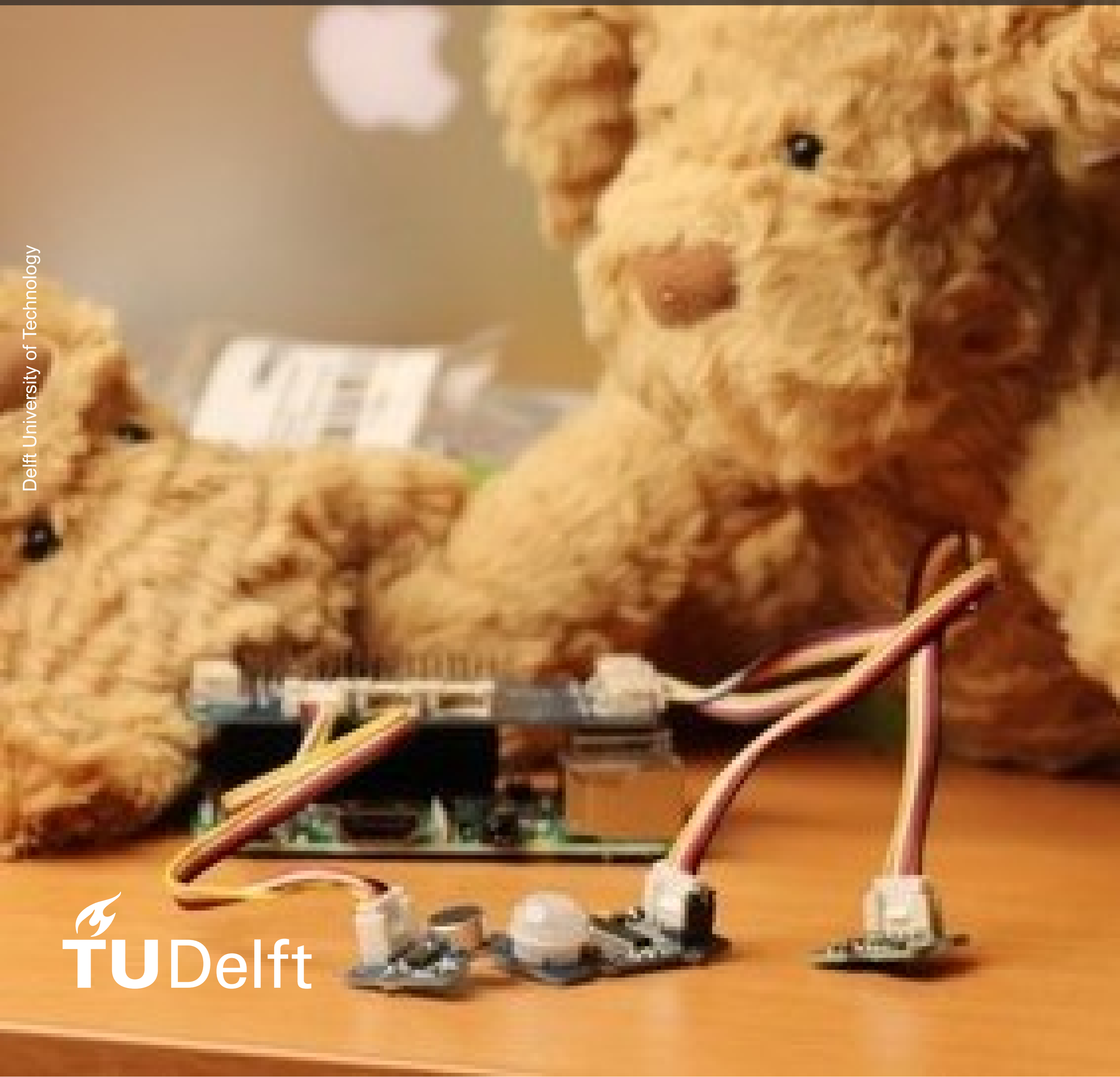
Smart Teddy: Elderly Monitoring and Support System Using Ambient Intelligence

Power Operations and Distribution

BSc Graduation Project Thesis

Taha Küçükçelebi & Lyana Usa



Delft University of Technology

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by

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Abstract

With the increasing demand in home-care service to provide early intervention at the homes of seniors suffering from early-stage dementia, the Smart Teddy prototype offers a technological solution to disburden caregivers, to promote and track the health and conditions of the senior and to prolong their independent life at home. The Smart Teddy is a project founded in 2018 by a research team of the Hague University of Applied Sciences. It is an interactive, companion robot - disguised as a toy dog - that serves as a therapeutic promoter while simultaneously monitoring the quality of life of the senior with pre-determined indicators. It consists of a Teddy to provide the interaction with the user and a Base Station for data processing and charging of the mount-in battery of the Teddy. The Power Operations and Distribution group carried out research on and developed suitable solutions to supply power to the Teddy with rechargeable batteries, to integrate controlled wireless charging of the battery for user-friendliness and to provide a streamlined power distribution throughout the Smart Teddy's system. Based on an iterated program of requirements and a power budget analysis on the set of installed electronics, a design is implemented for the power system of the Smart Teddy. A design sequence is followed consisting of four stages: (1) battery selection, (2) charger selection, (3) power conversion and distribution, and (4) safety and failure protection. A power system is developed for the Smart Teddy that is able to supply power with lithium-ion batteries with a battery life of at least 12 hours providing a battery capacity of 25.16 Wh. Thereafter, the installed batteries located in the Teddy can be charged wirelessly by placing the Teddy on the Base Station (a dog bed) to reinforce the less robot-like and a more natural look of the Teddy. Furthermore, this system ensures that all electronic modules with different operating voltages and current draws are provided with the necessary power specifications through power-sharing paths and the usage of power converters. Lastly, safety measures and failure protection methods are developed to ensure the safety of the user through the usage of fuses, switches and, cable and PCB management. The design has been verified using the appropriate verification methods where the program of requirements is used as a guideline and assessment tool. The Power Operations and Distribution is largely complying with the program of requirements and is performing according to the predetermined functionalities. Consequently, the power system of the Smart Teddy is integrated in a real, spatial prototype, namely in a toy dog (the Teddy) and its dog bed (the Base Station).

Keywords— dementia; wireless charging; therapeutic robot, companionship; power system; safety; lithium-ion battery

Preface

The Smart Teddy is a multidisciplinary project, tackling a societal issue by providing a technological solution. It is a research project from The Hague University of Applied Sciences that started in September 2018. Preceded by 18 students working on this research project, a team of six students started in April 2021 with the development of the fourth prototype of the Smart Teddy system over the course of 10 weeks. It is part of the Bachelor Graduation Thesis Project to complete the Bachelor of Science (BSc) in Electrical Engineering at the Delft University of Technology and all six students are BSc graduate candidates of 2021. Together with our fellow project partners, we, Taha and Lyana, have attempted to use our accumulated knowledge in Electrical Engineering to deliver a prototype in 11 weeks to our client (and supervisor incognito) Hani, who is representing the research team of the Smart Teddy. With pleasure and motivation, our aim was to contribute to a project with an impact on society whereby our engineering skills were being tested and our duty as engineers to work for the greater good.

We would like to thank both Zaid and Hani, for supervising and guiding us through these intensive 11 weeks of the project. It was a very pleasant and fruitful experience working with you on this project. We would also like to give our thanks to Francesca, Jianning and Thiago Batista from the Power Engineering Department of TU Delft for making time for us and for helping with our problems. Of course, we want to thanks Annemarie and Ezra for their input and enthusiasm towards this project, enabling us to gain in-depth insight into dementia and their experiences in the]is field. Last but not least, we want to thank our partners: Laura, Shea, Alan and Tim, for the joy, laughter, attitude, dedication and results shown while working on the prototype. We definitely had many learning experiences, working together with you.

Taha Küçükçelebi & Lyana Usa
Delft, June 2021

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1

Introduction

This chapter serves as an introduction to the context, the relevance and the pre-liminary analysis of the project. Firstly, Section 1.1 shows a background study on dementia and specifically, early-stage dementia amongst senior citizens. Thereafter, in Section 1.2, the Smart Teddy project is introduced and its interrelation with seniors diagnosed with dementia is explained. This section also presents the goal and the division of the project. Section 1.3 explains the problem definition relevant to the Smart Teddy that is to be solved in this thesis. It presents the situation assessment, the project scope, its bounds and the research questions. Section 1.4 discusses the state-of-the-art analysis on the introduced problem definition and research questions. Furthermore, it serves as an analysis of preceding and current solutions, and a premise on the relevance of the project. The chapter concludes with a thesis synopsis in Section 1.5.

1.1. Background Study: Early-Stage Dementia

Dementia is a generic term to express symptoms and processes related to the deterioration of cognitive functions, beyond what might be expected from normal aging. It affects memory, thinking, orientation, comprehension, calculation, learning capacity, language and judgment. This often goes hand in hand with deterioration in emotional control, social behavior or motivation leading to social seclusion and motor performance decline [12]. Since dementia is correlated with aging, it is a major cause of disability among senior citizens [34]. The chance of being diagnosed with dementia increases exponentially between the age of 65 and 90 [7]. As dementia worsens, it becomes harder to perform day-to-day tasks and self-care, resulting in the senior citizens requiring full-time care by caregivers. This increases the chance of moving to a nursing home significantly, placing a great burden on close family members and the person with dementia [34]. Moreover, a dementia diagnosis causes financial distress with a significant economic impact in terms of medical and social care costs. In fact, 10.5% of the total costs of Dutch healthcare is from costs made for dementia [2].

Seniors in their early stage of dementia experience mild to moderate cognitive decline (e.g. struggling with remembering events or names), yet they live at home independently or with their partner. As dementia progresses, the chances of the senior being committed to a care home increases significantly. It is roughly estimated that the senior suffering from dementia will lose their complete independence and arrives in the severe stages of dementia gradually. Dementia care is typically initiated as soon as the senior is diagnosed. This involves unofficial care from loved ones or at-home care services provided by caregivers to help with small tasks, reinforcing companionship and interaction, and monitoring the health [4]. As of today, there is no cure for dementia which makes it such a complex problem facing our society. The intervention from caregivers to disburden seniors expedite the principal goals of dementia care, namely [34]:

- Early diagnosis in order to promote early and optimal management;
- Optimizing physical health, cognition, activity and well-being;
- Identifying and treating accompanying physical illness;
- Detecting and treating challenging behavioral and psychological symptoms;
- Providing information and long-term support to carers.

Alternative solutions with the help of technology emerged to support seniors with dementia. Using technological advancement in form of assistive technology for seniors with dementia has its potential benefits. It can enable senior citizens with dementia to live independently for a longer period of time, reduce the stress and pressure on the person using it and its caregivers and ultimately enhance their quality of life [28]. The care for early-stage dementia senior patients is at risk as the aging population in the Netherlands is increasing and the demand and workload for proper care at home in this stage of dementia is increasing. Technological developments can be deployed to disburden the seniors suffering from dementia as well as the caregivers [28].

1.2. Smart Teddy: Interactive Companion Robot for Seniors

The "Smart Teddy" was founded in 2018, originating from a research group from The Hague University of Applied Sciences and functions as an interactive companion robot for seniors suffering from early-stage dementia. The aim of the research project is defined as follows:

The Smart Teddy is going to interactively accompany senior citizens in an early stage of dementia while acquiring data about their quality of life using predetermined indicators to prolong the time for which they can live at home independently.

The Smart Teddy shows relevance towards SDG (Sustainable Development Goal) 3 : ”Good Health and Well-Being” of which minimizing the impact of non-communicable diseases and the promotion of mental health and well-being are key aspects. Reduction of the risks and ramifications of dementia is part of the commitment to improve health coverage [10]. The development of the Smart Teddy led to three prototypes fostering the achievement of SDG 3 and the research process towards its final product. The latest prototype consists of two separate modules: a teddy bear and a base station. The interior of the teddy bear contains several sensors to collect data which is powered by batteries. The base station functions as a microcomputer to perform calculations on the collected data and as a battery charger. Throughout the thesis a distinction is made between those modules as follows:

- **Teddy**: The Teddy is a stuffed animal (previously mentioned as the ”teddy bear”) that will offer therapeutic companionship to seniors with early-stage dementia by exhibiting some forms of interaction like movement and producing sounds to touch or noise. The Teddy will also house various sensors and microprocessors to measure the daily activities of the user, collecting the data and sending it to the Base Station where further calculations and estimations are done. Based on this data, the quality of life of the user will be estimated. The Teddy will have a mount-in battery, that will provide the necessary power to all its components.
- **Base Station**: The Teddy interacts with the Base Station by sending data acquired from the sensors located in the Teddy. The Base Station will also have its own set of sensors that either cannot fit in the Teddy or is not preferred due to privacy issues. With all this data, the Base Station will do the necessary calculations in order to estimate the quality of life. The Base Station will also include power distribution in order to provide power to its components as well as to charge the Teddy.

The friendly-looking Smart Teddy effectively encapsulates the monitoring role of caregivers and promotes interaction and companionship. The acquired quality of life information can be sent to caregivers or close relatives of the person using it, enabling monitoring the progress of the user and interfering when necessary. Due to its monitoring features, it can also report when the user is in a dangerous situation such as when there is a gas leakage, fire or when the user falls and makes a loud noise. Caregivers and emergency services can be alerted based on these indications.

This thesis is part of the development of the next prototype of the Smart Teddy project. A group of six students from the TU Delft has been divided into three subgroups each consisting of a pair of students. Based on the classification of the general requirements of the project, the subgroups are defined as follows:

1. **Human Interaction and Integration (HI&I) group** focuses on the interaction between the senior user and the Teddy and is responsible for a smooth integration of the three subsystems within the interior of the Teddy. A communication line is established between the Teddy and the Base Station so that the Sensors and Data Acquisition group (explained below) can receive the data from the distant Teddy.
2. **Sensors and Data Acquisition group** is responsible for the sensing of quality of life indicators using ambient intelligence and performing calculations on the retrieved data. The data is retrieved from the Base Station and is received through a communication line from the sensors installed in the Teddy.
3. **Power Operations and Distribution group** is responsible for the power operations and their distribution in the Smart Teddy with the primary goal to deliver power to all loads of the device from batteries. Furthermore, this group is responsible for charging the batteries. In collaboration with the Sensors and Data Acquisition group, the Base Station will be designed in which the sub-modules from both groups can be physically integrated.

Figure 1.1 shows a general overview of the Smart Teddy system including the specific sub-modules that each group is responsible for. The total of the three subsystems encapsulates the prototype of the Smart Teddy. This thesis report is focused on the subgroup Power Operations and Distribution[1]. The group endeavors to make a power system complying with the requirements which will be presented later in the report. Eventually, this system will be integrated with the other systems to assemble the Smart Teddy's prototype.

[1] The Power Operations and Distribution group or system shall be referred to hereinafter as its abbreviated form ”the power group or power system” unless stated otherwise.

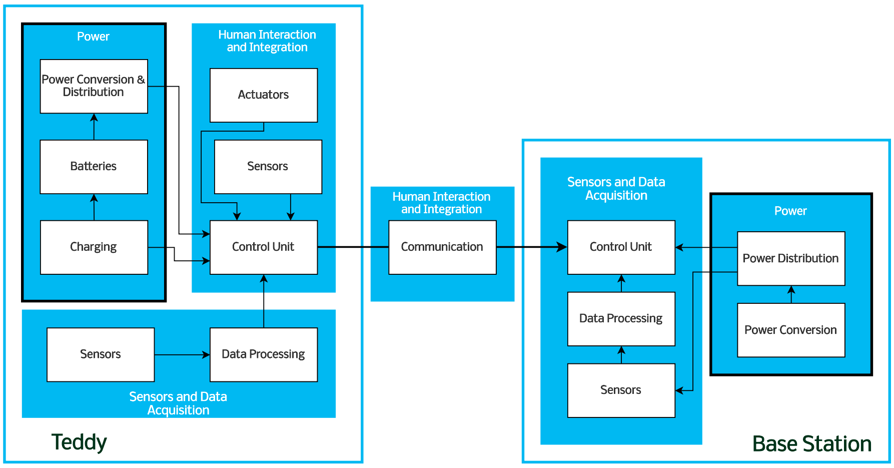

Figure 1.1: General system overview of the Smart Teddy project

1.3. Problem Definition

The Teddy and its Base Station, in which various sets of electronic devices such as sensors, microcontrollers and actuators will be installed, need to be provided with power in order to operate. The operation of the complete Smart Teddy relies on power provision and distribution to the other subgroups: Sensors and Data Acquisition, and Human Integration and Implementation. The previous three prototypes made by various students from The Hague University of Applied Sciences did not contain a power solution. The latest variant uses an external power bank in order to power the electronics in the teddy. The electronic components used in the latest version are also different from this project that requires different power specifications. Moreover, the Base Station does not have a prototype and only a digital draft exists. Therefore, this subgroup is going to develop a power system, whereby the guidelines of the original project proposal will be followed. From a power perspective, this project will be seen as a new project, where inspiration will be taken from similar and preceding work.

The power system should be able to provide sufficient power to all the components in the Smart Teddy, whereby the Teddy has its own power source which should be charged by connecting it to the Base Station. A missing or deficient power system will result in a non-functional Smart Teddy and is detrimental to the functionalities of the other subgroups. For this reason, the power system is considered to be a crucial part of the overall project. Both the end-user (people in the early stages of dementia) and caregiver want a teddy that is powered correctly that lasts for a reasonable amount of time without charging it (12 hours, set by project proposal). To design and test the power system with all its components communicating and interacting with each other, one should be familiar with various principles within the field of Electrical Engineering, such as: circuit design, power engineering, control engineering, microelectronics, instrumentation engineering and signal processing.

One of the biggest limitations faced is the uncertainty prevails in the initial phase of the project. The other subgroups do not have a pre-defined list of components and systems which is subjected to adjustments, additions and thus, iterations. This will affect the progress of the Power Operations and Distribution subgroup. Another limitation is the available cost budget that poses a limitation for purchasing components. Then, the Teddy should be able to fit on someone's lap and the Base Station is home-bound, which poses physical limitations on the design. Lastly, another important factor to keep in mind is that the teddy is intended for a specific vulnerable group (people in their beginning stage of dementia), and should be kept in mind when designing the power system. Potential dangerous situations for this group should be minimized. An example of one additional safety concern was discussed during an interview with professionals working with dementia: seniors with dementia often tend to bite on objects. This can be dangerous if an exposed power source like a battery is used as a power supply. Hence, knowledge of the user group is important in the development of the prototype.

This thesis focuses on the subgroup Power Operations and Distribution of the Smart Teddy. The process of its design, its implementation, and its final prototype are documented in this thesis. The following research questions within the scope of the electrical power system of the Smart Teddy project will be handled and answered:

1. Which battery complies with the requirements of the Power Operations and Distribution for the Smart Teddy, and thus should be used?
2. Which battery charging technology should be used in order to charge the selected battery for the Smart Teddy considering the requirements of the Smart Teddy?
3. Which components and systems are necessary in order to realize a properly working power system that complies with the program of requirements?

