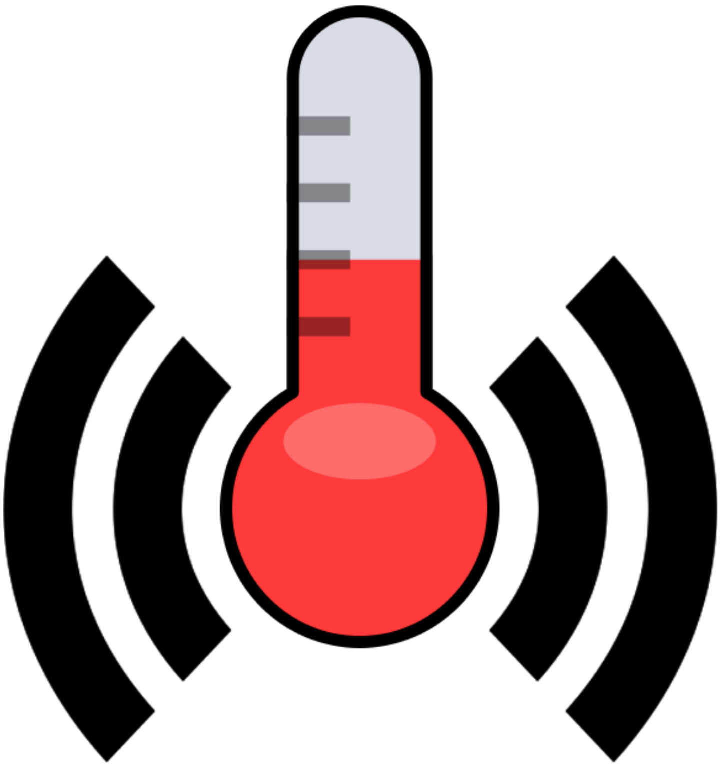

Development of a wireless device for temperature measurements in the automotive industry

A master thesis project using non-proprietary standards

VIKTOR HOLCK
CARL HORNBORG

Master thesis in Product and Production Development
Department of Product and Production Development
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A MASTER THESIS PROJECT

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Abstract

When conducting temperature tests for development and verification purposes within the automotive industry, the communication between sensors and data acquisition hubs is usually wired. Preparing a test vehicle requires it to be modified and partly disassembled, to be able to reach each measurement spot. The preparations are time consuming, especially when hundreds of sensors are used.

A wireless connection could reduce the resources needed to prepare a test vehicle and make test setups more flexible. However, the wireless devices available on the market do not fulfill the requirements and/or use proprietary standards to transfer data.

This report presents the development of a device that measures temperatures with thermocouple sensors and uses non-proprietary standards to transmit the measurement data. The wireless standard used is BLE (Bluetooth Low Energy) which brings a large selection of compatible hardware and software.

The resulting, small sized, physical prototypes shows great potential with low energy consumption.

Keywords: product development, non-proprietary, wireless, Bluetooth low energy, BLE, thermocouple, automotive, testing, temperature

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Secondly we would like to thank the supportive people at Chalmers University of Technology. Professor Gunnar Elgered has helped us during our validation. Professor Johan Malmqvist has been our examiner, and provided valuable feedback and guidance whenever we asked.

Viktor Holck and Carl Hornborg, Gothenburg, June 2017

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Acronyms and Glossary

ARIB Association of Radio Industries and Businesses. A standardization organization in Japan. 32

electromotive force "...force or electric pressure that causes or tends to cause a current to flow in a circuit, equivalent to the potential difference between the terminals and commonly measured in volts" [Collins English Dictionary n.d.]. 12

ETSI European Telecommunications Standards Institute. A European Standards Organization. 32

FCC Federal Communications Commission. Department of the United States government that"...regulates interstate and international communications by radio, television, wire, satellite and cable" [FCC n.d.]. 32

IDE integrated development environment. 24, 29

IoT internet of things. 8

IP 54 "Dust protected" and "Protected against splashing water" [IEC 1989]. 16, 46

IP 67 "Dust tight" and "Protected against the effects of temporary immersion in water" [IEC 1989]. 16, 46

ISEP Innovation, Science and Economic Development Canada. Formerly Industry Canada or IC. Canadian government department. 32

ISM Industrial, scientific, and medical radio band. 8

JTAG Joint Test Action Group. "...IEEE-1149.1 standard, also known as JTAG or boundary-scan, has for many years provided an access method for testing printed circuit board assemblies, in-system-programming, and more." [Corelis n.d.]. 32

master see explanation of 'slave'. 8, 11, 38–40, 46

Qi "The leading wireless charging standard embraced by hundreds of leading manufacturers [Wireless Power Consortium n.d.].". 33, 35

Seebeck coefficient "...the Seebeck coefficient is the ratio of the potential difference ... that arises due to a temperature difference..." [de Boor and Müller 2013]. 12

slave in a submissive relationship with a 'master'. Used to describe the relationship between a transmitter (slave) and a receiver (master). 8, 11, 37–40

SPI Serial Peripheral Interface. Uses four communication pins with a power and ground pin. 32, 35

1
Introduction

This chapter intends to give the reader a background of the project, why it is performed and what it aims to achieve. It starts with a description of the company this project have been done in collaboration with, that had the initial idea. The background of the project is then described, followed by the purpose, goals and scope of the project. The chapter ends with descriptions of the report structure and chapters.

1.1 Etteplan

Etteplan is a "...specialist in industrial equipment engineering, embedded systems and IoT and technical documentation solutions and services" [Etteplan n.d.]. It was founded in Finland in 1983, and have since grown to have 2500 experts employed in Finland, Sweden, the Netherlands, China, Germany, Poland and The United States.

The Etteplan branch in Gothenburg is an engineering consultancy firm with focus on vehicle industry, medtech, consumer products and the engineering industry. Founded in 1989 as 'Cool Engineering AB', they were fused with 'Etteplan Sweden AB' in 2012. As this report is written they have 50 employees, working in-house as well as outsourced to companies.

Etteplans customers include Volvo Group and Volvo Cars. Both have enlisted Etteplan to perform temperature tests during vehicle development. It was in the light of these tests that the idea for this master thesis was born.

1.2 Background

When conducting temperature tests for development and verification purposes within the automotive industry, the communication between sensors and data acquisition hubs is usually wired. Each sensor consists of a type K thermocouple wire which is made new for each test setup. Up to 200 thermocouples are used for each setup, and preparing them takes several days alone. The test setup for a passenger car can take up to three weeks to prepare. The thermocouples usually run from data acquisition hubs in the trunk of the car, to the measuring spots. When the tests are done, the thermocouples are discarded along with the car.

Placing the wires requires the mechanics to disassemble and/or modify parts of the car, in order to be able to pull the wires through. Because of the required work, the preparations for the tests are time consuming and the possibilities to add or replace sensors during testing are limited at best.

The tests can be conducted in several different environments such as climate chambers and outdoors, with temperatures reaching between -40 and +85 degrees Celsius. Some outdoor tests are performed as expeditions to warmer or colder climates than what is offered in the factories vicinity. An expedition can take up to 21 days, and the temperatures are often measured 6 hours daily.

1.2.1 Currently used system

Etteplan and the companies they work with currently use a wired system consisting of one or several data acquisition units, or hubs. The hubs communicate with a PC via CAN protocol, a CAN-to-USB converter, and a USB cable. The units are usually mounted to the floor of the boot, and draws power from the vehicle. An example of a possible setup is shown in figure 1.1.

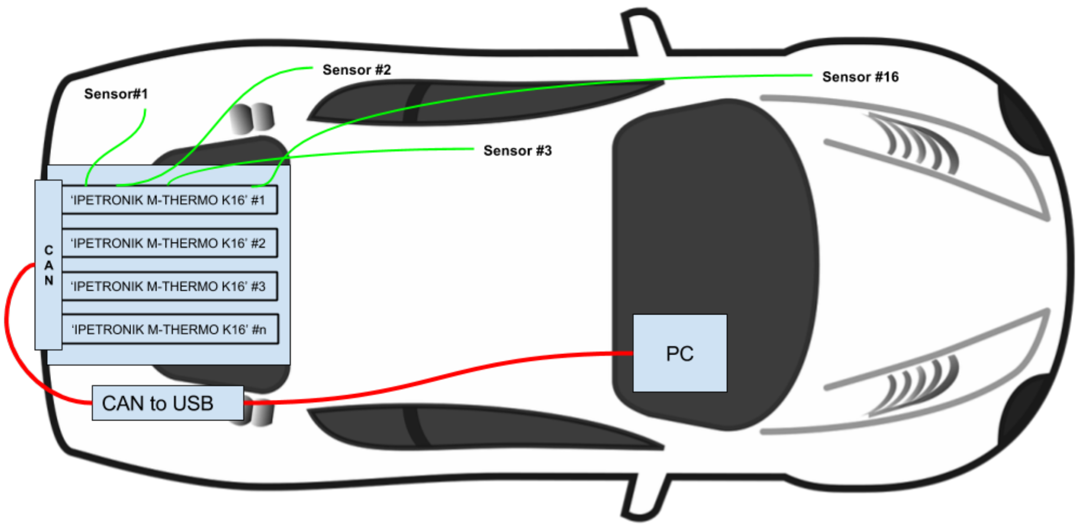


Figure 1.1: Currently used wired sensor network.

The data acquisition units generally used are 'M-THERMO-16' 16-channel data acquisition hubs from IPETRONIK [Ipetronik 2016] with type K thermocouple inputs, seen in figure 1.2.

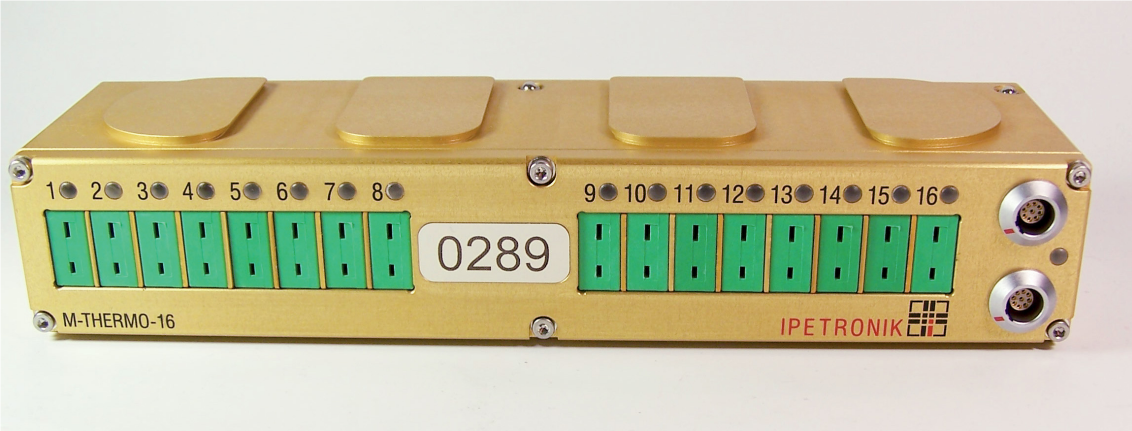


Figure 1.2: Ipetronik M-THERMO-16. [IPETRONIK 2008]

Etteplan wants the advantages a wireless system would have over the currently used wired system. The main identified advantages are flexibility, time savings during installation and a decreased need for modifications of the vehicle.

Etteplan wants to create their own wireless system since currently offered products use proprietary standards/software or lack other required properties. Proprietary standards could result in supplier lock-in's that reduces the amount of options for future purchases and development. The products using non-proprietary systems usually lack properties such as possibility to connect more than one sensor or good weather protection, according to Etteplan. This makes Etteplan reluctant to invest in any current wireless system.

1.3 Purpose

A non-proprietary wireless solution with required properties could decrease the time and resources needed to prepare a test, reduce the amount of needed modifications of the test vehicles, prevent supplier lock-in, and increase the flexibility during testing.

1.4 Goals

The goals of the project are to:

- identify the requirements a device needs to fulfill
- build and test a device that:
  - is a proof-of-concept.
  - uses a non-proprietary wireless standard.
  - uses non-proprietary data formats.
  - measures temperatures with thermocouples.
  - fulfills the identified requirements.
- document the development process and results in a master thesis report.

Fulfillment of these goals should show the potential to:

- reduce time and effort needed to prepare a test.
- increase flexibility during tests.
- avoid supplier lock-in.
- spark interest of potential customers, justifying further development.

1.5 Scope

All components may be bought 'off-the-shelf' if deemed good enough. Designing and building each component is too time consuming.

The receiver will be provided by Etteplan in order to test the device. As long as the device can send the temperatures and some sort of identification, Etteplan will manage the data.

The device should use thermocouples of type K.

Adding desired functions is prioritized over fulfillment of requirements if constrained by time, resources or availability.

1.6 Outline of the report

The report starts with two chapters that aim to provide the reader with the information needed to fully understand the report. First, an introduction chapter consisting of the background, purpose, goals and scope of this project. The chapter gives the reader an understanding of why this project was performed, and what it aims to achieve.

It is followed by chapter 2, that describes the intended system architecture and continues by explaining the important technologies involved.

Chapter 3 explains the compilation of knowledge that was needed in order to identify which requirements the device needs to fulfill. The resulting list of requirements was used as a screening tool during the selection of hardware and wireless standard presented in chapter 4. It further consists of a state of the art study, that concludes that there are no available products on the market that fulfills the previously mentioned requirements.

Since chapter 1 provided the "Why" and chapter 3 the "What", they are followed by chapter 4 which explains the "How". It presents the methodological approach, and how each step of the development was performed.

This is followed by a presentation of hardware, software and test results of the project as well as how well the earlier identified requirements are fulfilled in chapter 5.

The results and future of the project are discussed in chapter 6, followed by the conclusion of the project in chapter 7.

Finally, the appendix provides more extensive results in form of the full comparison of available products, the full list of requirements and the complete test results from the performance tests.

2
Technology

This chapter is intended to give the reader a brief explanation of the technologies and system architecture used in the project. This should give the reader required knowledge for further reading. The chapter starts with a presentation of the systems required sub functions and architecture and continues with describing BLE (Bluetooth Low Energy) and temperature measurement with thermocouples.

2.1 System architecture

Several areas of functionality must be included to develop a device with the desired functionality. Breaking down the system into functions helps identifying the main areas. A simplified sketch of a possible system architecture can be seen in figure 2.1.

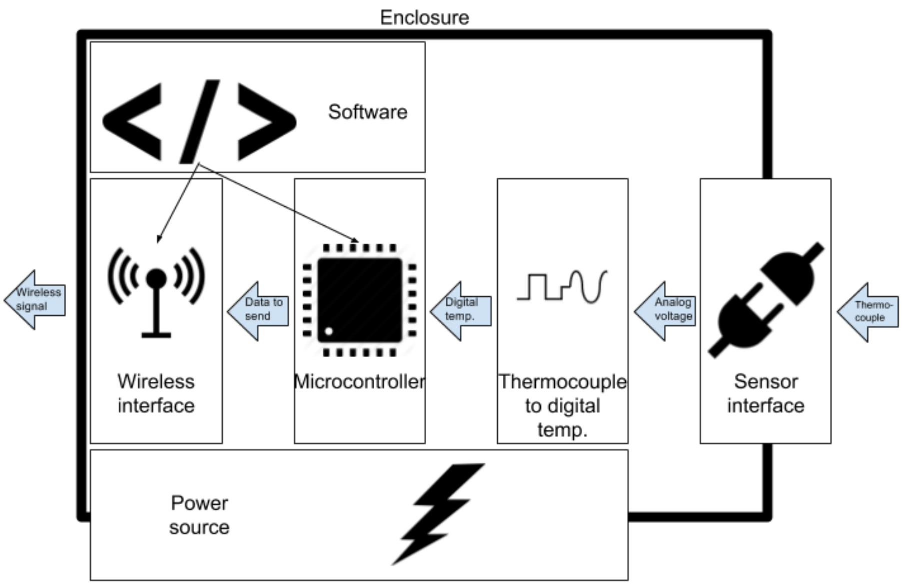


Figure 2.1: A system sketch of a possible sub function structure.

In subsections 2.1.1 to 2.1.5 each sub function in the system sketch seen in figure 2.1 is explained.

2.1.1 Enclosure

The enclosure has several functions. The main ones are: shielding internal components against the environment and making handling and mounting easy for the user. As shielding for internal components, the enclosure has to withstand and protect against the environment that otherwise may damage the device or decrease functionality. Examples are water, dust, wear and temperatures.

