Technische Universität Berlin

Institut for Aeronautics and Astronautics (ILR)
Chair of Space Technology

TU Berlin - Fakultät V
Marchstraße 12-14
10587 Berlin
http://www.mse.tu-berlin.de

Master Thesis

Development of Electrical Power System Distribution Board for a 6 Unit satellite

Pavel Grigorev

Matriculation Number: 1234567
01.01.2010

Supervised by
Prof. Dr. -Ing. Klaus Brieß

Assistant Supervisor
Dipl.-Ing. Daria Stepanova

Assistant Supervisor
Dipl.-Ing. Marc Lehmann

German Orbital Systems GmbH
Reuchlinstraße 10-11
10553 Berlin

This dissertation originated in cooperation with the German Orbital Systems.

First, I would like to express my gratitude to Prof. Klaus Brieß, Head of the Chair of Space Technology at Technical University of Berlin, for the giving support during this thesis and the lectures in Raumfahrt Antribe. I would like to thank Walter Ballheimer CEO - German Orbital Systems for giving me the opportunity to carry out state of the art research in this company. I express my gratitude to Dipl.-Ing. Daria Stepanova Senior.-Ing of German Orbital Systems for giving me the opportunity to carry out this research project. I would like to thank Marc Lehmann for his constant support and feedback in the revision for this thesis. Their gratitude helped me to conclude this interesting work in a very interesting space area.

Special thanks to the MSE team for all the support during these years, pecially Dipl. Ing. Cem Avsar and Dipl.-Kfrr. Olga Homakova and Nicole Lange. They continuously offered support and motivation during the master studies.

Last but not least, I would like to thank my family, specially my grandfather Vladimir, father Alexander and mother Elena for all the support on every decision that I have taken, for always being there. I dedicate this thesis to them.

Declaration of Authorship

I, Pavel Grigorev, hereby certify that this thesis has been composed by me and is based on my own work, unless stated otherwise. No other person's work has been used without due acknowledgement in this thesis. All references and verbatim extracts have been quoted, and all sources of information, including graphs and data sets, have been specifically acknowledged.

Berlin, 01.01.2050

. . . .
Pavel Grigorev

Agreement on rights of utilization

The Technische Universität Berlin, represented by the Chair of Space Technology, may use the results of the thesis at hand in education and research. It receives exclusive rights of utilization as according to § 31 Abs. 2 Urheberrechtsgesetzt (Urhg). This right of utilization is unlimited and involves content of any kind (e.g. documentation, presentations, animations, photos, videos, equipment, parts, procedures, designs,drawings, software including source code and similar).

Berlin, 01.01.2050

. . . .
Professor Dr.-Ing. Klaus Brieß
Head of the Chair of Space Technology

Abstract

Electrical Power System is a critical element in the success of a space mission. The main responsibility of Electrical Power System (EPS) is the energy generation, control and distribution for a satellite during the mission. Depending on a mission specifics, EPS is responsible for handling different power busses and loads and shall provide robust power channels to all spacecraft subsystems and payload. The Electrical Power System is also responsible for healthcare information collection and analysis.

Current work is dedicated to the development of a new EPS for 6 Unit CubeSat. Preliminary idea is to divide the EPS into two modules: Power Distribution (PDU) and Power Processing Unit (PPU). While PPU will be responsible for battery charging, energy conversion from the solar cells, power processing, PDU will be in charge of control and power monitoring. The present work will cover an architectural design of a whole system, while will be focusing on the design of a power distribution unit, which will be adjustable for different missions and responsible for a power handling.

This thesis aims to provide a full design iteration of a PDU of the 6 Unit CubeSat EPS. It will start with power budget analysis of 6U satellite. After that, the architecture of EPS distribution board will be reviewed. From the design side, electrical circuit and PCB of power distribution unit will be developed, manufactured and tested.

Keywords: Electrical Power System, 6 Unit CubeSat, Power Distribution, PCB design.

Zusammenfassung

Das Stromversorgungssystem ist ein entscheidendes Element für den Erfolg einer Weltraummission. Die Hauptverantwortung von Stromversorgungssystem (EPS) ist die Energieerzeugung, -steuerung und -verteilung für einen Satelliten während der Mission. In Abhängigkeit von den Missionsspezifikationen ist EPS für den Umgang mit verschiedenen Energiebussen und -lasten verantwortlich und muss allen Subsystemen und Nutzlasten des Raumfahrzeugs robuste Energiekanäle bereitstellen. Das Stromversorgungssystem ist auch für die Sammlung und Analyse von Gesundheitsinformationen verantwortlich.

Aktuelle Arbeiten widmen sich der Entwicklung eines neuen EPS für 6 Unit CubeSat. Die vorläufige Idee besteht darin, das EPS in zwei Module zu unterteilen: Power Distribution (PDU) und Power Processing Unit (PPU). Während die PPU für das Aufladen der Batterie, die Energieumwandlung aus den Solarzellen und die Stromverarbeitung verantwortlich ist, wird die PDU für die Steuerung und die Stromüberwachung zuständig sein. Die vorliegende Arbeit befasst sich mit dem architektonischen Entwurf eines gesamten Systems, wobei der Schwerpunkt auf dem Entwurf einer Energieverteilungseinheit liegt, die für verschiedene Missionen einstellbar ist und für ein Power-Handling verantwortlich ist.

Diese Arbeit zielt darauf ab, eine vollständige Design-Iteration einer PDU des 6-Einheiten-CubeSat-EPS bereitzustellen. Es beginnt mit der Analyse des Leistungsbudgets des 6U-Satelliten. Danach wird die Architektur des EPS-Verteilers überprüft. Auf der Entwurfsseite werden die elektrische Schaltung und die Leiterplatte der Stromverteilungseinheit entwickelt, hergestellt und getestet..

Contents

List of Figures

List of Tables

1 Introduction

Due to significant amount of new Missions, German Orbital System took a step up to create a type of satellite bus for 6U satellite. As a result of updating the bus from 3U to 6U, satellite functions have improved, which opens up the possibility for more subsystems and components, as well as for payloads. The configuration of the separate power distribution unit made it possible to place more components on which the number of working subsystems and payloads increased. Development process of the satellite including EPS is taking a sizable amount of time, to use time more efficient was decided to divide the EPS in to two units and create an universal Power Distribution Unit which is admissible for 6 Unit as well as for a 3 Unit CubeSats.

1.1 Motivation

The motivation of this research is to find the optimal solution of the Power Distribution Unit architecture of Electrical Power System for the 6U CubeSat. Development of Power Distribution Unit will make a responsible use of time for a next missions, by development only a Power Processing Unit, which will be configured for each mission individually.

1.2 Objective

What kind of problem do you adress? Which issues do you try to solve? What solution do you propose? What is your goal? 'This thesis describes an approach to combining X and Y... The aim of this work is to...'

1.3 Scope

Here you should describe what you will do and also what you will not do. Explain a little more specific than in the objective section. 'I will implement X on the platforms Y and Z based on technology A and B.'

Conclude this subsection with an image describing 'the big picture'. How does your solution fit into a larger environment? You may also add another image with the overall structure of your component.

'Figure 1.1 shows Component X as part of ...'

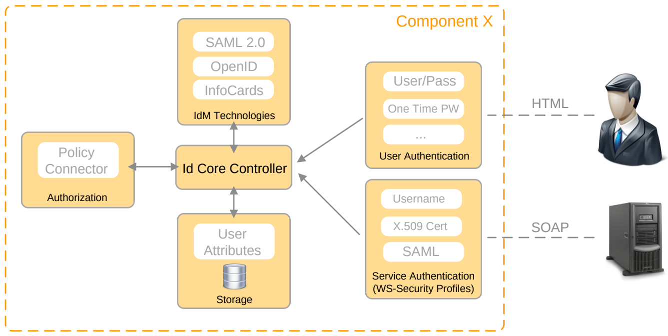

Figure 1.1: Component X

1.4 Outline

The 'structure' or 'outline' section gives a brief introduction into the main chapters of your work. Write 2-5 lines about each chapter. Usually diploma thesis are separated into 6-8 main chapters.