1.4. State-of-the-art Analysis

The research questions for the Power Operations and Distribution mainly involve battery and battery charging technologies. The Smart Teddy is classified as a portable device that is powered by batteries. This state-of-the-art analysis shows an overview of technologies that are previously and currently used to support the power supply of portable devices. This analysis is bounded by at-home use scenario whereby the size of the Smart Teddy does not significantly differ from the size of a regular teddy bear. However, it is not limited to Smart Teddy-like examples since analysis on a similar device will also be explained. In this state-of-the-art analysis, well-known and new rechargeable battery technologies used in portable electronic devices, as well as the charging methods, are discussed.

1.4.1. Rechargeable Battery Solutions

A battery can be classified into primary and secondary form [14]. The former encompasses batteries that are intended for one-time usage and thus, are not rechargeable. The latter entails batteries that can be recharged.
As the focus lies on the battery and its charging system of the Teddy, batteries of primary form are out of the scope and focus in this state-of-the-art analysis will be set on rechargeable batteries used in PED's (portable electronic devices) and that is commercially available. The Teddy can be classified as portable since by nature of the use case it has to be able to be picked up easily and moved from one place to another. Nowadays, there exist various rechargeable battery technologies for various usage scenarios. The main battery technologies used for PED's are [16]: lead-acid battery, nickel-cadmium battery (Ni-CD), nickel-metal hydride battery (Ni-MH) and lithium-ion battery (Li-ion).

Lead-Acid Battery and Nickel-Cadmium Battery

Lead-acid batteries which are around for the longest time of all four types are the first batteries invented that is able to be recharged [29]. Despite being old, lead-acid batteries are still used mainly due to them being cheap, easy to produce, easy to recycle and the resources being practically unlimited [24]. However due to their low volumetric and gravimetric energy densities [30] and the emergence of new technologies, it is not a commonly used battery for PEDs anymore. Ni-CD batteries came after the lead-acid battery as an improvement [29]. Ni-CD batteries are like lead-acid matured technologies and are mostly used in places with difficult environmental conditions and where long service life is required [14]. These batteries have several advantages over lead-acid in terms of charge/discharge rate, robustness and energy density. However, drawbacks such as the memory effect (losing maximum capacity when charged several times before fully charged) and environmental effects of the disposal of batteries pushed the industry from the use of these batteries and nowadays only specific applications are using these batteries [16] [29].

Nickel-Metal Hydride Battery

Ni-MH batteries are one of the most important technologies for various consumer applications and electronics [35]. These batteries are commonly available as AA size batteries in consumer electronics and are often used in digital high-drain devices. These batteries are a substantial improvement over the previous technologies, containing higher energy densities in terms of mass and volume, lower toxicity, lower price and more Eco-friendly [16]. Even though they do not contain a high energy density in terms of mass and volume as the latest technology (Li-ion), the price of this technology is lower making them still considerable. Nowadays, they are almost completely replaced by Li-ion batteries. Due to the coming of Li-ion batteries with better characteristics, no further development of these batteries is expected [29].

A well-known therapeutic robot, the Paro, is a baby seal-like robot that had been developed by the National Institute of Advanced Industrial Science and Technology (AIST) of Japan since 1993. The purpose of this project is to improve the social interaction of seniors and children suffering from psychological disorders [33]. This animal-like robot is powered by a rechargeable battery with an operating time of about 1 to 1.5 hours. However, Paro can continue operation during the use of a charger with a pacifier-shaped plug [32]. The rechargeable battery used in the Paro is composed of Ni-MH cells with generally a nominal cell voltage of 1.2 V [1].

Lithium-ion Battery

Lithium-ion batteries are currently dominating the market accounting for about 85% of the total electrochemical market [22]. Li-ion batteries are the first choice in many applications [29]. Li-ion batteries are very popular mainly because they contain the highest energy density in terms of mass and volume, which is especially important in portable devices nowadays. Other advantages are low maintenance, quick charging, long lifespan and low self-discharge. The major drawback is that they have a relatively higher material cost. Furthermore, they are relatively sensitive to overcharging and over-discharging requiring a dedicated protection circuit [9]. A great volume of research in Li-ion batteries has been done in electrode materials, whereby different materials provide different advantages, to tackle these problems. Different variants under Li-ion technology emerged such as LiPo and LiFePo4. Given its fundamental advantages compared to the rest, Li-ion batteries will in all likelihood continue to dominate the portable electrochemical energy storage for many years to come [21].

1.4.2. Battery Charging Technologies

The process of recharging a battery is the action of storing electrical in the form of chemical energy. There are several ways to do this. Figure 1.2 shows an extensive overview of existing battery charging technologies. The ways of charging batteries depend on the size of the battery, its charging capacity, the user demands and preferred scope of operation. Since this project is bounded to home usage, the research for battery charging technologies is mainly focused on teddy bear-sized electronic devices. Consequently, magnetic-gear charging can be discarded in further analysis as this is primarily used for wireless charging of electric vehicles using the rotation of magnetic gears [25] [23]. A concise overview of wired and wireless charging solutions is given below.

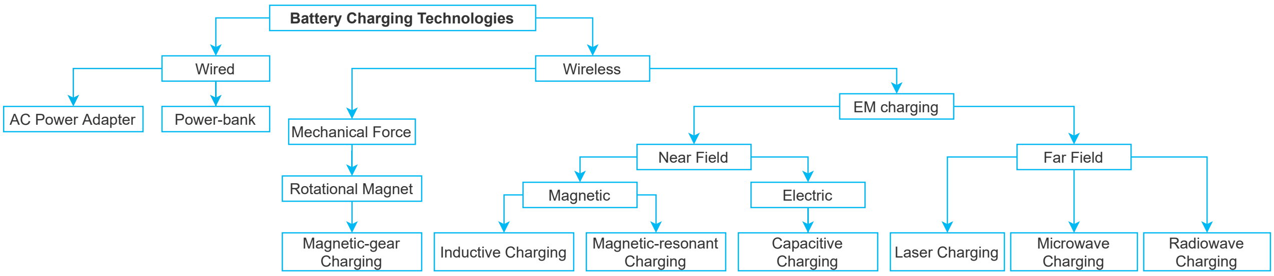

Figure 1.2: Overview of current battery charging technologies

Wired Charging Solutions

The most commonly used charging type is the wired charging solution. All wired chargers have the same architecture, namely that an intermediate electrical system ensures that the incoming voltage and current meets the charging demand of the load (e.g. a battery). The AC adapter is commonly used and it converts the AC voltage from the net to a DC voltage to power the electronic device. Another type of wireless charging is a portable option, whereby the usage of a portable power supply is used to charge electronic devices. The power-bank is a popular example as it can power for example a mobile phone by connecting the cable to the power-bank [8].A disadvantage of a power-bank is that the mount-in battery requires charging too which is done by connecting an adapter or to a USB port of a peripheral (e.g. laptop). USB namely supports power lines and thus most adapters support that by having a USB output. The previous example of the Paro robot uses an AC adapter disguised as a pacifier to charge [32].

Wireless Charging Solutions

Wireless power transfer is a two-compound charging system whereby power can be transferred between two distanced modules through a medium (typically air) based on electromagnetic principles [18]. As of today, groundbreaking developments have been achieved that lead to wireless phone chargers and to long-range energy transmission using emerging wireless technologies. This technology is used to prevent disruption of operation and to diminish the usage of charging cables in order to enhance the mobility of PEDs [20]. There are two types of wireless charging methods, classified on the range of operating distance, namely near-field and far-field charging.

Near-field charging is defined by the operation distance that is between mm up to several m [26]. There are three options: magnetic induction, magnetic resonance and capacitive charging. The latter uses an electric field that is created by a dielectric through capacitive coupling which thus forms a capacitor between two distant modules. Capacitive charging is a less popular option as its power transfer is greatly dependent on the size of the dielectric plates and hence more difficult to implement for charging small electronic devices [15] [23]. Magnetic resonance and magnetic induction are similar in terms of the operation: it uses coupling between coils to establish a power transfer. However, in the case of magnetic resonance multiple devices can be charged by one coil as the principle uses the coupling with the same resonance frequency [18] [27]. It is possible to have a wireless power transfer up to a few meters due to this characteristic. Magnetic induction is done over several cm whereby the efficiency of the transfer is the highest amongst all wireless technologies. This is due to the advanced development of this solution and currently used for wireless charging of electric toothbrushes and mobile phones. A drawback from magnetic induction is the coil alignment issue which is not a serious issue for magnetic resonance. Magnetic resonance and magnetic induction have interface standards to ensure compatibility across devices with typical operating frequencies and communication rules, e.g. QI for inductive charging, and AirFuel from AirFuel Alliance for magnetic resonance. Elaboration on these standards can be found in Appendix A.

Far-field charging is done over larger distances, namely from meters up to km. That is why it is mostly used for long-range charging applications. It is for example greatly endorsed in charging long-term applications such as flying robots, which can lengthen the duration of operation of long flights without interruption [3]. All three technologies are using antenna principles. In the case of laser charging and microwave charging, it is extremely important to ensure that no blocks are in the line that the wave is propagating [11] [18]. Microwaves typically require large antennas and line-of-sight [19].

Radiowaves can penetrate through media, but are subjected to strict government regulations on the usage of the frequencies. This is also the case for microwaves. Far-field charging also accounts for a significant biological impact and thus requires important safety regulations for radiation and human exposures. In Appendix A, a more detailed overview and comparison of these wireless technologies can be found along with a short market research on their availability and costs.

1.5. Thesis Synopsis

This thesis entails the relevant documentation and insights towards the completion of the BSc Graduation Project - ”Smart Teddy Power Operations and Distribution”. It also serves as a repository for future iterations of the Smart Teddy. The next chapter, Chapter 2, describes the program of requirements relevant to this subgroup of the Smart Teddy. It provides an overview of these requirements as well as an explanation of steps that had to be taken to construct the program. Chapter 3 elaborates on the design of the Power Operations and Distribution system where its high-level architecture will be explained after which it will be dissected into the relevant sub-modules. The complete design sequence and design choices will be discussed prior to presenting the final design. Then, in Chapter 4, the implementation of the design will be explained. The plan of implementation and integration with the other subgroups will be discussed. Furthermore, results will be presented in a verification of the program of requirements and contextual assessment. Chapter 5, explains the integration of the power system into the prototype of the Smart Teddy. In Chapter 6, the results will be discussed, ending with a conclusion and recommendations.

2
Program of Requirements

This chapter describes the program of requirements for the power system of the Smart Teddy. The client has provided an outline of general criteria for the Smart Teddy which was extrapolated over the subgroup. This was done by frequent consultation with the client and extracting the functional and non-functional requirements relevant to this subgroup, by iteration and in collaboration with the other subgroups. The program of requirements for the Power Operations and Distribution group is a combination of general requirements, which the overall Smart Teddy system must comply with, and specific requirements related to it. It should be noted that the draw up of the program of requirements is in progress under iteration and re-assessment of the prototype and its prototyping phase[1]. Therefore, the requirements are indicated with an identification number (ID) including their version numbers to indicate the iterated requirement from this project. Prior to presenting the program of requirements in Section 2.2, the context of the construction of the requirements is explained in Section 2.1 since the framework of the program was largely influenced by the demands and constraints from the other subgroups.

2.1. Context of Program Construction

Due to the high dependency on the design choices of the other subgroups, the program of requirements of the power system is governed by these groups. This is mainly a result of the necessity of knowing the pre-selection of electronic devices that will be installed in the Base Station and the Teddy to support the functionalities of the Smart Teddy. Therefore, the power group has made a so-called "power budget" with a provisional set of chosen electronic devices from the other subgroups. The power budget is an analysis and estimation of the current draw, the power consumption, the usage time and its required operating voltages of the system. This is done by examining each electronic device that the other subgroups wish to install in the system, i.e. the Base Station and the Teddy. The selected electronic devices operate at different voltages and have specific current and power ratings. In this chapter, the results of this preliminary analysis of the overall power characteristic of the Smart Teddy is used to define requirements related to the power system of the Smart Teddy. The analysis and the results are further elaborated in Section 3.2.

Then, in consultation with the other subgroups (Human Interaction and Integration) the Teddy's exterior had been selected in the beginning to serve as the foundation of the prototype. The availability and price of the Teddy (a toy dog) were considered, and eventually, a Teddy was chosen. The dimensions of the Teddy are stated in Requirement NF.03.v01 that is part of the non-functional requirement in Table 2.1. The exterior of the Base Station is based on the size of the Teddy as well as the necessity to enhance the natural overall appearance of the Smart Teddy compliant with Requirement NF.05.v01.

Eventually, with the pre-selection of the exterior of the Teddy and the analysis of the power budget of a provisional selection of components, a program of requirements was constructed within the given framework of general criteria of the Smart Teddy. In order to verify that the requirements are satisfied after assembly and integration of the power system, each requirement has a specific verification method. This is based on the systems engineering approach that uses four methods: test, analysis, inspection or demonstration. A detailed explanation of the verification methods can be found in Appendix B along with the specific verification procedure for each requirement.

2.2. Non-functional and Functional Requirements

An overview of the non-functional and functional requirements of the Smart Teddy are shown in Table 2.1 and 2.2, respectively.

[1] The project in progress is commissioned by the client who foresees and allows potential iterations and changes of requirements during prototyping based on preceding experiences with the Smart Teddy research and its prototypes.

Table 2.1: Table containing the non-functional requirements for the Power Operations and Distribution design. The non-functional requirements are labeled as NF.XX.vXX. Their version is indicated with .vXX.

ID	Non-functional Requirement	Rationale	Verification Method
NF.01.v01	The Teddy's Power system must be developed around batteries.	The portability of the Teddy is supported with batteries. The user must be able to move the Teddy and carry it around.	Demonstration
NF.02.v01	The weight of the Teddy shall not exceed 600 g.	The weight of the Teddy must be within the specified mass budget for the Power group.	Demonstration
NF.03.v01	The measurements of the Power system in the Teddy must not exceed the dimensions: head to tail 60 cm, body length 40 cm, body width 20 cm and body height 20 cm	Due to the pre-selection of the Teddy's exterior, the subgroup must select components that within the size.	Inspection
NF.04.v01	The Teddy and the Base Station must not contain parts that could be a choking hazard.	Some people who suffer from dementia might put foreign objects in their mouth. Exposed electronic components or protruding sharp parts are examples.	Inspection
NF.05.v01	The Smart Teddy's appearance must be non-intrusive.	The Smart Teddy cannot have protruding ports and/or cables that potentially harm the friendly appearance and should not make the Teddy look like a robot (e.g. avoid use of LEDs).	Inspection
NF.06.v02	The manufacturing costs for the Power Operations and Distribution shall not exceed €130.	This fixed cost limit has been agreed upon with the client and must be respected.	Analysis

Table 2.2: Table containing the functional requirements for the Power Operations and Distribution design. The functional requirements are labeled as F.XX.vXX, respectively. Their version is indicated with .vXX.

ID	Functional Requirement	Rationale	Verification Method
F.01.v01	The power system must provide power at the required specifications for the installed electronic devices of the Smart Teddy.	All electronic devices installed in the Teddy and the Base Station have different power specifications which must be satisfied.	Test
F.02.v03	The battery must comply with the power demand of the Teddy for a minimum of 12 hours.	The battery is delivering the required current demand under the correct operating voltages to the loads for the specified time.	Test
F.03.v01	The Teddy must contain an indicator of the state of the battery that is in agreement with requirement NF.05.v01.	It must be clear to the user when the Teddy needs charging, to avoid an empty battery.	Demonstration
F.04.v01	There shall be an indication that the Teddy is charging that is in agreement with requirement NF.05.v01.	This will help the user in knowing when the Teddy is placed correctly without having the Teddy look like a gadget.	Demonstration
F.05.v01	The Power system should have a safety and failure protection.	Whenever a fault occurs (e.g. short circuits, undervoltage, overvoltage, overcurrent) the system is able to ensure safety of the system and the user and able to take the proper action to protect.	Analysis

3
Detailed Design

This chapter describes the detailed design of the Power Operations and Distribution system for the Smart Teddy. It starts with a high-level description of the system where the system's architecture and the specification of functionalities of sub-modules are introduced. Then, in the next section, each sub-module will be elaborated upon and its design procedure and decisions are explained.

3.1. High-level Description of Design

A high-level description of the system was constructed and illustrated in Figure 3.1. The operations of the power system can be classified into (i) the Base Station and (ii) the Teddy. Both contain several sub-modules that are related to a specific operation or process. There are in total six modules.

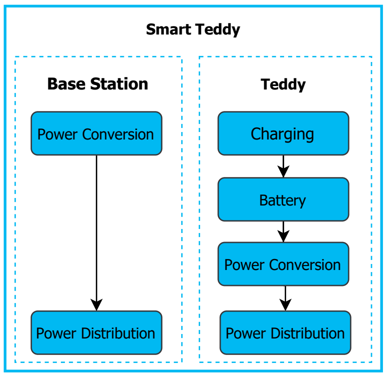

Figure 3.1: High-level architecture of the Power Operations and Distribution system.

The Base Station consists of two sub-modules, namely:

1. **Power Conversion**: The functionality of this sub-module is to convert the net voltage to the required operating voltage inside the Base Station. The value of the operating voltage is dependent on the selection of the needed system's voltage inside the Base Station.
2. **Base Station Power Distribution**: This sub-module is responsible for the distribution of the power to all electronic devices that are installed in the Base Station. Furthermore, the Power Distribution module ensures that the distributed power is reliable and at the required specifications which differs per electronic device.

The Teddy consists of four sub-modules, namely:

1. **Battery**: The battery serves as the power supply within the Teddy and requires charging.
2. **Charging**: The charging supports the operation of the rechargeable battery. The charging mechanism is able to put energy in the battery.
3. **Teddy Power Conversion**: This is the Teddy-equivalent sub-module of the Base Station Power Conversion.
4. **Teddy Power Distribution**: This sub-module has similar functionality as the Power Distribution module based in the Base Station. The difference lies in the loads it has to supply power to.

The sub-modules of the high-level system can be divided into a design sequence consisting of four design activities eventually leading to the product, being the final design of the Power Operations and Distribution system. The design sequence contains the following stages: (1) battery design of the Teddy, (2) battery charger design, (3) power conversion and distribution design in both the Teddy and Base Station and (4) safety and failure protection design. The following sections chronologically explain each design stage.

3.2. Battery Design

The battery is the heart of the Teddy. Without a properly working one, the Teddy cannot operate as intended. In order to design a proper power system, it is therefore important to carefully select the battery. In this section, after explaining the power budget of the Teddy, the best-suited battery technology will be chosen based on the requirements. After this selection, the specific battery and its configuration will be covered based on the power budget.

