Unmanned Solar Powered Airship Concept Evaluation

Critical Design Report

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Acronyms

APR Array Power Regulator

BCR Battery Charge Regulator

BJT Bipolar Junction Transistor

CDR Critical Design Review

COTS Commercial Of-The-Shelf

DM Development Model

ECSS European Cooperation for Space Standardization

EGSE Electrical Ground Support Equipment

EMC Electromagnetic Compatibility

EMI Electromagnetic Interference

EPS Electrical Power System

FM Flight Model

GaAs Gallium Arsenide

GPS Global Positioning System

IC Integrated Circuit

IGBT Insulated Gate Bipolar Transistor

IRF Swedish Institute of Space Physics

ITPU Imaging and Tracking Payload Unit

ITU International Telecommunication Union

LTU Luleå University of Technology

MCC Motor Control and Communication

MEA Main Error Amplifier

MGSE Mechanical Ground Support Equipment

MPP Maximum Power Point

MPPT Maximum Power Point Tracking

MPPTU Maximum Power Point Tracking Unit

MSE Mechanical Structure and Envelope

NTC Negative Temperature Coefficient

OpAmp Operational Amplifier

PCB Printed Circuit Board

PDR Preliminary Design Review

PSA Pressure Sensitive Adhesive

PWM Pulse Width Modulated

SA Solar Array

SAR Solar Array Regulator

SPA Solar Powered Airship

SSC Swedish Space Corporation

TBD To Be Decided

TV Thermal Vacuum

U-SPACE Unmanned Solar Powered Airship Concept Evaluation

UAS Unmanned Aircraft System

UVP Under Voltage Protection

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Chapter 1

Introduction

Unmanned Solar Powered Airship Concept Evaluation (U-SPACE) is a student project at the Rymdcampus of the Luleå University of Technology (LTU) in Kiruna under the supervision of Kjell Lundin (Swedish Institute of Space Physics (IRF)) and Alf Wikström (LTU). It is supported by the IRF and LTU. The goal of this project is to prove the concept of a small-scale student-built unmanned Solar Powered Airship (SPA). The solar cells that power the airship are mounted on a gas-filled envelope, with forward propulsion being achieved by propellers mounted onto the same envelope. The airship communicates via two separate wireless connections with a controller and a ground station. These communication channels enable human control over the airship, together with the retrieval of housekeeping and scientific payload data. The payload data consists of measurements from several sensors (magnetometer, accelerometer, gyroscope and Global Positioning System (GPS)) and images collected by a small on-board camera. On the ground station, the image data and the sensor data can be combined to construct an aerial map of the flight environment.

The concept of a SPA has attracted major interest in recent years [1, 2, 3, 4, 5, 6, 7, 8]. Applications for this type of airship reach far and wide, ranging from passenger and cargo transport [2, 5, 7, 8] over scientific research [3] and surveillance [1, 6, 7] to planetary exploration [4]. Also the actual implementation of the SPA concept varies greatly. Solar Ship [8] is a hybrid of an aircraft and an airship, while Project Sol'r [5] has the intention of building a manned SPA, in contrast to many of the other implementations. Some airships are intended for low-altitude flight [5, 7], while other airships are meant to fly at 18 km altitude or above [1, 3, 6]. Regardless of their exact implementation or application all SPAs benefit greatly from the advantages of this concept: simple flight control, reduced fossil fuel consumption and access to long duration flights. Apart from these inherent strong points, other advantages of SPAs are the possibility for autonomous take-off and landing, the elimination of large infrastructures like airports, reduced weather constraints and relatively low costs [1, 2].

Even though many research groups and commercial companies have investigated the possibilities of SPAs, very few student-driven projects exist. Projet Sol'r [5] for example, created by a team of French students, has the intention of piloting a SPA across the English Channel. This team is the exception in all projects discussed previously. The above-mentioned advantages of SPAs and the fact that few student projects exist, were the main drivers for the creation of the U-SPACE project at LTU.

1.1 Hardware

The hardware for the U-SPACE project can be divided into four subsystems, as visualized in the block diagram of figure 1.1. This hardware is present both in the airborne structure (the SPA) and in the ground-based part of the project.

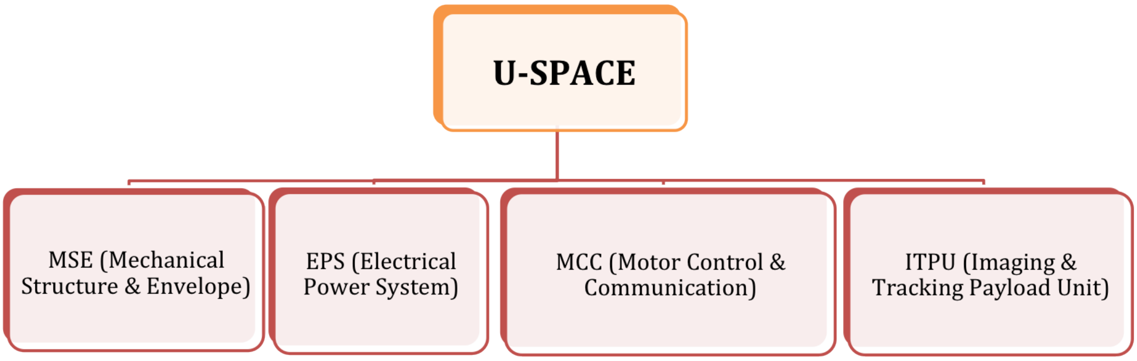

Figure 1.1 – *Hardware block diagram of the U-SPACE project.*

1.1.1 On-board Hardware

The first subsystem is the Mechanical Structure and Envelope (MSE). This subsystem is the principal mechanical structure of the airship. It includes a gas-filled envelope, a payload bay and structures to mount both the solar cells and the propellers. This subsystem is the support for all other subsystems and provides the lift to allow the SPA to fly. The second subsystem, the Electrical Power System (EPS), is responsible for generating solar power, distributing this power to all other subsystems and storing the generated energy when required. It makes use the MSE subsystem which supports the solar cells, while it also allows both forward propulsion and the generation of scientific payload data. The third subsystem, Motor Control and Communication (MCC), takes care of the forward propulsion of the airship by employing propellers mounted onto motors. The structural link to the airship is the responsibility of the MSE, while power is provided by the EPS. The motors are controlled via a wireless connection, which is also the responsibility of this subsystem. The final subsystem, the Imaging and Tracking Payload Unit (ITPU), is the scientific payload of the SPA. It consists of several different sensors (including a magnetometer, an accelerometer, a gyroscope and a GPS) mounted inside the payload bay (part of the MSE). The data from these sensors is processed with the help of a microcontroller. The payload bay also contains a camera which can take pictures from the ground that are saved on board or transmitted to a ground station via a second wireless connection. The sensor data is also sent to the ground station via this wireless connection. The power for the sensors, the microcontroller, the camera and the wireless connection is provided by the EPS.

1.1.2 Ground-based Hardware

The hardware for the ground station and for the wireless control are respectively part of the ITPU and MCC subsystems. This hardware consists of a receiver for the scientific payload data and a transmitter/receiver for the control of the SPA. In order to present the scientific payload data from the sensors and the camera, a means to visualize this ITPU data is required as well.