This example thesis is separated into 7 chapters.

Chapter 2 is usually termed 'Related Work', 'State of the Art' or 'Fundamentals'. Here you will describe relevant technologies and standards related to your topic. What did other scientists propose regarding your topic? This chapter makes about 20-30 percent of the complete thesis.

Chapter 3 analyzes the requirements for your component. This chapter will have 5-10 pages.

Chapter 4 is usually termed 'Concept', 'Design' or 'Model'. Here you describe your approach, give a high-level description to the architectural structure and to the single components that your solution consists of. Use structured images and UML diagrams for explanation. This chapter will have a volume of 20-30 percent of your thesis.

Chapter 5 describes the implementation part of your work. Don't explain every code detail but emphasize important aspects of your implementation. This chapter will have a volume of 15-20 percent of your thesis.

Chapter 6 is usually termed 'Evaluation' or 'Validation'. How did you test it? In which environment? How does it scale? Measurements, tests, screenshots. This chapter will have a volume of 10-15 percent of your thesis.

Chapter 7 summarizes the thesis, describes the problems that occurred and gives an outlook about future work. Should have about 4-6 pages.

2 Background: Electrical Power System Distribution Board

This section is intended to provide essential knowledge on Electrical Power System that will help to explain the development of Power Distribution Unit. Therefore, an overview of the EPS will be presented. The EPS power and data lines include protocols will be explained as well. Another subsection of this chapter provides a power consumption according to a modern space components. Also power budget of the satellite will be developed based on the power consumption of the modern space components.

2.1 Electircal Power System Overview

The Electrical Power Subsystem is a vital part of a CubeSat-Bus. It is responsible for generation and storage of energy, the processing of electrical power to a defined state and the distribution of power to all satellite subsystems. The EPS is a main, essential and frequently form the third of total spacecraft mass. Power generation technology combine a solar cells, charger. Power storage typically includes a batteries; primary batteries (non-rechargeable), or secondary batteries (rechargable). Power distribution consist of power switchers, which facilitate power control to a subsystems of the spacecraft.

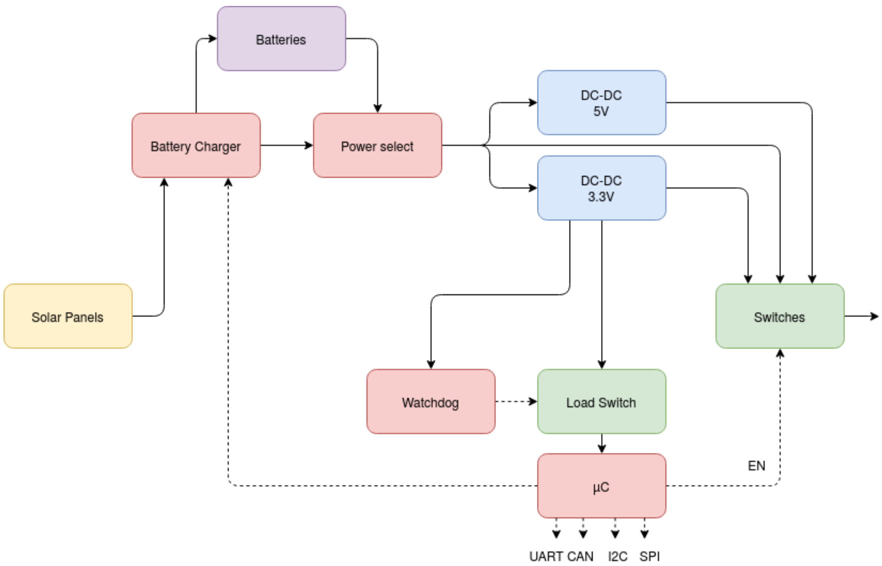

Figure 2.1: EPS Block Diagram

2.1.1 Power generation

Yost[1] Solar power generation is the most used method for the nano satellites to generate a power. Sollar cells are build of thin silicon disks (semiconductor wafers) which convert the energy of a light into electric current. Solar intensity of a solar array is light availability of the sun, which can vary according to a distance from the sun as well as angle of a projected surface area between the sun and a solar array.

Alia-Novobilski[2] The most common manufactured type of cells are single junction cells. Single junction type is commonly used on the Earth applications. Due to severe sensitivity to a space radiation energy and relatively low efficiency, single junction type is not preferable for a space applications. Although single junction solar cell is relatively cheap to design, modern spacecraft use a multi-junction solar cells. Manufactured of a light-absorbing materials, multiple layers are much tolerant to a radiation in a space environment and more efficiently Yost[1] "convert specific wavelength regions of the solar spectrum into energy, thereby using a wider spectrum of solar radiation". Green[3] In the space industry, triple-junction solar cells are the most common tu use due to their high efficiency and relatively affordable cost compared to an other types of solar cells.

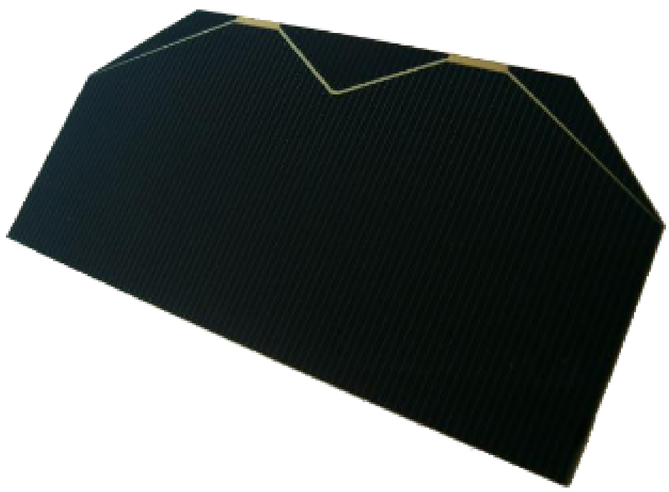

Figure 2.2: 30% Triple Junction GaAs Solar Cell [4]

Solar cells are usually interconnected to a solar array to get the desired power. Configuration of the solar array is flexible, such that it allowed adjustment of the cells connection. To achieve the desired voltage, solar cells get interconnected in series (strings). To achieve the desired current, solar cells get interconnected in parallel.

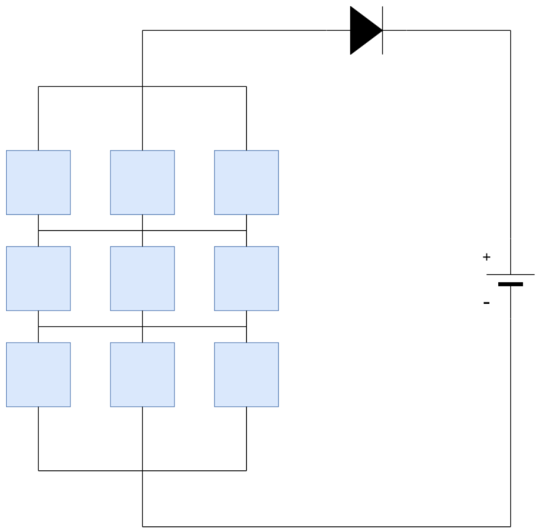

Figure 2.3: Solar array

Solar cell is strongly effected by a temperature. Honsberg[5] ”Increases in temperature reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material.”