3.2.1. Power Budget Teddy

The power budget is a critical part of scoping the power system and hence understanding what the battery should supply. An overview of the components used in the Teddy with their voltage, average current, average power and usage time specifications is shown in Appendix C. The voltage and current specifications are taken from the datasheets of these components and/or estimated where no clear data was available. The usage time of each component in hours is based on an estimation of how long the target user will use the Teddy during one day. These estimations are made together with the Human Interaction & Integration and, Sensors and Data Acquisition subgroup. Additionally, all these components have a maximum power consumption. It is important that the battery can also withstand this instantaneous maximum power draw from the components, in order to keep working properly without failing to deliver the necessary power. The final values are shown in Table 3.1. These values are needed in order to select a battery that complies with the requirements NF.01.v01, F.01.v01, F.02.v03 and F.05.v01.

Table 3.1: Summary of the Power Budget of the Teddy.

Total average energy usage in a day [Wh]	**Total average energy usage in 12h [Wh]**	**Average power usage [W]**	**Total max. instantaneous power usage [W]**	**Operating voltages of components [V]**
32.24	16.12	1.35	16.6	3.3 and 5

In these numbers losses due to voltage regulations and cables are also taken, which is approximated at 30% of the original values. Typical voltage converters have an efficiency of around 95% and cable losses will be in real life only about 1% since the length is short and the power transferred is low. The efficiency values chosen are pessimistic values, which will protect the design from marginal errors and real-life influences on components. The battery thus requires to deliver a minimum amount of energy of 16.12 Wh, which is 1.35 W of power in order to operate for at least 12 hours. The battery also has to be able to deliver the maximum amount of instantaneous power of 16.6 W in case every component draws the maximum power. Note that all the components in the Teddy operate either at 3.3 V or 5 V, which means that two different operating voltages in the Teddy are needed.

3.2.2. Technology Selection

Table 3.2: Overview of the different battery technologies. Some of the values are taken from [17].

Type	Lead-Acid	Nickel-Cadmium	Nickel-Metal Hydride	Lithium-Ion
Battery Cost [$/kWh]	100-200	250-550	250-500	300-700
Nominal Voltage	2.1	1.2	1.2	3.2-3.7
Gravimetric Energy Density [Wh/kg]	30-50	40-60	60-120	170-250
Volumetric Energy Density [Wh/L]	60-110	150-190	140-130	350-700
Cycle Life	300	1500	1000	500-2000
Fast Charging Time [h]	8-16	1	1-4	1 or less
Overcharge Tolerance	High	High	Low	Low-High

Every battery type can provide the necessary power if it is big enough. However, for the Teddy and for the power system itself, weight and size limitations must be considered (Requirement NF.02.v01 and NF.03.v01). It is also important that the technology is commercially available and is fitting the cost limit in compliance with Requirement NF.06.v02. The focus will lie on the main battery technologies used in PED's that are commercially widely available as mentioned in Section 1.4. In order to choose the best technology that complies with the requirements, an overview of the different technologies is shown in Table 3.2. Lithium technology is the most promising technology of all three options. This technology has the highest gravimetric and volumetric energy densities, meaning that with relatively light and small battery size, all of the components in the Teddy can receive sufficient power. Moreover, this technology has the shortest charging time and highest cycle life ensuring a long battery life. It also has the highest cell voltage of all the technologies compared, which will improve the conversion efficiencies in the system. The downside of this technology is that it has the highest cost compared to the other technologies. However, this will not have a big effect in our case since the amount of energy needed for the Teddy is relatively low. Some Lithium technologies like the basic Li-ion, also have a low overcharge tolerance, which means that it requires a dedicated charging protection and regulation board.

3.2.3. Battery Selection and Configuration

Table 3.3: Battery cell comparison.

Name	ENIX 26650	Nitecore NL 1834	RS PRO 2Ah LiPo	Samsung ICR18650-26F
Type	LiFePO4 Cell	Lithium-Ion 18650 Cell	LiPo pack	Lithium-Ion 18650 Cell
Price [euro]	15.99	Free (18 in market)	19,57	8.08
Nominal Voltage [V]	3.2	3.7	3.7	3.7
Capacity [Ah]	3.3	3.4	2	2.6
Energy [Wh]	10.56	12.58	7.4	9.62
Max. Instantaneous Power Delivery [W]	32	11.1	7.4	18.5
Weight [g]	80	55	40	47
Dimensions (LxW) [mm]	65.0x26.2	69.1x18.4	62x43	65x18.40
Cell Protection	Yes	Yes	Yes	No
Delivery Time [days]	1	None	1	1

Battery Selection: Nitecore

Within lithium-ion technology, there are various variants available. An overview of the cells available in the market is shown in Table 3.3. Based on this comparison a battery cell is selected. The selection of the battery is based on a trade-off of pros and cons for each battery variant with respect to the specifications as seen in Table 3.3. It should be noted that in fact all these options can satisfy the voltage demand, and the energy and maximum power demand of the Teddy through different battery configurations complying to the requirements NF.01.v01, F.01.v01, F.02.v03. Moreover, amongst the options, the dimensions do not deviate significantly and meet the size-related requirement (Requirement NF.03.v01). Therefore, the decisive factors are price, weight, pre-installed battery cell protection and delivery time. Consequently, the Nitecore battery was selected. The biggest reason for it is because one of the project partners (Laura) owns five of these cells making it free of charge, contributing to the budget requirement of NF.06.v02. This battery provides the best balance between price, available capacity, available energy and weight while also offering an integrated protection circuit which contributes to Requirement F.05.v01 and NF.02.v01 regarding safety and failure protection. A cell protection circuit protects the battery against overcharge and over-discharge voltage, over discharge current and shorting. Since this battery pack will be placed inside the Teddy, it will not cause any choking hazards, complying with Requirement NF.04.v01. Since this is a rechargeable battery, it will be fixed in the Teddy and not replaced during every charging session contributing to the safety.

Battery Configuration: Two Cells in Parallel

Connecting cells in series (S) results in an increase in the voltage rate, while keeping the same maximum discharge current. Connecting cells in parallel (P) results in an increased maximum discharge current while keeping the voltage rate the same. Looking back to Section 3.2.1, the maximum instantaneous power consumption is estimated at 16.6 W, which means that a cell of 3.7 V has to be able to deliver 4.49 A of current. Since one cell has a maximum discharge rate of 3 A, two cells have to be connected in parallel in order to achieve the threshold of 4.49 A. Moreover, the Teddy uses an average power of 1.35 W and a total amount of energy of 16.12 Wh in 12 hours. Since one cell can provide 3.4 Ah (12.58 Wh), at least two cells have to be placed in parallel in order to provide the necessary power and current specifications. An overview of the requirement and comparison between different battery configurations is shown in Table 3.4.

By placing one more cell in parallel, the discharge time increases by 9.27 hours and the discharge current increases by 3 A for the configuration. The configuration with 3 cells in parallel has a discharge time of 28 hours. When placing the cells in series and parallel, the configuration 2P2S is obtained as shown in Table 3.4. This configuration has the advantage of delivering less current at the same power rate compared to the 2P and 3P, due to the higher voltage level. This will result in a better battery lifetime, more efficiency and less stress. However, this configuration just like the 3P configuration has a larger weight than the 2p configuration. Since all of the three configurations comply to the requirements NF.01.v01, F.01.v01 and F.02.v03, the deciding factor is the weight requirement NF.02.v01. In order to save as much weight as possible, the configuration of 2P is chosen. This configuration is able to power up the Teddy over 18.63 hours and can also deliver a maximum current of 6 A (4.35 A maximum at 3.7 V). Furthermore, two of these batteries are easily fitted in the Teddy complying with Requirement NF.03.v01.

Table 3.4: An overview of the requirements in the Teddy and the capabilities of the selected battery with different configurations, whereby P stands for parallel and S stands for series.

	Requirements Teddy	2P 18650 Nitecore NL 1834	3P 18650 Nitecore NL 1834	2P2S 18650 Nitecore NL 1834
Maximum Instantaneous Power [W]	16.6	22.2	33.3	44.4
Maximum Discharge Current [A]	4.49 at 3.7 V 2.24 A at 7.4 V	6	9	6
Discharge Time With Average Power Consumption (1.35W) [h]	12	18.63	28	37.17
Total Energy Consumption/Usage (12 h) [Wh]	16.12	25.16	37.74	50.32
Voltage [V]	3.3 and 5.5	3.7 (Nominal)	3.7 (Nominal)	7.4 (Nominal)
Weight [g]	<600	110	165	220

Another advantage besides weight reduction of not using any cells in series is that when connecting two cells in series, cell balancing is required. Since no two cells are identical in practice and due to degradation, cells in series have to be balanced in voltage and state of charge (SOC) in order to maintain a healthy battery and avoid hazardous situations. This problem is bypassed by connecting the two cells in parallel since both cells will naturally balance when connected to each other. However, the battery voltage of 3.7 V still has to be matched for the different loads requiring 5 V or 3.3 V.

3.3. Charger Design

After selection of the battery type and configuration that is based on the expected maximum and average power demand from the loads inside the Teddy, the charger had to be designed. The functionality of the charger is to charge the battery when it needs to recharge. It also has additional functions to support the functionality and the implementation of the charging mechanism with the rest of the system. A set of activities was chronologically carried out to arrive at the design of the charger. Each phase of the sequence will be explained in the next subsections.

1. **Battery Charging Conditioning**: Pre-define the charging conditions and power ratings for the charger based on the battery type and configuration.
2. **Charging Technology Selection**: Select the charging technology to support the charging procedure of the battery.
3. **Battery Charger Module**: Select the physical charger module based on the charging technology.
4. **Charging Control**: Develop a method to control the charging in deployment, whereby a charging sequence is created to regulate the charging as well as the installed loads during charging.

3.3.1. Battery Charging Conditioning

The selected lithium-ion battery follows a charging procedure that is dependent on its configuration. An analysis on the procedure is relevant to understand the recommended charging conditions (e.g. Coulomb-rating and charging stages) for the battery as well as its power characteristics (e.g. charging current and voltage). Previously, it has been chosen to install 2 lithium-ion batteries in parallel, meaning that the process of charging fundamentally consists of two stages. A series configuration requires an additional management and cell balancing stage during charging, as explained previously, which is out of the scope for this design. The charging procedure for the chosen battery type and configurations consists of (1) constant-current (CC) charging and (2) constant-voltage (CV) charging. The battery itself has a specific charging procedure that is explained in its datasheet (Appendix K) with the required conditioning for one cell. Due to the parallel configuration, the conditions for the charging stages do not differ, however, the fully charged state is different: a higher cell capacity needs to be charged. Note that a parallel configuration of battery cells essentially forms one battery cell with the same nominal cell voltage of 3.7 V, but a larger capacity of 6.8 Ah.

Stage 1: CC charging

The battery package is subjected to a voltage, provided by the to-be-designed charger, that rises accordingly to ensure a constant current of 0.2 C. The voltage across the cell increases until 4.2 V, i.e. it reaches its full charge voltage. For this specific configuration of a (theoretical) rated capacity of 6.8 Ah, the value of the constant current is the rated capacity multiplied by the Coulomb rating of 0.2 C. Note that the charging in parallel is still based on separated cell charging. This means that the standard constant charge current is 3.4 Ah multiplied with 0.2 C that is 0.68 A. That gives a total of 1.36 A of charge current. This is the recommended charging current yet the maximum allowable value is 2A (per cell). In terms of a shorter charging time, the preferred charging current is therefore 2 A.

Stage 2: CV Charging

When the full charge voltage of 4.2 V is reached, the CV charging is initiated. The charging voltage is fixed whereby a deviation of ± 50 mV is allowed. In this stage, the current decreases to a termination-Coulomb rating of 0.05 C. As soon as each cell reached that termination rating, the battery is charged and thus the charging must stop.

In conclusion, the charger is rated with the following power specifications: a charger that is able to allow a maximum charging current of 2 A at the voltage of 4.2 V is recommended. In this way, it can charge the battery in its safe operating area.

3.3.2. Charging Technology Selection

The program of requirements was considered to narrow down the possible solutions for charging technologies, which was explained in the state-of-the-art analysis in Section 1.4. The most suitable charging technology for the selected battery was chosen after analysis on which technology satisfies the requirements. Since it is a priority to support the portability and the natural appearance of the Teddy (Requirement NF.01.v01), wired charging solutions were removed from the potential technologies for the Smart Teddy. Wired battery charging requires an intrusive cable network extending to the outside of the Teddy's exterior which is not desired. This would also conflict with the requirement for the Teddy to be non-intrusive and thus not robot-like (Requirement NF.05.v01). Charging with a power-bank is discarded due to the need for multiple parts (e.g. the charging cable, the power-bank case) and the necessity to perform prior charging of the power-bank itself. Eventually, these disadvantages will violate the appearance-related requirement (Requirement NF.05.v01) whereby the user will have to assemble the connection with the charger and the Teddy with a USB cable and the housing of the power-bank whenever charging is needed. Furthermore, the different parts of the power-bank can be considered a choking hazard that disobeys requirement (Requirement NF.04.v01). The overview of the charging technologies from Figure 1.2 is then reduced to a list of six options of wireless charging technologies. A comparison table shown in Table A.1 in Appendix A was constructed that showed the features, the level of design complexity and bottlenecks for each option. Moreover, the market availability and the costs per technology were assessed. High market availability and low costs are extremely desirable as to prototyping and the cost budget of the project. It should also be noted that for the popular charging technologies a global, interface standard exists such as Qi for inductive charging and AirFuel for magnetic resonance charging. Typically, these standards ensure that the market availability is higher than for other non-standard solutions. The information about these specific standards can be seen in Appendix A.

Each wireless technology is already satisfying the requirements which the discarded charging technologies did not. This holds for the requirements NF.01.v01, NF.05.v01, NF.04.v01. Therefore, this pre-selection is then assessed with a secondary filter on the functional requirements regarding the safety of the user (Requirement F.05.v01), the costs (Requirement NF.06.v02), market availability and the complexity of the design. The preferred selection is based on which technology shows the highest potential in satisfying the requirements and additional design considerations, which is presented in Table 3.5.

Table 3.5: Decision table for the wireless charging technology.

	Magnetic Induction	**Magnetic Resonance**	**Capacitive Charging**	**Microwave**	**Laser/IR**	**Radiowave**
Requirement ID						
F.05.v01	✓	✓	✓	✗	✗	✗
Design Features						
Costs	Low	High	Unknown	Very High	Very High	High
Market Availability	High	Medium	Extremely Low	Extremely Low	Extremely Low	Medium
Complexity	Low	Low	High	High	High	High

Table 3.5 shows that far-field charging technologies (microwave, IR and radiowave) will not satisfy the requirement related to the safety of the user which is not compliant with Requirement F.05.v01. Moreover, most of the far-field options require a government license to grant usage of a specific frequency band and therefore typically follows a complicated protocol to obtain the license and are cost-bound. It potentially accounts for a delay in the design process due to legislative approval procedures. For these reasons, the complexity of the design is high in comparison with the near-field options.
Eventually, from the three remaining (near-field) charging technologies, magnetic inductive charging was selected. It has a high market availability, ease of implementation and is characterized by its low costs. Additionally, this technology has the most efficient power transfer records of all options and the biological impact is extremely small.

3.3.3. Battery Charger Module

The design for the charger module is based on the design of the conventional inductive charging module. An inductive wireless charger typically includes three sub-blocks: (1) AC power supply, (2) receiver and transmitter coils, and (3) rectifying circuit. The receiver coil and the AC power supply will be placed in the Base Station, in other words, the primary side. This side outputs an AC power to induce a magnetic field with the complementary coil when placed in its proximity.

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The receiver coil and the rectifying circuit will be installed in the Teddy (the secondary side), which accounts for the conversion of the incoming AC current to a DC current to charge the lithium-ion batteries. A typical design of a wireless inductive charger is depicted in Figure 3.2.

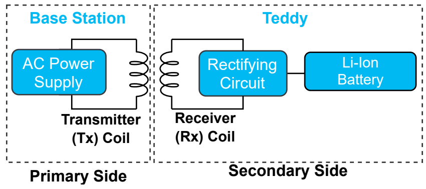


Figure 3.2: Typical design of a wireless inductive charger module for the charging of the battery inside the Teddy.

The power required for the charging is dependent on the charging requirements of the battery which was discussed earlier. Consequently, based on the chosen technology, a wireless charger module is selected by comparing the available market options.
Table 3.6 shows an overview of inductive charger modules that were considered. It should be noted that more options are available on the market with for example equal pricing or similar specifications. However, this table shows the final overview of options specifically for this application. The specifications analyzed are based on the battery's charging ratings (charging current and charging voltage) as well as the price and delivery time of the product. The wireless module from TinyTronics is selected because of the available power and supplier details regarding the delivery time and the price (Requirement NF.06.v02). Besides that after pre-filtering using the requirements NF.01.v01, NF.05.v01 and NF.04.v01, the charging is also compliant with Requirement F.01.v01 as the charger provides with the necessary charging ratings. However, the charger still must be tested for its safety (Requirement F.05.v01). As this wireless charging module can operate for different voltages, the 12 V input has been selected because at this voltage level the maximum output current can be drawn, namely 2 A.

Table 3.6: Possible wireless modules for inductive charging

	DC-DC Wireless Converter - 5V 2A	**Wireless Power 15 W Development Kit - Renesas Electronics**	**Module Inductive Charger Receiver + Transmitter**
Input voltage [V]	9 - 12	Adjustable	12
Maximum output current [A]	2	Adjustable	0.6
Output voltage [V]	5	Adjustable	5
Available power [W]	10	15	3.1
Supplier	TinyTronics	Würth Elektronik	Joom
Delivery Time	2 days	7 - 14 days	2 days
Price	€13	€90	€20

3.3.4. Charging Control and Charging Sequence

The process of charging the lithium-ion battery is executed in stages with specific conditions and bounds that must be regulated. Although the chosen batteries have a battery protective system to prevent failures such as overcharge, overcurrent, short circuit, it is also important to ensure that these stages are done securely. This will cause faster charging but also a healthier and longer battery life.

Charging Control

For the design of the charging control system, a charge controller was selected to ensure that the battery can be charged correctly. The charge controller satisfies the two-stage charging ratings of the selected lithium-ion battery as explained previously. Furthermore, a charge controller board was selected that is able to indicate that the battery is charging and the state of the battery (in compliance with Requirements F.04.v01 and F.03.v01, respectively). Based on these criteria, components were found on the market to realize this idea. There exist charge controller boards with charging algorithms integrated with an IC and electrical components. The charger boards have similar specifications and are from the same supplier (TinyTronics) with similar purchasing costs. The available market options only had charge controller boards that support a charging current of up to 1 A. This means that the charging time will increase but is not detrimental for the operation of battery charging. The selected board was the TP4056 Li-Ion Charger Control with a micro-USB port. The reason why this one was chosen is because it provides protection of the maximum discharge current and battery voltage, which is 3 A and 2.5 V respectively. Furthermore, it has built-in LED indicators of the status of the battery: (1) *charging* and (2) *charged*. The controller board is running on the TP4056 IC, like the other options found on the market and fundamentally requires the same electrical components. This IC controls the CC and CV charging of the battery and it provides a trickle charge threshold of 2.9 V meaning that a pre-indication is given to qualify and initiate charging. More information about the TP4056 IC can be found in Appendix K.