1.2 Software

The software required for the U-SPACE project is only present in the on-board ITPU subsystem and the ground station used to receive the scientific payload data from this subsystem. The other subsystems do not require the development of any software. A block diagram of the software is presented in figure 1.2.

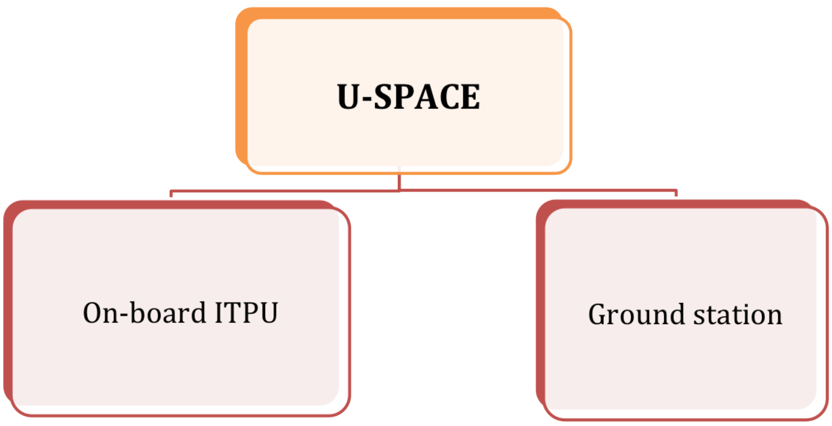

Figure 1.2 – *Software block diagram of the U-SPACE project.*

1.2.1 On-board Software

The software on board the SPA reads the data from the sensors (magnetometer, accelerometer, gyroscope and GPS) and fuses this data in order to obtain more accurate information about the orientation and position of the airship. The software is also responsible for sending this scientific payload data to the ground station via the dedicated wireless connection. Finally the on-board software is needed to control the camera and to take pictures from the ground below the airship. The pictures are saved on board or sent to the ground station via a wireless connection.

1.2.2 Ground-based Software

The ground station also requires the development of some software. This software is mainly responsible for receiving sensor data from the airship via the wireless connection, but it is also needed for the visualization of the scientific payload data. It runs an algorithm that combines the data from the sensors and the images taken by the camera in order to obtain a complete aerial map of the landscape over which the SPA is flying.

1.2.3 Operational Modes

With the development of the on-board and ground-based software modules, several operational modes become possible in the U-SPACE project. The basic modes are listed below:

1. Read out data from sensors and fuse the data
2. Control the camera to take pictures from the ground
3. Combination of mode 1 and mode 2

Chapter 2

Goals and Constraints

2.1 Project Goals

The principal goal of the U-SPACE project is to try and bridge the gap between a student-driven engineering project and the concept of an unmanned SPA. As very few examples of this type of design exist [5], much is to be gained from this project. Due to the many constraints that have to been taken into account (see section 2.2), the goal is necessarily modest. The goal of this project is thus designing, building and testing a small-scale SPA for low altitude flight, including support for a scientific payload. The basic targets are listed below:

- Design of a small unmanned SPA capable of forward propulsion, powered by solar cells and including a scientific payload
- Construction of such an SPA with minimal cost
- Flight test of this SPA at low altitude

2.2 Project Constraints

The design, construction and test of a small unmanned SPA is susceptible to many constraints, all of which have to be identified, examined and finally dealt with. These constraints take many forms, but may be divided into four categories: functionality, resources, environment and law.

2.2.1 Functionality

The U-SPACE project, being a proof of concept, consists of designing, building and testing a small version of a SPA with a limited scientific payload. Therefore reasonable limits have to be taken into account for some technical parameters. These parameters and their limits are listed below in table 2.1.

Table 2.1 – *Functional parameters and limits*

Parameter	Lower limit	Upper limit
Total mass	/	4.5 kg
Flight altitude	2 m	100 m
Electrical power	/	8 W
Forward velocity	/	1 m/s
Radius	10 m	/

2.2.2 Resources

Since the U-SPACE project is a student project supported by LTU and IRF, the available resources are limited. This imposes stringent constraints on all phases of the project. The main resources can be identified as the three elements of the project management triangle, shown in figure 2.1.

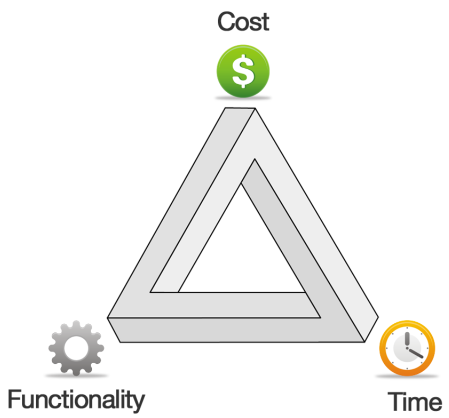

Figure 2.1 – *Project management triangle [9].*

The cost of this student project is limited by its approved budget, a sum between 10,000 and 12,500 SEK, provided by LTU. More funding can be applied for if required, but the budget nevertheless remains limited. This constraint implies a careful selection of components and the use of innovative engineering solutions throughout the entire project.

The time available for this project is also constrained, being a student project that has to be realized in concurrence with other academic duties. The estimated time frame is therefore between 2 and 6 months for a first prototype capable of test flight.

The final resource is related to the previously mentioned functionality. With a limited number of team members that have limited expertise in the field of airships, the project has to be technically balanced, taking into account the capabilities of the members of the team.

2.2.3 Environment

The SPA that will be developed during the U-SPACE project finally has to be tested outdoors. Since the U-SPACE project is being executed in the city of Kiruna during the spring, summer and early autumn, it is important to take the environmental conditions during this period of the year into account. Some of the these conditions are listed below in table 2.2, using data for the month of May [10] as a representation of the entire project period.

Table 2.2 – *Environmental conditions*

Parameter	Lower boundary	Upper boundary	Remarks
Temperature	-2 °C	11 °C	Average values
Wind speed	1 m/s	6 m/s	Usually from the south w
Probability of precipitation	61 %	61 %	Average value
Hours of sunshine	17:38 h	22:45 h	Daily values
Cloud cover	83 %	83 %	Median value
Solar incidence angle	46 °	46 °	Refer to document USPACE-PD

2.2.4 Law

The final constraints that have to be taken into account are possible legal issues that may arise during the construction and testing of the SPA. A first legal constraint is the compliance to the International Telecommunication Union (ITU) Radio Regulations [11] when using wireless connections. Secondly, when flying the SPA, the Swedish Transport Agency's regulations on Unmanned Aircraft System (UAS) [12] might have to be taken into account. As these application of these regulations depends on the final mass and size of the prototype airship, this constraint can only be investigated when a prototype is constructed.

2.3 Expected Functionality

Based on the project goals set forth in section 2.1 and taking into account the constraints discussed in the previous section, a realistic prediction of the functionality of the final product of the U-SPACE project can be made. The expected functionality of the small-scale SPA are summarized in table 2.3.

Table 2.3 – *Expected functionality*

Parameter	Value	Remarks
Autonomy	2 h	At peak power
Flight altitude	2-20 m	/
Forward velocity	0.5-1 m/s	/
Flight conditions	Daytime	Sunny and calm weather

The other functional constraints presented in section 2.2 will be discussed in subsequent chapters. In the future, this functionality might be expanded with features like autonomous attitude control and altitude control during flight.