The enclosure also needs to let wireless signals pass through and provide an interface to connect the thermocouples.

How the enclosure is designed impacts the ease of use. Examples of properties for the enclosure that impacts use and mounting of the device include shape, size, weight and positions of connections for thermocouples.

2.1.2 Power source

The device could contain its own power source such as a battery, use an external power source such as the car battery or a combination. An internal power source could increase the size and weight of the device but would reduce the need to route power to the device. Using an external power source would reduce the need to integrate a power source thus reducing size, weight and the need for low power consumption that an integrated power solution could have. Power is accessible in many places around the car but would require routing to the device.

2.1.3 Conversion from thermocouple reading to a digital temperature

Calculating temperatures using thermocouples requires a high precision reading of the thermocouples voltage and a high precision reading of a reference temperature. All of this can be done with a thermocouple converter. This is probably the component that affects the total measuring accuracy the most.

The calculated temperature needs to be converted into a format that can be sent over the wireless interface. This could be done by the same component that converts the thermocouples voltage, or by a separate microprocessor.

2.1.4 Wireless interface

The wireless interface is needed to wirelessly communicate with the receiver of the data, thereby acting as a link between the device and the receiver. Software required to handle the connection could be a part of the wireless interface or handled by a separate microcontroller. The wireless technology needs to be available, and easy to use with other suitable components for the device. Preferably the wireless technology should be integrated in a microcontroller, but it could also be used with a separate microcontroller. Low power consumption and an open standard are of high importance.

2.1.5 Microcontroller

The device's software will need memory and processing power to control the device's functionality. Temperature readings needs to be controlled, stored and processed when measuring. Measuring data needs to be sent to the wireless interface along with the identity of the sender. Preferably the microcontroller should decrease the need for as many components as possible that could be integrated. An example of components that could be integrated is the wireless interface. Low power consumption, ease of use and suitable interfaces for connectivity with other components are of high importance.

2.2 BLE - Bluetooth Low Energy

'Bluetooth Low Energy', or BLE, is a low-power version of the classic Bluetooth standard. It was announced along with Bluetooth Core Specification Version 4.0 in 2009 [Bluetooth SIG 2016b], and formally adopted in 2010.

BLE is "... perfect for devices that run for long periods on power sources, such as coin cell batteries or energy-harvesting devices." [Bluetooth SIG n.d.(c)]. It was developed for low frequency communications, which makes it suitable for IoT applications.

2.2.1 Network topology

BLE devices communicate using radio in the 2.4GHz ISM band, creating short-range star topology networks. In a star topology network, the slaves do not share a radio channel with the master and/or other slaves. Each slave has its own radio channel between the master and themselves. A slave advertises its presence, thereby inviting masters to connect to it.

For more information regarding the advertisement and the connection, see section 2.2.3. An illustration of a BLE star topology network is seen in figure 2.2.

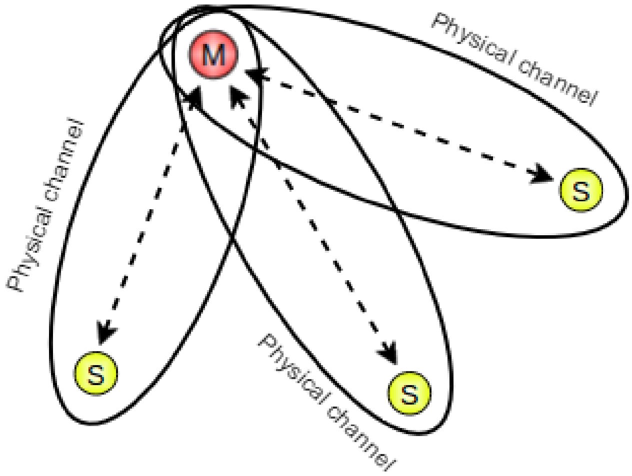


Figure 2.2: BLE star topology network.

2.2.2 Profiles

Bluetooth 'profiles' are "...definitions of possible applications and specify general behaviors that Bluetooth® enabled devices use to communicate with other Bluetooth devices" [Bluetooth SIG n.d.(e)].

A profile can be custom made, or follow Bluetooth standards. A profile that follows Bluetooth standards, will be recognized and its data interpreted correctly by a receiver, as long as it has a version that supports the profile. A graphical presentation of a profile structure is shown in figure 2.3.

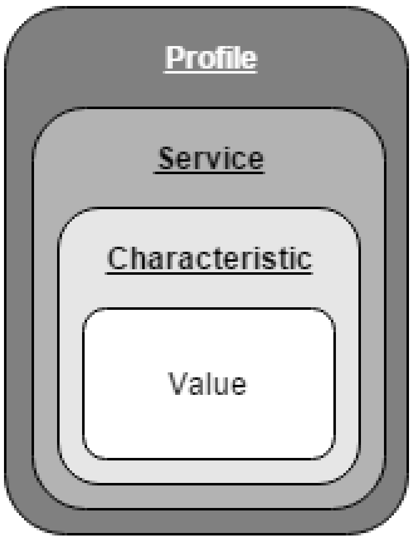


Figure 2.3: An example of a Bluetooth profile structure.

A profile contains one or more 'services'. A service usually represents a certain function of a profile. In section 5.4.1, the custom made profile for this project is described. It uses standard services to present temperatures and the battery level.

Each service is built up by 'characteristics'. A characteristic consists of at least a 'declaration' and a 'value'. The declaration tells if the value data can be read and/or written to, and holds other information about the value such as its unique identification. The value is a data field that can hold a sensor reading or a setting for example.

An example of a standard profile is the 'Environmental Sensing' which "... enables a Collector device to connect and interact with an Environmental Sensor for use in outdoor activity applications." [Bluetooth SIG 2014]. It contains three services: 'Environmental Sensing', 'Device information' and 'Battery Service'. The service 'Environmental Sensing' consists of 21 optional characteristics. Examples of the characteristics are: the current temperature, wind direction, elevation and humidity. An overview of the example profile is presented in figure 2.4.

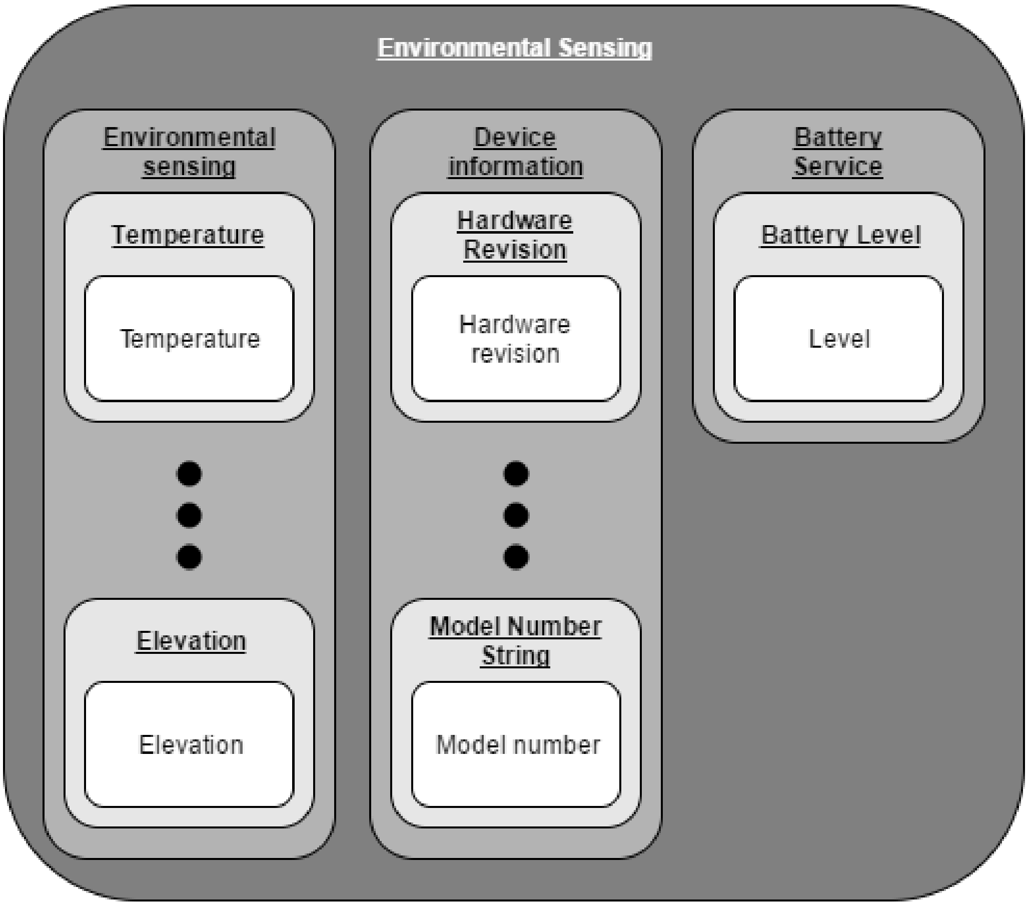


Figure 2.4: Overview of the Bluetooth profile 'Environmental Sensing'.

2.2.3 Connection parameters

The connection parameters determines how a slave should communicate with other Bluetooth units. Each slave has a preferred set of connection parameters. When a connection is established, the master decides which parameters to use. The three most important connection parameters for this project were the ’advertising interval’, the ’connection interval’ and the ’slave latency’.

When a Bluetooth slave is not connected to a master, it is in an advertising state. In the advertising state, the slave broadcasts its presence by sending advertising packets that can be received and read by all Bluetooth units in the vicinity. The advertising packet contains information such as the slave’s address and the name of the device. The packets are sent at a set interval called the ’advertising interval’ which can range from 20ms to 10.5s [Bluetooth SIG 2016a, p. 2611]. A short advertising interval shortens the time it takes for a slave and a master to connect, but draws more power since it forces the slave to transmit often. A long advertising interval reduces the energy consumption, but increases the time it takes to establish a connection.

As a connection is established, the ’connection interval’ and the ’slave latency’ determines how often the data is sent, instead of the advertising interval. The connection interval determines how often the master request a ’connection event’ [Texas Instruments 2016a, p. 72] i.e. exchange of data with the slave. The slave can not send data faster than this interval that ranges between 7.5ms to 4s. This is an important parameter when low delay is required. Long connection intervals makes the slave draw less power, but also increase the delay between when the slave has new data to when it is transmitted to the master. A short connection interval allows the data to be sent faster, but draws more power unless being combined with a large enough slave latency.

The slave latency specifies how many times the slave can skip the request from the master before it has to answer. Unless the slave has data to send, the slave will skip connection events until the number of skips is equal to the slave latency, or it has data to send. This can be used to save energy as it allows the slave to stay quiet when it has not got any new data to send. The slave latency can range from 0 to 499 skips.

The effective connection interval is described in equation 2.1. It is the maximum amount of time the slave can stay quiet until it has to reply to the master. For sensor application, such as this project, the effective connection interval should be longer than the intended measuring interval. That way the slave can send its data to the master with low latency, while maintaining a low power consumption.

$$\textbf{Effective connection interval} = \textbf{Connection interval} * (1 + \textbf{Slave latency}) \tag{2.1}$$

2.3 Temperature measurement with thermocouples

Thermocouples are by far the most widespread type of temperature sensor in the industry and have been used for over 150 years [Pentronic n.d.]. T.J. Seebeck invented thermocouples in 1821 after he discovered the electromotive force produced by two dissimilar metal or alloy wires joined in both ends. The reason for this is that when a metal wire is placed in a temperature gradient a Seebeck voltage will occur over the wire. Dissimilar metals and alloys have different Seebeck coefficients, and the difference is used to measure temperature with thermocouples.

A thermocouple is made of two dissimilar metal alloy wires having different Seebeck coefficients, called legs, that are joined in one end. The joined end, called (measuring) junction end, is placed where one wants to measure a temperature, and the free ends of the legs are connected to a thermocouple converter. That end is called the reference or cold junction end. In industrial use, the legs are isolated from each other and gathered as a single wire. This can be seen in figure 2.5.

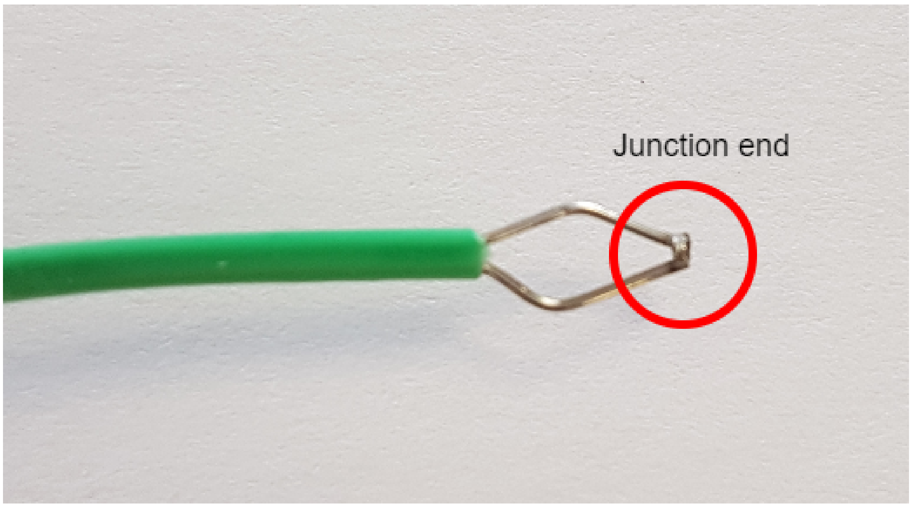


Figure 2.5: The measuring junction end of a thermocouple.

The two wires joined in both ends form a circuit. A temperature difference between the two junctions creates a voltage between the two wire ends at the cold junction. The larger the difference in temperature, the larger the voltage will be.

The thermocouple converter measures the voltage between the two ends at the reference/cold junction and the ambient temperature at that point is used as the reference temperature. The reference temperature, the measured voltage and the thermocouples characteristic function are then used to calculate the temperature at the measure junction.

The characteristic function depends on what type of thermocouple is used. Because both legs are made of a homogeneous alloy, the cable can be "exposed to temperature fluctuations without affecting the measurement" [Duffy 2003].

Table 2.1: Thermocouple type K tolerance classes.

	Tolerance class 1 [°C]	Tolerance class 2 [°C]	Tolerance class 3 [°C]
Range	-40<T<1000	-40<T<1200	-200<T<40
Greatest of	± 1.5 or $\pm 0.004 \cdot \lvert T \rvert$	± 2.5 or $\pm 0.0075 \cdot \lvert T \rvert$	± 2.5 or $\pm 0.0075 \cdot \lvert T \rvert$

Different wire combinations of dissimilar alloys have been named with letters in order to separate them according to the standard IEC 60584 [Pentronic n.d.]. Type K thermocouples are used for this application. Type K thermocouples have a temperature measurement range between -200°C up to 1260°C. The measurement error of a type K thermocouple is specified by IEC 60584:2013 [Pentronic n.d.], see table 2.1. In addition to this, other sources of measurement errors have to be considered, as reference temperature error and voltage measurement error.

3
Pre-study

A pre-study was made during the writing of the planning report for this project. It consists of a user study at Volvo PVKA in Gothenburg and discussions with employees at Etteplan Gothenburg. The knowledge gained during the study was used to write the background in section 1.2, and when creating the list of requirements in section 3.2. The list was then used in a state of the art analysis of products that are already on the market. The pre-study ends with the conclusion that there are no available products on the market that fulfills the requirements.

3.1 User study

The first visit to Volvo PVKA was made during the first week of the project. The goal of the visit was to get to know the test environment, procedures and the needs of the mechanics and technicians.

Volvo Cars explained and demonstrated the procedures concerning the testing. Examples are how the test equipment is purchased, how it is installed and how the data is acquired. They also gave their thoughts about how they would benefit from a wireless system, and which functions and properties a system "must" have.

The user study also included talking to several employees of Etteplan that work/have worked with the same kind of tests. Discussions and feedback with and from Etteplan have been part of the project throughout the entire project.