Charging Sequence

A charging sequence was designed to ensure that the charge controller board, the battery and the loads are properly managed during charging. The charge sequence contains the following stages:

1. **Charge Qualification:** The battery needs to be charged, because the battery voltage has reached its discharge cut-off voltage of 2.8 V. However, according to the datasheet of the battery (Appendix K), it is recommended to initiate charging at a higher voltage to avoid slow responses that would lead to complete exhaustion of the battery. The user will be provided with a signal to charge the battery inside the Teddy.
2. **Load Separation:** The loads need to be separated from the battery prior to battery charging because they cannot be connected to the battery when the battery is charging[1]. The reason is because of the necessity to comply with the requirement about charging indications and status (Requirement F.03.v01 and F.04.v01).
3. **Charging**: The Teddy is placed on the Base Station to initiate the charging via wireless power charger using the inductive charging module. The battery is charging according to its recommended charging procedure. The user will be notified by means of a signal that the Teddy is charging. This is based on the charge controller board that is overseeing the actual charging of the battery when the previous stages have been executed.
4. **Charge Termination:** The user will receive a signal that the battery is charged. The charging of the battery needs to be terminated which can be done by removing the Teddy from the Base Station.
5. **Load Reconnection:** The load can be reconnected to the battery and afterward the battery can discharge.

Charge Qualification

Based on Requirement NF.05.v01, no led-lights are desired by the client. The led-lights of the charging board can therefore not be used in order to indicate the state of the battery. The Teddy will whine instead, when the voltage of the battery drops below a certain level indicating that it has to be charged, complying with Requirement F.03.v01. The Power Operations and Distribution group will forward the voltage level of the battery to the Raspberry Pi Pico, whereby the Human Interaction and Integration group uses this information to design the necessary coding for the whining. The Raspberry Pi has an integrated 16-bit analog-to-digital converter that can measure an analog voltage level at its pin and convert it to a digital signal. The voltage of the battery can be sent to the Raspberry in many different configurations using the LM358 operational amplifier. However, due to the time limit faced during the end of the project, a much simpler voltage divider is opted for. Since the pins of the Raspberry can maximally allow a voltage of 3.3 V, the voltage divider will output a fraction of the input voltage of the battery such that the maximum level does not exceed 3.3 V. The maximum voltage level of the battery is 4.2 V, but a voltage of 5.5 V is matched to the maximum 3.3 V in order to ensure that the input at the Raspberry does not exceed this maximum value of 3.3 V. This results in a division ratio of 0.66. Taking a higher voltage than 4.2 V ensures room for errors and deviations from the maximum value.

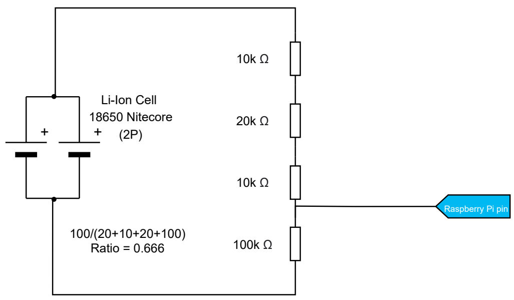


Figure 3.3: The design of the voltage divider used in the Teddy.

Based on the available resistors, the following design shown in Figure 3.3 is opted for. Resistor values in the range of tens of k are chosen, in order to have small currents in the divider. This ensures low power usage and protects the Raspberry Pi from high currents. Moreover, in reality, the resistors are subjected to resistor tolerances of approximately 1%. The Human Interaction and Integration group applied different voltages to the divider and calculated the ratio. Afterwards the code in the Raspberry is fine-tuned in order to reduce the error margin. Due to the characteristics of lithium-ion batteries, whereby below 3.3 V the voltage drops rapidly, a threshold of 3.0 V is opted for. This does not contradict with the discharge cut-off voltage of the battery of 2.8 V. In fact, as specified earlier, it is recommended to not allow the battery voltage to reach this discharge voltage since that could affect the battery's lifetime. So, when the battery has decreased to this threshold voltage of 3 V, the Teddy will go into a power-save mode (controlled by the other sub-group) and indicate with sound to the user that it has to be charged.

3.4. Power Conversion and Distribution Design

The Teddy and Base Station have electric components that operate at different voltages. This requires among other things power converters. In the Base Station, it is also necessary to convert the power coming from the socket to these voltages requiring multiple converters. In this section, the design of this is discussed.

3.4.1. Teddy Power Conversion and Distribution

The Teddy operates at two different voltages as stated before (3.3 V and 5 V). Even though all of the components operating at 3.3 V can be supplied from the Raspberry due to low power consumption, the 5V components need power supply directly

[1] This is due to the principle that a battery cannot discharge while charging and vice versa due to one-way current.

from the battery. Since the battery has a nominal voltage of 3.7 V, a step-up converter is required that outputs a steady 5V voltage, while being able to withstand the maximum power transfer of 16.6 W. This means the converter must allow 3.3 A at the output of the converter. An overview of the different converter options available in the market is shown in Table 3.7.

Table 3.7: Comparison table of different step-up dc-dc converters available in the market.

Name	MT3608 2A	XL6019 5A (new-variant)	QSKJ DC-DC 5V	QSKJ DC-DC 150W
Type	Non-Isolated	Non-Isolated	Non-Isolated	Non-Isolated
Input Voltage Range [V]	2-24	3.3-35	3-5	10-32
Output Voltage Range [V]	5-28	5-40	5	12-35
Max. Ouput Current [A]	2	5	3	10
Max. Efficiency [%]	96	94	92	94
Price [euro]	2	6.99	6	6
Weight [g]	4.4	15	10	60
Delivery Time [days]	1	14-30	1	1

For circuits that require low noise, Isolated converters are preferred. Non-isolated converters are only compared since this is not necessary, but also because the majority of the converters available in the market were non-isolated ones. The QSKJ 150 W variant is the converter with the highest current output in Table 3.7. This means that only one of this converter is required to power all the components. The maximum current-to-price ratio is also the best amongst these options. However, this converter is relatively heavy and does not support the voltage of the battery (3.7 V nominal). The XL6019 converter also has a higher output current than required, which means that also only one converter can be used to power up the whole Teddy. This will make the circuit simpler. The price point will also stay reasonable this way. However, due to its long delivery time, it could not be used for this project. The QSKJ DC-DC 5V converter has a maximum output current of 3 A, requiring two of these converters for the Teddy. This is in itself not a problem, however, the price will be than €12 whereas the MT3608 converter can deliver the same amount of current for €4 (two needed) with approximately the same maximum efficiency (two chosen so 0.96*0.96 = 92%) and lighter total weight, contributing to the requirements NF.02.v01 and NF.06.V02. The MT3608 is also the only converter in this table that can work in the whole voltage range of the battery. This means that only with this converter, the full available capacity of the battery can be used. This results in choosing two MT3608 converters for the Teddy. This converter can deliver more than the maximum required current of 3.3 A while boosting the voltage up to 5 V complying with Requirement F.01.v01 and NF.01.v01. Since the size of these converters is very small relative to the size of the Teddy, it consequently complies with the Requirement NF.03.v01.

3.4.2. Base Station Power Conversion and Distribution

In this section, the component selection for the Base Station will be discussed. The components needed for power conversion in the Teddy will also be discussed.

Power Budget Base Station

Even though there is no battery in the Base Station, it is still necessary to have a power budget in order to ensure that the AC/DC converter can deliver the power flow. However, the usage time will not be necessary anymore, and only the power, voltage and currents are stated as shown in Appendix D. The final values are shown in Table 3.8. The Base Station uses an average power of 24 W and a maximum power of 26.9 W when all components are running. This power has to be able to be delivered when selecting components.

Table 3.8: Power usage in the Base Station.

Average Power Usage [W]	**Maximum Power Usage [W]**	**Operating Voltages Of Components [V]**
24	26.9	3.3, 5 and 12

Here, a loss of 70% is also taken into account when calculating the total power ratings. Just like the power budget of the Teddy, this value is taken in order to account for margins and errors later in the design. Furthermore, the assumption that a loss of approximately 50% will take place in the wireless power charger is taken for the calculations. This value is lower since wireless power transfer does not have high efficiency values. This value is estimated and the legitimacy is verified by the power department of TU Delft during a short meeting.

AC/DC Converter

For the Base Station, the net power will be used to provide power to the loads, whereby an AC/DC converter will be used to convert 230 V AC to a steady DC voltage. Selecting an AC/DC converter that directly matches one of the two operating voltages in the Base Station (5 V and 12 V) shown, leads to a reduction of components used in the system and of power losses on load paths. Since the wireless power charger uses most of the power compared to the other components in the Base Station, and the fact that wireless power transfer has typically a low transfer efficiency, a 12 V output for the AC/DC converter is chosen. Various 12 V converter options available in the market are shown in Table 3.9.

Table 3.9: Comparison table of different 230V AC to 12V DC converters available in the market

Name	RS PRO 60W Adapter	Mean Well IRM-60-12ST	TDK-Lambda ZPSA60-12	SolaHD SilverLine
Power [W]	60	60	60	72
Max.Efficiency [%]	88	87.5	87	50
Type	Switched Mode Power Supply	Switched Mode Power Supply	Switched Mode Power Supply	Linear Mode Power Supply
Connection Type	Centre Positive Jack	Screw Terminal	Solder Points	Screw Terminal
Weight [g]	280	270	130	3400
Size LxWxH [mm]	117x51x33.5	109x52x33.5	101.6x50.8x27.10	229x70x124
Price [euro]	21.51	18.03	53.46	342.76
Delivery Time [days]	1	1	2-3	30-40

In order to support the maximum power rating of 26.9 W, while also taking into account the calculation errors and the possibility to change or add new components into the system, converters of around 60 W are compared. The SolaHD SilverLine converter has a price tag that is too expensive for this project according to Requirement NF.06.v02. This converter is a linear mode power supply type, which is ideal for low noise applications. They have excellent regulation and low ripple but a high price tag. They weigh heavy and are bigger in size. Furthermore, they have a low efficiency compared to Switched Mode Power Supplies. Besides, the delivery time of 30 to 40 days is also a big factor to not choose this converter, since it will be too late to integrate this converter in the final system before the final examination. The TDK-Lambda is just like the other two converters a Switched Mode Power Supply type, whereby the difference is that it can deliver the same amount of power with similar specifications, with half the weight of the competitors. However, this also comes with a high price tag, of almost 50% of the budget, resulting in not choosing this converter. The Mean Well and RS PRO converter do have very similar specifications in terms of efficiency, price, weight and size. However, the RS PRO converter comes with a Centre positive Jack whereby the Mean Well converter comes with a Screw terminal connection type. Since the Screw Terminal connection enables an easier integration by not requiring a port and a soldering board, this type is preferred. The Mean Well converter has also the best price-to-power ratio of all the converters. Overall, this converter can support the required average and maximum power of 26.9 W and is within the budget, complying with requirements F.01.v01 and NF.06.v02.

DC/DC Converter

The 12 V output from the AC/DC converter is sufficient for the wireless power charger that operates at 12 V, but not for the other components in the Base Station which work on 5 V. This requires a step-down DC/DC converter that converts the 12 V output from the AC/DC converter to a steady 5V input voltage. This converter should be able to output the maximum drawn current from the components in the Base Station (excluding the wireless power charger), which equals at 5 V: 2.5 A. The comparison of the different step-down converters is shown in Table 3.10.

The maximum output current of the Mean Well converter is more than enough with 6 A, making it possible to add more devices if necessary later. However, with a price of €15.36, it does not make the best option compared to the other much cheaper components in the table. The LM2596 converter delivers a decent current that can deliver the maximum output current of 2.5 A, with a 92% efficiency at a price of €3.50. The DC-STEPDOWN 5V-1.5A converter looks the cheapest of all three while delivering the second-highest efficiency in the table for a price of €2.50. However, due to the maximum output current being limited to 1.5 A, two converters have to be used in the design to be able to deliver the maximum current, making it in total €5 resulting in not being the cheapest option anymore. This will also result in a more complex system and losses which is not desired. The MINI 560 is the best option in the table. With its maximum output current of 5 A, its highest maximum efficiency and the price of €3, the MINI 560 would be the best choice in this table. However, due to the long delivery time of this component, it could not be used in the project and the decision is to use the second-best option which is the LM2596 converter. Overall, this converter can deliver the required power and current specifications, while also fitting into the budget, complying with requirements F.01.v01and NF.06.v02. It should be stated that since all of these components are based in the Base Station, they do not form any choking hazard for the user, complying with Requirement NF.04.v01. The same applies to the Teddy.

Table 3.10: Comparison table of different step-down dc-dc converters available in the market

Name	Mean Well PSD 45	LM2596 converter	DC-STEPDOWN 5V-1.5A	MINI 560
Type	Isolated	Non-Isolated	Non-Isolated	Non-Isolated
Input Voltage Range [V]	9.2-18	4-40	7-26	7-20
Output Voltage Range [V]	4.9-5.1	1.25-30	5	4.75-5.15
Max. Ouput Current (at 5V) [A]	6	3	1.5	5
Max. Efficiency [%]	74	92	96	98
Price [euro]	15.36	3.50	2.50	3
Delivery Time [days]	1	1	1	14-30

3.5. Safety and Failure Protection Design

The safety of the system is an important part and requires a design for safety methodology. This is done by defining what the point of failures are of the power system and determining what preventive measures can be taken in the design to ensure safety. The design of the system will be assessed after implementation on the possible point of failures and their locations in the system. Safety protection is essentially a pre-implementation analysis of faults in the electric system that could have detrimental consequences on the functionality of the sub-modules of the power system. Ultimately, it affects the other subgroups and their operation. Hence, an fault analysis was carried out for each design stage in the sequence.

3.5.1. Preventive Safety Measures: Battery

The battery can charge and discharge, which has to be done safely in order to prevent explosion and/or fire. Lithium-ion batteries are especially very sensitive to overcharge and over-discharge. The protection circuit that comes with the cells is largely accounting for several points of failure, such as the overcharge, over-discharge and short circuit. Therefore, this circuit can be regarded as a preventive safety measure for the battery. Furthermore, between the battery and the rest of the components (loads and charging system), a charge controller board is located. This board ensures the correct charging of the battery for a safer and longer battery lifespan. It also ensures that the charging and discharging of the battery are within its safe operating area, which accounts for an extra layer of protection besides the integrated protection circuit. Hence, the chosen battery charge controller board (TP4056 Li-Ion Charger Control) is a preventive safety measure.

3.5.2. Preventive Safety Measures: Charging

The coils of the charger must be aligned in such a way that it does not interfere with the other high-frequency components such as the mmWave sensor and the antenna for wireless communication. So, by examining the line-of-sights of these modules and their operating frequencies, the following preventive measures were taken to guarantee safe execution of their assigned tasks: (1) each of the three operate at different frequencies hence the EMI (electromagnetic interference) is already small. However, (2) the mmWave Sensor has a line-of-sight of 110° where no metal objects can be placed and thus no electrical components will be placed within this region. Then, (3) the litz-wired[2] coils are extremely sensitive for alignment. To ensure a fixed alignment, a supportive arrangement of neodymium magnets (the strongest permanent magnets on Earth) will be placed around the coils. The configuration is similar to magnetic alignment used in wireless phone chargers. Furthermore, to ensure that the user is not directly in contact with the coil, a fabric (namely mesh) is covering the coils. The test on the fabric can be found in Appendix G.2.

[2] Litz wire is a multistrand wire that carries high frequency signals configured in such a way that it reduces AC losses.

3.5.3. Preventive Safety Measures: Power Conversion and Distribution

All of the conversion modules, charger and Raspberry Pi's, have some sort of overcurrent or overvoltage protection either at the input or output, to protect from overload or short circuits. However, in order to have a system that is completely safe from it, protection against overloads and shorts is necessary at places in the circuit where this protection is on default not present. This can be done by using fuses to break the load path whenever one of the two fault events occurs. This will cause a local shut down of a load path for a short amount of time (less than milliseconds). It is chosen to place fuses that are re-usable (PPTC) and reinforce a local or full system restart without replacement or rehabilitation. This is in compliance with Requirement F.05.v01. Furthermore, these conversion modules are directly connected to the loads via wires in the Base Station and with a PCB in the Teddy. Hence, secure fastening of the cables is required. Lastly, the Base Station is connected to the net for which, according to the standardized electrical wiring guideline for Europe (IEC 60364), the user must be protected from direct contact to the net and against electrical shocks. That is why a manual switch will be placed in the power cable connecting the Base Station to the net. Furthermore, the stripped power wires will be isolated using heat shrink tubes or electrical tape to prevent exposure to running current.

4

Implementation and Verification

This chapter describes the implementation and the verification of the Power Operations and Distribution. It elaborates on how the design for the different sub-modules (battery, charging, power operations and distribution, and safety and failure protection) were put into effect. The implementation and the followed procedures of each of these sub-modules will be explained in Section 4.1. Then, Section 4.2 describes the verification of the design of the Power Operations and Distribution with the program of requirements and the corresponding verification methods. The results from verification will be presented and the achievement of requirements will be assessed.

4.1. System Implementation: Battery, Charger and Power Converters

Figure 4.1 shows an extensive overview of the system's implementation whereby the connection of the modules and loads are presented. It is to understand how the various electrical parts of the designed sub-modules are connected to each other and how the loads are distributed in the power sharing.

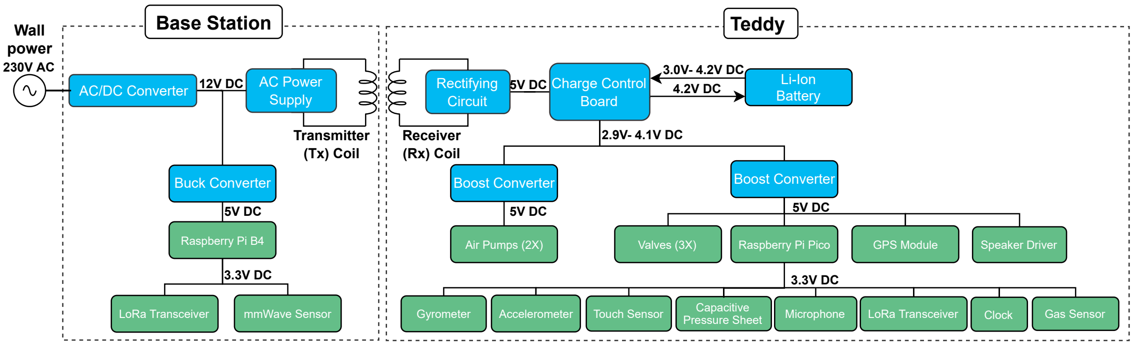


Figure 4.1: General overview of the Power Operations and Distribution implementation whereby all installed loads of the Smart Teddy are listed. The loads are given in green.