2.4 Fault Tolerance Design and Safety Concept

Since the goal of the U-SPACE project is to design, build and test a prototype of a small-scale SPA the focus of this project is not on a fault-tolerant design of the airship, but rather on a performant design that meets the project goals. Nevertheless some safety features are included in the design, construction and flight test of the airship. These features will be discussed in the chapters dedicated to the different subsystems and in chapter 9.

2.5 Materials

With the limited time and funding inherent to this student-driven project great care needs to taken with regards to the selection and processing of the materials. The materials need to be as performant as possible for their specific function while at the same time their cost should be as low as possible. In general all materials should also be as light as possible. The specific material requirements for each subsystem are discussed in the subsequent chapters.

With regards to the processing of the materials, low cost is again the main discriminator to select an appropriate technique. Therefore the simplest techniques are preferred during the construction of the airship, with as less mechanical work as possible. A certain amount of experience with such techniques is present in the team, allowing short construction times and limited delays.

Chapter 3

Mechanical Structure and Envelope

This subsystem is considered to be the foundation of the whole airship, given that it has to act as the pillar that withstands and holds all the other subsystems together. Aside from this structural requirements, it also includes the device that will be generating lift, which is in this case the same blimp. This adds to the picture additional light weight requirements, which consequences will be explained on this section.

The fact that we decided to use the ESRANGE blimp, rather than building our own due to the time constraint, has modified virtually every single requirement that was previously estimated in the preliminary calculations (see PDR). Therefore, one of the aspects that will be covered in this document are the updated requirements and constraints together with the view on the possible alternatives to overcome the problems that we are currently facing with the project. Nevertheless, the current design under construction will be also presented, however the reader should bear in mind that this are only guidelines to take the firsts steps, given that the design is not closed due to the uncertainty surrounding the final components to be used.

3.1 Functional and Technical Requirements

This section will cover the updated requirements that are consequence of the choices taken during the evolution of the project. As it will be seen, obviously the functional requirements have not change, however the same cannot be said about the technical ones.

3.1.1 Functional Requirements

- The structure has to be stable aerodynamically

- The structure has to act has a support for the solar cells and/or the payload
- The lift has to be large enough to overcome the weight of the total system
- The material of the balloon must have low diffusivity

3.1.2 Technical Requirements

The previous calculated/estimated parameters have been modified to fit the constraints imposed by the ESRANGE blimp.

- Lenght = 4.88 m
- Diameter = 1.89 m
- Volume = 15 cubic m
- Max. Lift Weight = 2.59 kg
- Max. Lift Payload Weight = 0.5 kg
- Max. Lift Structure Weight = 1 kg
- Max. Lift Power System Weight = 1 kg

Comparing the new available maximum lift weight provided by the blimp, it can be seen that the new total weight is half of the one that it was initially assumed on the PDR. This entails that the weight budgets available for each of the subsystems had to be redistributed. For this system in particular, the consequence was a complete redesign of the structure, leaving the initial idea of a rigid structure completely out of place. The next section will explain how this design was redone with the corresponding suggested new structure components.

3.2 Mechanical and Structural Design

As was mentioned in the Preliminary Design Review (PDR), the initial mechanical design of the U-SPACE project included the development of a blimp (envelope) that would then accommodate the solar panels of the EPS, the cargo bay for the ITPU and the propelling system of MCC. An initial sketch of this concept is presented in figure 3.1.

This simplified view of the mechanical design shows that it included the total development of the envelope of the airship. The idea was to include the solar panels on the top, mounted on a wired mesh, with the cargo bay attached in the bottom together with the propelling system.

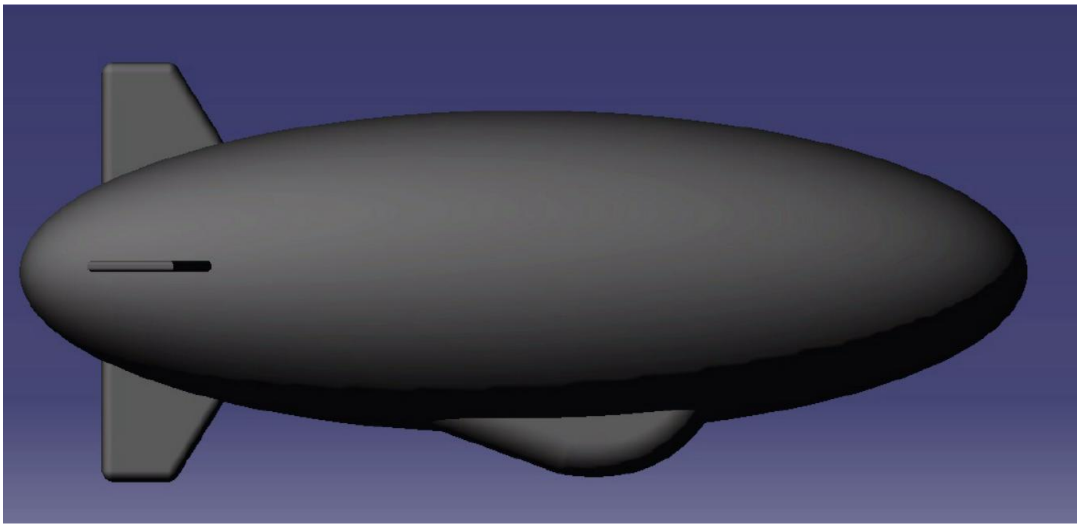

Figure 3.1 – *Initial 3D sketch of the airship*

However, due to new developments in the project that included the introduction of an already built blimp (envelope), the focus of the mechanical design changed. The blimp to be used would be the TIF - 250 (Tethered Aerostats), shown in figure 3.2. This blimp has the capacity to lift a payload of about 2.5 kg, has a length of approximately 5 m and has a diameter (in the center) of about 1.9 m.

This blimp serves the purpose of the U-SPACE project very well, as its use would allow to focus only on the construction of the support for the power system, the cargo bay (for the payload) and the integration of the propelling system. However, because it is a ready-built blimp with a purpose different than the one envisioned, it is not as lightweight as might be needed. Nevertheless, an effort will be made to include light structures in the integration of all the other systems in this airship.

3.2.1 Envelope

As it was already stated, the blimp to be used is a ready-built one. This blimp is normally used to accurately measure the wind direction. Nevertheless it will have to fit the purpose of the U-SPACE project, due to the lack of time to build a new envelope. This way, the envelope is constituted by the blimp itself.

3.2.2 Cargo Bay

The cargo bay is intended to accommodate both the payload and the electronics required for the purpose of the project. The main challenge in the construction of this cargo bay is the weight. It has to be lightweight (the total maximum weight of all the structures should be less than 1 kg) but at the same time rigid enough to resist some stress during the normal operation of the airship. To achieve this, balsa wood reinforced with carbon fibres

Figure 3.2 – *TIF - 250 Blimp*

was used. Figures of the expected final cargo bay design and of the current construction status are presented in figures 3.3 and 3.4, respectively.