Most of the lessons are presented in section 1.2. Other lessons that are relevant are:

- The data units and wiring in the trunk take up space, and can be damaged during loading/unloading of the car.
- A supplementing wireless system will not be used if it increases the complexity of the testing procedure.
- A wireless system that can not be used/integrated with the current system will not be used.
- The engine compartment is the most difficult part of the car to route thermocouples to.
- Preparing the thermocouples takes several days. A large part of the time goes to attaching connectors.
- Not all thermocouples are made new. Some are attached to frames that are placed on the floor and headrests in the interior. The frames are removed when the test vehicle is discarded, and reused in the next vehicle.
- The computer used to collect the data is connected to the data units with a USB cable, and can be placed inside or outside the vehicle.
- Due to the required equipment and effort it is often impossible to replace/add a measuring spot during an expedition.
- Size and weight of the device is not crucial as along as it can fit in proximity to the measuring point. A shape that fits in tight spaces is more important than a low volume.
- Each device needs to be able to read multiple thermocouples simultaneously to be considered as an alternative and to be usable in many areas of the car.

3.2 List of requirements

The list of requirements is based on requirements from Etteplan and from the visit to Volvo PVKA. Etteplan requested that the wireless standard is open i.e non-proprietary, and that the overall performance is close to the currently used wired system. The properties of the currently used units are shown in table 3.1.

Table 3.1: Properties of Ipetronik M-THERMO-16.

Property	Value
Sensor inputs	16
Minimum polling interval	0.05 s
Operating temperature	-40°C to +125°C
Measuring accuracy	±0.5°C
Weather protection	IP 67

An initial list of critical requirements was made for the state of the art analysis and can be seen in table 3.2. The revised list that was later used to evaluate the project can be seen in full in appendix B.

As mentioned in section 1.2, the test vehicles can be exposed to temperatures between -40°C and +85°C. That range was set as a demand for the operating temperature. Although the Ipetronik hub has a measuring accuracy of ±0.5°C, the demand was set to ±1°C as that was the demand from Volvo Cars and Etteplan. Volvo Cars wish to have the battery last for a full 21 day expedition with about 6 hours of use daily. A usage of 24 hours per charge would still make the device usable, and was therefore set as a demand. Since the device might be placed where it is not shielded from dust and water, it must have its own protection. A protection equivalent to IP 54 should be sufficient.

Table 3.2: Initial list of critical requirements.

Property	Target value
Open wireless standard	Yes
Minimum polling interval	1 s
Operating temperature	-40°C to +85°C
Measuring accuracy	±1°C
Usage per charge	24 h active
Weather protection	IP 54

3.3 State of the art

The compared products are a sample of what is sold, and the authors have yet to find products with better properties than the ones presented below. The comparison was based on the list of requirements from section 3.2.

Eleven products for wireless temperature measurements were compared against the initial requirements list. The data for each product was gathered from the manufacturers data sheets, and promotional information. Products that did not have an internal power source, were not included in the comparison.

A condensed version of the comparison can be seen in table 3.3, where the values have been replaced with a 'Y' for yes, if the product pass the requirement and a 'N' for no if it does not. When the manufacturer has not specified a property in the products data sheet, the value is replaced by a '-'.

Table A.1 in appendix A connects the letters to a manufacturer and a product. It is followed by the full comparison with values, in table A.2.

Table 3.3: Condensed comparison of available products.

Property \ Product	A[1]	B[2]	C[3]	D[4]	E[5]	F[6]	G[7]	H[8]	I[9]	J[10]	K[11]
Open wireless standard	Y	Y	N	N	N	N	Y	Y	Y	N	N
Minimum polling interval	Y	N	Y	N	N	-	N	Y	Y	N	N
Operating temperature	N	N	N	N	N	Y	N	N	N	Y	Y
Measuring accuracy	Y	N	N	Y	Y	N	Y	Y	-	Y	N
Usage per charge	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N
Weather protection	N	N	-	-	-	Y	Y	-	Y	-	-

As seen in table 3.3, none of the reviewed products pass all of the requirements. Very few of the reviewed products can operate in the required temperature span. A probable cause for that is that there are few batteries that can handle that range. No compared product can be connected to more than one thermocouple at the same time. That makes all of them inappropriate for this application.

The property "Open wireless standard" only considers which wireless standard is used to transmit the temperature data. It does not consider if the data is packaged/encoded in a standardized and open way. It is therefore uncertain if any of the compared products could be used with a non-proprietary receiver hardware and/or software without complex decoding of the data.

The comparison does not take the size of the product in consideration. Therefore, some products are included even though their size make them unsuitable for the application.

[1]Cooper-Atkins "20100-K Blue2 Instrument" [Cooper-Atkins n.d.]
[2]DataQ Instruments "EL-WiFi-TC" [DataQ Instruments n.d.]
[3]MicroStrain "TC-Link®-1CH -LXRS®" [MicroStrain n.d.]
[4]Newport "MWTC" [Newport n.d.(a)]
[5]Newport "MWTC-D" [Newport n.d.(b)]
[6]Oleumtech "TC" [Oleumtech n.d.]
[7]Omega "UWTC-2-NEMA" [Omega n.d.(b)]
[8]Omega "UWBT-TC" [Omega n.d.(a)]
[9]OneTemp "ZHEAD-TC" [OneTemp n.d.]
[10]Paragon Robotics "SC32" [Paragon Robotics n.d.]
[11]Phase IV "WSN Thermocouple" [Phase IV n.d.]

3.4 Conclusion

The current test setup takes a lot of effort and time to prepare. A wireless system would reduce the need to modify the test vehicles, thereby saving time and resources.

The state of the art analysis confirmed Etteplans claim that there are no available products with the needed properties on the market. It is unclear whether this has to do with technical limitations or if it has to do with marketing strategies. It is clear, however, that there is a need for a wireless device using non-proprietary standard communications and data.

4

Methods

In this chapter, the 'How' of this project is presented. It starts by explaining the methodological approach of this project. It continues with how the wireless- standard development board was chosen, with descriptions of the most important factors for the comparison. After that, the choice and development of the hardware are described. This is followed by a description of the software development and ends with the how the final prototypes performance was tested.

4.1 Methodological approach

Figure 4.1 illustrates the methodological approach, that was used during this project.

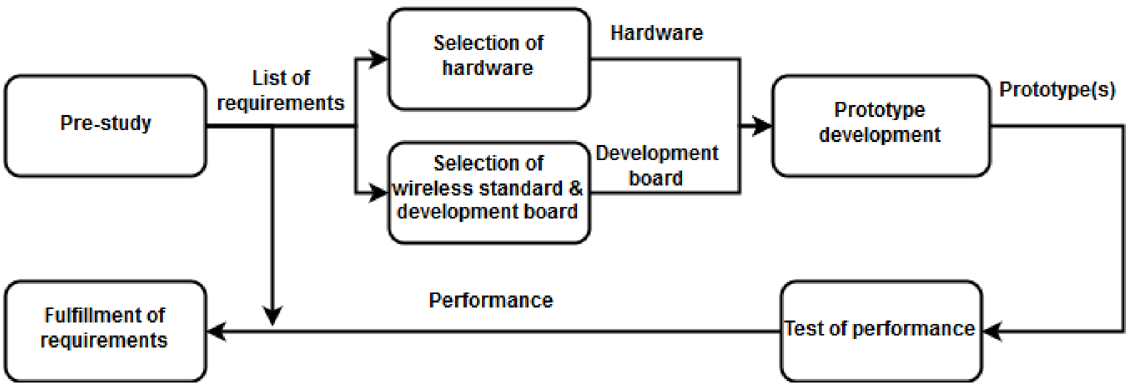


Figure 4.1: A flow chart of the methodological approach

The project started with a pre-study that is described in chapter 3. The pre-study resulted in a list of requirements, presented in appendix B. The list was needed as a screening tool during the selection of hardware and the selection of wireless standard and development board simultaneously. The selection of a wireless standard and development board is described in section 4.2. The selections resulted in hardware that was put together during the prototype development. The prototype development consisted of several different phases that are described in section 4.3. The development resulted in two identical prototypes whose performance were tested in order to see if they fulfilled the list of requirements. The testing is described in section 4.4.

4.2 Selection of wireless standard and development board

When choosing a wireless standard, there are several things to consider. A selection of the more important factors are presented in subsection 4.2.1 to 4.2.7. To be able to pick a wireless standard, several standards had to be compared against each other. The comparison started with a wide search for standards that could later be compared. The standards were compared with the challenges in the previously mentioned subsections in mind. This worked as an initial screening.

A study of previous work was done in parallel to aid the comparison.

It is important to consider that a standard can be suitable in theory, but have poor hardware implementations. It was therefore necessary to look at the implementations of the standards that passed the initial screening. In this project, implementations of a wireless standard refers to a microcontroller with built-in radio transmitter/receiver. Since buying standalone microcontrollers would require designing the circuit board, the selection was limited to more development friendly solutions including a microcontroller i. e. development boards.

There are many development boards that use a microcontroller with one or more wireless standard. In order to make the selection smaller, development boards were excluded unless available for immediate purchase and shipping. The selection was reduced further by comparing the size of the communities around a development board. The size and helpfulness of a community affects the difficulty of development, as a good community can aid with guides and examples on how to solve common issues.

The results of the comparison is presented in section 5.1.

4.2.1 Power consumption

The power consumption of the standard during idle and active use dictates the time the device can be used with a set size of the energy source. The size of the required energy source is determined by the power consumption and required usage time. A larger energy source means a larger device, which makes the device's size and weight dependent on power consumption.

A standard with a low power consumption, can be restricted by the available hardware implementations of the standard. The goal was to find a standard with low power properties with a low power implementation.

4.2.2 Scalable network size

The standard needs to enable the use of a large amount of concurrent units in one or several systems in proximity to each other. This can for example be limited by how many units a receiver can handle simultaneously, or the amount of data that can be transmitted at the same time.

The amount of needed sensor inputs per unit is dependant on the possible concurrent units since the measurement spots are distributed over them. The possibility to have a large amount of concurrent units enables a more flexible setup where each unit can have few or plenty sensor inputs. This affects the units when it comes to size as each sensor input needs its own hardware.

The need for this will vary between each test setup and needs to be possible to scale.

4.2.3 Throughput

The throughput is equal to how fast data can be transmitted. The throughput of the standard limits the frequency of updates, concurrent devices/sensors and size of the transmitted data. The higher the throughput, the shorter time the device has to receive/transmit. Less time receiving/transmitting enables the device to sleep more to save power. Throughput needs to be high enough for the standard to be scalable for future needs.

4.2.4 Signal penetration

The device is meant to be placed within a vehicle sending data to a receiver placed in a different part of the vehicle or outside the vehicle. The signal needs to be able to reach the receiver in these conditions.

4.2.5 Robustness

The standard must not be sensitive to interference such as wireless traffic, as it would be too difficult to shield it from it. The units will be used in environments where other common wireless networks such as WiFi and Bluetooth, exists.

4.2.6 Availability now and tomorrow

The standard must be implemented in a way that can be purchased and used. Preferably it is so established that there is a range of components and manufacturers to choose between. Another factor to consider is the future availability of components and compatible products.

4.2.7 Latency

In this context, latency is the delay between when a temperature is measured to when it is received. It is important to have a short latency since the measurements will be used in conjunction with the measurements from the wired system. The wireless measurements will not be comparable with the wired if the temperatures are "old" when they are received.

4.3 Prototype development

To enable parallel development and testing throughout the project, two identical prototypes have been built side by side. This made troubleshooting easier, as the two prototypes could be compared. Comparisons were also used to identify differences that could indicate hardware defects and/or faulty configurations. Another aspect of working with two prototypes was that it enabled simultaneous development work by more than one person. The two prototypes have in the later parts of the project enabled parallel testing of different aspects of the device.

When choosing the hardware for the prototype, the priorities have been (without respect to order) compatibility with other required hardware, power consumption, availability, documentation and estimated time to implement as part of the prototype. The microcontroller and wireless interface hardware are the most important factors for future development, adaptability and for building a good starting point for continued work. The reason for this is that the developed software needs to be tailored for the hardware. The time dedicated to the choice of prototype hardware have therefore in large been dedicated to this hardware. Other parts were chosen for ease of use and compatibility with previously mentioned hardware.

The purpose of the prototype is to showcase a proof of concept. The implementation of functionality within the time frame of the project was therefore prioritized over properties such as power consumption, size, cost and to fully meet the list of requirements. Parts that were superior in performance but deemed to require too much time to acquire or implement were disregarded to ensure a working system within the projects time frame.

Prototypes have been built in several stages, adding functionality and improvements incrementally. Initial prototypes focused on a single function or test to minimize the risk of errors or interference from other functions or hardware. This way, trouble shooting could focus on fewer things at a time. Simplified functionality of each function or hardware often had to be used before integrated with other parts of the system. Integration of hardware and functions were done in small steps to reduce unnecessary complexity and to ease troubleshooting and testing.

The hardware development was divided in seven phases as seen in table 4.1. The development began with the start up phase. The phase consisted of doing required research and tests to setup and program a minimum hardware configuration (Phase: Start up).

Table 4.1: Phases of hardware development.

Phase	Main development content	Power	Main assembly
Start up	Initial setup and tests of hardware and software environment.	External	Breadboard
Alpha 1	Independent development and tests of hardware and software functions.	External	Breadboard
Alpha 2	Interaction of hardware and software functions.	External	Breadboard
Switch	Setup and migration of software and hardware to the smaller less development friendly hardware.	External	Breadboard
Beta 1	Internal power source, charging and regulated power delivery. Switch to soldered assembly.	Internal	Soldered
Beta 2	Minimize required device volume.	Internal	Soldered
Showcase	Encapsulation of hardware.	Internal	Soldered

Hardware and software development was initially focused on adding functionality, flexibility and ease trouble shooting by using a breadboard based assembly. Development was in this stage performed with an external power source (Phase: Alpha 1 and Alpha 2).

As intended functionality was achieved, a transition to a smaller but less development friendly hardware was performed (Phase: Switch). In this stage the software configuration had to be adopted to the new hardware.

Focus then switched to reducing size and adding an internal, regulated and chargeable power source (Phase: Beta 1 and Beta 2). Another major change was the transition from breadboard based assembly to soldered assembly, to increase reliability and reduce the size.

When the final configuration for the showcase was decided, all of the different parts were placed in many different combinations to determine the smallest possible volume for the device. Finally an enclosure was modeled in CAD and 3D-printed. The purpose was to package the hardware in a mobile package for testing, to protect the hardware, ease transportation and usage as well as to showcase the device's functionality and form factor (Phase: Showcase). The enclosure was never intended to satisfy all requirements the final product will need to.

4.3.1 Software development

The software was written in C, using Texas Instruments IDE (Integrated development environment) 'Code Composer Studio' [Texas Instruments 2017] that comes with several built-in sample projects. Starting from the sample project 'Project Zero', the required functions were added and tested one by one to make the debugging easier.

The main part of the software development took place at the same time as the first four phases (start up, alpha 1, alpha 2 and switch) of the hardware development see table 4.1. The software development was used to test and verify the hardware setup and configuration in each phase before continuing to the next phase.

The three main areas of software development was communication with the thermocouple converters, wireless communication (and data formatting) and software configurations. The software configurations were needed make the different hardware configurations seen in section 4.3 work.

4.4 Testing of performance

The final prototypes needed to be tested in order to verify if they fulfill all requirements or not. The first test was to see if the wireless signal could travel from the engine compartment of a vehicle to its trunk. The second test was to see how accurate the prototypes can measure temperatures, and the third test was done in order to measure the power consumption.

4.4.1 Test of signal penetration

Several tests were done on the different prototypes. A recurring test was to see if the signal penetration was satisfactory. The prototypes were placed under the hood of a Volvo V60, and connected via BLE to a smart phone that was placed in the trunk. After logging temperatures for a while, the smart phone was moved outside of the trunk. The distance to the vehicle was then increased until the smart phone lost connection with the prototype.

4.4.2 Measurement accuracy

In order to test the measurement accuracy of the device, one of the prototypes and its thermocouple converters were connected to a 'Martel 3001 Lab Standard Multi-Function Precision Bench Calibrator' [Martel Electronics n.d.] using thermocouples. The calibrator was set to provide voltages to the thermocouples, that corresponds to temperatures, T_{set}, between -40°C and +125°C, in steps of 5°C. The range was chosen because it contains the most commonly measured temperatures during Volvo Cars expeditions.

The tests were performed in room temperature. The ambient/room temperature were not monitored or controlled during the tests.

The prototype was connected to a smart phone using BLE (Bluetooth Low Energy) and the app 'nRF Connect for mobile ' by Nordic Semiconductor ASA [Nordic Semiconductor n.d.]. The temperatures, $T_{measured}$, reported by the prototype were read and logged using the app.