The battery is the lead of the power system and is supplying the power to the loads within the Teddy. The lithium-ion battery is connected to the control board with the TP4056 IC to control the charging.
The loads in the Teddy are preceded by two boost converters. The boost converters are necessary to ensure that the voltage coming from the battery (between 3.0 V and 4.2 V whereby 3.7 V is the nominal voltage) needs to be boosted to the 5 V needed by these loads. One boost converter is feeding the air pumps to support the deflation and inflation of the lungs of the Teddy. The other one is supplying power to feed the valves, the GPS module, the Raspberry Pi Pico and speaker driver. The reason for this split is because of the speaker driver and GPS module being in idle mode with a very little current draw (see Appendix C). The air pumps, however, are the most power consuming elements with a total operating current of 1 A (see Appendix C). The Teddy has several low power loads (in the range of 1 to 7 mA each) that operate at 3.3 V which are considered secondary loads. The Raspberry Pi Pico is able to provide an output current of 300 mA at 3.3 V which is why these secondary loads are fed by the microcontroller. It should be noted that the clock was not considered in the power budget as it was added to the loads set at a later stage. However, it does not have any detrimental effects on the total power consumption of Teddy as the current draw is 200 A and operates at 3.3 V. It is therefore considered secondary load and thus connected to the Raspberry Pi Pico power output pins. Figure 4.3b shows the output ports of the boost converters that will be connected to the loads of the other subgroups which will be integrated with the other subgroups in the prototype assembly (Chapter 5).
The charger is the wireless charger module consisting of the AC power supply

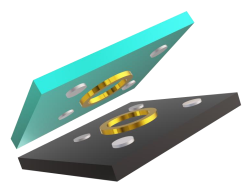
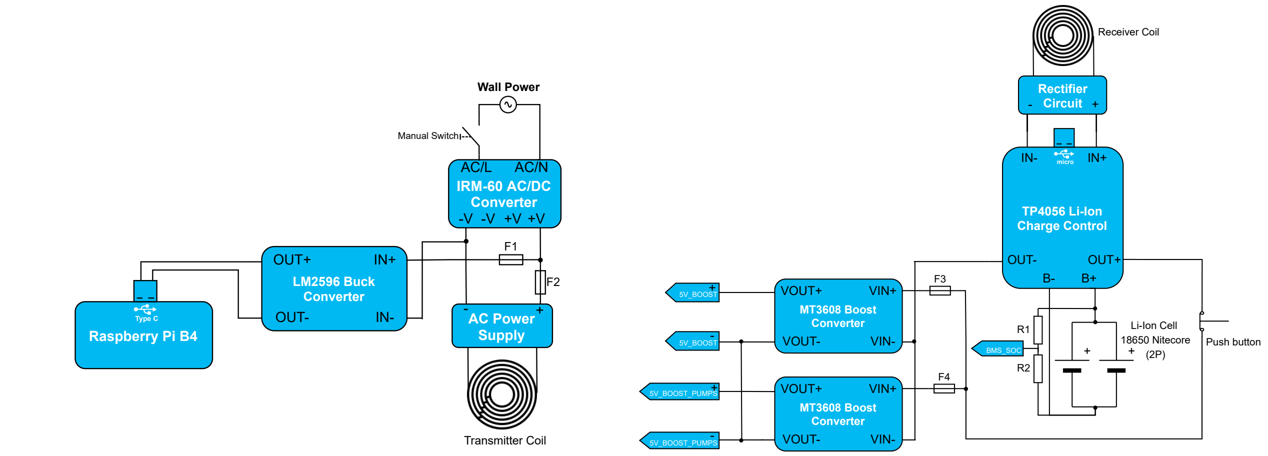


Figure 4.2: Neodymium magnets placements around the coil for alignment. This will be done for both the transmitting (in black) and receiving (in green) coils.

(Base Station), the transmitter coil (Base Station), the receiver coil (Teddy) and the rectifying circuit (Teddy). The implementation of these parts is essentially connecting the corresponding elements using wires (stranded conductors) to constitute the transmitting part in the Base Station and the receiving part in the Teddy. In order to account for the potential alignment issues, four neodymium magnets will be placed around the coils using a "holder" to ensure that proper alignment is done (see Figure 4.2). In this way the alignment issues can be solved and later into the prototype chapter (Chapter 5), it is explained how these implemented magnets and coils are integrated in the prototype. The receiving part of the wireless charger module is connected to the charge controller board to ensure that the charging is controlled by the charging algorithm for a lithium-ion battery integrated into the IC of that board. As seen in Figure 4.1, the charging control board is a central unit with connector pins for the battery and the receiving charger part. These connectors are secured with the use of wires.

The Base Station contains the AC/DC converter that converts the net voltage from 230 V AC to 12 V as specified by the selected converter type. This is eventually connected to the AC Power supply with wires as well as to the buck converter that steps down the voltage to 5 V to supply power to the Raspberry Pi B4. The implementation of the modules can be seen in Figure 4.3a. F1,F2,F3 and F4 are the fuses installed.



(a) Implementation of the AC/DC converter, Buck Converter and Charger for Power Distribution and Generation, and Charging sub-module

(b) Implementation of the Battery, Charger and Boost Converters, including ports to the clustering PCB of Human Interaction and Integration.

Figure 4.3: Teddy and Base Station implementation diagrams

4.1.1. Safety and Protection Implementation

In the design chapter, it is highlighted that secure fastening of the wires is important. For the implementation of the submodules in the Teddy and the Base Station, it is opted for thicker wires to have a lower resistance in the wire to increases cross-sectional area for charge to flow. The length of cables is reduced to the least amount to reduce the resistance even further. This is applicable to all connections within the Power System. Moreover, to account for the spacing between modules and distance for the current to flow which adds to cable losses, the modules were placed in such a way that the distance is reduced and the total cable length (thus the losses) are reduced. To follow the guidelines on the safety and failure protection, an AC switch is implemented in the wiring of the AC/L wire. Hence, the switch must be switched on to supply power and to do the operations. A switch is placed in between to disconnect the loads whenever charging of the battery is needed. Lastly, fuses are places on the load paths where considered to have potential short circuits as part of preventive measure. This can be seen in Figure 4.3

4.1.2. Charging Sequence Implementation

The charging sequence has five stages of which their implementation will be explained below.

Stage 1: Charge Qualification

Based on the threshold voltage for discharge cut-off of the battery, the charge qualification can be determined. The charge controller board can sense when the battery is charging, yet it cannot sense when the battery has reached its discharge cut-off voltage and thus requires charging. Therefore, the voltage across the battery will be measured and its level will be compared with the pre-set threshold voltage with the Raspberry Pi Pico. By means of a voltage divider, the battery voltage is brought to its equivalent value within the range from 0 V to 3.3V. The Raspberry Pi Pico namely cannot receive voltage exceeding 3.3 V and since the battery can have a voltage up to 4.2 V, the voltage divider is sending a fraction of the actual, analog signal from the battery which the Raspberry Pi Pico can manage. The Human Integration and Interaction group has set the equivalent discharge cut-off voltage to 3 V. So, in the event the equivalent battery voltage reaches this threshold, the dog will send a signal in the form of a weeping sound to indicate that charging is required.

Stage 2: Load Separation and Stage 3: Charging
Prior to charge initiation, the load needs to be separated so that all charging current can be used for the battery and not for powering the loads. Moreover, this is to avoid conflicting current flows from the battery to the loads. There are two options: (1) a switch needs to be implemented to disconnect the loads from the controller board so that no current can flow and all charging current can be used for the charging of the battery (2) two switches are implemented of which one is connecting the loads directly to the charger when battery charging and the other is disconnecting the loads from the board. In both cases, to actually charge the battery, the receiving coil must be placed on the transmitting coil. So, when the user knows to charge the battery (the weeping sound of the dog), it is expected from the user to place the Teddy (with the receiving coil) on the Base Station (with the transmitting coil). Eventually, the first option is chosen as this reduces the complexity of the implementation. Furthermore, the latter requires discrete logic algorithm to ensure that the closing and opening of switches are done properly. The first option is implemented by means of a switch (a push button) that will be placed inside the Teddy so that whenever the Teddy cries, the user can press the button to disconnect the loads and subsequently charge the battery.

Stage 4: Charge Termination and Stage 5: Load Reconnection
Charge termination involves the signaling of when the battery is charged and thus it can start discharging. For the chosen controller board, the termination is indicated by turning on a LED to say that the *battery is charged*. This can be derived from the charge controller board as this has a LED that can say when the battery is charged. The same switch to disconnect the loads can be used to reconnect the loads to the battery. Consequently, the battery can discharge again. An additional feature in compliance with Requirement F.03.v01 is that the Teddy makes a barking sound when the load is reconnected again to indicate that the Teddy is (sufficiently) charged as well as that the Teddy is in operation.

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4.2. Verification
Since the Teddy uses two Li-ion batteries in order to power all the components in it, no external power sources are used that limits the portability of it, satisfying Requirement NF.01.v01. An overview of the total amount of weight of these components (including the battery), used by the Power Operations and Distribution in the Teddy is shown in Appendix F.1. With 183 g, the weight is well below the Requirement NF.02.v02 of a maximum of 600 g. Upon inspection, the power system is well within the dimensions of the Teddy. The total area of the power system is within 100 mm by 50 mm. It covers such a small portion of the available area that it has no influence on the other subgroups, complying with Requirement NF.03.v01. Since all the components of the Teddy as well as the Base Station will be integrated into its casings, no loose components are exposed causing possible choking hazards. This integration is done in cooperation with the Human Interaction and Integration subgroup. The choice to use a wireless charging solution also contributed to this. Moreover, the pads of the charging system integrated into the Base Station and Teddy are fixed in place. In Chapter 5, the picture of the Teddy and Base Station prototype is shown, displaying that it contains no choking hazard, complying with Requirement NF.04.v01. The use of a wireless power charger, a Base Station in form of a dog bed and a Teddy that has no exposed cable or electronics whatsoever ultimately contributes to making the Smart Teddy non-intrusive, complying with Requirement NF.05.v01. The only cable that is noticeable is the one going to the socket from the Base Station. Since this cable is in the back of the Base Station, it does not affect its appearance. Regarding the costs made by the Power Operations and Distribution subgroup, a total overview including every component that has been bought is given in Appendix E. The amount spent is in total €120,82 and therefore, requirement NF.06.v02 that the budget must not exceed €130 is satisfied. Note that these costs include all the costs made and not limited to the components used in the prototype since this was the requirement. The costs of the components used in the prototype are shown in Appendix E.

4.2.1. Charging
For the charging system, three different tests are set up, explained in detail in Appendix G: (1) maximum power transfer of wireless power transfer; (2) test of wireless power transfer with fabric as a medium and (3) battery charging with charging board and voltage divider test. From the first test, a maximum power of 15.7 W is realised at the output of the charger with an efficiency of 62.6%, validating the minimum efficiency of 50% taken in the Chapter 3. The second test is meant for a verification of which kind of fabric is better suited, as a cover for the charging pads. From the test, it became clear that a mesh fabric between the coils causes much less losses than a stretch tule. This information is forwarded to the Human Interaction and Integration subgroup, who will design the casing of the Teddy and its components. The final test resulted in a verification that the battery can be charged via the wireless power charger and charging controller board, according to the two stages, as stated in Chapter 3, including overcharge and current protection. The charging board itself indicates when the battery is charging but also when it is fully charged. Moreover, the voltage divider is able to divide the voltages and presents it to the Raspberry Pi Pico, with an accuracy of 1%. This test result is verifying Requirement F.03.V01. The LED is unfortunately not visible in order to comply with Requirement NF.05.v01, consequently failing Requirement F.04.V01.

4.2.2. Base Station

For the Base Station, one test set up is constructed and used that includes all components and loads of the Base Station installed in it. The purpose of this test is to test if the power system in the Base Station can power all the components but also if the predictions about the maximum power usage are accurate. A test code was written for the Raspberry, in order to mimic a heavy usage scenario. An elaborate explanation of this test is shown in Appendix H. During the test, the correct working of all components is verified. One small issue that occurred was a low power supply voltage warning from the Raspberry due to a voltage drop when connecting a load to it. This is fixed by slightly increasing the output voltage of the converter that goes into the Raspberry. The total power consumption of all the loads (charger and Raspberry Pi with mmWave sensor and LoRa) is measured and equals 19.2 W. Compared to the estimated 26.9 W shown in Appendix D, this is well within the limits of the components chosen from it, causing no further problems. The difference of 7.7 W is because in the estimation conversion losses for the charger were also taken into account, while in the test, the charger is directly connected to the 12 V output of the AC/DC converter. This is a conscious choice which led to an efficiency improvement of the system, as expected and explained in the choice of the AC/DC converter in Chapter 3.

4.2.3. Teddy

The Teddy's power supply verification is done by measuring the power consumption with voltmeters and amp-meters and calculating the average and maximum power consumption with use case scenarios. The use case scenario is a prediction of the deployment of the product that says something about the power consumption for the assumed use case of the Smart Teddy as well as the duration and the battery life. This analysis is solely focused on the Teddy's actions and the battery energy capacity. Therefore, this is primarily relevant to verify whether the power system complies with Requirement F.02.v03 regarding the battery life of at least 12 hours. The user can touch (i.e pet) the Teddy after which the Teddy executes a sequence of movements, namely tail wagging and breathing with its lungs. Together with the Human Interaction and Integration group, a sequence was defined, consisting of the following movements executed by pumps and valves with specific time lengths: tail inflates (3.5 s), tail deflates (3 s), breathing in (8 s), breathing out (8 s) and idle. The breathing requires two valves and one pump. Tail wagging requires one valve and one pump[1]. A full sequence can be seen in Figure 4.4 that has a duration of 61 seconds. During a movement, the pumps and/or valves are operating or idle. Each movement has a specific power rating that is multiplied by its duration to calculate the energy. This is also done for the Raspberry Pi Pico[2] and GPS module that are in operation during the sequence of 61 seconds. The energy required is then compared with the available energy capacity of the battery (25.16 Wh). Two use-case scenarios are analyzed as they are considered to be most relevant. It should be noted that the use-case may vary between persons and may alternate per day for the same user.

1. Maximum use case scenario: The user is extensively petting the Teddy. The total power consumption is calculated consisting of all electronic components of the Teddy. Then, the corresponding discharge time of the battery is found. This is an exhausting situation for the pumps and therefore not recommended for the Smart Teddy to retain the state of the electronics. The battery will discharge in 7 hours for this maximum usage.
2. Average use case scenario: The user is stroking the Teddy for a maximum number of 30 times which may be spread over a course of a 12-hour time frame (as specified in Requirement F.02.v03). Its total power consumption will be calculated and subtracted from the available energy capacity of the battery. Then, the remaining energy in the battery will be evaluated over the remaining time of 11.5 h to see whether the battery has enough capacity to execute other operations (idle modes, GPS' acquisition mode when the senior is outside[3] and weeping for low-battery signaling using the speaker). In this scenario, the Teddy can continue to operate for at least 11.5 hours.

The maximum power consumption of the Teddy is 7.11 W, where the highest power consumption for each module (breathing, GPS, Raspberry Pi Pico including the secondary loads and speaker module) is selected. This applies to both use case scenarios as it is an instantaneous maximum power consumption. The table, Table I.2 in Appendix I shows the overview of how the value for the maximum power consumption is calculated. This value is less than half the predicted maximum power (16.6 W). In the power budget (Section 3.2) a correction factor of 70% was used to account for potential losses in cable and transmission, so the actual predicted value was 11.6 W. Hence, it can be concluded that these losses impact the power transfer very little.

In conclusion, the Teddy is able to comply with the power requirements as specified in Requirement NF.01.v01. Furthermore, the battery being able to power the loads in Teddy for at least 12 hours, in an average usecase scenario, that complies with Requirement F.02.v03.

[1] Power to the pumps are fed by one boost converter whereas the Raspberry Pi Pico, GPS and valves (and the speaker driven) are fed through the other boost converter. See Figure 4.1

[2] The Raspberry Pi Pico and the secondary loads connected to it, are assumed to be operating at their maximum power, because its power consumption has not been measured.

[3] When the Teddy is more than 500 meters away from the Base Station, the GPS will advance to acquisition mode with a higher power consumption.

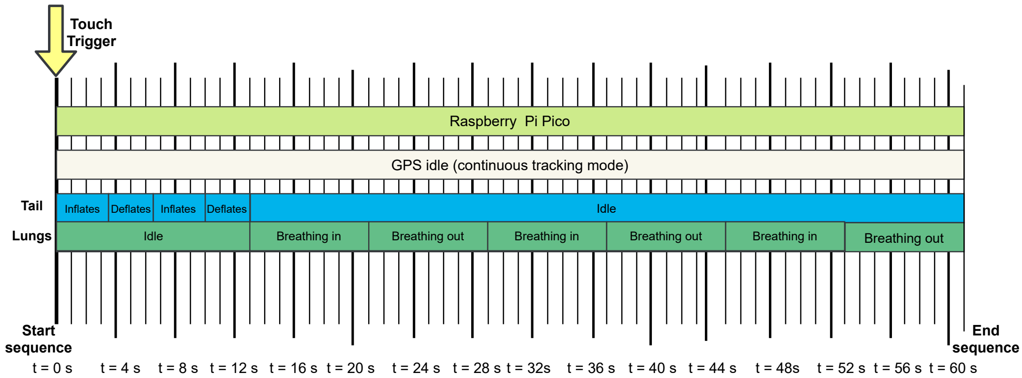


Figure 4.4: Timeline of one sequence of 61 s (two times tail wagging followed by 3 times breathing) and idle. The touch sensor is triggered at time t= 0s.

Table 4.1 shows a table of the verification of the program of requirements, whereby the verification methods or procedures for each requirements and the results are summarized. Thereafter, the verification is graded with a pass or fail as to complying with the requirements.

Table 4.1: Table of the program of requirements containing the verification methodologies or procedures with the results after which a pass or fail is given. The non-functional and functional requirements are labeled as NF.XX.vXX and F.XX.vXX, respectively. Their version is indicated with .vXX.