3.2.3 Power System

The biggest challenge of this project is to accommodate the power system, taking into account the maximum lift weight and also the power requirements that consequently influence the solar panel quantity and weight. Because different solar panels are still under test, it is still not decided how they will be mounted on the blimp. Nevertheless, the idea is to use a lightweight wired mesh that serves as a support to the solar panels, which are attached to the wires with carbon fibre. This mesh will then be connected to the blimp making use of 3 bands that will round the blimp, distributing the weight along the envelope. These bands will be made of fibre glass reinforced rubber tape. An idea of how the final product should look like is presented in figure 3.5.

3.2.4 Propelling System

The propelling system is to be integrated in a carbon fibre rod mounted on the top of the cargo bay. The 2 motors will be attached at the ends of the rod, outside the influence of

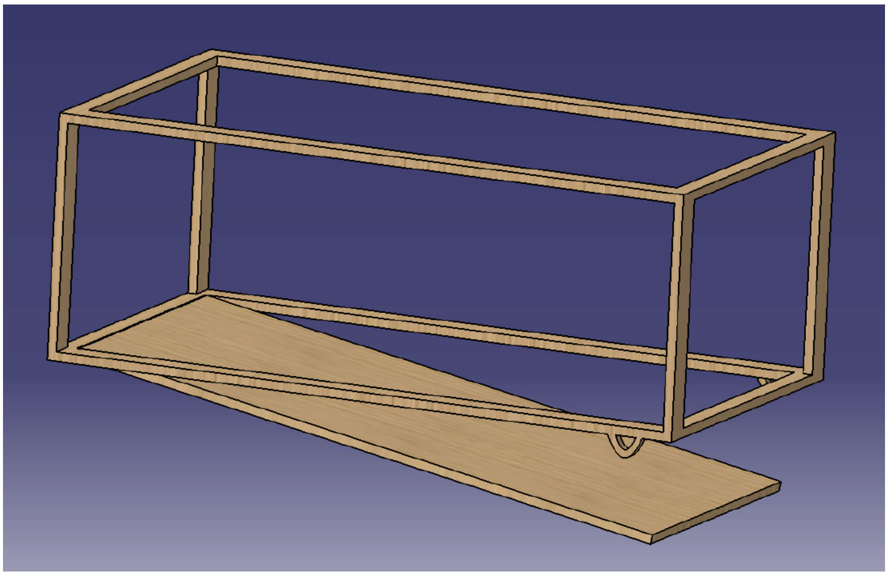

Figure 3.3 – *3D sketch of the cargo bay*

the envelope and free to achieve their maximum aerodynamic capabilities. A hand sketch of this principle is showed in figure 3.6.

3.3 Future Developments

All the previously explained designs have to be built and tested. Conclusions have to be made and inputs from the other subsystems have to be taken into consideration. Only after a careful building of the different structures to accommodate all the required subsystems, it will be possible to check if the requirement of the maximum lift weight - the most important requirement - is achieved. For now, the 3D designs, the envisioned materials and previous experiences in the field give hope that this constraint will be surpassed.

The following steps should be to finish the construction of the cargo bay, accommodate the propelling system into it and then proceed with the construction of the wiring mesh and the consequent attachment of the solar panels.

Topics such as physical properties, structural and mechanisms analysis and mounting attachments will be discussed in the final version...