Three readings were done for each temperature with a total of 102 readings per thermocouple converter. The measurement error was calculated by using equation 4.1.

$$Error = |T_{measured} - T_{set}| \tag{4.1}$$

The results are presented in section 5.5.2.

4.4.3 Power consumption

The power consumption was measured at a measuring laboratory at Chalmers University of Technology. An initial test was done with two prototypes of the final design, to verify similar power consumption. A large difference could have indicated hardware error. Since similar power consumption was verified, all documented tests were performed with one of the prototypes. The initial tests are not documented in this report.

Calculations have been simplified to use the battery's nominal voltage of 3.7V as a fixed voltage. This eliminates the need to include voltage in the equations, and makes it possible to express power as mA/mAh for time calculations. This also means that the result does not take the battery's varying voltage in consideration.

The setup used is presented in figure 4.2. A voltage generator was set to provide the prototype with 3.7 volts since it is the nominal voltage of the used battery, and the voltage was monitored with a 'Fluke 75' multimeter. The prototype was connected to the multimeter through a 10 Ohm 0.1 % precision resistor. The voltage over the resistor was observed and measured using a 'Tektronix TDS 2002B' oscilloscope, and a passive 10x attenuating oscilloscope probe. According to Ohm's law, the voltage measured over the resistor would have to be divided by the resistors resistance in order to get the current flowing through. Since a 10x attenuating probe was used, a "division" of the same numerical value as the resistor was made. This means that the voltage measured with the oscilloscope, had the same value as the current drawn from the prototype.

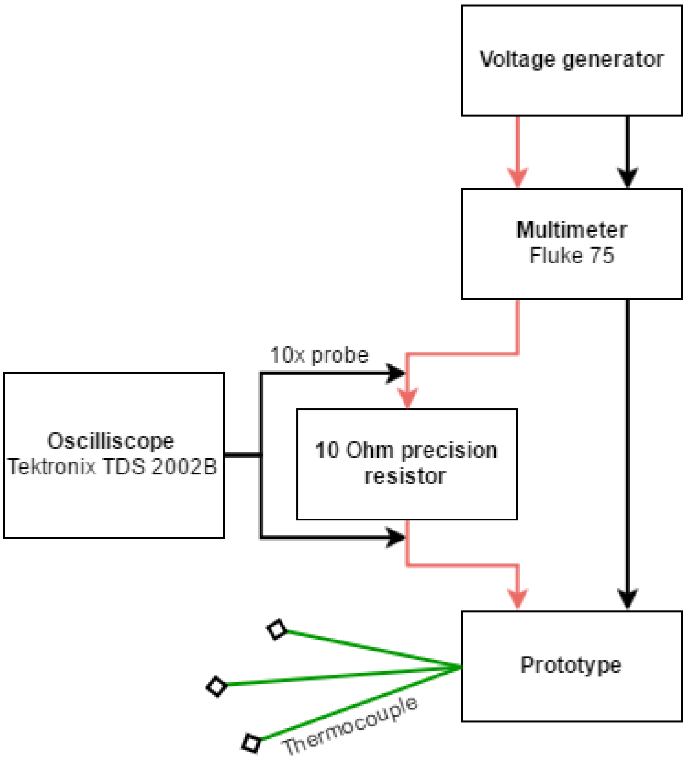


Figure 4.2: Measure setup for power consumption

The test was split into five parts: Advertising state, connected state, measuring using one sensor, measuring using two sensors and measuring using three sensors.

Five averages of the current was sampled over 10 seconds, in 10 second intervals for every part. This was then repeated a second time, resulting in two measure series of 25 sampled averages each. The prototype was power cycled between the series.

In the first part, the prototype was powered and then left to advertise. After that, it was connected to a smart phone via Bluetooth. During the last three parts, the sensors were started one by one so that all three were measuring during the last part. The prototype was configured to transmit with its maximum transmission power of 5dB.

The results from the test is presented in section 5.5.3.

5
Results

The chapter starts by presenting which wireless standard was selected for the project, and why other standards were not. It is followed by a comparison of development boards, after which one board is selected. This is followed by a presentation of all the hardware that the prototype consists of, and how they are assembled. The chapter continues with a description of how the software works using flow charts and text. The results from tests of the final prototypes' power consumption and measuring accuracy are then presented. Examples of two scenarios are given for the power consumption. The chapter ends with a check of how the prototype fulfills the list of requirements.

5.1 Selection of wireless standard

As mentioned in section 4.2, the selection of a wireless standard started with a compilation and an initial screening of applicable standards.

5.1.1 Initial screening of standards

The screening removed several of the initial selection of wireless standards. Standards such as Z-wave [Sigma Designs n.d.], ANT+ [Dynastream Innovations Inc n.d.], Digimesh [Digi International Inc 2017] and EnOcean [EnOcean Alliance Inc n.d.] were excluded because they are proprietary. Other standards such as Thread [Thread Group n.d.] and WirelessHart [Siemens AG n.d.] were excluded because of poor availability of hardware implementations that could be bought off-the-shelf. The standards that passed the screening were Wi-Fi, BLE and ZigBee.

5.1.2 Wi-Fi vs. ZigBee vs. BLE

All three standards that passed the initial screening are probably feasible alternatives for this project. Since one had to be picked, they were compared extensively in terms of robustness and power consumption. Previous studies and comparisons were used for the comparison. The results are presented below.

Robustness

Some of the previous work that compare the robustness of the standards are contradicting each other. An empirical study by Lin *et al.* of Wi-Fi, ZigBee and BLE's robustness against interference from coexistence, concluded that BLE "seems to be a better candidate [than ZigBee] for intra-vehicular wireless sensor networks when robustness against interference is a main concern" [Lin et al. 2013]. This is contradicted by Garroppo *et al.* in "Experimental assessment of the coexistence of Wi-Fi, ZigBee, and Bluetooth devices" , where they conclude that "Bluetooth showed an even more degradation [than ZigBee]" [Garroppo et al. 2011]. According to Garroppo *et al.*'s assessment, Wi-Fi is barely affected by coexistence with Wi-Fi and/or Bluetooth networks [Garroppo et al. 2011].

The authors conclusion is that ZigBee is less robust than BLE, and that Wi-Fi is the most robust standard of the three.

Power consumption

Shahzad and Oelmann's comparison between the ZigBee, BLE and Wi-Fi concludes that ZigBee is the better choice when the data transmitted is less than 500 bytes. If larger than 800kB, Wi-Fi consumes less, and for a data load between 500 bytes and 800kB they recommend BLE [Shahzad and Oelmann 2014]. The comparison was based on estimations, and no measurements were done. The compared hardware are now considered as previous generation, but the comparison still gives an indication on how the standards stand against each other.

Siekkinen *et al.* measured the power consumption of the ZigBee and BLE hardware that was compared by Shahzad *et al.*. The results were presented in "How Low Energy is Bluetooth Low Energy? Comparative Measurements with ZigBee/802.15.4". Siekkinen *et al.* conclude that "compared to ZigBee, BLE is indeed very energy efficient" [Siekkinen et al. 2012, p 232].

Dementyev *et al.* performed measurements on an earlier hardware generation than Shazad *et al.* and Siekkinen *et al.*. They "found that BLE achieved the lowest power consumption" [Dementyev et al. 2013] when compared with ZigBee.

Experiments conducted by Putra *et al.* concludes that "BLE is about 30% more energy efficient than WiFi" [Putra et al. 2017].

The authors conclusion is that ZigBee and BLE currently have a similar power consumption, which is less than Wi-Fi's.

5.1.3 Conclusion

BLE and ZigBee seems to have a similar power consumption, although BLE tends to use less power. Both are believed to have a lower power consumption than Wi-Fi. Wi-Fi is more robust than both BLE and ZigBee, who can be seen as equals with regards to robustness.

5.2 Selection of development board

As mentioned in 4.2, many development boards were considered for this project. The most promising development boards are listed in table 5.1.

Table 5.1: Development boards.

Development board	Standard	MCU
TI - BOOSTXL-CC2650MA	BLE, ZigBee	Texas Instrument CC2650
TI - SimpleLink CC3200 LP	Wi-Fi	Texas Instrument CC3200
RedBear - BLE Nano Kit v2	BLE	Nordic Semicond. nRF52832
SparkFun - nRF52832 Breakout	BLE	Nordic Semicond. nRF52832
RedBear - WiFi Mini	Wi-Fi	Texas Instrument CC3200

The development boards with Wi-Fi were excluded because the risk of high energy consumption. BLE was chosen over ZigBee because of it being a widely used standard that you find in almost every laptop and smart phone. The development board from Texas Instrument was chosen over the boards from RedBear and SparkFun for several reasons. One reason is that the community and documented use of the nRF52832 MCU from Nordic Semiconductors was deemed too small. Another reason was that the IDE of Texas Instrument was considered to be easier to get started with.

The CC2650 micro controller on the BOOSTXL-CC2650MA supports BLE 4.2 as well as ZigBee. Another micro controller, Texas Instruments CC2640 [Texas Instruments n.d.(c)], contains the same BLE 4.2 capabilities without support for the additional wireless standards CC2650 supports and is cheaper. CC2650 further provides the same capabilities for BLE 4.2 and, unlike CC2640, is available on several development boards from Texas Instruments making development easier.

The CC26xx series of BLE enabled micro controllers provide some of the most energy efficient micro controllers with BLE 4.2 on the market. They are significantly more energy efficient than Texas Instruments prior generations of BLE hardware [Texas Instruments n.d.(b)] and most competing hardware found by the authors.

To conclude: The chosen development board was the BOOSTXL-CC2650MA from Texas Instrument, which includes the CC2650 Bluetooth Low Energy micro controller. More information regarding the development board and micro controller is presented in subsection 5.3.1.

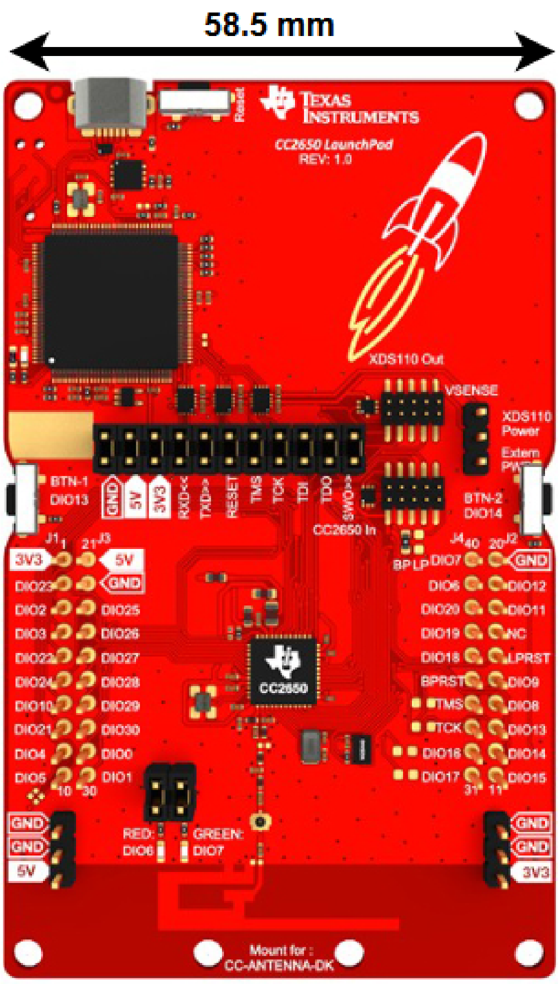
5.3 Prototype hardware

The hardware used in the prototypes consist of a micro controller with a wireless interface, three thermocouple converters, a power source and an enclosure. The properties of these parts and how they are assembled, is described in this section.

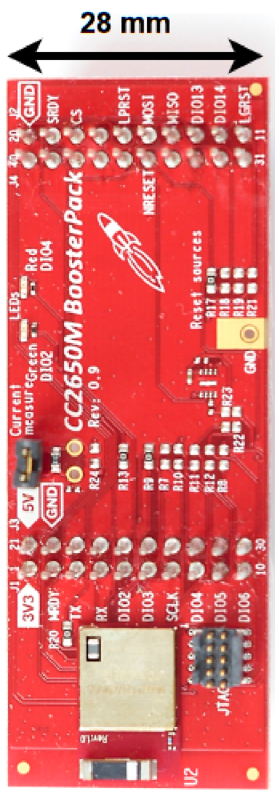
5.3.1 Microcontroller and wireless interface

As described in section 5.2, the development board chosen for this project is the BOOSTXL-CC2650MA (TI SimpleLink™ Bluetooth® low energy CC2650 Module BoosterPack™ Plug-in Module) [Texas Instruments n.d.(a)].

An additional development board, the LAUNCHXL-CC2650 (SimpleLink™ CC2650 Wireless MCU LaunchPad™) [Texas Instruments n.d.(e)], was purchased to aid the development of the software. One of the major differences between the two development boards is that LAUNCHXL-CC2650 has a built in micro USB port that enables debugging and programming of the micro controller. Another difference is the available number of accessible IO pins and that the LAUNCHXL-CC2650 is significantly larger (95.3 x 58.5 mm vs. 75.3 x 28 mm), see figure 5.1a and figure 5.1b.



(a) LAUNCHXL-CC2650 [Texas Instruments n.d.(e)]



(b) BOOSTXL-CC2650MA [Texas Instruments n.d.(a)]

(c) CC2650MODA [Texas Instruments n.d.(a)]

Figure 5.1: CC2650 hardware.

Another difference is that the BOOSTXL-CC2650MA contains the CC2650 micro controller integrated in a CC2650MODA [Texas Instruments n.d.(d)] module, see 5.1c, that is pre-certified for operation under the regulations of the FCC, ISEP, ETSI, and ARIB. This could reduce costs and resources needed to produce a consumer product, significantly. The CC2650 module is available for sale separately and has a footprint of 16.9x11mm, see figure 5.1c, enabling small footprint devices. The CC2650MODA module is rated to operate in temperatures in the range -40 to +85°C.

The BOOSTXL-CC2650MA and the LAUNCHXL-CC2650 had to be modified according to the guide "Running Standalone Bluetooth® low energy Applications on CC2650 Module" [Texas Instruments 2016b] from Texas Instruments. This was done in order to enable the BOOSTXL-CC2650MA to be programmed and used by itself, since it is primarily intended as a BLE add on board to other development boards. The BOOSTXL-CC2650MA board was then connected to the LAUNCHXL-CC2650s' JTAG (Joint Test Action Group) port. The LAUNCHXL-CC2650 was connected to a computer via USB.

5.3.2 Thermocouple converter

The thermocouple converter used in this project is the MAX31856 [Maxim Integrated n.d.] from Maxim Integrated. This converter communicates over SPI (Serial Peripheral Interface) and can interface K, J, N, R, S, T, E and B type thermocouples. The measurement range is -210°C to +1800°C with a resolution of 0.0078125 °C. Functionality includes fault detection such as open thermocouple circuitry. MAX31856 is rated to operate in temperatures in the range -55 to +125°C.

The breakout board "Universal Thermocouple Amplifier MAX31856 Breakout" [Adafruit 2016] from Adafruit with Maxims's MAX31856 circuit, was used to simplify development. The breakout board is pre-assembled with recommended configuration from Maxim integrated, it includes resistors and filter capacitor as recommended and easy accessible connections. Measurement accuracy of the MAX31856 is highly dependent of the implementation but not specified for this breakout board. Tests of the measurement accuracy can be seen in section 5.5.2. The breakout board with soldered pins and 2 pin terminal block for testing can be seen in figure 5.2, the board is 25 x 22 mm.

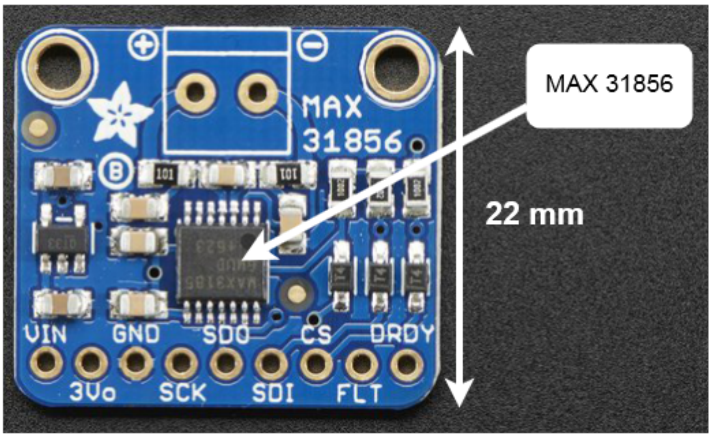


Figure 5.2: Adafruit MAX31856 breakout board [Adafruit 2016].