ID	**Verification Method**	**Methodology or Procedure**	**Results**	**Pass or Fail**
NF.01.v01	Demonstration	A demonstration that the electronics are fed by the lithium-ion batteries only.	The Teddy's power supply is solely coming from mount-in lithium-ion batteries.	Pass
NF.02.v01	Demonstration	The complete power system of the Teddy (excluding the loads) have been weighed.	The weight of the Teddy is 183 g.	Pass
NF.03.v01	Inspection	The electronics are measured with a ruler.	Electronics do not exceed the dimensions.	Pass
NF.04.v01	Inspection	Inspect that the electronics are housed.	In the Teddy, all electronics are in the interior. In the Base Station, all electronics are in the casing except for the power cable.	Pass
NF.05.v01	Inspection	Inspection of the appearance of the Teddy.	No cables or ports are protruding except for the power plug, which is hidden. No LEDs are implemented in Teddy's exterior.	Pass
NF.06.v02	Analysis	Check if the manufacturing cost does not exceed the limit	Total costs were €120,82 .	Pass
F.01.v01	Test	Based on measurements findings (voltage and current) the power specifications are tested during operation.	The system is able to deliver power to all installed electronics in the Smart Teddy.	Pass
F.02.v03	Test	A simulation of use case scenarios in combination with test results render conclusions.	The Teddy can be powered for at least 12 hours based on a use case scenario.	Pass
F.03.v01	Demonstration	The Teddy is tested in a simulation of low battery voltage using Raspberry Pi Pico from HII.	Raspberry Pi Pico indicates a low voltage at a battery voltage of 3 V after which a signal is sent to user to charge (Teddy weeping).	Pass
F.04.v01	Demonstration	During the test an indication of charging and battery's state is given.	During charging the battery controller board turns on a LED, but that is not visible to the user. The battery cannot show its state of charge.	Fail
F.05.v01	Analysis	The system is analysed on its load paths, possible faults locations and preventive measures.	The system has a safety mechanism with fuses, switches and preventive measures, but was not fully tested and assembled.	Fail

5 Prototype

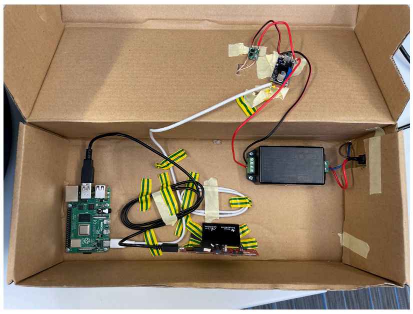
This chapter presents how the Power Operations and Distribution is integrated with the other subsystems to constitute the physical prototype of the Smart Teddy. The focus lies on spatial and real integration and assembly of the Power Operations and Distribution with the other two subsystems in the prototype. Firstly, the Base Station's integration will be explained. Its integration was executed by this sub-group ensuring that the electronics of the Base Station fit the dimensions. Secondly, the Teddy's implementation is discussed of which the integration in the Teddy is managed by the Human Interaction and Integration group.

5.1. Base Station

As part of Power Operations and Distribution tasks, a casing was chosen to place and cluster the electric modules for the Base Station. This is then placed in a dog basket where the casing is covered with soft materials. A challenge is the plug cable and the placement of the switch since it should be the least non-intrusive option on the appearance of the Smart Teddy. A cardboard box was selected with the following dimensions: length of 42 cm, width of 17 cm and height of 11.3 cm. This fits within the chosen dog bed (length of 61.5 cm, width of 45 cm and height of 21.5 cm), which is used as the casing of the electronics of the Base Station (Figure 5.1a). All the electronics are placed in such a way that the wiring distance and the EMI are as little as possible. The power switch, that can disconnect and connect the net to the power system in the Base Station, is placed on the side of the cardboard box. The switch is covered with soft materials to ensure that the user cannot see the switch during use. The receiving coil is placed on top of the casing surrounded by the designed square-formation of neodymium magnets. The coil as well as the magnets are fixed with tape.

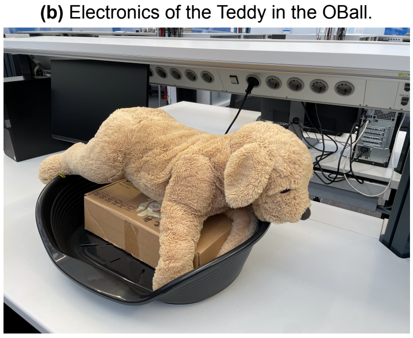
5.2. Teddy

The Teddy looks like a toy dog. In consultation with the subgroup Human Interaction and Integration, the integration of the electronics inside the Teddy is placed in the *Oball* (a flexible, toy ball for toddlers). All electronics from this subgroup, including the two boost converters on a PCB, the battery and charge controller board are placed inside the *Oball* (Figure 5.1b). This is then placed inside a soft pouch (made of fabric), where the receiving coil with the alignment magnets are protruding. Furthermore, the switch for disconnecting and connecting the loads to the battery is protruding and will be placed under the outer layer of the Teddy's fabric so that the user can press it when required. In this way, the switch is not visible. The Human Interaction and Integration designed a PCB (see Appendix J) that collects and connects all loads of the Teddy in one location without the use of wires. The outputs of the boost converters as shown in Figure 4.3a are connected to the corresponding input ports of the PCB.
The Teddy can be placed on top of the Base Station during charging whereby the coils are aligned as the Teddy's torso with the receiving coil is fixed on the transmitting coil (Figure 5.1c).



(a) Electronics of Power Operations and Distribution in the Base Station.

(b) Electronics of the Teddy in the OBall.



(c) Set-up wireless charging of the Teddy on top of the Base Station.

Figure 5.1: Photos of the integration of the power system in the prototype of the Smart Teddy.

6 Conclusion and Recommendations

This thesis explained the process of the development of the Power Operations and Distribution group for the Smart Teddy research project. The Smart Teddy is an interactive, companion robot disguised as a dog teddy (named Teddy) with monitoring skills to sense the indicators for the quality of life. The target group is senior citizens with early-stage dementia. The Teddy is supported by a Base Station to process collected data and to charge the batteries installed in the Teddy. The project is divided into three groups (Human Interaction and Integration, Sensors and Data Acquisition, and Power Operations and Distribution) each assigned to a specific domain of the research project.
The aim of the project is to carry out research on (1) the suitable battery type and configuration to function as the power supply of the Teddy whilst supporting its portability, (2) the battery charging technology and design to charge the battery in a non-intrusive and not robot-like way, and (3) selection of components to ensure reliable power distribution throughout the Smart Teddy's power system. Eventually, a prototype with the other subgroups is made that integrated the various modules constituting the Smart Teddy.
The project was bound by several criteria regarding safety, weight restrictions and user-friendliness concerns as to the vulnerable end-users. The challenges encountered during the project were related to the iterative nature of a power system since the set of electronics was not predetermined at the start of the project. This was resolved by making an extensive worst-case power budget that analyzes a provisional set of to-be-installed electronics regarding the average and maximum power consumption of the system. Furthermore, the Smart Teddy is an interactive system that should look as natural as possible. Hence, the design and development of a battery charger were subjected to this requirement. An inductive charger is chosen, whereby the transmitting coil and the AC power supply is located in the Base Station and the receiving coil with a rectifying circuit in the Teddy. A charging procedure was designed that requires low-impact intervention of the user when the battery needs to be charged. In collaboration with the Human Integration and Interaction group, a low-power signal can be sent in the form of a weeping sound to notify the user to start charging the Teddy by placing it on the Base Station after pressing a push button switch. The power system of the Teddy with a total weight of 183 g is eventually a constellation of power converters and boards connected to the loads, powered by two lithium-ion batteries connected in parallel with an energy capacity of 25.16 Wh with a battery life of 12 hours. Given the deployment of the Smart Teddy, a safety and protection failure design was made, consisting of fuses and PCB and cable management. However, due to time constraints, fuses were not implemented in the prototype and thus not tested. After the design and implementation, the system was tested and it was verified by means of a constructed verification method or procedure whether the requirements were satisfied. The Power Operations and Distribution group has designed a system that complies with 9 out of the 11 requirements and provided a suitable working system after having found answers to the research questions.

This thesis presented the fourth prototype of the Smart Teddy and is encouraged to be used for future research and improvements. For this purpose, some recommendations should be considered. Regarding the power system of the Smart Teddy, a suggested improvement in the system can be the number of cells used in the Teddy. Since the total weight of the power system is 183 g, there is still room for around two cells, making the total cell count four instead of two. This can increase the battery life of the Teddy significantly, ensuring the user to for example interact more with the Teddy without limitations. Another improvement lies in the charging board of the Teddy. This board can withstand a maximum charging current of 1 A, whereby one cell of the Teddy can withstand a maximum current of 2 A. The battery in this prototype can therefore allow a maximum charging current of 4 A. A board with a higher maximum charging current will ensure faster charging. Even though this is not a requirement, it also ensures a more pleasant experience for the user, using the Teddy. Then, the implementation of an automatic load switching circuit between loads of the Teddy and the charger would reinforce the the Smart Teddy's user-friendliness and avoids manual intervention. Lastly, it is highly recommended to implement and test the preventive safety measures (e.g. fuses) to ensure the safety of the user and to make the system more robust and fault tolerant.

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Appendix

A

Wireless Charging Technologies: Theory and Standards

This chapter elaborates on the comparison of six different wireless charging technologies, shown in Table A.1. Furthermore, two well-known interface standards for inductive and magnetic resonance charging are described.

Table A.1: An overview of the wireless charging technologies accumulated from the following sources [6] and [31]

Technology	**Magnetic Induction**	**Magnetic Resonance**	**Capacitive Charging**	**Microwave**	**Laser/IR**	**Radiowave**
Operating Distance	Up to several cm	Up to several m	Up to several mm	Up to tens of km	Up to tens of km	Several m
Frequency	110-300 kHz (RF)	kHz - MHz (Microwave)	Up to MHz	Several GHz up to hundreds GHz to 1 THz	Hundreds of GHz	kHz - MHz
Interface Standard	Qi	AirFuel Alliance	N/A	N/A	N/A	N/A
Costs	Low	High	Unknown	Very High	Very High	Unknown
Market Availability	High	Medium/Little	Scarce	Scarce	Scarce	Medium
Efficiency	High (70 - 90 %)	Medium (40 - 60 %)	Low	Low	Low	Very low (< 1%)
Received Power	Several W to kW	Hundreds of W	Up to 1 W	Up to tens of kW	Expected MW	mW to several W
Biological Impact	Minor	Medium	Minor	Significant	Significant	Significant
Design Complexity & Bottleneck	Very short range	Difficulties in maintaining high quality factor (Q)	Electrodes, Capacitor surface area	Line-of-sight propagation, high energy, high frequency	Line-of-sight propagation	low frequency, Low energy, penetration
Government Licence Required	No	No	No	Yes	No	Yes

Qi

The Wireless Power Consortium (WPC) is a consortium of more than 400 companies (such as Qualcomm, Samsung, Cisco) that constitute a multinational in the development for market standards for inductive wireless charging. WPC developed the open-interface Qi standard that is nowadays used in most of the charging devices. It has become the standard for mobile phone charging and companies such as Apple, Asus, Google and Samsung utilize the Qi standard in their technologies. Qi uses the inductive charging technology between coils with a communication protocol between the transmitting and receiving pad to control the power transfer. It can support power transfer between 5 to 15 W at operating frequencies ranging from 87 to 205 kHz [5].

AirFuel Alliance

AirFuel Alliance is a merger of preceding companies competing against Qi. This interface standard, called Airfuel, is based on magnetic resonance and can support power transfer of up to 50 W at a frequency of 6.78 MHz. This usually is combined with unique products that are not easily saleable for private usage and rather focused on sale amongst companies.

B
Verification Methods

Verification methods are a means to evaluate whether the requirements are met once the Smart Teddy prototype is completed. The systems engineering approach governs four methods used for determining whether or not a requirement has been met [13]. These methods are:

Inspection An examination of the product using human senses, i.e. touch, sight, hearing, smell and taste.

Demonstration The product is being subjected to an act similar to the intended, predefined purpose.

Test Through execution of a predefined procedure subjected to specific inputs and operating conditions, the output of the test is verified with the requirement under test.

Analysis A mathematical approach or simulation is used to check the typical performance of the product based on the requirement. Usually the product is also analysed - in an simulation - under stressed conditions using confirmed results to come with new conclusions of the product and to find its limits, e.g. breaking points.

C

Power Budget Teddy

For the power budget of the Teddy, efficiency values for the final conversion of the total power and energy levels are taken at 70%. These values are pessimistic values, which will protect the design from marginal errors, deviations and real-life influences on components such as cable losses.

Table C.1: Estimated Power-Budget of the Teddy, for a use case of 24 hours.

Subgroup	**Component**	**Quantity**	**Nominal Operating Voltage [V]**	**Operating Current [A]**	**Total Power Usage [W]**	**Usage Time In A Day [hours]**	**Total Energy Usage [J]**
HI&I	Adafruit 4699 DC Motor	2	5	0.35	3.50	3	37800
	Adfruit 997 Valve	3	5	0.12	1.80	3	19440
	Raspberry Pi Pico	1	5	0.050	0.25	24	21600
	MAX 9814 Microphone	1	5	0.002	0.01	24	864
	Visaton Speaker Driver	1	5V	0.2	1	0.25	900
Sensors	Capacitive Pressure Sheet	1	3.3	0.0001	0.00	0.5	0.59
	Accelero + Gyro MPU-600	1	3.3	0.0039	0.01	6	277.99
	GPS_MOD+ SIM808 board	1	3.3	0.0036	0.01	2	83.16
	Touch Sensor AdaFruit	1	3.3	0.00005	0.00	0.5	0.30
	MQ9 Gas Sensor	1	5	0.0015	0.008	6	173
	RFM95 Transceiver	1	3.3	0.02	0.07	0.5	126
Total Average Energy Usage in a day (70%η)$[Wh]$	**32.24**	**Total Average Energy Usage in 12h (70%η)$[Wh]$**	**16.12**	**Average Power Usage (70%η)$[W]$**	**1.35**		

Table C.2: Estimated maximum instantaneous power-budget of the Teddy.

Subgroup	**Component**	**Quantity**	**Nominal Operating Voltage [V]**	**Max. Operating Current [A]**	**Max. Power Usage [W]**
HI&I	Adafruit 4699 DC Motor	2	5	0.500	5
	Adfruit 997 Valve	3	5	0.160	2.40
	Raspberry Pi Pico	1	5	0.300	1.5
	MAX 9814 Microphone	1	5	0.003	0.02
Sensors	Visuaton Speaker Driver	1	5	0.4	2
	Capacitive Pressure Sheet	1	3.3	0.0001	0.00
	Accelero + Gyro MPU-600	1	3.3	0.0039	0.01
	GPS_MOD+ SIM808 Board	1	3.3	0.0035	0.01
	Touch Sensor AdaFruit	1	3.3	0.00005	0.00
	MQ9 Gas Sensor	1	5	0.0068	0.34
	RFM95 Transceiver	1	3.3	0.1	0.33
Total Max. Instantaneous Power Consumption (70%$\eta)[W]$	**16.6**				

D

Power Budget Base Station

For the power budget of the Base Station, efficiency values for the final conversion of the total power and energy levels are taken at 70%. These values are pessimistic values, which will protect the design from marginal errors, deviations and real-life influences on components. Furthermore, the assumption that a loss of approximately 50% will take place in the wireless power charger is taken for the calculations. This value is lower since wireless power transfer does not have high efficiency values. This value is estimated and the legitimacy is verified by the power department of TU Delft during a short meeting.

Table D.1: Power ratings of the components in the Base Station.

Subgroup	**Component**	**Quantity**	**Operating Voltage [V]**	**Operating Current [A]**	**Max. Operating Current A]**	**Power Rating [W]**	**Max. Power Rating [W]**
Sensors	Raspberry Pi B4	1	5	1	1.25	5	6.25
	Mmw Sensor	1	5	0.35	0.5	1.75	2.5
	MAX981 Microphone	1	5	0.002	0.003	0.01	0.015
HI&I	Lora RFM95	1	3.3	0.0108	0.012	0.036	0.04
Power	Wireless Power Transfer	1	9-12	1.11-0.83	1.11	10	10
Total Power Rating (70%η)$[W]$	**24**	**Total Max. Power Rating (70%**η)$[W]$	**26.9**				

E

List of Expenses

E.1. Total Costs of Power Operations and Distribution

Table E.1: An overview of the total expenses made by the Power Operation and Distribution subgroup.

Item	Quantity	Cost [€]	Comment	Item	Quantity	Cost[€]	Comment
LM2596 Buck Converter	3	9		Green Switch	1	3	
MT3608 Boost Converter	3	6		PPTC Polyfuse 2A	3	3.90	
Wireless Power Transfer Module	1	13		PPTC Polyfuse 1A	3	3.60	
18650 Battery Holders	4	4		PPTC Polyfuse 0.5A	3	3	
Mean Well IRM-60-12ST	1	18.03	Funded by TU Delft	Rocker Switcher	1	1	
MCP73833 IC	5	0.75	Funded by TU Delft	Neodynium Magnet	10	6	
ADA-259 Charger	1	14.59		KW-157 extension Cable	2	4.50	
TP4056 1A	2	3		JST-PH Kabel KW-1480	2	1.90	
Seed Lipo Rider Plus	1	6		Dog Bed	1	12.68	
RobotDyn TP4056 With Protection	2	5					
TP4056 1A With Protection	2	4					
Total Delivery Costs [€]	16.65						
Total Costs (exluding funding TU Delft) [€]	**120.82**						

E.2. Costs of Prototype

Table E.2: Total costs of the prototype Power Operations and Distribution.

Item	Quantity	Cost[€]	Comment	Item	Quantity	Cost[€]	Comment
LM2596 Buck Converter	1	3		Green Switch	1	3	
MT3608 Boost Converter	2	4		Rocker Switcher	1	1	
Wireless Power Transfer Module	1	13					
18650 Battery Holders	2	2					
Mean Well IRM-60-12ST	1	18.03	Funded by TU Delft				
Neodynium Magnet	8	4.8	Funded by TU Delft				
Dog Bed	1	12.68					
TP4056 1A With Protection	1	2					
Total Delivery Costs [€]	16.65						
Total Costs of Prototype [€]	**80.16**						

F

Total Weight Teddy

Table F.1: Total weight of all the components used in the Teddy, regarding the Power Operation and Distribution subgroup.

Component	**Quantity**	**Weight [g]**
Nitecore NL1834	2	110
MT3608 Converter	2	10
TP4056 1A Without Protection	1	17
Battery Casing	2	20
Wireless Power Charger Receiving Side	1	8
Wires	1	3
Voltage Divider Circuit	1	5
Soldering Boards	3	10
Total Weight [g]		**183**

G

Charging System Test

In this section, the tests and their results regarding the wireless power charger are displayed and explained. In all these tests, the coils were aligned for maximum efficiency in that particular situation. The medium between the coils is air unless stated otherwise. The measurements are done with the help of digital multimeters.