Brieß[Kla18] The dependency of a temperature to the electric power can be described as:

$$P = P_{ref}[1 - K_P(T - T_{ref})] \tag{2.1}$$

where:
P_{ref} - Power at reference temperature
K_P - Correction factor of power losses, $0.005K^{-1}$
T_{ref} - Reference temperature (e.g. 25°C)

High temperature:

- reduce cell voltage
- increase a cell current
- reduce power

Low temperature:

- increase cell voltage
- reduce a cell current
- increase power

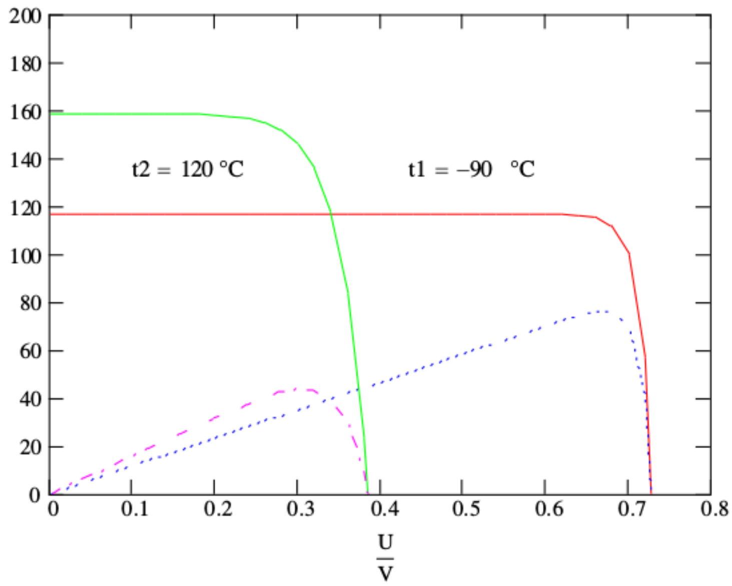

Figure 2.4: Solar cell characteristics at different temperatures[Kla18]

During the circuit design of the solar panels, it is important to consider the redundancy and a cause in which one of the cells will be damaged. For that reason diodes are used. The diodes ensure the power can bypass a damage solar cell. On the fig 2.5 shown that the diodes D1 and D2 are placed in th parallel with the solar cells. Diode D3 which also observed on the figure 2.3 is used to prevent the reverse current. Reverse current has a negative effect on the solar panel efficiency. When reverse current occurs, one effect is that current it's drawn from the batteries, therefore, discharging them. Secondly, reversed current adds additional current to the affected solar cell which shifts the maximum power point.

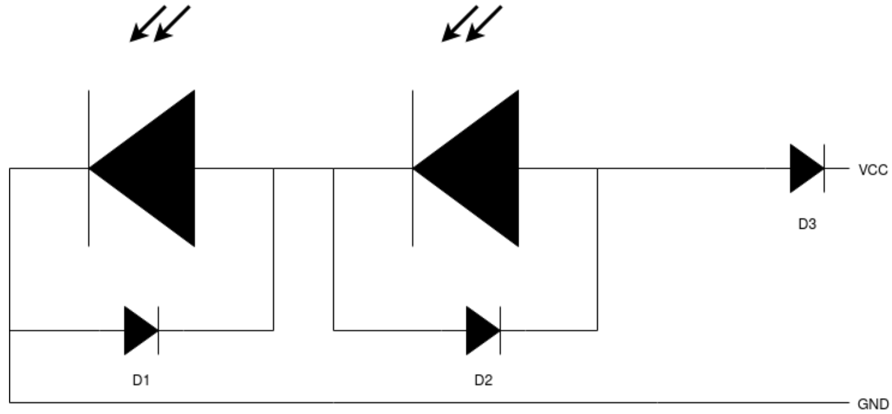

Figure 2.5: Solar cell characteristics at different temperatures

2.1.2 Power storage

Yost[1] During the the mission duration, solar energy is not always available due to eclipse. For this cause primary and secondary batteries used to store power. All batteries are classified according to their chemical characteristics. For a short mission duration (up to one week) usually used primary type of batteries due to it's lack of recharge opportunity. the common chemical type of a primary battery is a silver-zinc, which is easier to handle, Yost[1] "however there is also a variety of lithium-based primary batteries that have a higher energy density including: lithium sulphur dioxide (LiSO2), lithium carbon monofluoride (LiCFx) and lithium thionyl chloride (LiSOCl2) 20."

Secondary-type batteries are rechargeable and provide an energy on demand. Secondary-type batteries are connected to a primary energy source of the satellite (usually solar panels) via battery charger. This type include: nickel-cadmium (NiCd), nickel-hydrogen (NiH2), lithium-ion polymer(LiPo), lithium-ion(Li-ion).

Nickel Cadmium

Buchmann[7] Nickel Cadmium is a type of rechargable batteries using nickel oxide hydroxide and metallic cadmium. This chemical connection allowed battery to well perform by working in the savage conditions such as low or hot temperature. NiCd battery is the type which prefer to be charge fast instead of slow as types of secondary batteries. Full periodic discharge of a NiCd is an important process and necessary for battery performance. In case of absence Buchmann[7] " large crystals will form on the cell plates (also referred to as memory) and the NiCd will gradually lose its performance."

Advantages:

• Big variety of size and performance options
• Low price
• One of the most robust rechargeable batteries
• Good performance in the low temperature
• Simple and fast charge
• Big number of discharge cycles

Disadvantages:

• Low energy density
• NiCd has to be periodically discharged
• NiCd contains toxic metals

Figure 2.6: NiCd battery[9]

Nickel Hydrogen

Buchmann[7] Nowadays Nickel Hydrogen batteries are mostly used in the satellite applications where long time operation needed. The development of the NiH2 battery started in early 1970 year. In that time metal hybrid alloy was unstable, what slowed down development of the NiH2. In 1980 new alloy was established and stable enough to use it in the cell. [10]"The replacement of cadmium with hydrogen electrodes has double the energy of Ni-Cd, but the specific energy of Ni- H2 is similar to Ni-Cd because of the cylindrical configuration of the pressure. The first Ni- H2 battery was used in a GEO (geostationary mission) Intelsat V in 1983. Almost all GEO spacecrafts now use Ni-H2 batteries. The first NASA LEO spacecraft to use Ni-H2 was in 1990."

Wenige[8] Despite the fact that memory effect on NiH2 is undoubtedly less than on a NiCd batteries, it still exist and needs a special treatment in order to accommodate the normal level of the battery. Wenige[8] "Typical calendar life of more than 20 years can be reached by NiH2, i.e. five years ground storage plus 15 years orbital life in GEO."

Advantages:

- High energy density
- Environmentally friendly
- Cheap
- Less prone to memory effect
- Suitable for a long life Satellite missions

Disadvantages:

- Lose performance after deep discharge with high load
- Requires long charge time due to heat generation
- Require regular discharge to prevent memory effect
- More expensive than a NiCd
- Long life cycle

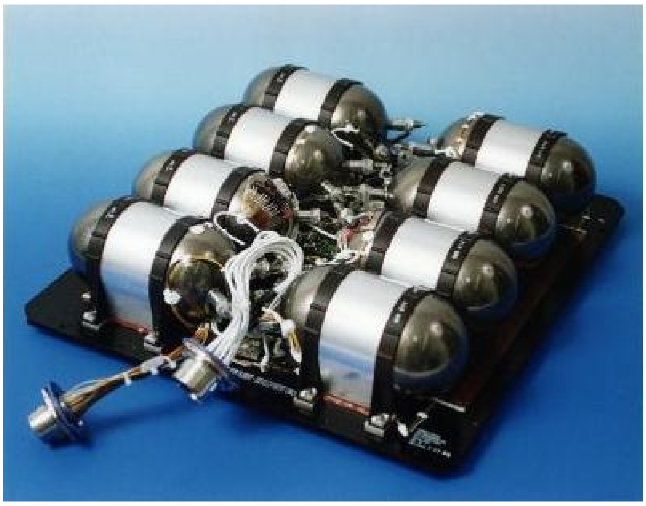

Figure 2.7: NiH2 battery [10]

Lithium Ion

Buchmann[7]Today lithium ion batteries is the most progressive and most promising batteries. Lithium is the lightest metal and able to provide the biggest energy density per weight. The energy density of a Lithium Ion batteries is about two times bigger then a NiCd. In addition, discharge characteristics of a Li-ion are similar to a NiCd, which offers a save utilization of a Li-ion batteries. Another advantage of a Li-ion batteries is a high cell voltage, which allows to allows to keep power properties with the light mass. Despite the fact that Li-ion batteries have many advantages, they also have their drawbacks. Li-ion batteries are very sensitive to an overcharge as well as an over discharge. For that reason Li-ion batteries usually used with protection circuits, which limit the peak voltage. In addition Li-ion batteries are prone to age even if not used Buchmann[7] Over two or perhaps three years, the battery frequently fails.