5.3.3 Power source

The power source consists of three different parts: a battery, a wireless power receiver and a circuit for charging and voltage regulation. The battery is a 3.7 volt, 1200 mAh, Lithium Ion Polymer (LiPo) battery from Adafruit [Adafruit n.d.(a)].

The wireless power receiver is Adafruits "Universal Qi Wireless Receiver Module" [Adafruit n.d.(b)]. The Qi wireless receiver enables wireless charging with chargers following the Qi standard. The wireless receiver outputs 5 volt and 500 milliampere while placed on a Qi transmitter/charger.

A battery charger with built-in voltage regulation from Sparkfun called "Power Cell" [SparkFun n.d.] was used to charge the battery and provide regulated 3.3 voltage.

5.3.4 Enclosure

Several iterations of enclosures were modeled in CAD and 3D-printed to accommodate the device hardware. The enclosure is in no way a final product design but an indication of device size. It also makes testing and transportation of the device easier, as well as protecting the electronics.

The device can easily be completely sealed with all functionality preserved, as both recharging and data transmission are fully wireless. This allows for an enclosure with a simple design and assembly without the need to be re-sealable. Not having to open the enclosure, reduces the risk of malfunction because of handling errors and leakages.

See figure 5.5 for a picture of the last iteration of the enclosure.

5.3.5 Assembled prototype

The final prototypes consists of the components described in previous sections of this chapter. All connections are soldered except the connection of the battery that uses a JST-PH connector (can be seen in figure 5.5a). A system sketch can be seen in figure 5.3.
The system sketch has a similar layout to the conceptual system sketch in section 2.1. The same symbols for functionality has been used for both sketches.

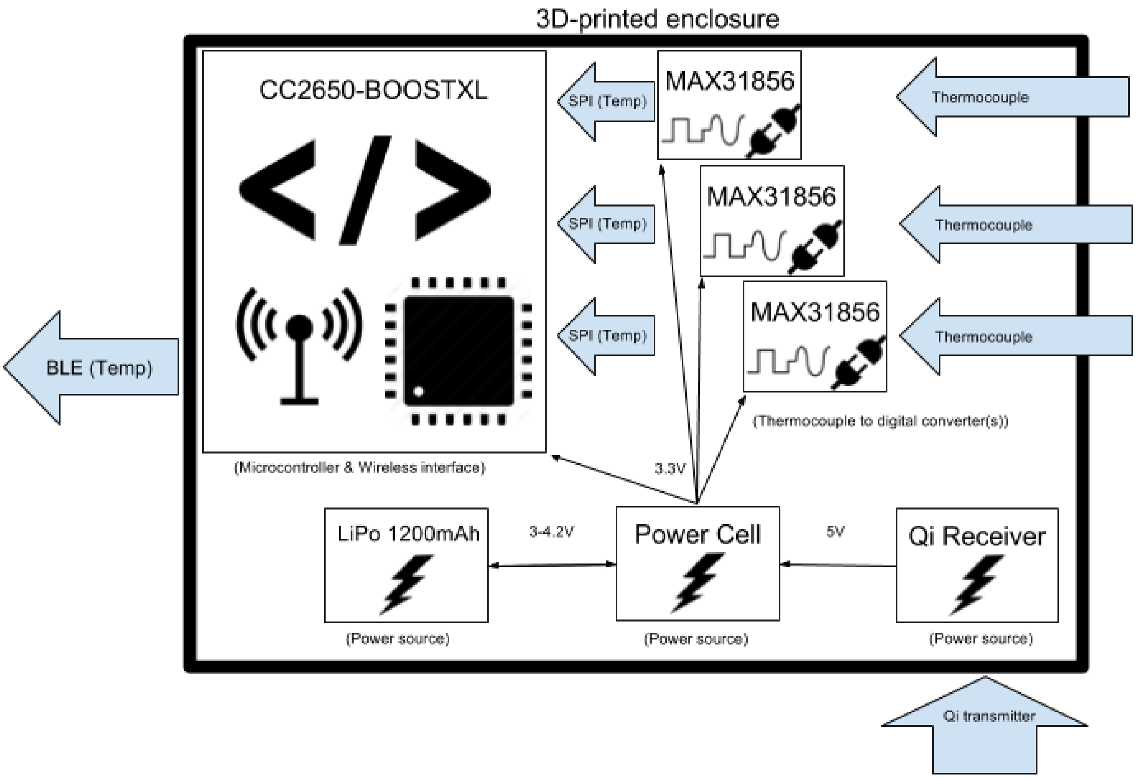


Figure 5.3: A system sketch of the assembled prototype.

In the following text aliases will be used instead of part/product names to make reading easier. All parts and aliases can be seen in table 5.2. The number for each part in the table can be used to identify the part in figure 5.4, showing a photo of the final prototype hardware without enclosure.

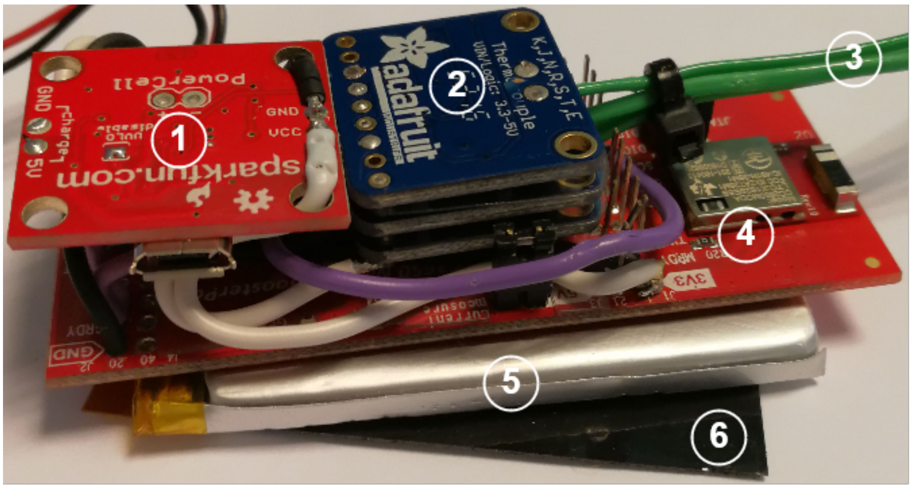


Figure 5.4: Final prototype hardware without enclosure.

Table 5.2: Parts with number and alias.

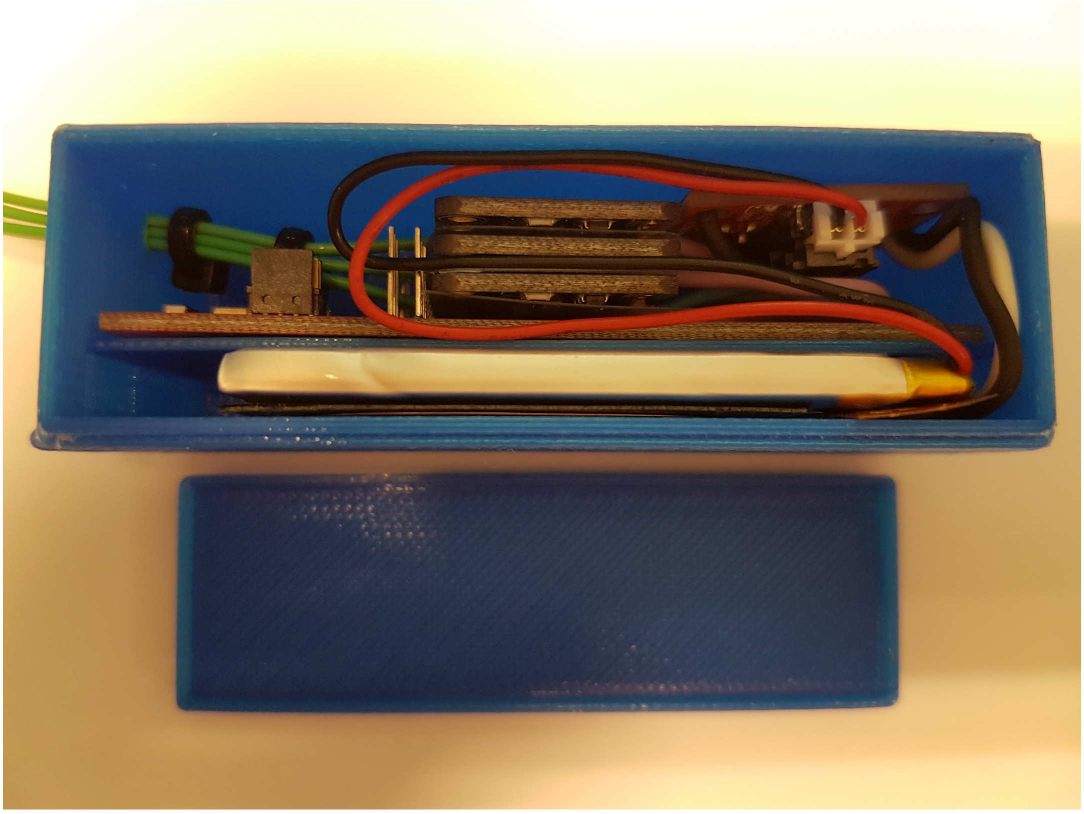
#	Part	Alias
1	SparkFun Power Cell - LiPo Charger/Booster	Power Cell
2	Adafruit Universal Thermocouple Amplifier MAX31856 Breakout (x3)	Thermocouple converter(s)
3	Thermocouple type K (x3)	Thermocouple(s)
4	BOOSTXL-CC2650MA	BOOSTXL
5	Adafruit 3.7 volt, 1200 mAh, Lithium Ion Polymer battery	LiPo
6	Universal Qi Wireless Receiver Module	Qi receiver

The prototypes use three thermocouples. Each thermocouple is connected to a thermocouple converter, see section 5.3.2. The digital temperature is transferred over SPI to the CC2650MODA on the BOOSTXL, see section 5.3.1. Temperature data is transferred over BLE from the CC2650MODA to the receiver.

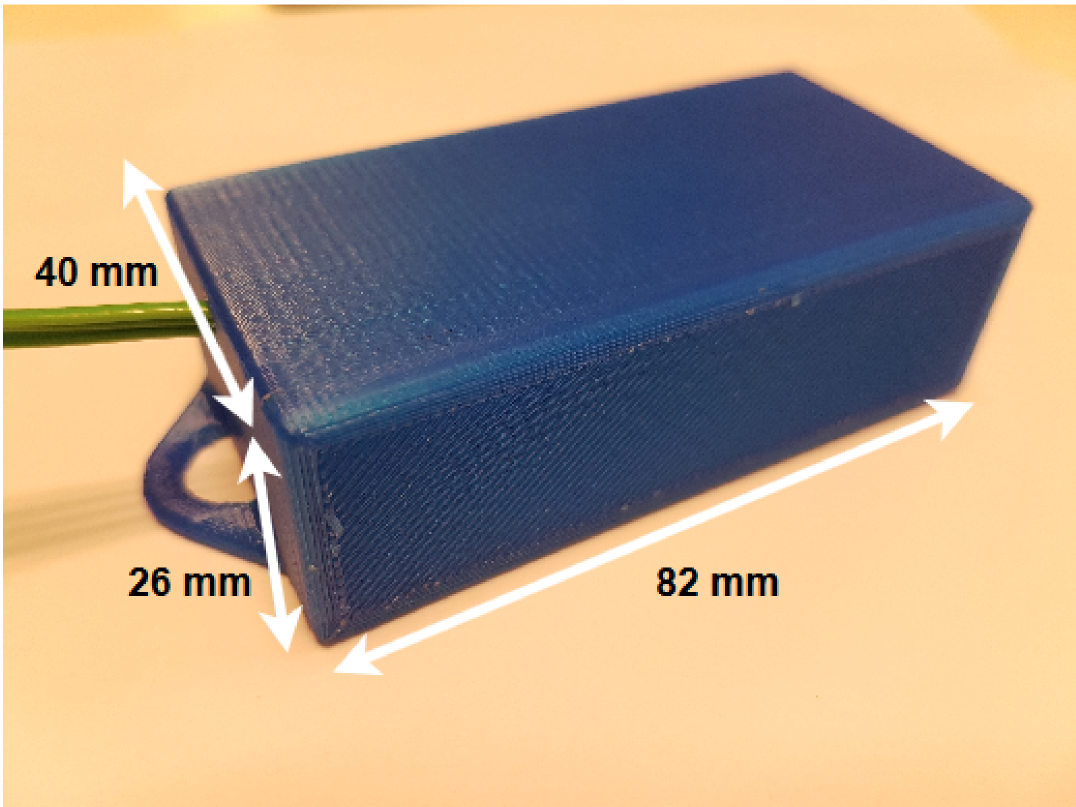
Regulated 3.3V is delivered by the power source that consists of a battery, a voltage regulator/charger and a Qi receiver, see section 5.3.3. Power is regulated and delivered to the BOOSTXL and the three thermocouple converters by the Power Cell. This enables the device to be fully functional as long as the voltage stays above the battery's internal cut off voltage of 3V.

The Power Cell also handles the charging of the LiPo battery when a Qi transmitter/charger is in proximity of the connected Qi receiver.

All components are mounted in the 3D-printed enclosure described in section 5.3.4, with the thermocouples being thread through a hole in one of the sides. See figure 5.5 for pictures of the final assembled prototype.



(a) Enclosure open



(b) Enclosure closed

Figure 5.5: Assembled prototype.

As can be seen in figure 5.5b the only connection needed from the inside to outside of the enclosure are the thermocouple wires. This enables the enclosure design to be simple to seal as nothing needs to be open/closed or moved after assembly. The enclosure's lid and the hole where the thermocouples passes through the enclosure can be permanently sealed. The prototypes' enclosures have not been permanently sealed for demonstration and testing purposes.

5.4 Prototype software

The software was optimized to lower the power consumption, and decrease the latency of the device, acting as a slave. The main way that the software lowers the consumption, is by making sure that the slave is spending most of its time in low power states. The latency is kept low, by keeping a short response time. In this section, the means to achieve this will be presented.

5.4.1 Bluetooth profile

The Bluetooth profile was created using 'Bluetooth Developer Studio' [Bluetooth SIG 2017]. It consists of four services. Three of the services present an interface to the temperature sensors, and contain two characteristics each. The first characteristic contain the object name i.e. sensor 1, sensor 2 etc, and the second contains the temperature. The fourth service has a characteristic with the battery level expressed in percentage. The outline of the profile is visualized in figure 5.6.

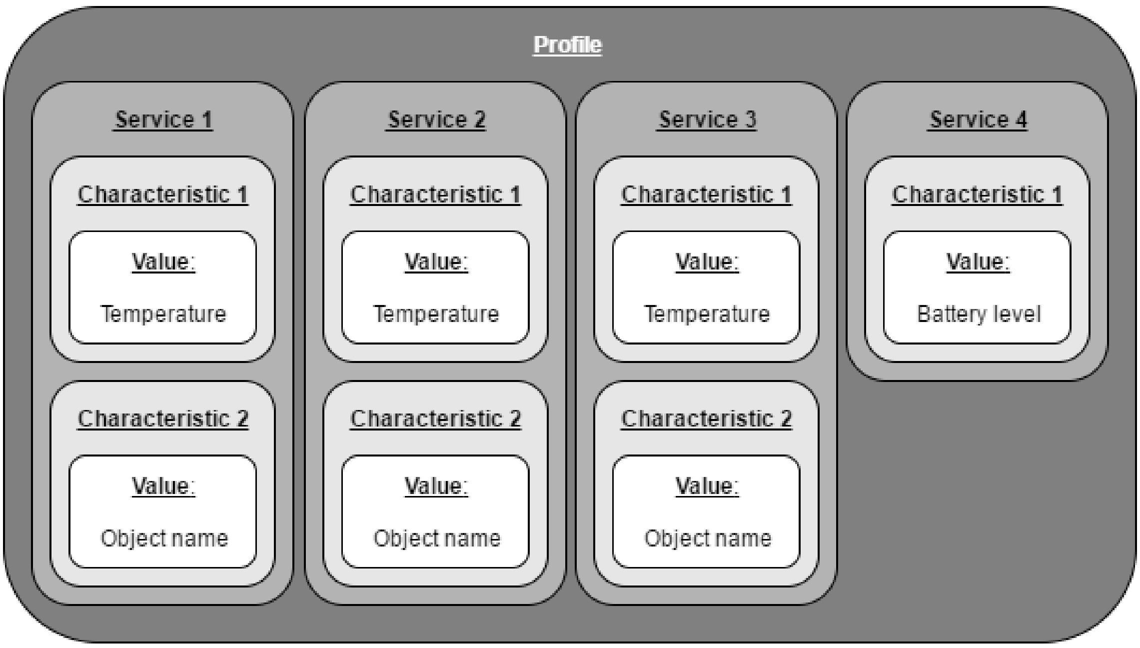


Figure 5.6: Outline of the Bluetooth profile.