G.1. Wireless Power Charger with Load Test

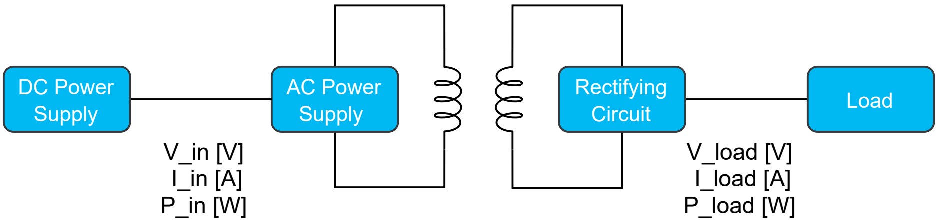


Figure G.1

Table G.1: Overview of the values measured from a load-test with the wireless power charger.

Load (Ω)	**2.6**	**Distance [mm]**				
V_in [V]	**I_in [A]**	**V_load [V]**	**I_Load [A]**	**P_in [W]**	**P_Load [W]**	**η [%]**
9.000	1.000	3.874	1.530	9.000	5.927	65.86
10.000	1.130	4.247	1.660	11.300	7.050	62.39
11.000	1.220	4.606	1.820	13.420	8.383	62.47
12.000	1.310	4,985	1.957	15.720	9.756	62.06

The test setup of the wireless power charger load test is executed as shown in Figure G.1, whereby the results are shown in Table G.1. Different input voltages are applied to the power system, whereby the input and output voltage and current values are measured, calculating the power from it. From these input and output power values, the efficiency is derived. The purpose of this test is to determine the output power and efficiencies at different input voltages the wireless power charger can handle (9 V up to 12 V). From these results, it can be concluded that the 12 V input voltage results in a maximum power transfer of 9.756 W, with an efficiency of 62.06%. This efficiency is just 3.82% lower than the highest efficiency, which takes place at an input voltage of 9 V. This value is higher than the efficiency value of 50% estimated in the Detailed Design 3, confirming a right assumption. As long as the measured efficiency value is not below the estimated value, the assumption is considered to be correct. A picture taken during the testing of the wireless charging system with a load is shown in Figure G.2.

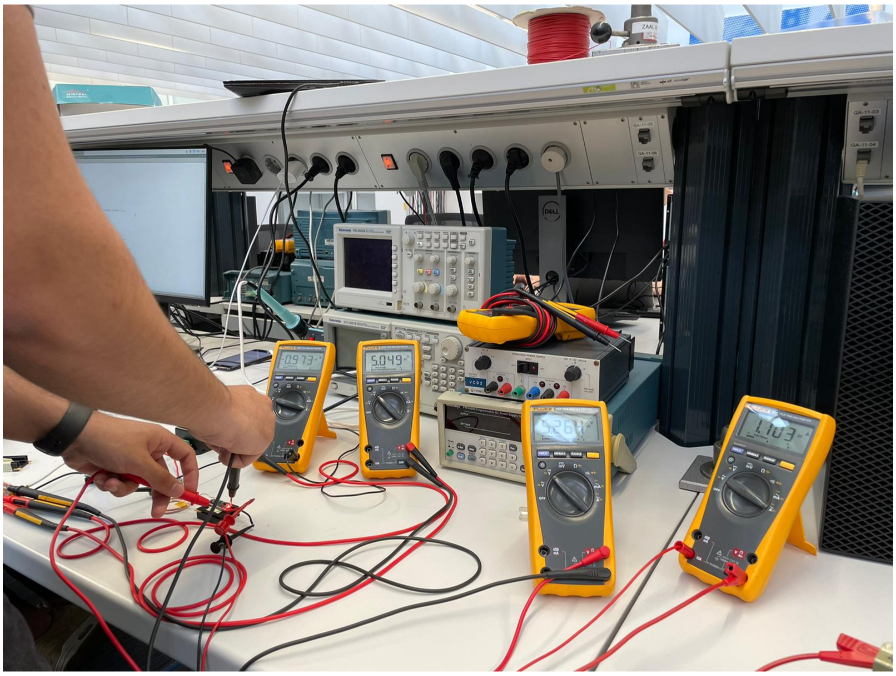


Figure G.2: A picture taken during the testing of the wireless power transfer using loads.

G.2. Fabric Test of Wireless Power Charger

Table G.2: Efficiency values of stretch tule fabric.

Fabric Type	Fabric Thickness	Efficiency With Respect To No Sheet Being Used [%]
stretch tule	1 sheet	100
stretch tule	2 sheets	100
stretch tule	3 sheets	98
stretch tule	4 sheets	92
stretch tule	5 sheets	78.3
stretch tule	6 sheets	61.6
stretch tule	7 sheets	54.6
stretch tule	8 sheets	42.88

Table G.3: Efficiency value of the Mesh fabric.

Fabric type	Fabric Thickness	Efficiency With Respect To No Sheet Being Used [%]
Mesh	1 sheet	100
Mesh	2 sheets	99.50
Mesh	3 sheets	100
Mesh	4 sheets	100
Mesh	5 sheets	100
Mesh	6 sheets	95
Mesh	7 sheets	86
Mesh	8 sheets	72.50

The setup for this test is the same as Figure G.1, whereby the only difference is that piece of fabric is placed between the coils. Two different fabric types (stretch tule and mesh) are hereby placed between the coils of the charging system and different input voltages are applied to the power system, whereby the input and output voltage and current values are measured and calculated. The purpose of this test is to determine the output efficiency at different fabric thicknesses between the coils. Based on this, the fabric type and its maximum thickness is selected. The Human Integration and Interaction subgroup will use this information in designing the covering of the charging pads in the prototype.

The results are shown in Table G.2 and Table G.3. One sheet of stretch tule equals 0.3 mm and one sheet of mesh equals to fabric equals 0.5 mm. The stretch tule is thinner but also denser with respect to the mesh fabric resulting in a lower efficiency when using multiple sheets on top. This results in choosing mesh as the fabric to go for the prototype. Five sheets will be opted for since these are the maximum layers where no efficiency drop is measured.

G.3. Battery Charging Test with Charging Board and Voltage Divider

In order to test the charging function of the charge controller, it is placed between the wireless power charger and battery, as shown in Figure G.3. Hereby it is verified that this setup can indeed supply a maximum current of 1 A while operating at the two stages, as stated in Chapter 3.2. This is verified by monitoring the voltage and current behavior at the terminals of the battery. The charging board also has 2 Led lights, indicating whether it is charging and when it is fully charged. Moreover, with the help of the voltage divider, the voltage level of the battery is presented to the Raspberry with an accuracy of 1%. When the voltage of the battery drops below 3 V, it triggers the Raspberry, activating the speakers and notifying the user that the Teddy has to be charged.

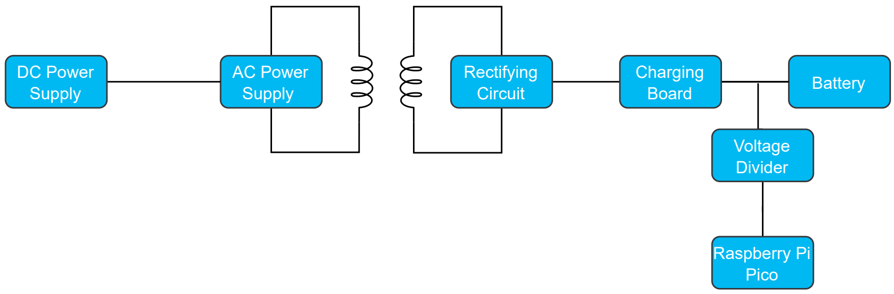


Figure G.3: Test setup for testing the charging board.

H Base Station Test

The Base Station test is a fully integrated test of all the loads and components installed in it. The voltage and current are measured at the output of the AC/DC converter, input of the charger and DC/DC converter and at the output of the DC/DC converter with the help of multimeters. This test is done in order to verify if the selected components can indeed support the power consumption of the loads but also in order to verify the estimated power consumption of the loads in the Base Station as stated in Appendix D. The only missing load here is the microphone, but since it consumes a very low power of 0.01 W and does not affect the ability of the overall system, it can be disregarded. The test setup and its results are shown in Figure H.2. The coding of the Raspberry Pi B4 is based on a heavy usage case, written by the Sensors subgroup in order to test our system. Moreover, a screen and a mouse are also connected to the Raspberry, which is not shown in the figure.

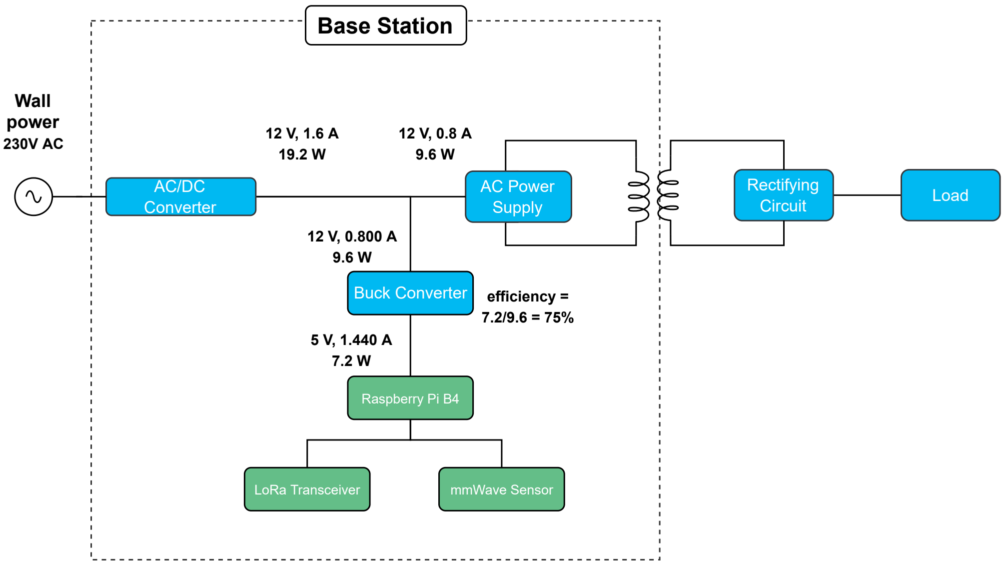


Figure H.1: Test setup of the Base Station with all the components installed in it.

Upon connecting the power to this system, all of the components worked fine without any problems. The total power consumption at the output of the AC/DC converter is equal to 19.2 W, whereby the estimated maximum value according to Table D.1 is equal to 26.9 W. The power consumption branching to the buck converter equals 9.6 W, which was theoretically defined at 8.805 W in Table D.1. This is because the mmW sensor uses more power than estimated. A clear value in the datasheet of this sensor was not defined, which lead to making an assumption for this part. However, the difference is only 0.795 W, causing no problems. The AC/DC converter can support up to 60 W after all. The conversion efficiency of the buck converter equals 75 % which comes close to the 70 % value taken into the calculation in Table D.1. Unfortunately, the maximum efficiency of 92 % stated in Table 3.10 is not achieved, which is reasonable due to the high current going through it. In order to test the Base Station with maximum conditions, a load is connected to the wireless power charger which draws a total power of 10 W from it. Since this charger does not have any converters between itself and the AC/DC converter, no losses exist between it. This explains the lower measured power output at the AC/DC converter compared to the theoretical value. A picture of the test, whereby the Raspberry Pi B4 is connected to the mmW sensor and a screen being powered by the system made by Power Operations and Distribution is shown in Figure H.2.

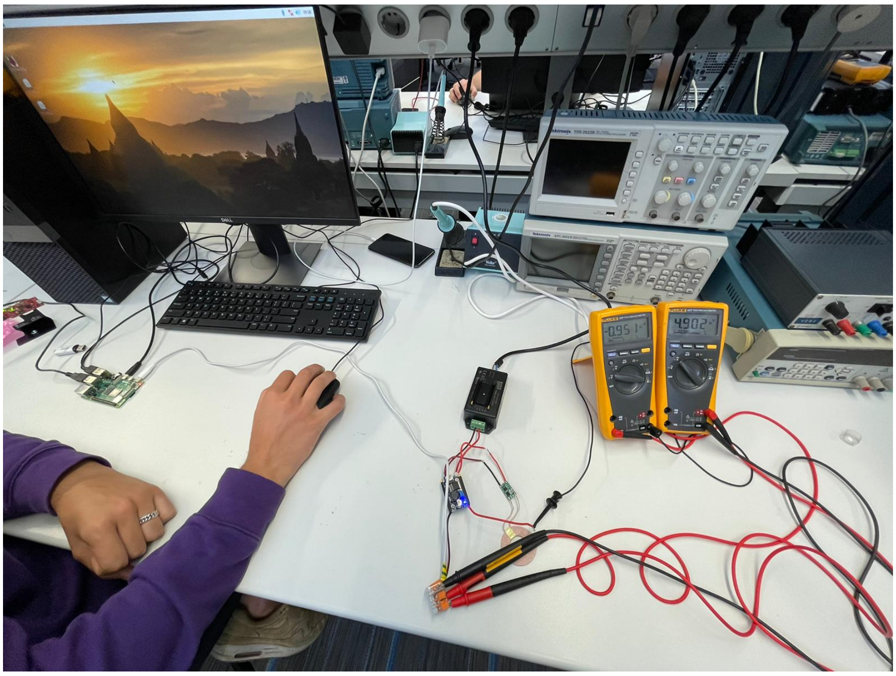


Figure H.2: A picture taken during the testing of the Raspberry Pi B4 connected to a screen and a mmW sensor attached to it, with the help of the designed power system.

Teddy Power Consumption

This chapter elaborates on the calculations on how the power consumption of the final system of the Teddy was computed. Namely, two possible use-case scenarios on a 12-hour timeframe were simulated and analyzed. It is to ensure that the battery can provide the power for the different cases for at least 12 hours. Then, it is necessary to understand what the potential usage period is for the Teddy which is relevant to know for the consumer and to deduce the battery life. The cases that were analyzes are the following:

1. Maximum use case scenario: The user is extensively petting the Teddy. The total power consumption is calculated consisting of all electronic components of the Teddy.
2. Average use case scenario: The user is stroking the Teddy for a maximum number of 30 times which may be spread over a course of a 12-hour time frame (as specified in Requirement F.02.v03).

Table I.1 shows an overview of the power consumption of the pumps and valves during one sequence containing two times tail wagging and three respiration of the Teddy's lungs. It is assumed that simultaneously the GPS module is its continuous tracking mode (idle), for which it holds that the current draw is 24 mA at 5 V. The Raspberry Pi Pico (to which secondary low power loads are connected) is assumed to be working at its maximum and therefore has a power consumption of 1.5 W (300 mA at 5 V).

Table I.1: Power consumption overview for one cycle breathing and tail wagging with pumps and valves

	Movement	Power Consumption [W]	Duration [s]	Energy [J]
1	Tail inflates	2.98	3.5	10.43
2	Tail deflates	0.17	3	0.51
3	Tail inflates	2.98	3.5	10.43
4	Tail deflates	0.17	3	0.51
5	Breathing in, tail deflates	3.40	8	27.2
6	Breathing out, tail deflates	3.31	8	26.48
7	Breathing in, tail deflates	3.40	8	27.2
8	Breathing out, tail deflates	3.31	8	26.48
9	Breathing in, tail deflates	3.40	8	27.2
10	Breathing out, tail deflates	3.31	8	26.48
		Total	**61**	**182.92**
		Total Power Consumption [W]		**2.999**

Table I.1 shows the overview of the power consumption of each movement during the execution of the sequence of 61 s. The energy for one sequence equals 182.92 J.
The power consumption of the Raspberry Pi Pico is estimated to be 1.5 W (300 mA at 5 V), which yields an energy of 91.5 J. The GPS module power consumption is 0.12 W (24 mA at 5V) which yields an energy of 7.32 J. So, the total energy of the sequence is 281.74 J. This is equal to the energy consumption of 0.078 Wh for one sequence of 61 seconds. The total power consumption of the movements the power consumption of the Raspberry Pi Pico and the GPS module is 4.61 W.
Since the battery has an energy capacity of 25.16 Wh (when fully charged), then the amount of discharge time is equal to 5.44 hours. Meaning that if the user were to stroke the Teddy for 5 hours long, the battery will be discharged. This is regarded as a maximum use case scenario at the cost of a lower battery life.
However, in fact, the predicted use of stroking times equals the predicted on-time of the touch sensor which is 30 minutes. That is why the actual energy used is circa 30 times 0.078 Wh which yields 2.34 Wh of stroking per day (of 24 hours). This leaves the battery with a remaining capacity of 22.82 Wh, which can be used for (1) idle and (2) for low-powering signaling.

1. Pumps and valves in idle: the power consumption is measured to be 0.18 W. The total power consumption of the Teddy is then 1.8 W by adding the power consumption of the Raspberry Pi Pico and the GPS module in idle. With the remaining battery capacity of 22.82 Wh, the battery can supply power for another 12 h in idle mode. This brings the battery life of the Teddy to a total of 12.5 hours.

2. Low-powering signaling: when the battery is approaching its discharge cut-off, meaning that it requires charging, the Human Interaction and Integration is sensing a threshold voltage after which a signal is sent to the speaker driver to make the weeping sound. This requires power. The speaker driver is drawing a current of 0.4 A at 5 V for 2 seconds and repeats every 60 seconds until the user pushes the push button to disconnect the loads (including the Raspberry Pi Pico) from the battery. The energy required is 4 J and if it is assumed that this is going to happen three times (in intervals of 60 seconds) before the user notices, then the total energy required is 12 J. So this is subtracted from the actual remaining capacity before the idle modes were calculated. Hence, the remaining capacity is then 22.817 Wh. This allows the Teddy to be in idle mode for still another 12 hours approximately.

It is thus concluded that the battery life of the Teddy in the average use case scenario is 12.5 hours. In these calculations, the low-power signaling was considered as well as the overall Teddy system in idle.
There is a small deviation of this use case scenario, as the GPS inside the Teddy can be in ”acquisition mode” when the Teddy is at least 500 meters away from the Base Station. The power consumption is then 0.21 W (42 mA at 5 V). This, however, has little effect on the battery life as it for example has an energy consumption of 0.01 Wh if the senior is outside for 3 hours. This consequently affects the battery life to be lowered to 12 h, but is still complying with the requirement. Yet to ensure that this is covered in the final statement of the battery life, a value of 12 h is chosen.

Below a maximum power consumption of the Teddy is shown in Table I.2.

Table I.2: Maximum power consumption of the Teddy

Maximum Power Consumption	Power [W]	Current [mA]
Breathing in, tail deflates (1 pump, 2 valves)	3.40	701
Raspberry Pi Pico	1.5	300
GPS (Acquisition mode)	0.21	42
Speaker driver	2	400
Total	**7.11**	

In Figure I.1, a picture taken during the testing of the loads in the Teddy, using the battery is shown.