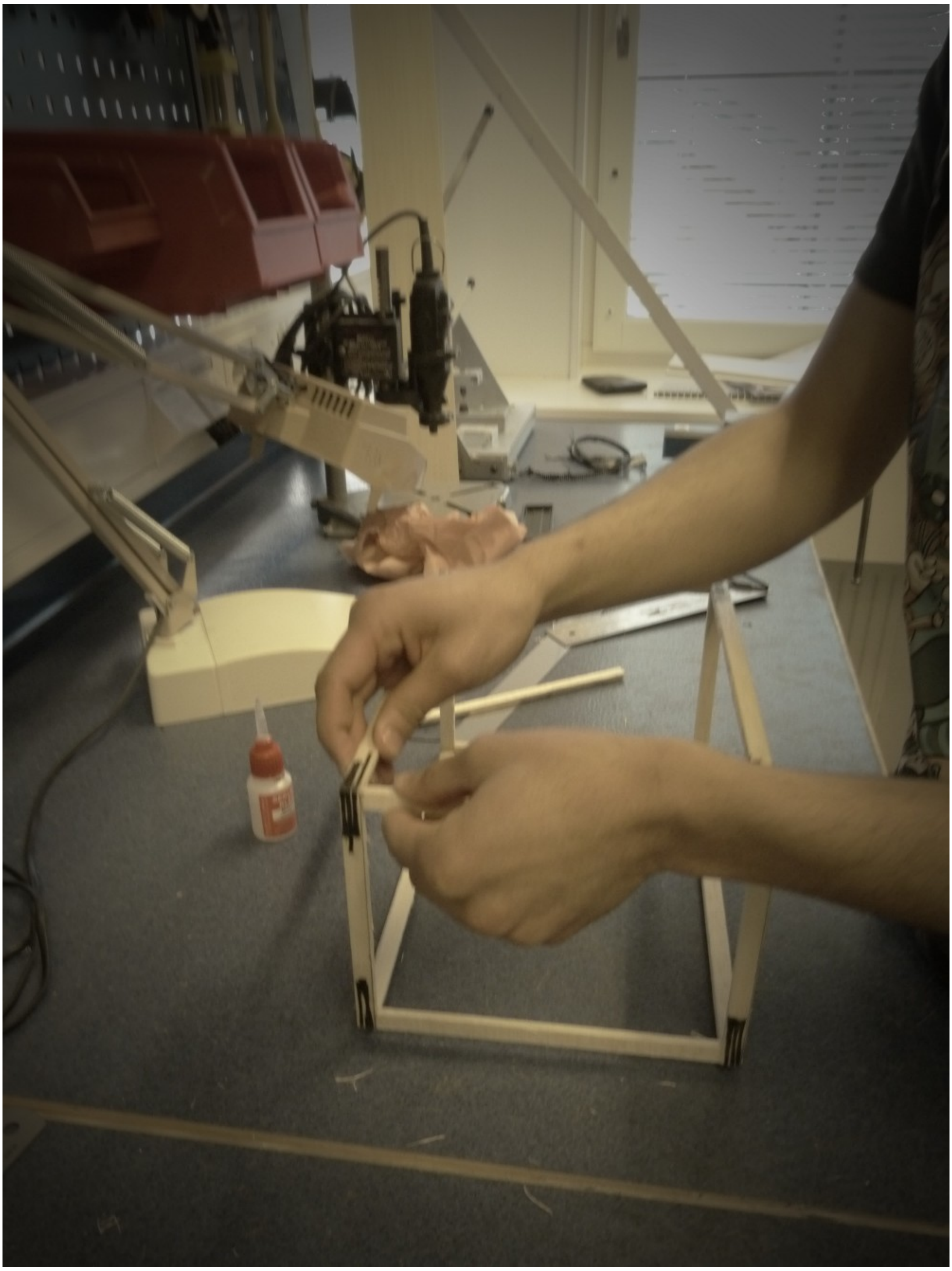

Figure 3.4 – *Initial construction phase of the cargo bay*

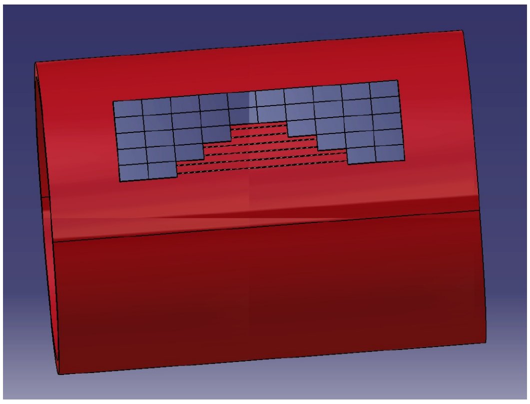

Figure 3.5 – *3D sketch of the integration of the power system*

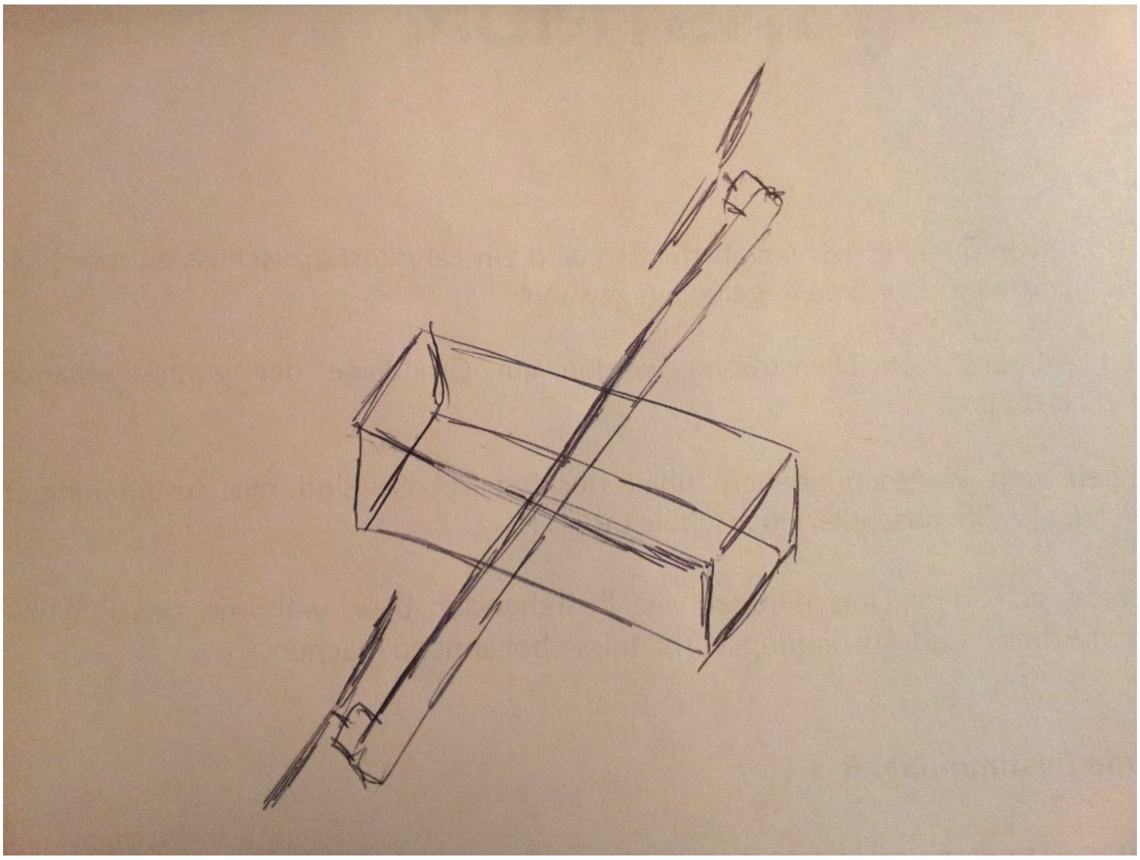

Figure 3.6 – *Hand sketch of the integration of the propelling system*

Chapter 4

Electrical Power System

4.1 Introduction

The EPS will provide sufficient power to the motors, communication system and payloads. Power is generated from solar cells and stored in batteries. DC-DC regulators are used to control the operating voltage of the solar cell and to provide regulated voltages to payloads and onboard computers.

4.1.1 Changes from PDR to CDR

The U-SPACE PDR for the EPS is documented in [13]. Table 4.1 lists the major EPS design changes between the PDR and the Critical Design Review (CDR) and the argumentations behind these design changes.

Table 4.1 – *U-SPACE EPS design changes from PDR to CDR*

Area of change	**Changed parameter**	**Argumentation for change**
Total power budget	increased to $> 40\,W$	Increased airship total mass and size
Solar cells	New part	Old solar cell was much heavier than listed in manufacturer datasheet due to a glass cover
Total system cost	increased to $> 12000\,SEK$	Increased power requirements and new light-weight solar cells are more expensive
Solar cell mounting	New part	New solar cell is flexible instead of rigid and can be mounted with Pressure Sensitive Adhesive (PSA)

4.2 Functional and Technical Requirements

4.2.1 Functional Requirements

Below are listed the primary functional requirements for the EPS:

- Provide adequate power to motors and payload
- Proof that flying on solar energy is possible i.e more power produced than consumed

Additional desired requirements are:

- Scalability to higher power levels
- Flexible and robust design, allowing flight in more extreme conditions (altitude, weather etc.)
- Provide adequate protection circuits for battery and loads
- Optimal design and high performance to increase power capability and minimize system mass

4.2.2 Technical Requirements

The EPS technical requirements are listed in table 4.2.

Table 4.2 – *Technical requirements for the EPS*

Minimum power output	$40\,W$
Maximum mass	$1000\,g$(including solar arrays)
Maximum cost	$5000\,SEK$[a]
Output voltages	$6.0 - 9.2\,V$(un-regulated), $5\,V$(regulated)
Maximum output current (worst case)	$10.5\,A$
Regulator phase margin	$60\,deg$
Regulator gain margin	$10\,dB$
Control loop bandwidth	$> 10\,kHz$
Operational temperature	$-20°C\,to + 25°C$
Battery capacity	$> 5\,Wh$

[a]Initial budget for 2 students.

4.2.3 Expected Performance

Table 4.3 – *Expected performance of the EPS*

Power conversion efficiency(overall)	$80 - 90\%$
Power output(overall)	$\sim 57 - 65\,W$
Battery capacity	$7.3\,Wh$
Mass	$\sim 910\,g$
Total cost	$\sim 12000\,SEK$[a]

[a] Solar cells are significantly more expensive than anticipated. A request for more funds is under preparation.

4.3 Critical Design

This section describes in more detail the EPS design. A simple block diagram of the EPS design is shown in Figure 4.1.