All characteristics follow Bluetooth standards on how to present data, predefined by Bluetooth SIG (Special Interest Group). The battery level uses the characteristic "Battery Level" [Bluetooth SIG n.d.(a)], the object name uses "Object name" [Bluetooth SIG n.d.(d)] and the temperatures use the "Temperature" characteristic [Bluetooth SIG n.d.(f)]. The temperature data is formatted as 16-bit signed integers. Since the standards are followed, any Bluetooth receiver that support the same standard will understand how the data should be interpreted. This enables the use of non-proprietary receivers, as the documentation on the standard is open for anyone to read.

5.4.2 Connection parameters

The connection parameters play an important role both when it comes to power consumption and latency. Ideally, the slave sleeps between each measurement and only wake up to read and send temperatures. The used parameters can be seen in table 5.3.

Table 5.3: Connection parameters.

Parameter	**Value**
Advertising interval	10.24 s
Connection interval	7.5 ms
Slave latency	499 connection events
Effective connection interval	3750 ms

The advertising interval is set to the maximum allowed value (10.24 s) in order to save power when the slave is not connected to a master. This allows for 10+ seconds of sleep, before the slave wakes up and broadcasts its presence.

By setting the connection interval to the minimum (7.5 ms), the slave will send a new temperature maximum 7.5 ms after the temperature is measured. This also means that the time between each request for a connection event is very short, resulting in a potentially increased power consumption. The increased power consumption is countered by using a high slave latency, which in this case has the highest possible value: 499 (connection events). This way the slave is allowed to skip up to 499 connection events, until it has new data to send. This means that the slave does not need to send data more often than every 3750th ms instead of every 7.5th ms. This saves power when the slave is connected but not measuring. When the slave is measuring, it will send new temperature data every second.

5.4.3 Flow chart

Flowcharts are used to represent the processes handled by the software. The used building blocks are explained in figure 5.7. To make the flow charts easier to understand, the program has been simplified and split into three different flow charts. The first represents the main program and can be seen in figure 5.8. The second represents part of the program that controls the sensors and is seen in figure 5.9. The third and last part is shown in figure 5.10 and shows how the sync clock works. The example only shows how it works when two sensors are connected, in order to make the flow charts smaller. It should be somewhat easy for the reader to understand how a slave with more than two sensors would work.

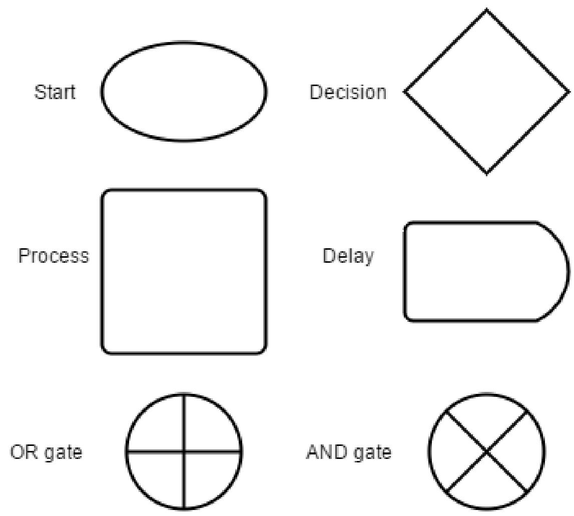


Figure 5.7: Used building blocks.

Figure 5.8 represents the main program. The slave will stay in advertising mode until a connection is established between the slave and the master, waiting one advertising interval before transmitting each advertising packet.

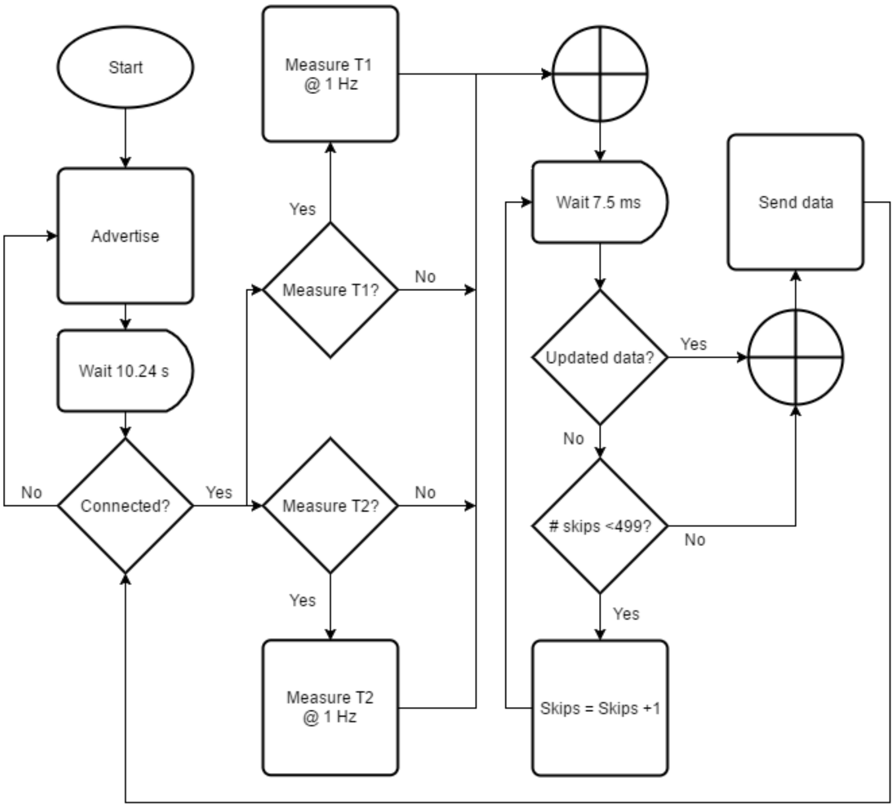


Figure 5.8: A flow chart of the main program.

When a connection is established, the slave checks if the master has requested temperature measurement from either of the sensors. If so, the sensor controller in figure 5.9 is told to start measuring with the requested sensor(s).

Regardless if the sensors are measuring or not, the program will then wait a connection interval for the next connection event. It then checks if the slave has updated its temperature data. If there is no updated data to send, the slave will skip every connection event until the temperature data is updated (at 1 Hz) or the amount of skips exceeds the slave latency. The slave will only send the temperature data if it was just updated. If the data is "old", the slave will only send the data needed to maintain the connection to the master.

When the data is sent, the program goes back to checking if it should advertise or not.

The sensor controller, represented in figure 5.9, ensures that the multiple sensors' temperatures are measured at the same time. This is solved by using a sync clock, represented by figure 5.10. When the sensor controller is told to measure with a sensor, it first checks whether the sync clock is running or not. If it is not, the sync clock is started.

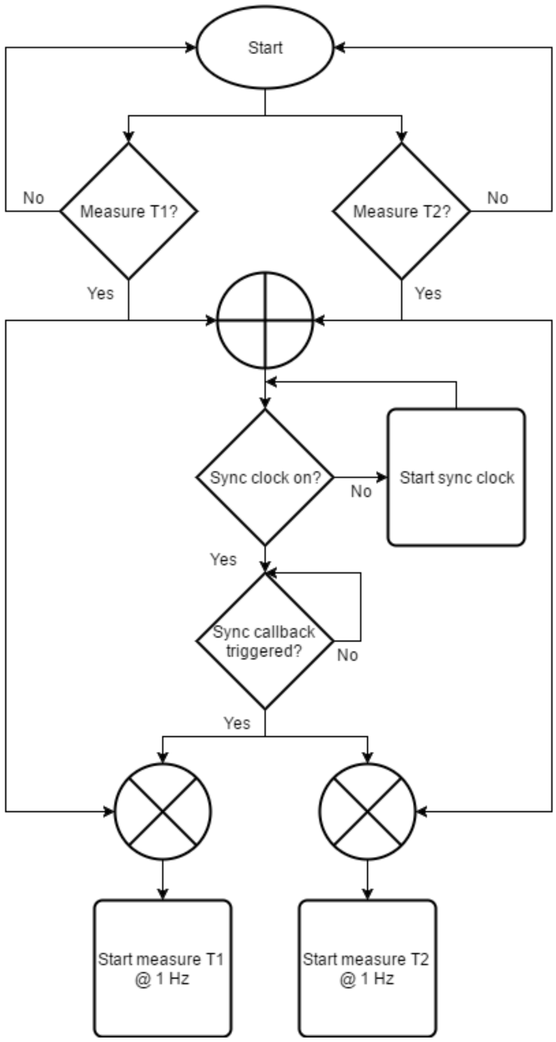


Figure 5.9: A flow chart of the sensor controller.

When running, the sync clock triggers a callback at a frequency of 1 Hz. The callback gives the sensors a "green light" to measure. In order to measure, a sensor first needs a permission from the sensor controller. It will then wait for a sync callback before it starts to measure and update the temperature data at a frequency of 1 Hz. The temperature data is updated a fraction of a second after the sync callback is triggered.

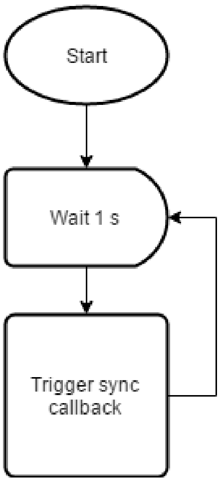


Figure 5.10: A flow chart of the sync clock.

Since all sensors need to wait for a sync callback before they measure, they will be synchronized when started.

An example of how a time course could look when two sensors are started at a dissimilar time, is shown in figure 5.11. Each pulse on the curves is meant to represent an event. The height and width of a pulse is of no significance.

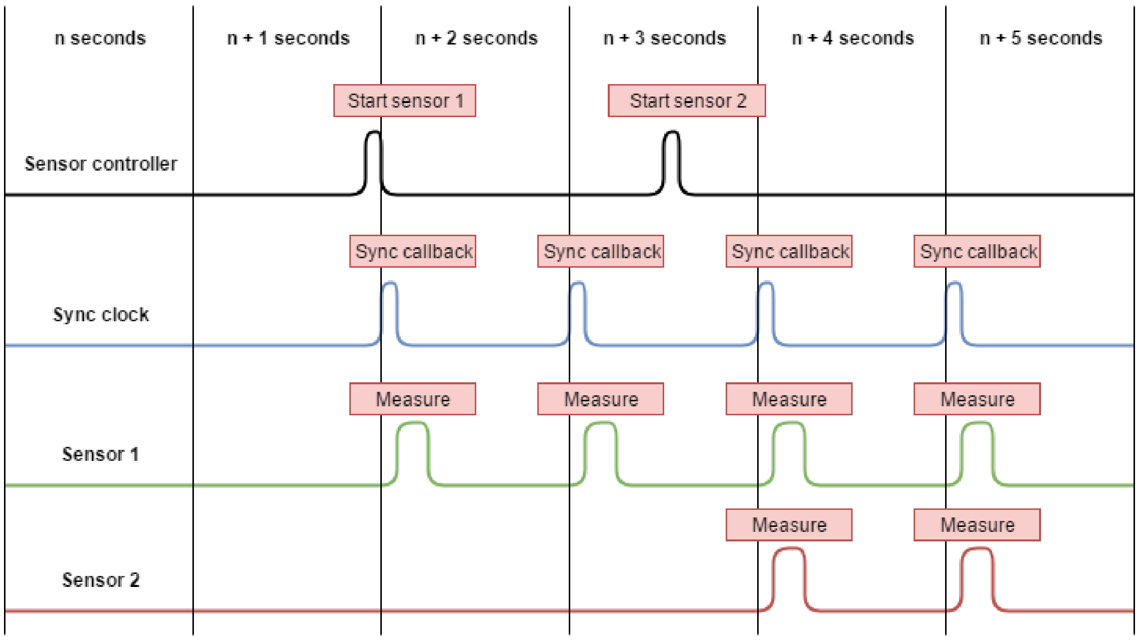


Figure 5.11: An example of a time course when two sensors are used.

5.5 Test results

This section presents the results from the measurements of power consumption and measurement accuracy. The section ends with examples of how the measured power consumption can be used to calculate expected battery life in different scenarios. The results are meant to be used to evaluate fulfillment of requirements and show the performance of the device.

5.5.1 Test of signal penetration

The results were not considered to be vital, since the communication also depends on the receiver. A high performance receiver will make up for a weak signal penetration and vice verse. The tests showed that it was possible to establish and maintain connection between the smart phone in the trunk and prototype in the engine compartment. The smart phone could be placed 60+ meters from the engine compartment before the measurements were affected or the connection was lost.

5.5.2 Measurement accuracy

The sizes of the measuring errors for the three converters are presented in table 5.4. The full tables with all measured values for each temperature and converter and their respective errors, can be viewed in appendix D.

Table 5.4: Measurement errors for three thermocouple converters.

Converter	Avg. error [°C]	Min. error [°C]	Max. error [°C]
1	0.65	0.50	0.80
2	0.63	0.50	0.85
3	0.78	0.66	0.88

All three converters have similar average, maximum and minimum error. The measured temperature was never less than the set temperature, and there is only a 0.15°C difference between the smallest and the largest average. The combined average measurement errors for all three converters are presented in table 5.5, and the error distribution is presented in figure D.1 in appendix D.

Table 5.5: Measurement errors of the prototype.

Avg. error [°C]	Min. error [°C]	Max. error [°C]
0.68	0.5	0.88

In figure 5.12, the average and maximum error of all measurements are plotted against the set temperatures that were measured. The average and maximum measurement error for all sensors are presented in figure 5.13 and 5.14 respectively.

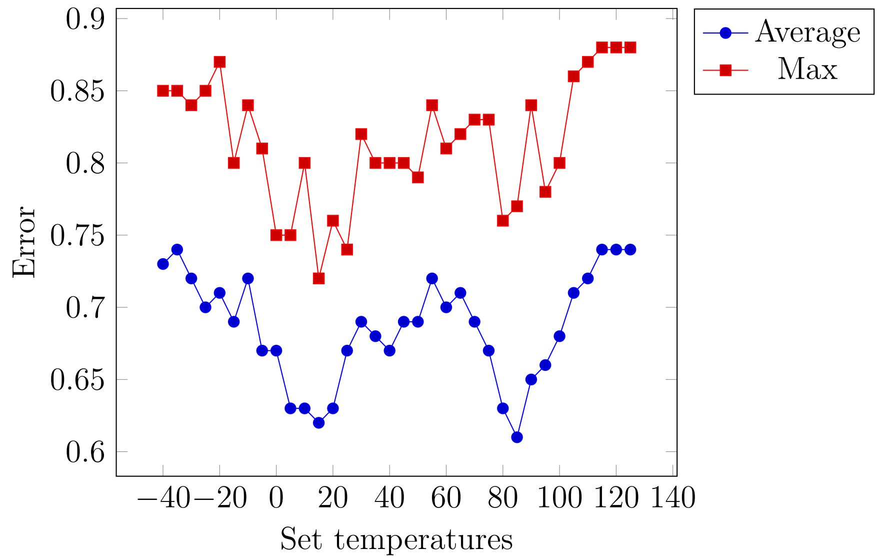


Figure 5.12: Measurement error vs Set temperatures.

As can be seen in figures 5.13 and 5.14, the average and maximum error for all three converters looks similar. Converter 3 shows a slightly higher average and maximum error but have the same shape of the curve. Why converter three shows a different offset is not known. It could be a result of variations in the configuration or the converter hardware for example. The results indicates that adding a temperature offset would decrease the measurement error significantly in this test scenario.