Advantages:

- High energy density
- Low self discharge
- No memory
- High cell voltage

Disadvantages:

- Require protection circuit
- Aging without using
- Does not apply for a long term use
- Proper storage needed

Figure 2.8: Li-ion battery [11]

Lithium Polymer

In 1970, when the original design of lithium polymer batteries was invented, dry solid polymer electrolyte was used instead of porous separator. Dry polymer design, allowed to simplify manufacture process and the most important - to have a thin thickness geometry. However Dry solid polymer electrolyte experienced poor conductivity due to internal resistance of a the battery. Thereby, gelled electrolyte has been added to enhance ion conductivity. LiPo batteries have a slightly lower energy density and amount of charge/discharge cycles compare to Li-ion batteries. Nonetheless LiPo batteries have a bigger overcharge tolerance, which making them more robust to overcharge conditions.

Advantages:

- Low profile
- Flexibility to produce any shape
- Weight
- Resistant to overcharge

Disadvantages:

- Lower energy density
- Expensive
- Does not apply for a long term use
- Proper storage needed

Figure 2.9: LiPo battery [12]

Charging

Santoni[STAP02]The hight capacity and low weight make Li-ion batteries very well suited for a nano satellite space applications. Nonetheless performance and safety charging issues should be taking into account. Insidor[14] The chargie of a LI-ion batteries is very strict on the correct settings, mostly due to a high sensitivity to a overcharge. Typical Li-ion battery voltage per cell can vary from 4.1 to 4.3, which is defined in the datasheet. However, typical and most common value is 4.2V. Exceed of a battery voltage limit will increase capacity, but will also stress a battery, which can seriously harm a cell and and significantly reduce battery performances.

Li-ion/Po battery charge process can be divided into 2 main stages:
• constant current charge
• constant voltage charge

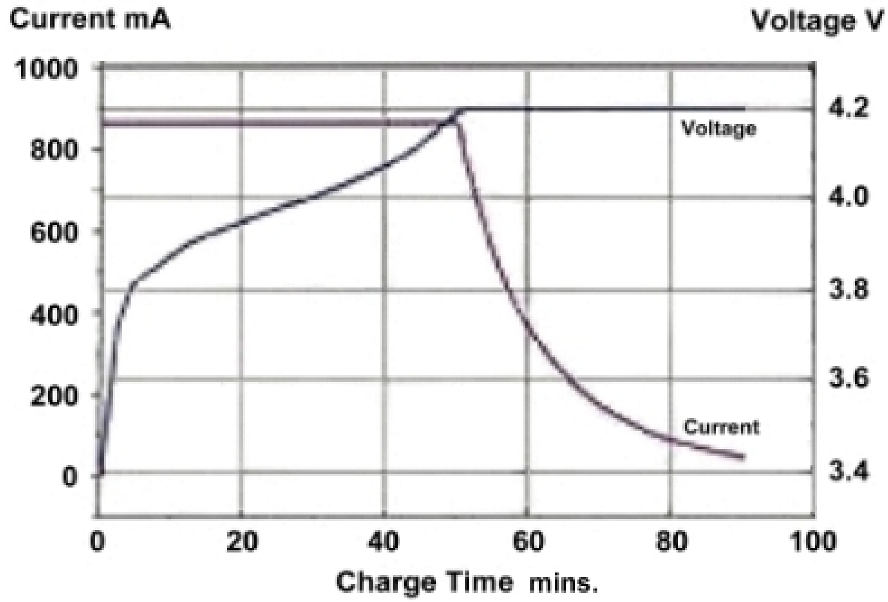

Figure 2.10: Charge stages [14]

Charging rate of a battery measures in C. In cause of 1000mAh battery cell 1C charging rate will be 1000mA and 500mA for 0.5C. Usually, recommended charging given in the datasheet.
Charging process starts with a 100% constant current (according to a charging rate) process. During the time while battery voltage reaching the upper voltage threshold, its pushing a constant current into a battery. Once voltage reaches threshold point, charging process changes from the constant current mode into a constant voltage mode. In a constant voltage mode, voltage keeps its maximum level while current starts to slightly drop until it gets down to a threshold level, which usually written in a datasheet (around 3%). After current drops below the threshold battery is fully charged.

In most cases, IC chargers are used to provide constant current and constant voltage for lithium-ion / Po batteries. [14] One of those IC chargers is a MAX745. This IC is able to set a charge up to 4 cells in series, as well as set a current and charging voltage. This IC use PWM signal to control a charge voltage which does not allowed IC to get too hot.
This IC is an example of a charger microchip which has all necessary tools to charge a Li-ion/Po batteries.

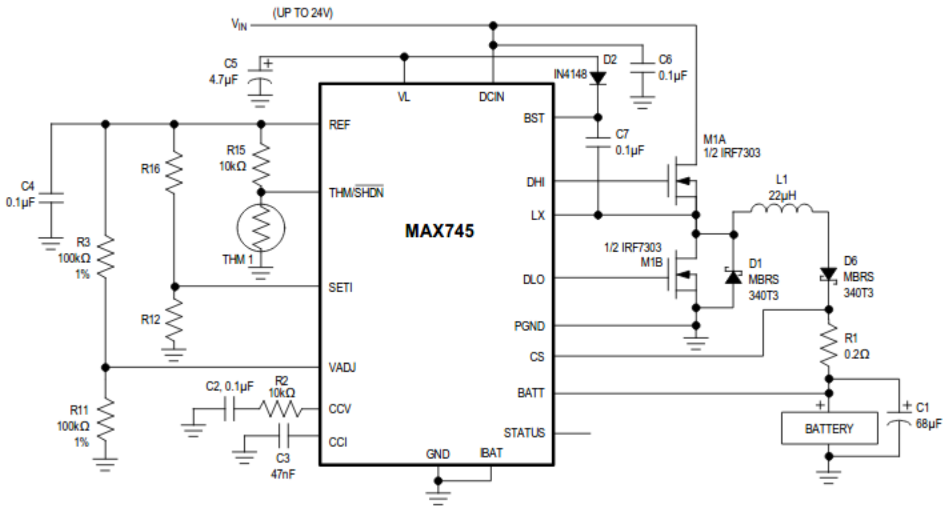

Figure 2.11: Li-ion/Po charger MAX745 [15]

The figure 2.11 shows an example of a standard MAX745 application circuit. On the left side of the schematics pins SETI and VADJ are used to adjust a charge voltage and charge current. External resistors R16,R12 are connected to a reference voltage to adjust a charge current and resistors R3,R11 used to adjust charge voltage. On the right side of the schematics MAX745 use two external N-channel MOSFETs which control power from the input source which controlled by current mode, PWM controller. [15]"The heart of the PWM controller is a multi-input com-parator. This comparator sums three input signals to determine the switched signal's pulse width, setting the battery voltage or current. The three signals are the current-sense amplifier's output, the GMV or GMI error amplifier's output, and a slope-compensation signal that ensures that the current-control loop is stable.The PWM comparator compares the current-sense amplifier's output to the lower output voltage of either the GMV or GMI amplifiers (the error voltage). This current-mode feedback reduces the effect of the inductor on the output filter LC formed by the output inductor (L1) and C1 figure 2.11. This makes stabilizing the circuit much easier, since the output filter changes to a first-order RC from a complex, second-order RLC."