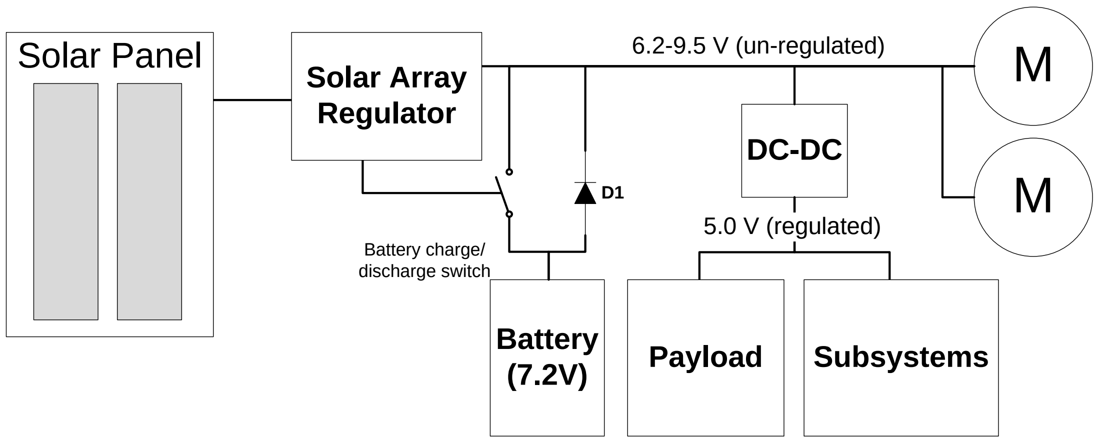

Figure 4.1 – *EPS simple blockdiagram*

4.3.1 Solar Array Design

As was mentioned in section 4.1.1, a new solar cell has been selected. This solar cell is shown in Figure 4.2 and Table 4.4 lists the important specifications for this cell.

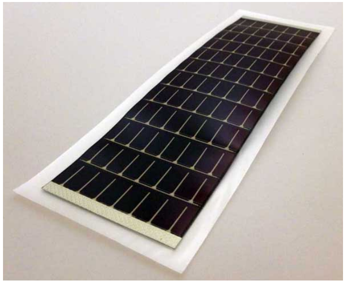

Figure 4.2 – *Chosen solar cell*

Table 4.4 – *Specifications of chosen solar cell*

Nominal output current	$100\,mA$
Nominal output voltage	$7.2V$
Nominal output power	$0.72\,W$
Dimensions	$270\,mm \times 90\,mm \times 0.2\,mm$
Weight	$7.6\,g$
No. of required cells 100[a]	
Total solar panel area	$2.43\,m^2$ (assuming $100\,\%$ fill factor)

[a][14] offers good discount for +100 units order

The solar panels will be configured with two series-connected solar cells thus having an output voltage of:

$$V_{panel,out} = 14.4\,V \tag{4.1}$$

4.3.2 Battery Design

Two Panasonic PA-L60.K02 [15] Li-ion batteries are used. The battery has the following important specifications:

Table 4.5 – *Specification of chosen battery*

Chemistry	Li-ion
Nominal voltage	$3.6\,V$
Capacity	$1.03\,Ah$ / $3.61\,Wh$
Weight	$25\,g$
Dimensions	$56\,mm \times 34.2\,mm \times 5.8\,mm$
Maximum charge current	$970\,mA$
Maximum discharge current (continuous)	$1.455\,A$

Future Recommendations The chosen type of Li-ion battery supports only a relative low charge- and discharge rate of about $1\,C$. For bigger battery capacity and higher loads, it is recommended to use a battery like [16] which provides much higher discharge rates ($> 20\,C$) and also cheaper price per Wh. Only disadvantage is a mass increase of around $15 - 25\%$.

Battery Charge Regulator

From the battery datasheet, maximum charge current is $I_{REG} = 970\,mA$. From the Battery Charge Regulator (BCR) datasheet, the minimum current sense resistor value is calculated as

$$\begin{aligned} R_{sense} =& \frac{V_{FCS}}{I_{REG}} \\ R_{sense} =& \frac{120\,mV}{970\,mA} = 123\,m\Omega \end{aligned} \tag{4.2}$$

The required thermal rating of the pass transistor is calculated as

$$P_{max} = (V_{in,max} - V_{bat,min}) \cdot I_{charge} = (9.5\,V - 5.5\,V) \cdot 970\,mA = 3.88\,W \tag{4.3}$$

Battery Temperature Monitoring

The BCR chip includes a temperature monitoring feature. The battery is rated, in charge-mode, to temperature in the interval $10 - 45°C$. The maximum allowed temperature is set slightly lower to $40°C$. The Li-ion battery has a build-in Negative Temperature Coefficient (NTC) thermistor with $B = 3980\,K$ and $R_{25} = 10k\,\Omega$. The required restance values of the temperature control resistors are determined from the BCR chip datasheet as

$$\begin{aligned} R_{cold} &= R_{25} e^{B(\frac{1}{T} - \frac{1}{T_0})} = 10\,k\Omega e^{3980\,K(\frac{1}{283\,K} - \frac{1}{298\,K})} = 20.3\,k\Omega \\ R_{hot} &= 10\,k\Omega e^{3980\,K(\frac{1}{313\,K} - \frac{1}{298\,K})} = 5.3\,k\Omega \\ R_{T1} &= 2\frac{R_{cold}R_{hot}}{R_{cold} - R_{hot}} = 14.2\,k\Omega \\ R_{T2} &= 2\frac{R_{cold}R_{hot}}{R_{cold} - 3R_{hot}} = 47.8\,k\Omega \end{aligned} \tag{4.4}$$

Battery Discharge Current Limiter

The selected MOSFET has a typical gate threshold voltage of $V_{Gth} = 550\,mV$. The chosen Bipolar Junction Transistor (BJT) has a typical collector-emitter voltage drop of $V_{CE} = 120\,mV$. The battery is rated for a maximum discharge current of $I_{discharge} = 1.455\,A$. The required current sense resistor is then calculated as

$$\begin{aligned} V_{sense} &= V_{Gth} - V_{CE} = 550\,mV - 120\,mV = 430\,mV \Rightarrow \\ R_{sense} &= \frac{V_{sense}}{I_{discharge}} = \frac{430\,mV}{1.455\,A} = 295\,m\Omega \end{aligned} \tag{4.5}$$

The exact required resistance must be determined by testing the precise parameters of the discrete components.

4.3.3 Maximum Power Point Tracking Regulator

In [13] it was decided to use a Maximum Power Point Tracking Unit (MPPTU) for the Array Power Regulator (APR) due to its high efficiency and robustness to changing environmental constraints.

In first step, only the DC-DC converter will be implemented. When time and resources allows the Maximum Power Point Tracking (MPPT) part will be added. A simple buck DC-DC converter topology is used, comprising a transistor, free-wheel diode, inductor and output capacitor. When the full MPPTU is implemented, it will operate in three different operation regions:

- Battery discharge MPPT - when the solar array input power is insufficient to cover the load power demand, the battery is slowly discharged in order to maintain the output voltage.
- Battery charge MPPT - when the solar array input is greater than the load power, the excessive power is used to recharge the battery.
- Input power limitation - when the battery is fully charged, the regulator will operate the solar array at a non-optimal voltage, thus limiting the input power to keep the output voltage constant. The extra potential input power is dissipated as heat externally on the solar arrays.