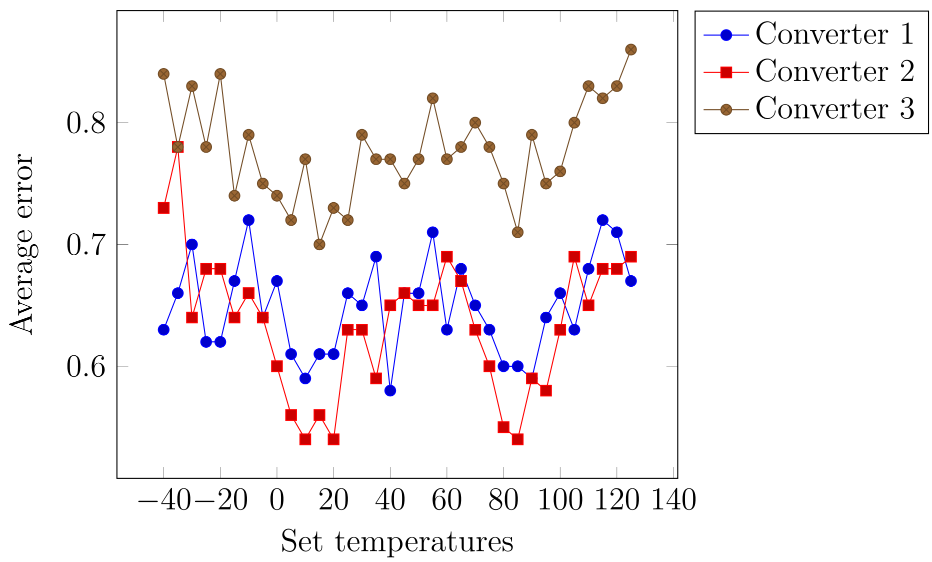


Figure 5.13: Avg. measurement error vs Set temperatures.

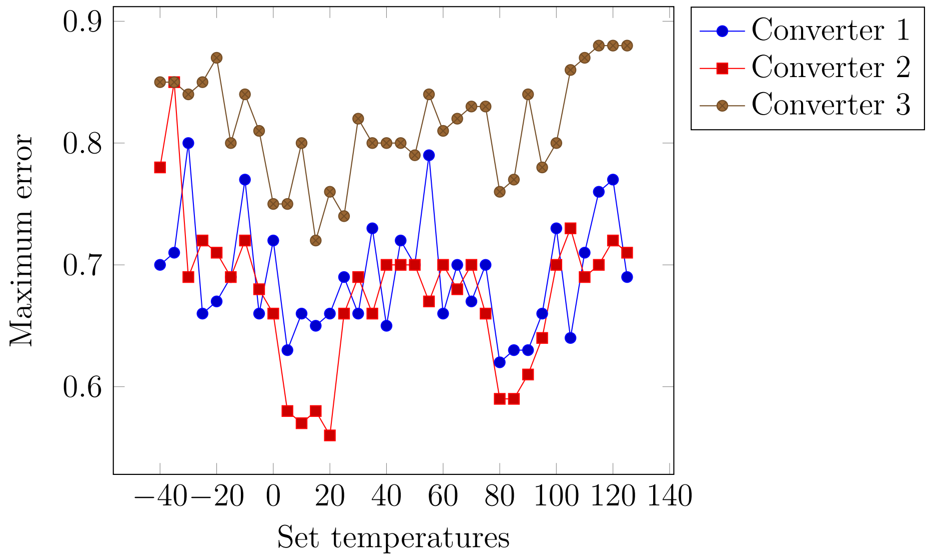


Figure 5.14: Max. measurement error vs Set temperatures.

5.5.3 Power consumption

The power consumption can be divided into three scenarios: advertising, connected and measuring (1,2 and 3 sensors).

The averages when combining the two measuring series, see 4.2.1, are presented in table 5.6.

Table 5.6: Average power consumption, both series at 3.7V.

Scenario	Avg. current cons. [µA]	Avg. power cons. [µW]
Advertising	717	2653
Connected	713	2638
Measuring 1 sensor	994	3678
Measuring 2 sensors	1267	4688
Measuring 3 sensors	1431	5295

Examples

The following examples were calculated using the values in table 5.6 and the prototypes battery size of 1200 mAh. The battery capacity is affected by the ambient temperature, which means that the battery life of the device will vary with the temperature.

Neither example has been tested in real life. All three sensors are presumed to be started at the same time, and the prototype is in advertising mode when not measuring. The time it takes to connect to the device is neglected.

The first scenario is an expedition where the temperatures will be measured for 6 hours daily over a course of 21 days. When the temperatures are not measured, the prototype is disconnected from the master and put in advertising mode. The theoretical power consumption during a day of an expedition is presented in table 5.7. With a daily consumption of 21.5 mAh, a 21 day expedition would consume ~451 mAh, not considering capacity losses because of ambient temperatures. This means that the current battery could lose ~60 % of its capacity due to ambient temperatures, and still provide enough power for a full expedition. If the prototype kept measuring all the time during the full expedition, it would only consume ~720 mAh, not considering losses because of the ambient temperature.

Table 5.7: Current consumption during an expedition.

State	**Duration [h]**	**Consumption [µA]**	**Daily cons. [mAh]**
Advertising	18	717	12.9
Measure 3 sensors	6	1431	8.6
Total	**24**	-	**21.5**

The second scenario is storage. It is presumed that the device has been fully charged before being stored, without a charger connected to it. During the storage, it stays in advertising mode. A full day of advertising would consume 17.2 mAh, making the battery last for almost 70 days.

5.6 Fulfillment of requirements

The fulfillment of the requirements is presented in table 5.8. The final prototype passes 13 of the 16 demands. The demands it does not fulfill are: maximum delay, operating temperature and measuring accuracy. It has not been verified if the maximum delay is less than one second. Therefore it can not be regarded as a fulfilled requirement. Further tests needs to be done in order to know if it passes the requirement or not. The only verified failed demand is that the prototype cannot operate within the required temperature range due to the limitations of the battery.

As explained in section 4.4.2, the testing of measurement accuracy was limited. The result is therefore not considered to pass the demand. Further tests on the full temperature range with varying ambient temperatures needs to be done in order to verify the measurement accuracy.

The demand of a weather protection equivalent to IP 54 and the wish for IP 67 is considered to be passed. The prototype has not yet been permanently sealed and the authors see no reason to why the enclosure would not provide protection equivalent to IP 67 after it is.

Out of the 10 wishes, 7 are considered to be passed. In addition to operating temperature and measuring accuracy, a failed wish is the battery indicator. The software and interface for the battery indicator is implemented, but minor hardware adjustments are needed for it to work as intended.

A comparison between the target values and achieved values is presented in table 5.8.

Table 5.8: Fulfillment of requirements.

Property	D/W[1]	Target value	Achieved value	Pass
Battery indicator	W	Yes	No	✗
Charging w/o disassembling	W	Yes	Yes	✓
Concurrent devices/receiver	D	5	Not limited [2]	✓
Concurrent devices/receiver	W	$\geq$ 20	Not limited [2]	✓
Cost for parts w/o tc conv.	W	<500:- SEK	270:- SEK [3]	✓
Cost per added sensor input	W	<200:- SEK	60:- SEK [3]	✓
Internal sync between sensors	D	Yes	Yes	✓
IP67 equivalent	W	Yes	Yes	✓
IP54 equivalent	D	Yes	Yes	✓
Maximum delay	D	0.5 s	$\leq$ 1 s [4]	?
Measuring accuracy	W	$\leq$ 0.5°C	0.88°C [5]	✗
Measuring accuracy	D	1°C	0.88°C [5]	?
Measuring range	D	[-40°C,+1000°C]	[-210°C,+1800°C]	✓
Measuring resolution	D	0.1°C	0.01°C	✓
Open wireless standard	D	Yes	Yes	✓
Operating temperature	D	[-40°C,+85°C]	[-30°C,+85°C]	✗
Operating temperature	W	[-40°C,+125°C]	[-30°C,+85°C]	✗
Sensor ID	D	Yes	Yes	✓
Sensor inputs/device	D	$\geq$2	3	✓
(Possible) Sensor inputs/device	W	$\geq$ 5	Exceeding	✓
Software device ID	D	Yes	Yes	✓
Standardized temp. data	D	Yes	Yes	✓
Thermocouple compatibility	D	Type K	Type K	✓
Update interval	D	1 s	1 s	✓
Usage per charge	W	21 d x 6h[6]	Exceeding	✓
Usage per charge	D	$\geq$ 24 h active	Exceeding	✓

[1]Demand/Wish
[2]Limited by the receiver
[3]Estimated cost for serial production
[4]Not able to verify if less than 1s
[5]Maximum error during tests
[6]6h active/day and 18h advertising/day

6 Discussion

In this chapter, the authors share their reflections on the project. It starts with whether the goals set at the start of the project were reached or not. This is followed by a review of the verification methods, how the results can be used, an evaluation of the development process and an evaluation of environmental aspects. Finally the authors recommendations for future work are presented.

6.1 Results

The aim to develop a non-proprietary wireless device that measures temperatures using thermocouples, has been successfully met. When combined with a properly configured receiver, it can be used together with the currently used wired system. It reached a maturity level that is suitable for a proof-of-concept, and shows potential for future development. The prototype performed well when compared to the list of requirements.

The requirements the prototype fails to meet are not considered to be very difficult to improve given more time. The measuring accuracy will be improved if the thermocouple converters are exchanged for better performing ones. Another possibility is to improve the hardware configuration. Examples could be to calibrate the current hardware or design a custom board instead of using a pre-built board.

The prototypes do not meet the operating temperature requirement. Finding a suitable replacement for the battery, is considered to be more difficult than to find replacements for the other parts. The search for suitable batteries and discussions with one of Etteplan's experts on batteries can be summarized with that finding a suitable battery is not easy. It will likely result in trade-offs with other properties such as being rechargeable or the energy density. The battery and/or alternative energy sources might be the part that needs the most future attention to fulfill all requirements. It is for example possible to draw power from the car battery, thus removing the need for a internal power source. The requirement can not be changed, since it is the temperature range that is used during the tests.

The results are satisfactory considering the wide scope and limited time/previous experience.

6.2 Verification and testing

The purpose of the tests was to get estimations of the performance of the prototypes. The accuracy and the results of the tests are considered to fulfill this purpose.

Since the battery's voltage will vary from when it is fully charged to when it is empty, the tests on power consumption could have been improved by performing additional tests with different voltages.

Further measurements are needed in order to know how long the battery would last in non-optimal temperature conditions. The ambient temperature should then vary in the intended operating temperature range.

The tests on measuring accuracy indicated that the accuracy could be improved by adding an offset. The required offset could vary depending on different ambient and measured temperatures, and additional tests are therefore required to determine which offsets to use. Additional tests should also consider the full range of expected temperatures and not just the most common range. The tested thermocouple converters had measurement errors of same polarity and similar size. General offsets that depend on the ambient and measured temperatures could therefore probably be used instead of unique offsets for each thermocouple converter, with good results.

The receiver software developed by Etteplan that would connect the prototype with the current test equipment was not finished in time to test the prototype in the intended environment. No extensive tests were therefore done on the signal penetration and robustness against wireless interference. In order to discover possible connectivity problems, the prototype should be tested as a part of an intended test setup. Changing antennas on the receiver and/or prototype is recommended if the quality of the connection is insufficient. The transmission power can be decreased to save power if the signal strength is higher than necessary, as it is currently set to the maximum.

These tests could also give valuable feedback on the usability of the prototypes from the users. The feedback could consist of previously unknown wishes and demands for a future product. This would aid a possible future development resulting in a successful product.

6.3 Development process

The overall development process has been carried out according to the initial planning with no obvious errors that should/could have been anticipated.

When choosing a wireless standard, the authors first believed that the choice could be made based on the standards' properties and traits alone. A lot of time was therefore invested comparing them with each other, in the search for a single standard that would be "the one", before looking at the implementations. The comparison between Wi-Fi, ZigBee and BLE took especially long time, before the implementations were considered. As actual performance depends on the hardware implementation, early comparisons of implementations could have saved time and helped to limit the scope of the research.

We would not have achieved this result without the support and encouragement we got from Etteplan. The room they provided has been a good work environment, and we were allowed to borrow plenty of equipment to fill it with. Whenever we needed equipment that we could not borrow from Etteplan, we were allowed to purchase it. This meant that we seldom had to change our initial plans because of lack of equipment or funds. The access to Etteplans work shop made building the prototype a lot easier. We never needed a tool that they could not provide, and they always seemed happy to assist us.

In retrospect, the project consisted of too many tasks for the given time. Often when we got a software/hardware function to work, we had to move on to the next step immediately. This left little time for improvement and fine tuning, which was frustrating. In the end, several parts were left in a less mature state than we had envisioned from the beginning. That said, we still consider the level of maturity of the hardware/software high enough to show a large potential of a wireless solution. As a proof-of-concept, we consider this project as a success.

6.4 Environmental aspects

The wireless solution requires more hardware per sensor. This means more material in form of casings, electronics and possible batteries etc. More material could mean more waste, both economically and environmentally. On the other hand, time, energy and material can be saved by decreasing the need to modify and disassemble the car during preparation.

Being able to put the device closer to where the temperature is to be measured, decreases the need for long wires running from all measuring spots to the trunk. Since the wires are discarded after each test, there is material to save by decreasing the total amount of wires used for each test. The decreased need to modify and disassemble parts of the car would also contribute to energy and material savings.

6.5 Future work/recommendations

Recommendations and suggested focus areas of future work are listed below.

- **Power source** - The power source is considered to be the largest obstacle in order to meet all requirements due to the operation temperature. One alternative could be to circumvent the problem and use an external power source if the internal power sources' trade-offs make them unsuitable.

- **Measuring accuracy** - The measuring accuracy should be improved and verified to meet requirements.

- **Power consumption** - The current power consumption could be reduced significantly according to the specifications of the used parts and other available hardware. This could compensate for a possible loss of battery capacity when choosing a battery with a better operating temperature range.

- **Tests** - Further tests are needed to get user feedback, guide development, identify possible problems and weaknesses and to verify if the requirements are fulfilled or not.

- **Bluetooth 5** - An upgrade to newly launched Bluetooth 5 could increase the range fourfold, double the speed and have 8 times larger broadcast capacity according to Bluetooth SIG [Bluetooth SIG n.d.(b)].

7
Conclusion

The aim was to develop a ‘proof-of-concept’ of a non-proprietary wireless device that measures temperatures using thermocouples. This aim has been fulfilled.

The result is two identical battery powered prototypes using BLE (Bluetooth Low Energy) to communicate. The prototypes can be recharged wirelessly and uses three thermocouple converters and thermocouples to measure temperatures. The use of the BLE standard makes it possible to connect the prototypes to a large selection of receivers.

The projects pre-study showed an opportunity to reduce the time and effort needed during the preparation of Volvo Cars temperature tests, by going wireless. The pre-study further identified the required properties of such a solution, and determined that currently sold solutions are inadequate.

Using open standards is important to prevent supplier lock-in and to allow future development and purchases to be supplier independent. Several standards were considered for the wireless communication, and BLE was eventually chosen because of its low power consumption and good availability. Non-proprietary standards are used, both for the wireless communication and the formatting of the temperature data. This makes it possible to use and/or develop receivers without knowing more than what version of Bluetooth is used, and how the data is formatted.

The resulting, small sized, physical prototypes shows great potential with low energy consumption. It passes 13 of 16 demands from the list of requirements, and the largest limitation is that the operating temperature does not cover the required temperature range. Unfortunantly, that is a hard requirement that cannot be relaxed or traded. This must be one of the main focus areas of further development in order for a future product to succeed.

More development, tests and verification are needed to reach a product with all of the required properties. As the project consisted of too many parts to make any part mature enough for a final product, tuning and improvements in all areas of the prototype are needed. The possibility to fulfill all requirements with continued development looks promising.

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A

Comparison of available products

Table A.1: List of compared products.