Protection

Despite the fact that, Lithium-ion/Po batteries have a high density, they also require a careful handling. For that reason important to use safety protection circuits which prevent Li-ion/Po batteries from: overcharge, over-discharge and quick discharge.
[16] Overcharge of a Li-ion/Po batteries cause an immense battery stress which creates a safety hazard with a possibility of fire. Li-ion batteries have a less tolerance to an overcharge and require a protection circuit.
The over-discharge of a Lithium batteries is also harmful. The consequence of over-

discharge is a reduced battery life, due to the dissolution of copper from the anode into the electrolyte, which can cause a short circuit during a battery charge.
Protection ICs used to comply all upper mention conditions. A main principal of a protection IC is to switch on and off a power line usually by using external MOSFETs to keep a batteries safe and not exceed a voltage threshold. The simple example of a protection IC is a BQ29700D which is a one cell protection device.

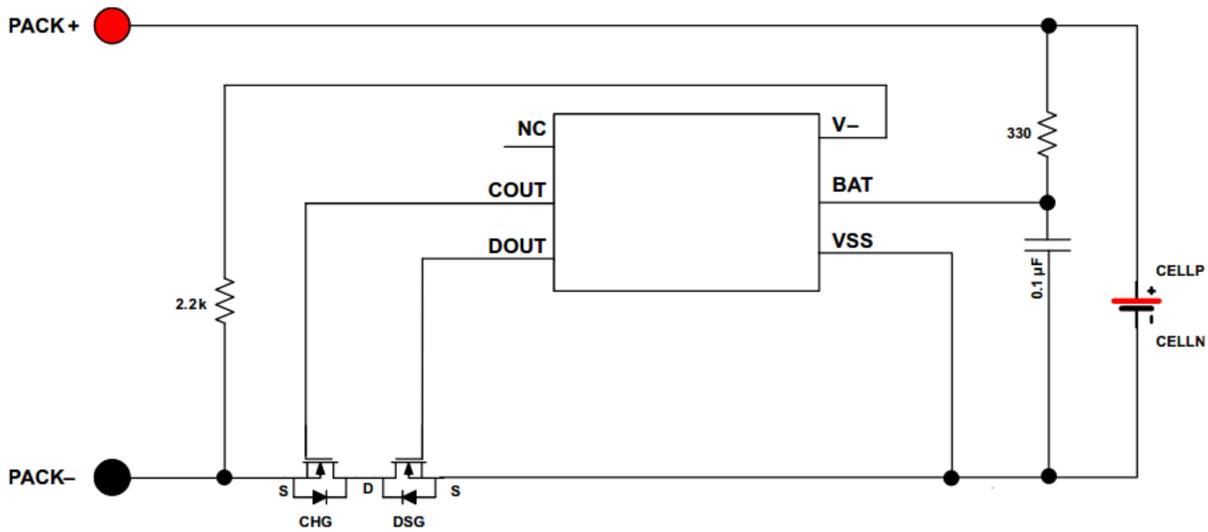

Figure 2.12: BQ29700D protection IC [Hem13]

Figure 2.13 illustrate a typical schematics of a protection circuit where BQ29700 connected with two MOSFETs defined as CHG and DSG, and a battery cell. In cause of overcharge detection, COUT pin pulls a CHG MOSFET which disconnect ground line and stops charging process. In cause ocer-discharge detection, DOUT pin pulls a DSG MOSFET which dissconect ground line and stops discharging process of a battery.

2.1.3 Power processing

Power processing is an important part of an EPS which is responsible for transforming voltages to be suitable for satellite subsystems and payloads. Nowadays there are many converters available; each type has it's own advantages and disadvantages. Hemmo[Ch.90] A converter has to be chosen according to subsystem requirements such as voltage range, maximum power output, output voltage tolerance, efficiency and footprint. The power efficiency of a converter is a very important criterion of stored energy due to the fact that battery energy is limited. High efficiency of power conversion reduces the power dissipation of components, thereby decreasing the power consumption if batteries. Furthermore, the need for any heat sinks is reduced or altogether eliminated.

Linear voltage converters

Hemmo[Ch.90] One of the oldest methods to convert a power is a linear voltage conversion. This method based on power dissipation into a resistor, which cause a voltage drop. Power dissipation of a linear voltage converter can be calculated by using formula:

$$P_{diss} = U_{drop} \times I \tag{2.2}$$

where:
U_{drop} - resistor voltage drop
I - current through a resisor

Tietze [Ch.90] Linear voltage conversion is a simple method, which does not require many additional passive components, relatively cheap and easy to use. Nonetheless due to a power dissipation linear voltage converters are getting hot, which make them ineffective while current through a resistor is large or difference between V_{in} and V_{out} is high according to (2.2). For that reason Linear voltage converters used only in cause of low current and low voltage drop for example to convert power into a micro controller or to provide a voltage reference.

There are two types of linear voltage voltage converters, the shunt converter and the series converter. The simple example of a linear voltage converter is a linear series regulator with a negative feedback. This type of a linear voltage converter based on reference voltage. Reference voltage can be proceed via z-diode from unregulated source voltage.

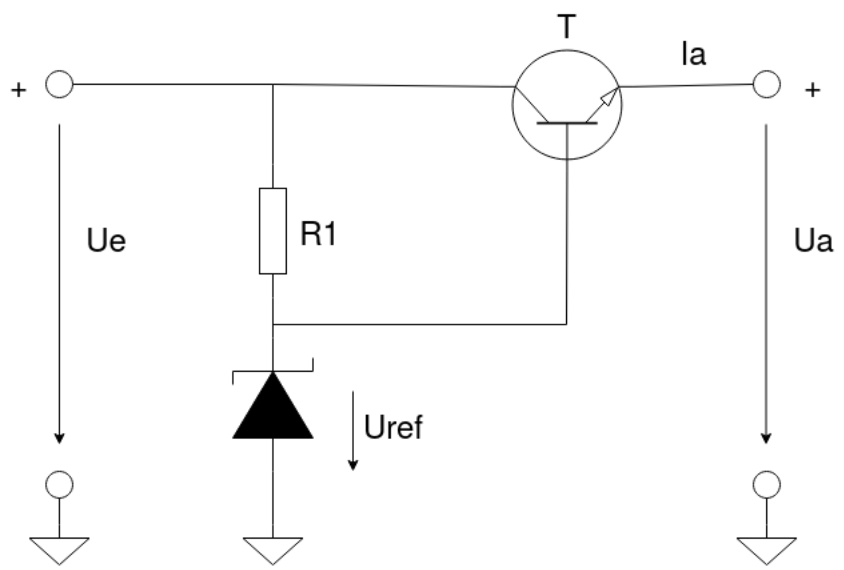

Figure 2.13: Voltage stabilization with emitter follower

Z-diode sets a constant voltage to a base of a NPN transistor. The output voltage can be defined by :

$$U_a = U_{ref} - U_{BE} \tag{2.3}$$

$$I_{R1} = I_{ref} + I_b \tag{2.4}$$

$$I_a = (\beta + 1)I_B \tag{2.5}$$

Z-diode is influenced by the base current of the NPN transistor which load is divided by a β parameter of a NPN transistor. Formula (2.4) illustrate that current flowing through R1 resistor equal to the sum of transistor base current and z-diode current. The output current of emitter I_a will be equal (2.5) according to a current of the base and its β parameter. There are other types of series voltage regulator exists, such as series voltage regulator with feedback.

Inductive DC-DC converters

Tietze[Ch.90] Each inductive DC-DC converter consist of three passive components: inductor L, power switch S and capacitor C. The use of these components in various topologies, allow to create various types of DC / DC converters such as a step-down converter where output voltage U_a , step-up (step-up) or step-down step-up converter.

2.2 PDU Overview

Nowadays most of the companies designing their Electrical Power System boards for a nano cubesats as whole unit, consisted of all important devices for power management. This configuration is common and allowed to create space for a hardware in the tiny cubesat which is essential for a nano satellites due to its limited size and mass.

Despite the fact that mechanical space of the satellite is important, the space on the EPS board is also limited for a components which is limiting satellite possibilities with bigger missions and more developed bus.