Figure I.1: A picture of the testing of the components in the Teddy.

J
Integration PCB

The Human Interaction and Integration group designed a PCB for the Teddy to connect their loads and the modules of the power system without extensive wiring. Figure J.1 shows a three-dimensional view of the integration PCB. The ports with the label *5V_BOOST* and the *5V_BOOST_PUMPS* are connected to the two boost converters. The voltage divider is seen on bottom right that is connected to the *BMS* ports.

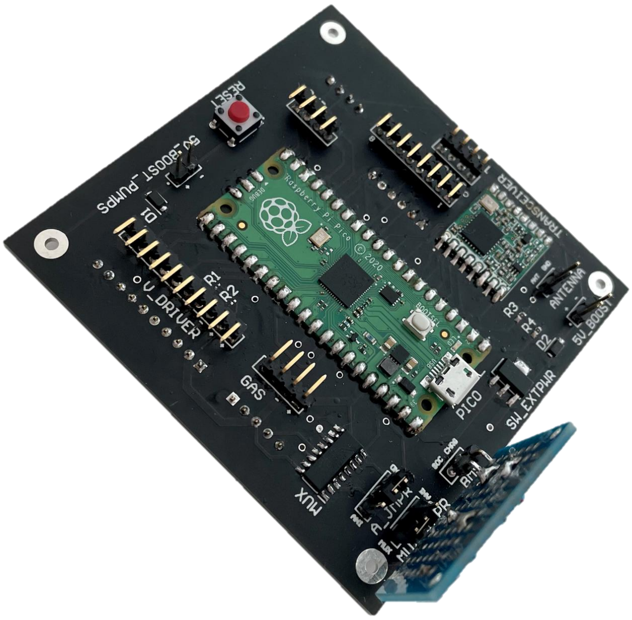


Figure J.1: 3D view of the integration PCB from the Human Interaction and Integration group.

K
Battery and TP4056 Charge Control Board Datasheets

The lithium-ion Nitecore battery has specific charging and discharging ratings which are explained in its datasheet. It has protection embedded on the side of the cell, which includes short circuit prevention, overcharge detection and over-discharge detection.
The charger controller board with the TP4056 IC is managing the charging procedure of the battery. This IC is placed on a PCB (Figure K.1 to provide the charging control components. Below, the datasheet of this IC can be seen. The characteristics of the IC fit the required charging ratings and scheme of the Nitecore 18650 battery.

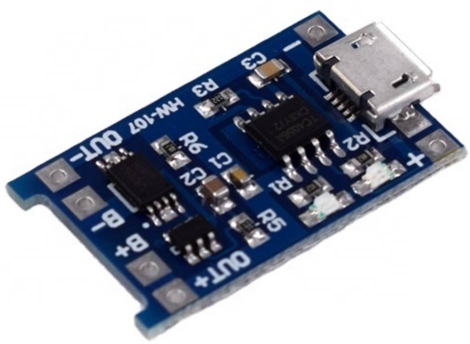


Figure K.1: TP45056 lithium-ion charger board

Customer:___

Lithium Battery

Specification

MODEL:NL1834

Prepared By/Date	Checked By/Date	Approved By/Date

Customer Approval	**Signature/Date**
	Company Name
	Company Stamp

Amendment Records				
Edition	Description	Prepared by	Approved by	Date
A	First Edition			2016-10-25

1．Scope

This document describes the Product Specification of Li battery supplied by SYSMAX.

2. Product Specification

Table 1

No.	Item	General Parameter	Remark
1	Rated Capacity	3400mAh	Standard discharge（0.2C）after standard charge（0.2C）
2	Minimal Rated Capacity	3300mAh	
3	Nominal Voltage	3.7V	3.7V/Cell 1P1S
4	Cycle Life	Higher than 60% of the Initial Capacity of the Cells	◆Charge: CC @ 0.2C to 4.2V, then CV till current to 0.05C ◆Rest: 30min. ◆Discharge: 0.2C to 2.75V ◆Temperature:20±5°C ◆Carry out 500 cycles
5	Discharge cut-off voltage	2.8V/cell	
6	Charging cut-off voltage	4.2V/cell	
7	Cell and assembly method	18650-3400mAh	1P1S
8	Internal Resistance	≤150mΩ	
9	Packing material	PVC	
10	Capacity- Temperature Performance A: dishcharge current is 1C; B: discharge current is 0.5C	-10°C: A—30%; B—40%	
		0℃: A—70%; B—75%	
		23℃: A—100%; B—100%	
		55℃: A—90%; B—95%	
11	Residual Capacity After Storage	Min. 90%@28days and 25℃	

Continuous the table 1

No.	Item	General Parameter	Remark
12	Operation Temperature Range	Charge: 0~45℃ Discharge: -20~55℃	60±25%R.H.
13	Storage Temperature Range	Less than 1 year : 0~25℃ Less than 3 months:-5~35℃	60±25%R.H. at the shipment state
14	Weight	Approx: 55g	
15	Pack Dimension	High: 69±0.5mm Diameter: 18.8±0.1mm	
16	PCM Main Data IC: SEIKO S8621-G2J MOS: SIS8205A*2	Over charge Detection Voltage	4.325±0.025V
		Over discharge Detection Voltage	2.500±0.025V
		Over Discharge Current	3.50-8.50A
		short circuit protection delay time	7.2-11.0ms
		Suggest working conditions	Max continuous discharge : 3A Max continuous charge: 2A
		Normal Current consumption of PCM	Max 7.0μA

3. Performance And Test Conditions

3.1 Standard Test Conditions

Test should be conducted with new batteries within one week after shipment from our factory and the batteries shall not be cycled more than five times before the test. Unless otherwise specified, test and measurement shall be done under temperature of 20±5℃ and relative humidity of 45~85%. If it is judged that the test results are not affected by such conditions, the tests may be conducted at temperature 15~30℃ and humidity 25~85%RH.

3.2 Measuring Instrument or Apparatus

3.2.1 Dimension Measuring Instrument

The dimension measurement shall be implemented by instruments with equal or more precision scale of 0.01mm.

3.2.2 Voltmeter

Standard class specified in the national standard or more sensitive class having inner impedance more than 10kΩ/V

3.2.3 Ammeter

Standard class specified in the national standard or more sensitive class. Total external resistance including ammeter and wire is less than 0.01Ω.

3.2.4 Impedance Meter

Impedance shall be measured by a sinusoidal alternating current method (1kHz LCR meter).

3.3 Standard Charge/Discharge

3.3.1 Standard Charge : 0.2C

Charging shall consist of charging at a 0.2C constant current rate until the battery reaches 4.2V/cell. The battery shall then be charged at constant voltage of 4.2V/cell while tapering the charge current. Charging shall be terminated when the charging current has tapered to 0.05 C_5A. Charge time: Approx 7h, The battery shall demonstrate no permanent degradation when charged between 0 ℃ and 45 ℃.

3.3.2 Standard Discharge : 0.2C

Battery shall be discharged at a constant current of 0.2C to 2.75V/cell @ 20 º± 5C

3.3.3 If no otherwise specified, the rest time between charging and discharging is 30min.

3.4 Appearance

There shall be no such defect as crack, rust, leakage, which may adversely affect commercial value of battery.

4. Handling of battery

4.1 Prohibition short circuit

Never short circuit battery. It generates very high current which causes heating of the battery and may cause electrolyte leakage, gassing or explosion that is very dangerous.

The poles may be easily short-circuited by putting them on conductive surface.

Such outer short circuit may lead to heat generation and damage of the battery.

An appropriate circuitry with PCM shall be employed to protect accidental short circuit of the battery pack.

4.2.Mechanical shock

Falling, hitting, bending, etc. may cause degradation of battery characteristics.

5. Others

Prevention of short circuit within a battery pack

Enough insulation layers between wiring and the cells shall be used to maintain extra safety protection.

The battery pack shall be structured with no short circuit internally, which may cause generation of smoke or firing.

6. Period of Warranty

The period of warranty is 12 months from the date of shipment. SYSMAX guarantees to give a replacement in case of battery with defects proven due to manufacturing process instead of the customer abuse and misuse.

7. Storing the Batteries

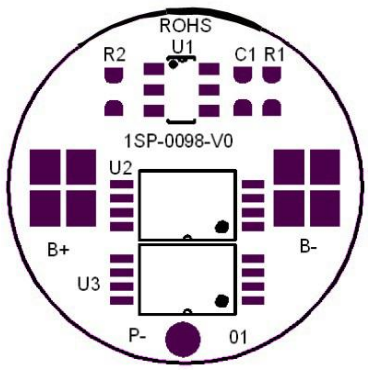
The batteries should be stored at room temperature, charged to about 30% to 50% of capacity.

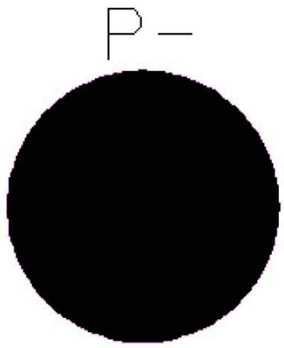
We recommend that batteries be charged about once per half a year to prevent over-discharge.

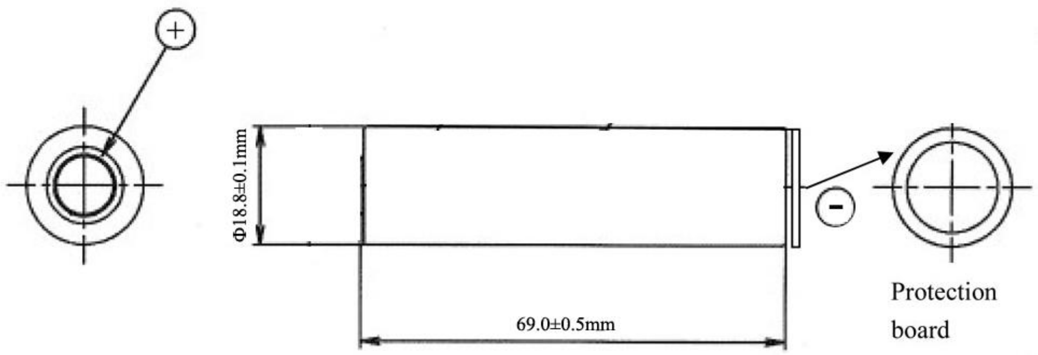
8. Other Chemical Reaction

Because batteries utilize a chemical reaction, battery performance will deteriorate over time even if stored for a long period of time without being used. In addition, if the various usage conditions such as charge, discharge, ambient temperature, etc. are not maintained within the specified ranges the life expectancy of the battery may be shortened or the device in which the battery is used may be damaged by electrolyte leakage. If the batteries cannot maintain a charge for long periods of time, even when they are charged correctly, this may indicate it is time to change the battery.

9. Photo:







10. Any other items which are not covered in this specification shall be agreed by both parties.

TP4056 1A Standalone Linear Li-lon Battery Charger with Thermal Regulation in SOP-8

DESCRIPTION

The TP4056 is a complete constant-current/constant-voltage linear charger for single cell lithium-ion batteries. Its SOP package and low external component count make the TP4056 ideally suited for portable applications. Furthermore, the TP4056 can work within USB and wall adapter.

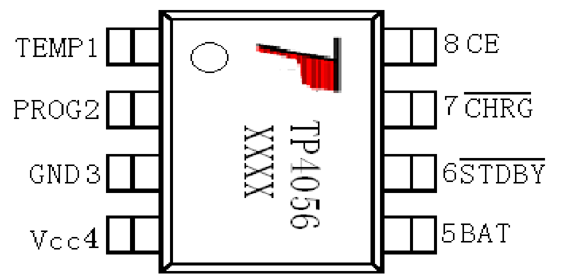
No blocking diode is required due to the internal PMOSFET architecture and have prevent to negative Charge Current Circuit. Thermal feedback regulates the charge current to limit the die temperature during high power operation or high ambient temperature. The charge voltage is fixed at 4.2V, and the charge current can be programmed externally with a single resistor. The TP4056 automatically terminates the charge cycle when the charge current drops to 1/10th the programmed value after the final float voltage is reached.

TP4056 Other features include current monitor, under voltage lockout, automatic recharge and two status pin to indicate charge termination and the presence of an input voltage.

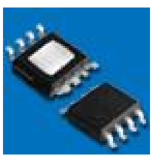
FEATURES

- Programmable Charge Current Up to 1000mA
- No MOSFET, Sense Resistor or Blocking Diode Required
- Complete Linear Charger in SOP-8 Package for Single Cell Lithium-Ion Batteries
- Constant-Current/Constant-Voltage
- Charges Single Cell Li-Ion Batteries Directly from USB Port
- Preset 4.2V Charge Voltage with 1.5% Accuracy
- Automatic Recharge
- two Charge Status Output Pins
- C/10 Charge Termination
- 2.9V Trickle Charge Threshold (TP4056)
- Soft-Start Limits Inrush Current
- Available Radiator in 8-Lead SOP Package, the Radiator need connect GND or impending

PACKAGE/ORDER INFORMATION



SOP－8

photo	ORDER PART NUMBER TP4056-42-SOP8-PP
	**PART MARKING** TP4056

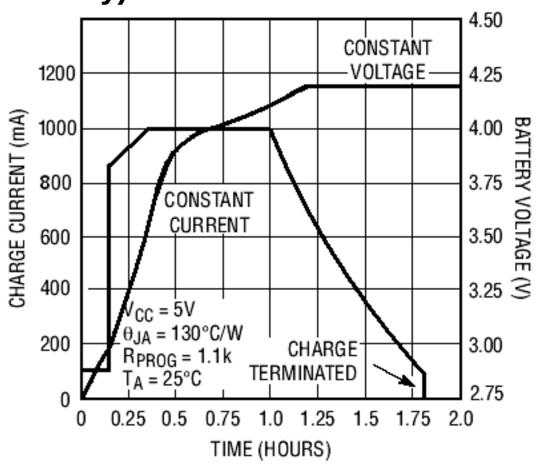
ABSOLUTE MAXIMUM RATINGS

- Input Supply Voltage(V_{CC})：-0.3V～8V
- TEMP：**-0.3V**～10V
- CE：**-0.3V**～10V
- BAT Short-Circuit Duration：Continuous
- BAT Pin Current：1200mA
- PROG Pin Current：1200uA
- Maximum Junction Temperature：145℃
- Operating Ambient Temperature Range：-40℃～85℃
- Lead Temp.(Soldering, 10sec)：260℃

APPLICATIONS

- Cellular Telephones, PDAs, GPS
- Charging Docks and Cradles
- Digital Still Cameras, Portable Devices
- USB Bus-Powered Chargers,Chargers

Complete Charge Cycle (1000mAh Battery)



TEMP(Pin 1) :Temperature Sense Input Connecting TEMP pin to NTC thermistor's output in Lithium ion battery pack. If TEMP pin's voltage is below 45% or above 80% of supply voltage V_{IN} for more than 0.15S, this means that battery's temperature is too high or too low, charging is suspended. The temperature sense function can be disabled by grounding the TEMP pin.

PROG(Pin 2): Constant Charge Current Setting and Charge Current Monitor Pin charge current is set by connecting a resistor R_{ISET} from this pin to GND. When in precharge mode, the ISET pin's voltage is regulated to 0.2V. When in constant charge current mode, the ISET pin's voltage is regulated to 2V.In all modes during charging, the voltage on ISET pin can be used to measure the charge current as follows:

$$I_{BAT} = \frac{V_{PROG}}{R_{PROG}} \times 1200 \quad (V_{PROG}=1V)$$

GND(Pin3): Ground Terminal

Vcc(Pin 4): Positive Input Supply Voltage V_{IN} is the power supply to the internal circuit. When V_{IN} drops to within 30mv of the BAT pin voltage, TP4056 enters low power sleep mode, dropping BAT pin's current to less than 2uA.

BAT(Pin5): Battery Connection Pin. Connect the positive terminal of the battery to BAT pin. BAT pin draws less than 2uA current in chip disable mode or in sleep mode. BAT pin provides charge current to the battery and provides regulation voltage of 4.2V.

$\overline{STDBY}$(Pin6): Open Drain Charge Status Output When the battery Charge Termination, the $\overline{STDBY}$ pin is pulled low by an internal switch, otherwise $\overline{STDBY}$ pin is in high impedance state.

$\overline{CHRG}$ (Pin7): Open Drain Charge Status Output When the battery is being charged, the $\overline{CHRG}$ pin is pulled low by an internal switch, otherwise $\overline{CHRG}$ pin is in high impedance state.

CE(Pin8): Chip Enable Input. A high input will put the device in the normal operating mode. Pulling the CE pin to low level will put the YP4056 into disable mode. The CE pin can be driven by TTL or CMOS logic level.

ELECTRICAL CHARACTERISTICS

The ● denotes specifications which apply over the full operating temperature range, otherwise specifications are at **T_A=25℃，V_{CC} =5V**，unless otherwise noted.

SYMBOL	PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
V_{CC}	Input Supply Voltage		●	4.0	5	8.0	V
I_{CC}	Input Supply Current	Charge Mode, R_{PROG} = 1.2k StandbyMode(Charge Terminated) Shutdown Mode (R_{PROG} Not Connected,V_{CC} < V_{BAT}, or V_{CC} < V_{UV})	● ● ●		150 55 55	500 100 100	µA µA µA
V_{FLOAL}	Regulated Output (Float) Voltage	0℃≤T_A≤85℃，I_{BAT}=40mA		4.137	4.2	4.263	V
I_{BAT}	BAT Pin Current Text condition:VBAT=4.0V	RPROG = 2.4k, Current Mode RPROG = 1.2k, Current Mode Standby Mode, V_{BAT} = 4.2V	● ● ●	450 950 0	500 1000 −2.5	550 1050 −6	mA mA µA
I_{TRIKL}	Trickle Charge Current	V_{BAT}<V_{TRIKL}, R_{PROG}=1.2K	●	120	130	140	mA
V_{TRIKL}	Trickle Charge Threshold Voltage	R_{PROG}=1.2K, V_{BAT} Rising		2.8	2.9	3.0	V
V_{TRHYS}	Trickle Charge Hysteresis Voltage	R_{PROG}=1.2K		60	80	100	mV
T_{LIM}	Junction Temperature in Constant Temperature Mode				145		℃

indicator light state

Charge state	Red LED $\overline{CHRG}$	Greed LED $\overline{STDBY}$
charging	bright	extinguish
Charge Termination	extinguish	bright
Vin too low; Temperature of battery too low or too high; no battery	extinguish	extinguish
BAT PIN Connect 10u Capacitance; No battery	Greed LED bright，Red LED Coruscate T=1-4 S	

Rprog Current Setting

RPROG (k)	IBAT (mA)
10	130
5	250
4	300
3	400
2	580
1.66	690
1.5	780
1.33	900
1.2	1000

TYPICAL APPLICATIONS