Letter	Manufacturer	Product name
A	Cooper-Atkins	20100-K Blue2 Instrument[1]
B	DataQ Instruments	EL-WiFi-TC[2]
C	MicroStrain	TC-Link® -1CH -LXRS®[3]
D	Newport	MWTC[4]
E	Newport/Omega	MWTC-D[5]
F	Oleumtech	TC[6]
G	Omega	UWTC-2-NEMA[7]
H	Omega	UWBT-TC[8]
I	OneTemp	ZHEAD-TC[9]
J	Paragon Robotics	SC32[10]
K	Phase IV	WSN Thermocouple[11]

References

1 [Cooper-Atkins n.d.]
2 [DataQ Instruments n.d.]
3 [MicroStrain n.d.]
4 [Newport n.d.(a)]
5 [Newport n.d.(b)]
6 [Oleumtech n.d.]
7 [Omega n.d.(b)]
8 [Omega n.d.(a)]
9 [OneTemp n.d.]
10 [Paragon Robotics n.d.]
11 [Phase IV n.d.]

Table A.2: Comparison of available products.

Property \ Product	A	B	C	D	E	F	G	H	I	J	K
Sensors [pcs]	1	1	1	1	1	1	1	1	1	1	1
Open wireless standard	Y	Y	N	N	N	N	Y	Y	Y	N	N
Minimum polling interval [s]	1	10	0.002	2	2	-	2	1	1	10	600
Operating temperature [C]	0 to 50	-20 to 60	-20 to 60	-10 to 70	-10 to 70	-40 to 85	-10 to 70	-20 to 60	-200 to 55	-40 to 85	-40 to 85
Measuring accuracy [C]	0.3	1.5	2	1	1	1.1	1	0.8	-	1	2.8
Usetime per charge @ interval	500h @ 1 s	120 d @ 10 s	26 d @ 1 s	330 d @ 1min	7.2 m @1min	10 y @ 15 min	3 y @ 1 min	50h @ 1 min	3 y @ 10 s	7y	4-10 y @ 1 h
Weather protection	IPX7	IP44	-	-	-	IP66	IP65	-	IP65	-	-
Price [$]	-	-	-	-	175	-	220	240	306	179	375

B

List of Requirements

Source	Property	Control method	Target value	D/W
Authors	Battery indicator	-	Yes	W
Authors	Charging w/o disassembling	-	Yes	W
Authors	Concurrent devices per receiver	-	5	D
Authors	Concurrent devices per receiver	-	≥ 20	W
Authors	Cost for parts w/o tc converter	Data from re-sellers and estimations	<500:- SEK	W
Authors	Cost per channel #>1	Data from re-sellers and estimations	<200:- SEK	W
Etteplan, Volvo	Internal sync between sensors	-	Yes	D
Authors	IP67 equivalent	-	Yes	W
Volvo, Etteplan	IP54 equivalent	-	Yes	D
Etteplan, Volvo	Maximum delay	Calculations and estimations	0.5 s	D
Etteplan	Measuring accuracy	Manufacturers data sheet	≤ 0.5°C	W
Volvo	Measuring accuracy	Manufacturers data sheet	1°C	D
Etteplan	Measuring range	Manufacturers data sheet	-40°C to +1000°C	D
Etteplan, Volvo	Measuring resolution	Manufacturers data sheet	0.1°C	D
Etteplan	Open wireless standard	-	Yes	D
Volvo	Operating temperature	Manufacturers data sheet	-40°C to +85°C	D
Volvo	Operating temperature	Manufacturers data sheet	-40°C to +125°C	W
Etteplan	Sensor ID	-	Yes	D
Authors	Sensor inputs per device	-	$\geq$2	D
Authors	Possible sensor inputs per device	-	$\geq$5	W
Etteplan	Software device ID	-	Yes	D
Authors	Standardized temperature data	-	Yes	D
Etteplan	Thermocouple compatibility	Manufacturers data sheet	Type K	D
Etteplan, Volvo	Update interval	Data logger at receiving end	1 s	D
Volvo	Usage per charge	Measure current when active and idle	21 d x 6h	W
Authors	Usage per charge	Measure current when active and idle	$\geq$ 24 h active	D

C

Power consumption

Table C.1: First test of power consumption.

State	1st read	2nd read	3rd read	4th read	5th read	Avg.
Advertising	740	774	759	732	717	744
Connected	706	676	745	798	701	725
Transmitting 1	955	980	1020	950	1090	999
Transmitting 2	1280	1360	1250	1130	1380	1280
Transmitting 3	1510	1410	1470	1410	1430	1446

Table C.2: Second test of power consumption.

State	1st read	2nd read	3rd read	4th read	5th read	Avg.
Advertising	708	696	664	657	721	689
Connected	728	692	634	760	691	701
Transmitting 1	917	1000	991	997	1040	989
Transmitting 2	1290	1250	1260	1170	1300	1254
Transmitting 3	1370	1480	1430	1420	1380	1416

D

Test of measuring accuracy

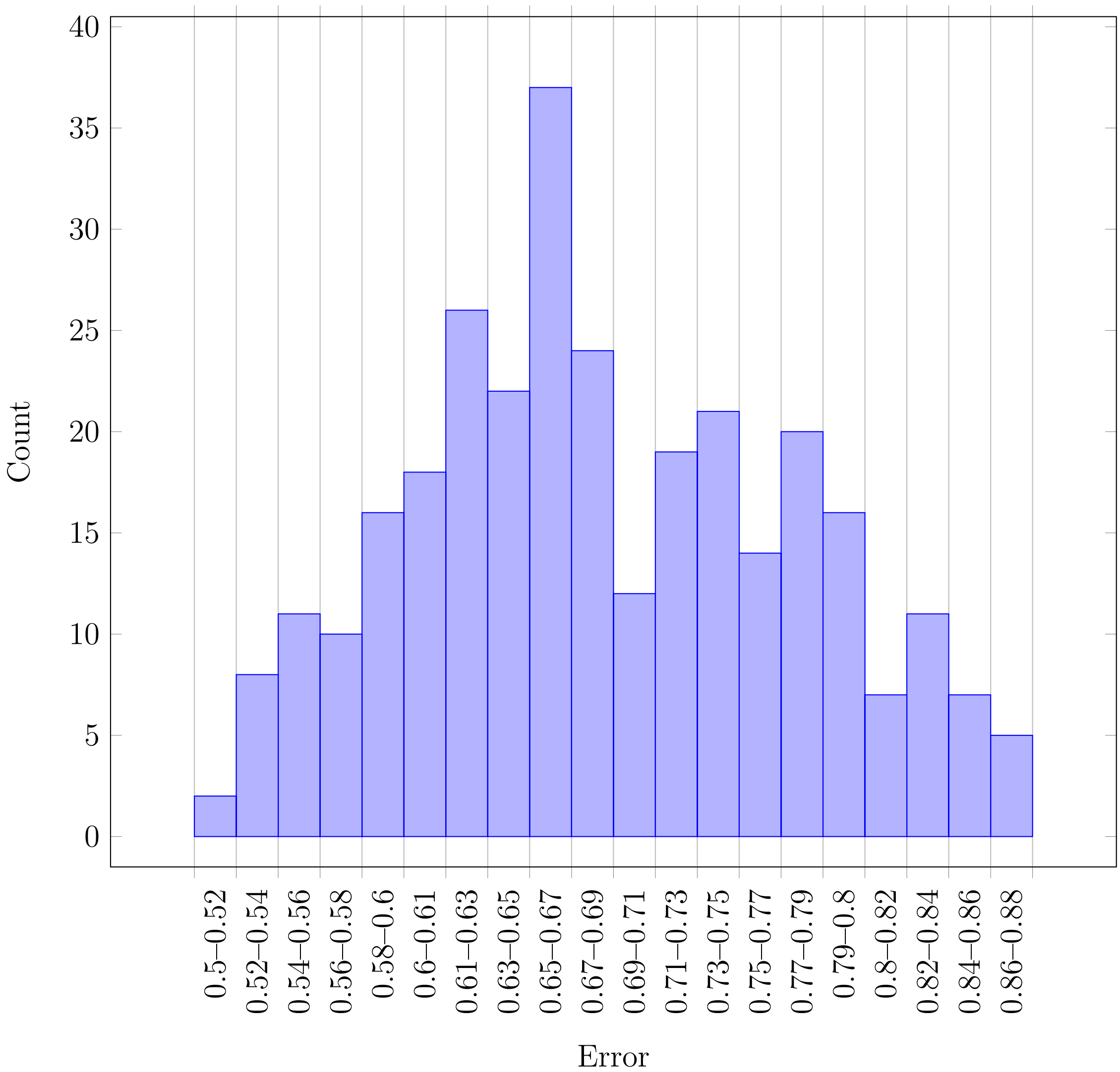

Figure D.1: Distribution of errors.

Table D.1: Test of the 1st converter.

T.	1st read	2nd read	3rd read	1st error	2nd error	3rd error	Avg. error
-40	-39.3	-39.4	-39.42	0.7	0.6	0.58	0.63
-35	-34.37	-34.36	-34.29	0.63	0.64	0.71	0.66
-30	-29.34	-29.2	-29.35	0.66	0.8	0.65	0.7
-25	-24.34	-24.41	-24.38	0.66	0.59	0.62	0.62
-20	-19.45	-19.33	-19.35	0.55	0.67	0.65	0.62
-15	-14.32	-14.35	-14.31	0.68	0.65	0.69	0.67
-10	-9.23	-9.28	-9.34	0.77	0.72	0.66	0.72
-5	-4.34	-4.37	-4.38	0.66	0.63	0.62	0.64
0	0.66	0.63	0.72	0.66	0.63	0.72	0.67
5	5.59	5.63	5.61	0.59	0.63	0.61	0.61
10	10.66	10.61	10.5	0.66	0.61	0.5	0.59
15	15.55	15.63	15.65	0.55	0.63	0.65	0.61
20	20.54	20.63	20.66	0.54	0.63	0.66	0.61
25	25.66	25.63	25.69	0.66	0.63	0.69	0.66
30	30.66	30.64	30.66	0.66	0.64	0.66	0.65
35	35.64	35.71	35.73	0.64	0.71	0.73	0.69
40	40.57	40.53	40.65	0.57	0.53	0.65	0.58
45	45.72	45.58	45.69	0.72	0.58	0.69	0.66
50	50.7	50.67	50.6	0.7	0.67	0.6	0.66
55	55.68	55.79	55.65	0.68	0.79	0.65	0.71
60	60.6	60.66	60.62	0.6	0.66	0.62	0.63
65	65.68	65.65	65.7	0.68	0.65	0.7	0.68
70	70.66	70.63	70.67	0.66	0.63	0.67	0.65
75	75.7	75.63	75.56	0.7	0.63	0.56	0.63
80	80.62	80.57	80.61	0.62	0.57	0.61	0.6
85	85.57	85.59	85.63	0.57	0.59	0.63	0.6
90	90.53	90.6	90.63	0.53	0.6	0.63	0.59
95	95.64	95.63	95.66	0.64	0.63	0.66	0.64
100	100.63	100.73	100.61	0.63	0.73	0.61	0.66
105	105.62	105.62	105.64	0.62	0.62	0.64	0.63
110	110.69	110.64	110.71	0.69	0.64	0.71	0.68
115	115.73	115.76	115.67	0.73	0.76	0.67	0.72
120	120.77	120.65	120.72	0.77	0.65	0.72	0.71
125	125.66	125.67	125.69	0.66	0.67	0.69	0.67

Table D.2: Test of the 2nd converter.

T	1st read	2nd read	3rd read	1st error	2nd error	3rd error	Avg. error
-40	-39.32	-39.28	-39.22	0.68	0.72	0.78	0.73
-35	-34.37	-34.34	-34.31	0.77	0.85	0.73	0.78
-30	-29.39	-29.38	-29.31	0.61	0.62	0.69	0.64
-25	-24.28	-24.29	-24.38	0.72	0.71	0.62	0.68
-20	-19.29	-19.34	-19.33	0.71	0.66	0.67	0.68
-15	-14.31	-14.36	-14.4	0.69	0.64	0.6	0.64
-10	-9.4	-9.34	-9.28	0.6	0.66	0.72	0.66
-5	-4.32	-4.4	-4.37	0.68	0.6	0.63	0.64
0	0.58	0.66	0.55	0.58	0.66	0.55	0.6
5	5.54	5.58	5.55	0.54	0.58	0.55	0.56
10	10.54	10.57	10.52	0.54	0.57	0.52	0.54
15	15.58	15.56	15.54	0.58	0.56	0.54	0.56
20	20.53	20.56	20.54	0.53	0.56	0.54	0.54
25	25.66	25.6	25.63	0.66	0.6	0.63	0.63
30	30.69	30.62	30.57	0.69	0.62	0.57	0.63
35	35.59	35.52	35.66	0.59	0.52	0.66	0.59
40	40.65	40.7	40.59	0.65	0.7	0.59	0.65
45	45.7	45.63	45.65	0.7	0.63	0.65	0.66
50	50.65	50.7	50.61	0.65	0.7	0.61	0.65
55	55.66	55.61	55.67	0.66	0.61	0.67	0.65
60	60.69	60.7	60.67	0.69	0.7	0.67	0.69
65	65.66	65.67	65.68	0.66	0.67	0.68	0.67
70	70.59	70.59	70.7	0.59	0.59	0.7	0.63
75	75.59	75.56	75.66	0.59	0.56	0.66	0.6
80	80.59	80.54	80.52	0.59	0.54	0.52	0.55
85	85.52	85.5	85.59	0.52	0.5	0.59	0.54
90	90.61	90.55	90.61	0.61	0.55	0.61	0.59
95	95.64	95.53	95.58	0.64	0.53	0.58	0.58
100	100.61	100.7	100.57	0.61	0.7	0.57	0.63
105	105.66	105.73	105.68	0.66	0.73	0.68	0.69
110	110.64	110.63	110.69	0.64	0.63	0.69	0.65
115	115.65	115.69	115.7	0.65	0.69	0.7	0.68
120	120.72	120.67	120.65	0.72	0.67	0.65	0.68
125	125.71	125.66	125.69	0.71	0.66	0.69	0.69

Table D.3: Test of the 3rd converter.

T	1st read	2nd read	3rd read	1st error	2nd error	3rd error	Avg. error
-40	-39.16	-39.17	-39.15	0.84	0.83	0.85	0.84
-35	-34.23	-34.15	-34.27	0.77	0.85	0.73	0.78
-30	-29.16	-29.2	-29.16	0.84	0.8	0.84	0.83
-25	-24.15	-24.27	-24.24	0.85	0.73	0.76	0.78
-20	-19.2	-19.15	-19.13	0.8	0.85	0.87	0.84
-15	-14.31	-14.27	-14.2	0.69	0.73	0.8	0.74
-10	-9.16	-9.26	-9.22	0.84	0.74	0.78	0.79
-5	-4.34	-4.19	-4.23	0.66	0.81	0.77	0.75
0	0.73	0.75	0.74	0.73	0.75	0.74	0.74
5	5.71	5.69	5.75	0.71	0.69	0.75	0.72
10	10.8	10.74	10.76	0.8	0.74	0.76	0.77
15	15.72	15.67	15.71	0.72	0.67	0.71	0.7
20	20.73	20.76	20.69	0.73	0.76	0.69	0.73
25	25.68	25.73	25.74	0.68	0.73	0.74	0.72
30	30.82	30.75	30.79	0.82	0.75	0.79	0.79
35	35.8	35.73	35.78	0.8	0.73	0.78	0.77
40	40.75	40.76	40.8	0.75	0.76	0.8	0.77
45	45.73	45.72	45.8	0.73	0.72	0.8	0.75
50	50.77	50.79	50.74	0.77	0.79	0.74	0.77
55	55.82	55.79	55.84	0.82	0.79	0.84	0.82
60	60.81	60.77	60.74	0.81	0.77	0.74	0.77
65	65.77	65.82	65.75	0.77	0.82	0.75	0.78
70	70.77	70.81	70.83	0.77	0.81	0.83	0.8
75	75.73	75.83	75.77	0.73	0.83	0.77	0.78
80	80.73	80.76	80.75	0.73	0.76	0.75	0.75
85	85.77	85.66	85.7	0.77	0.66	0.7	0.71
90	90.84	90.75	90.77	0.84	0.75	0.77	0.79
95	95.77	95.78	95.69	0.77	0.78	0.69	0.75
100	100.72	100.77	100.8	0.72	0.77	0.8	0.76
105	105.8	105.75	105.86	0.8	0.75	0.86	0.8
110	110.87	110.78	110.83	0.87	0.78	0.83	0.83
115	115.88	115.78	115.8	0.88	0.78	0.8	0.82
120	120.79	120.81	120.88	0.79	0.81	0.88	0.83
125	125.85	125.84	125.88	0.85	0.84	0.88	0.86