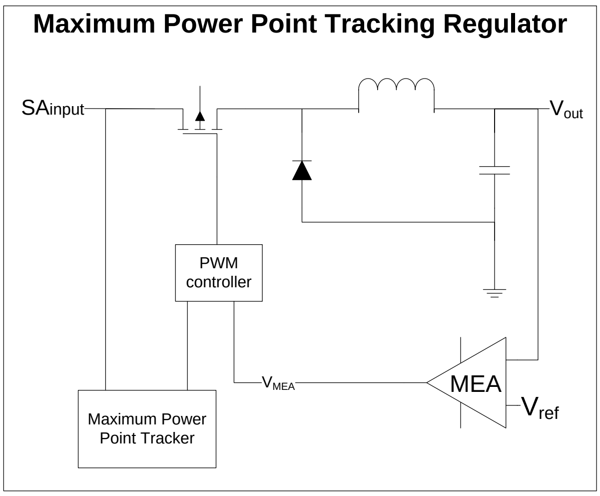

Figure 4.3 – *MPPT regulator diagram*

Mainbus Under Voltage Protection

The power from battery and solar cells is limited. It is thus possible that the motors will try to draw more current than what can be delivered. If this happens, the output capacitor of the APR will quickly discharge and the main output voltage drops out. To prevent this situation, an Under Voltage Protection (UVP) circuit is added. This is implemented using an $STN888$ PNP BJT along with two resistors, $R3$ and $R4$ as shown in Figure 4.4. When the main output voltage is around $6.2\,V$ the Base-Emitter voltage drop is close to $1.2\,V$ and the BJT is fully conducting and effectively works as a short circuit. If the output voltage drops significantly below $6.2\,V$ the BJT will begin to decrease the output current until the output voltage stabilizes. The current gain of $STN888$ is about 100, hence to allow an maximum output current of $10\,A$, the resistors $R3$ and $R4$ must be designed to pass $100\,mA$ at $6.2\,V$ output voltage. To minimize efficiency it is important that the forward voltage drop of the BJT is kept as low as possible.

Further Recommendations It is hard to find suitable BJTs rated for much more than $5\,A$. If the power output is increased in future designs, it is suggested to either parallel connect several BJTs however this might cause issues with thermal runaway. Alternatively high current Insulated Gate Bipolar Transistors (IGBTs) can be used, however they have higher forward voltage drops and thus they are more suitable for a design with a higher output voltage.

4.3.4 Complete EPS Diagram

The complete EPS diagram is shown in Figure 4.4. For providing the $5\,V$ regulated voltage to the payloads, Commercial Of-The-Shelf (COTS) DC-DC regulator(s) are used. The battery charging/discharging is controlled by the Solar Array Regulator (SAR).

4.3.5 External Interfaces

The interfaces of the EPS external are listed in table 4.6.

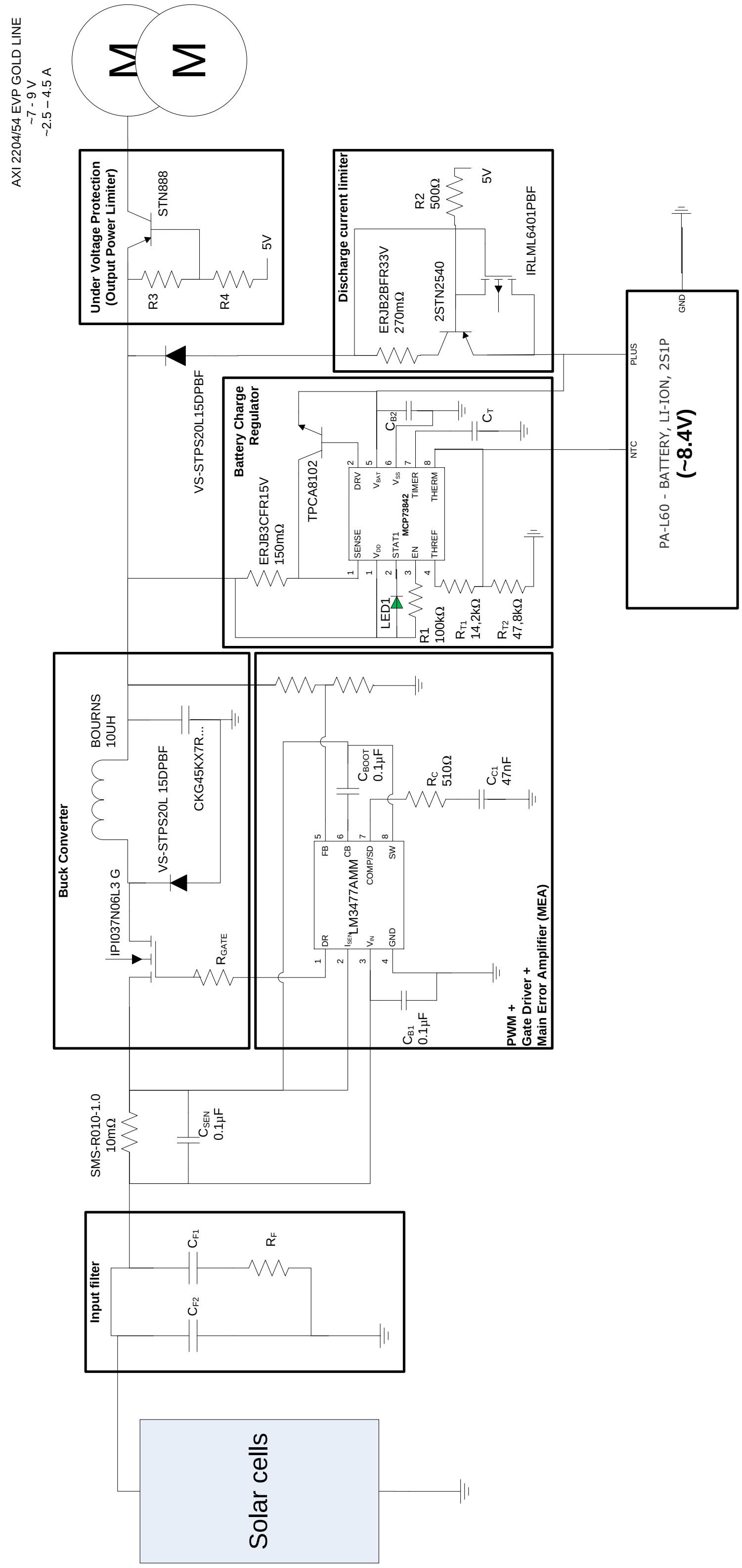

Figure 4.4 – *EPS detailed block diagram diagram*

Table 4.6 – *External interfaces*

External interface	Implementation
Solar cells mounting	PSA
DC-DC regulators	Mounted on PCB which sits in system housing. Thermal contact points should be included, to remove internal heat dissipation.
Battery telemetry	Analog signals to Microcontroller
Mounting of batteries	To Be Decided (TBD)
Supply voltages	$6.0 - 9.2\,V$ (unregulated) and $5.0\,V$(regulated)

4.3.6 Telemetry and Telecommands

The required/recommended telemetry and telecommands, EPS , are listed in table 4.7.

Table 4.7 – *Telemetry and telecommands*

Telemetry	Data rate/frequency	Data size
Battery voltage	Every 30 sec	2 bytes
Battery temperature	Every 5 sec	2 bytes

4.4 Test and Verification of Design

4.4.1 Preliminary Verification of Design

Will be included in the final version...