2.3 Technologies

One unit configuration is a common type of an EPS design, which is mostly used by nano cubesat developers. This type of EPS design allowed to combine all components of the EPS in one unit to save mechanical space for the rest of the bus hardware and a payload of a nano cubesat. Second type of technology is a separated type of the EPS which is divided in to Power Processing Unit (PPU) which is responsible for a power generation from a solar panels, battery charging and balancing as well as power processing and power convertation and Power Distribution Unit (PDU) which has a function of the power distribution. PDU consist mostly of switchers and current sensors, this architecture allowed to place significant amount of switchers and connectors for a payloads, which are necessary for a missions requiring amount of payload connections which will not be enough for a standard one unit EPS board type.

2.3.1 Load research

Due to the one of the requirements, to make PDU universal for all types of buses and payloads, development of the PDU require to have a detailed research of the newest bus and payload components and devices which are more likely to be used on the future satellites.

Considering that PDU distribute power to the bus and payload, one of the main requirements is to set a PDU to be able to handle different loads of a bus and payload. To accomplish this requirements it is necessary to know how much power each subsystem consume. Taking in to account that nano satallites produce usually from 2 to 22 W of power, depending on the satellite configuration, amount of payloads and subsystems are limited.

Here is a list of possible components for a subsystems with a power consumption, which can be considered as relevant.

Sun Sensors

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
Fine Sun Sensor	New Space Systems	0.035	0.01	33x11x6
BiSon64-ET-B	LR & D	0.0217	0.00175	49x49x17
BiSon74-ET	LR & D	0.0245	0.00175	49x49x17
SS-411	Sinclair Int.	0.034	0.0375	34x32x21
MAI-KE	Maryland aerospace	0.0055	0.005	50x19x2
Nano-SSOC-A60	SolarMEMS	0.004	0.001	27x14x5.9
NSS CubeSat	New Space Systems	0.005	0.0033	33x11x6

Magnetometers

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
Magnetometer	New Space Systems	0.085	0.75	96x43x17
MicroMag3	PNI Corp	0.2	0.0005	25x25x19
MAG-3	SpaceQuest	0.1	0.03	35x32x82
HMC2003	Honeywell	0.055	0.1	27x19x11
BMM150	Bosch	0.01	0.0005	1.56x1.56x0.6
LIS3MDL	ST	0.078	0.0002	2x2x1
Troyka Module	amperka	0.002	0.001	25.4x25.4x1

GPS Receivers

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
SGR-05U	Surrey	0.04	1	105x65x12
OEM615	Novatel	0.021	1	46x71x11
piNAV-NG	SkyFox Labs	0.024	0.5	67x40x10

Horison Sensors

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
MAI-SES	Adcole Maryland Aerospace	0.033	0.132	43.3x31.8x31.8
Mini Digital HCI	Servo	0.050	0.024	25.4x35x31.75

COMMS

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
HISPICO	Iqspaceco	0.1	5	95x46x15
Slink	Iqspaceco	0.46	13	65x65x13
Xlink	Iqspaceco	0.2	15	90x65x28

Startrakers

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
MAI-SS Space Sextant	AMA	0.282	1.5	50x50x47
ST200	BST	0.04	0.65	30x30x38
Standart NST	BCT	0.04	1.5	100x55x50
ST400	Hyperion	0.28	0.7	53.8x53.8x90.5
NST-3	TY-Space	0.165	0.65	50x50x50
AZDK-1	AZMERIT	0.19	0.5	56x60x93
ST	KU LEUVEN	0.025	1	95x50x45
STAR-T3	SPACE-INVENTOR	0.35	1	60x60x88
SBST-01	SATbyoul	0.175	0.3	56x60x92.8

Payloads

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
Argus 1000	Thorth	0.23	1.26	45x50x80
Gecko imager	SCS Space	0.48	3.5	97x96x60
DeCor	MSU	0.1	0.8	PC104
Aura	MSU	0.12	0.2	PC104
Linear transponder	GOS	0.1	2.6	PC104
MPS	Cosine	0.7	1.5	80x70x70
ECAM-C30	MSSS	0.25	0.25	78x58x45
ECAM-C50	MSSS	0.25	2.5	78x58x45
Monitoring cam	Cristal Space	0.27	0.5	82x88x39
CAM1U	Cristal Space	0.05	0.24	45x25x45
xScape100	Simera	1.2	4.5	100x100x200
TriScape	Simera	1.2	4.5	100x100x200
OS90	SatByl	1.4	4.2	98x98x243

Gyros

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
MASIMU01	Micro-AS	0.06	0.6	63.5x55.8x35.5
MASIMU02	Micro-AS	0.02	0.6	50x50x38
MASIMU03	Micro-AS	0.1	1.3	100x75x38
STIM202	Sensonor	0.05	1.5	35x38x20
STIM210	Sensonor	0.05	1.5	44.8x38.6x21.1
STIM300	Sensonor	0.05	1.5	44.8x38.6x21.1
M-G370	Epson	0.01	0.05	24x24x10
M-G362	Epson	0.01	0.05	24x24x10
M-V340	Epson	0.01	0.05	10x12x4
VN100	VectorNav	0.015	0.2	36x33x9
ADIS16334	Analog Devices	0.012	0.235	24x33x11
ADIS16350	Analog Devices	0.016	0.165	23.5x21x31
ADIS16365	Analog Devices	0.016	0.25	23.5x21x21

Magnetorquers

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
NCTR-M002	New Space	0.03	0.2	70x9x9
ISIS board	ISIS	0.2	1.2	95x90x17
MTQ board	Nanoavionics	0.2	0.55	pc104
GST-600	GomSpace	0.2	0.4	90.5x97x17
CubeRod	CubeSpace	0.03	0.2	60x10x10
MT01	EXA	0.007	0.25	50x50x3
MTQ200	Hyperion	0.04	0.225	80x10x10
CubeCoil	CubeSpace	0.05	0.2	96x90x6
NCTR-MO12	New Space	0.05	0.8	94x15x13
nanoMR	StarSpace	0.23	0.45	135x47x27
nanoMR2	StarSpace	0.06	0.18	70x14x14
nanoMTCoil	StarSpcae	0.04	0.1	80x80x3.2

Reaction wheels

Product	Manufacturer	Mass [kg]	Power [W]	Dimensions [mm^3]
RW-0.03	Sinclair Interp.	185	1.8	50x50x40
RW-0.003	Sinclair Interp.	0.05	0.3	33.5x33.5x17
RW-0.01	Sinclair Interp.	0.12	1	50x50x30
RW210	Hyperion	21-48	0.8	25x25x15
RW1	Astrofein	0,024	0.625	21x21x12
4RWO	Nanoavionics	0.137	0.1	43.5x43.5x24
Small	Cubespace	0.06	0.15	28x28x26.2
Small+	Cubespace	0.09	0.19	33.4x46x31.5
Medium	Cubespace	0.15	0.19	46x46x31.5
Cybermotor	Wittenstein	0.02	0.15	20x20x20
GSW600	GOMspace	0.18	0.5	44x44x27
RW	KU Leuven	0.05	0.6	40x40x28.9
REWL-30	Space inventor	0.055	-	30x30x18
RW40	Comat	0.26	0.5	65x65x40

Exmple: Tim-Berners-Lee describes the "WorldWideWeb" as follows:
"The WorldWideWeb (W3) is a wide-area hypermedia information retrieval initiative aiming to give universal access to a large universe of documents." [BL]

You can also cite different claims about the same term.
According to Bill Gates *"Windows 7 is the best operating system that has ever been released"* [Gat] (no real quote) In opposite Steve Jobs claims Leopard to be *"the one and only operating system"* [Job]

If the topic you are talking about can be grouped into different categories you can start with a classification. Example: According to Tim Berners-Lee XYZ can be classified into three different groups, depending on foobar [BL]:

- Mobile X
- Fixed X
- Combined X

2.3.2 Technology B

For internal references use the 'ref' tag of LaTeX. Technology B is similar to Technology A as described in section 2.3.1.

