect from the business is that it solves the problem of discovering suitable work that could be distributed to computing heaters which provide calculations only under certain conditions and may not perform when needed. The obvious selling points here would be the more advanced control features provided the system over the older electric space heaters, somewhat higher energy efficiency, the ability to provide computing power and services to the end-user. To keep the cost down in this scheme, possibly the best hardware approach would be to reuse old computers that can still provide decent amount of computations but are no longer considered state of the art. A possible candidates to which this approach might be truly interesting are manufacturers of business computers, which have typically offering highly standardized models and sell or lease them in large quantities to other businesses. By modifying their computer designs to support easy refurbishment to heaters, these companies could arrange the recycling and refurbishment of their models as heaters after their usable life as workstations or servers has ended. As a result, these computers would effectively used twice and in a sense could be sold twice, once as a workstation and once as a part of a heater. Additionally, the would enable these companies to sell state-of-the-art heaters as well, built directly from computer models in their current product line-up.

Third approach: Using the computers as heat sources in different ways, preferably by making the availability of computing power more reliable and predictable. Improvements and ideas covered in the previous chapter would fall partially under this approach. Any new improvement achieved could then either be applied in similar fashion as the two other approaches described in previous paragraphs, but they might also open unforeseen new possibilities for the technology. In a sense, this would be the research approach for the technology.

Naturally, these three approaches are not necessarily exclusive and could be combined in any possible way. These approaches could also define the structure of entirely new area of business computerized heating, where the hardware is constructed by computer companies and sold and utilized by companies concentrating in data services in cooperation with electrical companies.

The problem with all of these is that the heaters need to be over-scaled in order to have sufficient power to respond quickly to sudden changes in temperature and to have sufficient leeway in case the ambient temperature falls below the expected range, as can be the case in very cold climates. The latter is especially true if we consider combining the heaters with heat pumps, as these gradually lose their efficiency as the temperature falls. While it is technically easy to add additional computers to the computerized heaters, these computers will increase the cost of the system and add little computational benefit to the system as they remain unused for most of the time. This is evident from the experimentation and testing done with the prototype, as we can see in many of the test scenarios the full power of all the computers in the heater are only needed when trying to reach new temperature target or when operating near the limits of the heater. That is, near the maximum change the prototype can induce to the test environment. We can also see situations where the a drop in the ambient temperature causes the prototype to reach given target temperature. Of course, it would be possible to program the system to rotate the use of the computers so that the hardware is stressed evenly, but the benefit from this is likely minuscule compared to the cost.

In light of these facts, it is questionable if the approach of constructing the heaters entirely from state-of-the-art computers is valid or whether hybrid of expensive and cheap machines should be used. In this sense, constructing the heaters from older computers is more sensible approach as these cost less and also reduce the environmental impact of the machines in terms of used materials.

Chapter 7

Conclusions

In this work the concept of computerized heaters and their performance was explored through construction and testing. In the process, a temperature control mechanism was created and perfected for controlling computational loads in multiple computers based on temperature measurements. The concept of computerized heater is sound from physical standpoint, given that when combined with good enough control mechanism and stead supply of workload to calculate the computers in the heater were more than capable of maintaining a desired temperature within the test environment used in this work. Also, the prototype did this in very varying conditions and for extended periods of time.

At the same time, the computers in the prototype performed over 300000 BOINC credits (1500 GFLOPS) worth of calculations to various projects, fulfilling the computational aspect of the system. It is also noteworthy that the computers used in the heater contain processor technology from 2005 and with more modern equipment much higher number calculations would be achieved. However, if the prototype is evaluated from the standpoint of practicality, the operating noise and the system size compared to the heat output are issues if compared to normal electric space heaters. The practicality is also shadowed by the possibility of costly hardware failures, which are more likely in complex computer systems than in simple electric heaters. Although the testing did not reveal any major problems, this fact cannot yet be eliminated. If these problems can be overcome through further design improvements or alternate approaches, the computerized heaters could outmatch the electrical space heaters in efficiency and match them in every other area of operation and practicality.

As for the financial and commercial aspects that were also looked into in this work, the electrical space heaters still hold an edge against their computerized counterparts in terms of cost. This means that in order to make these new devices commercially successful, either the cost of the devices needs to be kept were low to make competing with existing technology possible or the computing power of the devices should be commercially utilized. Considering the nature of the computerized heaters, finding suitable workloads to fulfil the latter business approach may be challenging to say the least. As the computerized heaters will only process workloads when heating is needed, which can vary due to several different factors including weather, end-users actions, etc. , it may be difficult to predict when computing power is available to customers in need of it. If suitable market for such computation services can be found, then this could be a very profitable business indeed for both the household owners and for the providers of the computerized heaters.

What these findings and conclusions emphasize is that while the system currently is not perfect, it could be a very reasonable solution both commercially and practically through further research and development. This is also evident through emerging businesses revolving about the concept of utilizing the heat of the computers both in small and large scale. There are also other areas of development that might find the computerized heating and the related temperature control systems very interesting, such as the area of home automation. But again, this is something that could be proven through further improvement of the technology and means to transfer the heat from the computers into the houses and buildings.

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