2.3.3 Comparison of Technologies

Name	Vendor	Release Year	Platform
A	Microsoft	2000	Windows
B	Yahoo!	2003	Windows, Mac OS
C	Apple	2005	Mac OS
D	Google	2005	Windows, Linux, Mac OS

Table 2.1: Comparison of technologies

2.4 Standardization

This sections outlines standardization approaches regarding X.

2.4.1 Internet Engineering Task Force

The IETF defines SIP as '...' [RSC^{+}02]

2.4.2 International Telecommunication Union

Lorem Ipsum...

2.4.3 3GPP

Lorem Ipsum...

2.4.4 Open Mobile Alliance

Lorem Ipsum...

2.5 Concurrent Approaches

There are lots of people who tried to implement Component X. The most relevant are ...

3 Requirements

This section determines the requirements necessary for X. This includes the functional aspects, namely Y and Z, and the non functional aspects such as A and B.

3.1 Overview

In this chapter you will describe the requirements for your component. Try to group the requirements into subsections such as 'technical requirements', 'functional requirements', 'social requirements' or something like this. If your component consist of different partial components you can also group the requirements for the corresponding parts.

Explain the source of the requirements.

Example: The requirements for an X have been widely investigated by Organization Y.

In his paper about Z, Mister X outlines the following requirements for a Component X.

3.2 Technical Requirements

The following subsection outlines the technical requirements to Component X.

3.2.1 Sub-component A

Interoperability
Lorem Ipsum...

Scalability
Lorem Ipsum...

3.2.2 Sub-component B

Lorem Ipsum...

3.3 Social Requirements

Component X must compete with Y. Hence, it is required to provide an excellent usability. This includes ...

4 Concept

This chapter introduces the architectural design of Component X. The component consists of subcomponent A, B and C.

In the end of this chapter you should write a specification for your solution, including interfaces, protocols and parameters.

4.1 Sub-component A

The concept chapter provides a high-level explanation of your solution. Try to explain the overall structure with a picture. You can also use UML sequence diagrams for explanation.

Figure 4.1 illustrates the situation between Alice and Bob. (sequence diagram from www.websequencediagrams.com)

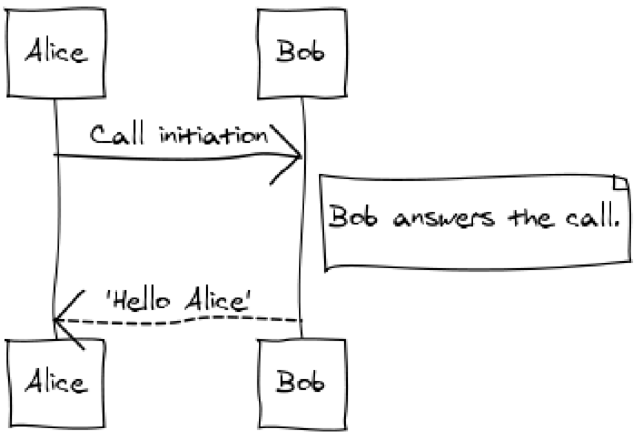

Figure 4.1: Alice and Bob

4.2 Sub-component B

Lorem Ipsum...

4.3 Proposed API

Lorem Ipsum...

4.4 Layer X

Lorem Ipsum...

4.5 Interworking of X and Y

Lorem Ipsum...

4.6 Interface Specification

Lorem Ipsum...

5 Implementation

This chapter describes the implementation of component X. Three systems were chosen as reference implementations: a desktop version for Windows and Linux PCs, a Windows Mobile version for Pocket PCs and a mobile version based on Android.

5.1 Environment

The following software, respectively operating systems, were used for the implementation:

- Windows XP and Ubuntu 6
- Java Development Kit (JDK) 6 Update 10
- Eclipse Ganymede 3.4
- Standard Widget Toolkit 3.4

5.2 Project Structure

The implementation is seperated into 2 distinguished eclipse projects as depicted in figure 5.1.

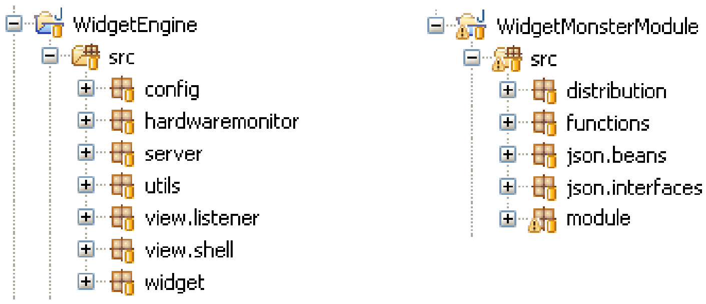

Figure 5.1: Project Structure

The following listing briefly describes the single packages of both projects in alphabetical order to give an overview of the implementation:

config
Lorem Ipsum...

server
Lorem Ipsum...

utils
Lorem Ipsum...

5.3 Important Implementation Aspects

Do not explain every class in detail. Give a short introduction about the modules or the eclipse projects. If you want to explain relevant code snippets use the 'lstlisting' tag of LaTeX. Put only short snippets into your thesis. Long listing should be part of the annex.

Listing 5.1: JSON String Code Snippet

```
{
        id: 1,
        method: "myInstance.getGroup",
        params: ["Teammates", 2, true]
}

{
        id: 2,
        result: [
                "groupDesc":"These are my teammates",
                {
                        "javaClass":"src.package.MemberClass",
                        "memberName": "Bob",
                }
        ]
}
```

You can also compare different approaches. Example: Since the implementation based on X failed I choosed to implement the same aspect based on Y. The new approach resulted in a much faster ...

5.4 Graphical User Interface

Lorem Ipsum...

5.5 Documentation

Lorem Ipsum...

6 Evaluation

In this chapter the implementation of Component X is evaluated. An example instance was created for every service. The following chapter validates the component implemented in the previous chapter against the requirements.

Put some screenshots in this section! Map the requirements with your proposed solution. Compare it with related work. Why is your solution better than a concurrent approach from another organization?

6.1 Test Environment

Fraunhofer Institute FOKUS' Open IMS Playground was used as a test environment for the telecommunication services. The IMS Playground ...

6.2 Scalability

Lorem Ipsum

6.3 Usability

Lorem Ipsum

6.4 Performance Measurements

Lorem Ipsum

7 Conclusion

The final chapter summarizes the thesis. The first subsection outlines the main ideas behind Component X and recapitulates the work steps. Issues that remained unsolved are then described. Finally the potential of the proposed solution and future work is surveyed in an outlook.

7.1 Summary

Explain what you did during the last 6 month on 1 or 2 pages!

The work done can be summarized into the following work steps

- Analysis of available technologies
- Selection of 3 relevant services for implementation
- Design and implementation of X on Windows
- Design and implementation of X on mobile devices
- Documentation based on X
- Evaluation of the proposed solution

7.2 Dissemination

Who uses your component or who will use it? Industry projects, EU projects, open source...? Is it integrated into a larger environment? Did you publish any papers?

7.3 Problems Encountered

Summarize the main problems. How did you solve them? Why didn't you solve them?

7.4 Outlook

Future work will enhance Component X with new services and features that can be used ...

List of Acronyms

3GPP	3rd Generation Partnership Project
AJAX	Asynchronous JavaScript and XML
API	Application Programming Interface
AS	Application Server
CSCF	Call Session Control Function
CSS	Cascading Stylesheets
DHTML	Dynamic HTML
DOM	Document Object Model
FOKUS	Fraunhofer Institut fuer offene Kommunikationssysteme
GUI	Graphical User Interface
GPS	Global Positioning System
GSM	Global System for Mobile Communication
HTML	Hypertext Markup Language
HSS	Home Subscriber Server
HTTP	Hypertext Transfer Protocol
I-CSCF	Interrogating-Call Session Control Function
IETF	Internet Engineering Task Force
IM	Instant Messaging
IMS	IP Multimedia Subsystem
IP	Internet Protocol
J2ME	Java Micro Edition
JDK	Java Developer Kit
JRE	Java Runtime Environment
JSON	JavaScript Object Notation
JSR	Java Specification Request
JVM	Java Virtual Machine
NGN	Next Generation Network
OMA	Open Mobile Alliance
P-CSCF	Proxy-Call Session Control Function
PDA	Personal Digital Assistant
PEEM	Policy Evaluation, Enforcement and Management
QoS	Quality of Service
S-CSCF	Serving-Call Session Control Function
SDK	Software Developer Kit
SDP	Session Description Protocol
SIP	Session Initiation Protocol
SMS	Short Message Service

SMSC	Short Message Service Center
SOAP	Simple Object Access Protocol
SWF	Shockwave Flash
SWT	Standard Widget Toolkit
TCP	Transmission Control Protocol
Telco API	Telecommunication API
TLS	Transport Layer Security
UMTS	Universal Mobile Telecommunication System
URI	Uniform Resource Identifier
VoIP	Voice over Internet Protocol
W3C	World Wide Web Consortium
WSDL	Web Service Description Language
XCAP	XML Configuration Access Protocol
XDMS	XML Document Management Server
XML	Extensible Markup Language
EPS	Electrical Power System
MPPT	Maximum Power Point Tracking

Bibliography

[1] *Bruce Yost. Power.* https://sst-soa.arc.nasa.gov/03-power. Accessed: 2020-02-19.

[10] *Batteries in Space.* https://www.upsbatterycenter.com/blog/batteries-space/. Accessed: 2020-02-25.

[11] *18650 battery 3.7 Li-ion.* https://www.ebay.de/itm/18650-Battery-3-7V-3000mAh-Li-ion-Rechargeable-Cell-For-Headlamp-Torch-Radio-D8-/254352951966. Accessed: 2020-02-25.

[12] *Renata ICP303450PA LiPo.* https://www.conrad.de/de/p/renata-icp303450pa-spezial-akku-prismatisch-kabel-lipo-3-7-v-500-mah-1214020.html?WT.mc_id=google_pla&WT.srch=1&ef_id=Cj0KCQiAwP3yBRCkARIsAABGiPp-kEbfaUMu4N7Z-01Uy28KpGE9v4nHiCX5T7MrBQiYGYc0SRUbBRwaAh8
wcB:G:s&gclid=Cj0KCQiAwP3yBRCkARIsAABGiPp-kEbfaUMu4N7Z-01Uy28KpGE9v4nHiCX5T7MrBQiY
wcB&hk=SEM&s_kwcid=AL!222!3!326955887699!!!g!! Accessed: 2020-02-25.

[14] *Charging Lithium-ion.* https://batteryuniversity.com/learn/article/charging_lithium_ion_batteries. Accessed: 2020-02-25.

[15] *MAX745.* https://datasheets.maximintegrated.com/en/ds/MAX745.pdf. Accessed: 2020-02-26.

[16] *Li-ion cell protection.* https://www.digikey.com/en/maker/blogs/lithium-ion-cell-protection. Accessed: 2020-02-30.

[2] *Alia-Novobilsk. Advanced multi-junction solar cells deliver high efficiency, reduced costs for space.* https://phys.org/news/2018-01-advanced-multi-junction-solar-cells-high.html#jCp. Accessed: 2020-02-19.

[3] *Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002., New Orleans, LA, USA, 2002, pp. 1330-1334. (Third generation photovoltaics: comparative evaluation of advanced solar conversion options,).*

[4] *30 Triple Junction GaAs Solar Cell Type: TJ Solar Cell 3G30C.* http://www.azurspace.com/images/products/0004148-00-01_DB_GBK_80%C2%B5m.pdf. Accessed: 2020-02-20.

[5] *Effect of Temperature.* https://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-temperature. Accessed: 2020-02-21.

[7] *What's the Best Battery.* https://batteryuniversity.com/learn/archive/whats_the_best_battery. Accessed: 2020-02-22.

[8] *POWER STORAGE FOR SMALL SATELLITES: COMPARISON OF NIH2 AND LIION BATTERIES.* https://www.dlr.de/iaa.symp/Portaldata/49/Resources/dokumente/archiv5/1103_Wenige.pdf. Accessed: 2020-02-23.

[9] *Saft VT D NiCd.* https://www.akkushop.de/de/saft-vt-d-nicd-mono-akku-hochtemperatur-ca.-603mm-x-323mm/. Accessed: 2020-02-24.

[BL] Berners-Lee, Tim: *WWW Book (no real book, just an example).*

[Ch.90] Ch.Schenk, U.Tietze.: *Halbleiter-Schaltungstechnik.* Springer-Verlag, 1990.

[Gat] Gates, Bill: *no real citate.*

[Hem13] Hemmo, Jussi: *Electrical Power Systems for Finnish Nanosatellites.* 100:95, 11 2013.

[Job] Jobs, Steve: *no real citate.*

[Joh03] Johnston, Alan B.: *SIP, understanding the Session Initiation Protocol, Second Edition.* Artech House Publishers, 2003. ISBN: 1580536557.

[Kla18] Klaus, Briess: *Electrical Power Subsystem.* Satellite Technology, 2018.

[RSC+02] Rosenberg, J., H. Schulzrinne, G. Camarillo, A. Johnston, J. Peterson, R. Sparks, M. Handley and E. Schooler: *SIP: Session Initiation Protocol.* RFC 3261 (Proposed Standard), June 2002. Updated by RFCs 3265, 3853, 4320, 4916, 5393.

[STAP02] Santoni, Fabio, Paolo Tortora, F. Alessandrini and Stefano Passerini: *Commercial Li-Ion Batteries for Nanosatellite Applications - a Flight Experiment.* 502:653, 04 2002.

Annex

```
<?xml version="1.0" encoding="UTF-8"?>
<widget>
         <debug>off</debug>
         <window name="myWindow" title="Hello Widget" visible="true">
                 <height>120</height>
                 <width>320</width>
                 <image src="Resources/orangebg.png">
                        <name>orangebg</name>
                        <hOffset>0</hOffset>
                        <vOffset>0</vOffset>
                </image>
                 <text>
                         <name>myText</name>
                         <data>Hello Widget</data>
                         <color>#000000</color>
                         <size>20</size>
                         <vOffset>50</vOffset>
                         <hOffset>120</hOffset>
                 </text>
        </window>
</widget>
```

Listing 1: Sourcecode Listing

```
INVITE sip:bob@network.org SIP/2.0
Via: SIP/2.0/UDP 100.101.102.103:5060;branch=z9hG4bKmp17a
Max-Forwards: 70
To: Bob <sip:bob@network.org>
From: Alice <sip:alice@ims-network.org>;tag=42
Call-ID: 10@100.101.102.103
CSeq: 1 INVITE
Subject: How are you?
Contact: <sip:xyz@network.org>
Content-Type: application/sdp
Content-Length: 159
v=0
o=alice 2890844526 2890844526 IN IP4 100.101.102.103
s=Phone Call
t=0 0
c=IN IP4 100.101.102.103
m=audio 49170 RTP/AVP 0
a=rtpmap:0 PCMU/8000

SIP/2.0 200 OK
Via: SIP/2.0/UDP proxy.network.org:5060;branch=z9hG4bK83842.1
;received=100.101.102.105
Via: SIP/2.0/UDP 100.101.102.103:5060;branch=z9hG4bKmp17a
To: Bob <sip:bob@network.org>;tag=314159
From: Alice <sip:alice@network.org>;tag=42
Call-ID: 10@100.101.102.103
CSeq: 1 INVITE
Contact: <sip:foo@network.org>
Content-Type: application/sdp
Content-Length: 159
v=0
o=bob 2890844526 2890844526 IN IP4 200.201.202.203
s=Phone Call
c=IN IP4 200.201.202.203
t=0 0
m=audio 49172 RTP/AVP 0
a=rtpmap:0 PCMU/8000
```

Listing 2: SIP request and response packet[Joh03]