4.4.2 Design Models and Verification Methods

PSpice Simulations

PSpice transient and average simulation models of the SAR will be created. These will help in the design and testing of the regulator performance and system stability during transient loading.

Development Model

A Development Model (DM) will be build using self-made "mini-mount" pads and mainly surface-mount components, to minimize parasitic effects. System stability will be tested using a Network Analyzer and MPPT performance will be tested in a Thermal Vacuum (TV) chamber cycling the solar array temperature.

Flight Model

If time allows, a dedicated Flight Model (FM) will be build, using a custom designed Printed Circuit Board (PCB) schematic layout. An optimized PCB layout will minimize the system mass and size while maximizing the efficiency and system robustness.

4.5 Resources and Scheduling

4.5.1 Main Tasks

Will be included in the final version...

4.5.2 Parts List and Costs

Will be included in the final version...

4.5.3 Electronics Ground Support Equipment (EGSE)

Will be included in the final version...

Chapter 5

Motor Control and Communication

The Motor Control and Communication subsystem is responsible for providing sufficient thrust to the airship for its movement and communication from ground. Two motors with propeller will be used for controlling the flight of the airship. Communication will be handled with commercial transmitters/receivers operating at 2.4 GHz.

5.1 Functional and Technical Requirements

Below are listed the primary functional requirements for the MCC:

5.1.1 Functional Requirements

- Reliable communication between ground controller (transmitter) & airship (receiver)
- Independent speed control for each of the motors and provision of sufficient thrust to the airship
- Operation of the airship from ground

5.1.2 Technical Requirements

MCC's technical requirements:

- Maximum power consumption: 50 to 60 W Approx.
- Mass: 50 g Approx with mountings
- Maximum cost: 2500 SEK
- Input Voltage: 3.8 V Approx

- Transmission frequency: 2.4 GHz
- Receiver channels: 6

As it was decided to use the blimp from ESRANGE instead of the structure that was supposed to be built by MSE, the whole system had to be re-designed. The main reasons were the dimensions of the blimp and the limitation on the total weight it is able to carry. This required for the MCC to use more powerful and efficient motors since the power system was affected as well, while the transmitter/receiver system remained unchanged.

Brush-less motors were chosen as they are known to be more powerful and lighter at the same time ($38g$) and dimensions of $27.6 \times 11mm$ (see figure 5.1). However this motors require a bit more current than the ones that were chosen originally. Therefore suitable ESC were chosen which are able to supply a maximum current of 10 A.

Figure 5.1 – *Motors purchased from http://www.rcflight.se*

5.1.3 Expected Performance

- Motor efficiency: 77 %
- RPM (for each motor): 1400 RPM/V

5.2 Design of the System

The functioning of the MCC subsystem is shown in figure 5.2. The transceiver consists of 2.4 GHz transmitter and receiver. The receiver gets the motor speed control commands to the ESC which in turn actuate the motor to the desired speed.

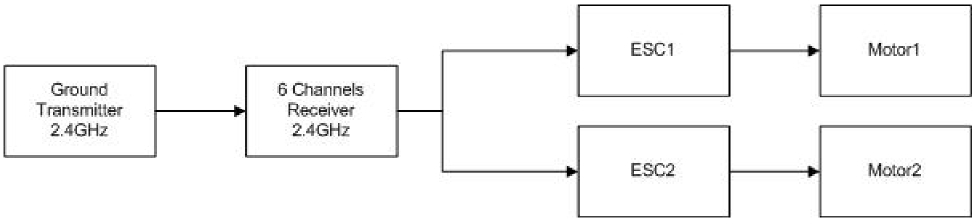

Figure 5.2 – *Block Diagram of the MCC Subsystem*

5.2.1 Trade-Off Analysis of Concepts

For the transceiver system the available options are to use

- A 72 MHz transceiver system that uses Amplitude/Frequency Modulation
- A 2.4 GHz transceiver system that uses Spread Spectrum Technology

Parameter:	**2.4 GHz Transceiver**	**72 MHz Transceiver**
Frequency Used	2.4 GHz	72 MHz
Crystal Used	No	Yes
Change in Frequency	On next power up	By changing the crystal
Ability to transmit through obstacles	Weak	Very Good
Band Width	Wide	Narrow
Date Rate	High	Low
Power Usage	Less	More
RF Noise Immunity	Very Good	Less

Table 5.1 – *Trade off analysis*

It is clear from the Table 5.1, that a 2.4 GHz Transceiver System is a clear winner for chosen application. The only disadvantage of using a 2.4 GHz transceiver system is that the receiver should have really good batteries and the voltage should be maintained at a particular level. The reason being that there are small processors in the transmitter and receiver that carry out many complex calculation every second without mistake. These processors require constant steady supply of current to work properly. If there is an interruption in the supply current of the receiver then there would be problems with the communication channel.

The speed of the motor can be controlled by the following methods:

- Use a commercial off the shelf Electronic Speed Controller(ESC) for each motor.

- Build a Motor Speed Controller using a microprocessor.

The primary advantage of using commercial off the shelf Electronic Speed Controller is the ease of use. This would reduce the development cycle to a large extent. The disadvantage of using it is no scalability i.e. function like autonomous control and telemetry and telecommanding are not possible.

5.2.2 Argumentation for Chosen Concept(s)

The 2.4 GHz transceiver system would be used for communication. The transceiver used 2.4 GHz frequency band and uses the spread spectrum technology for transmission of signals. This helps in removing all interfering frequencies caused by other electronic equipments and this helps in having a better communication channel. The other major advantage of using this transceiver using spread spectrum technology is that the communication channel would not be affected even by someone using the same frequency band.

Commercial off the shelf Electronic Speed Controllers would be used to control the speed of the motors because of time constraint in the project. If time permits it would be desirable to build a speed controller with the help of microprocessor.

5.2.3 Feasibility Study of Concept(s)

The important part in the communication part of the subsystem is deciding upon transceiver system which would allow bidirectional control of the motor. Since transceiver is commercial of the shelf, configuring it would be a short task. Again in the case of motor speed control, choosing the correct ESC and motor combo is the most important task and given maximum time after which assembly is relatively easier and less time consuming.

Chapter 6

Imaging and Tracking Payload Unit

The Imaging and Tracking Payload Unit (ITPU) is the scientific payload of the airship, and is in general independent of the airship's control system, but uses the airships power system. However it would be possible in an extended version to also incorporate a controlling interface and connect the motor ESCs for the motor control to the computer of the ITPU.

The purpose of ITPU is to take aerial images from different positions, acquire accurate position and attitude data and use those combined information to create aerial image maps.

The system is further divided into the following parts:

- Attitude determination: Usage of advanced data fusion method to facilitate GPS, Gyro, Accelerometer and Magnetometer information, to extract accurate position and attitude information together with reasonable error estimates.
- Imaging system: A megapixel resolution webcam will provide images in regular timesteps in the order of a second. The image data will be saved on a SD memory card together with attitude information for offline processing.
- Communication system: Attitude data and spacecraft telemetry will be transmitted to ground.
- Image processing software: Image matching and evaluation will be done on a standard PC after payload recovery.

6.1 Functional and Technical Requirements

- Measure absolute and accurate position and pointing angles.
- Take images in regular steps and save them together with attitude data.
- Receive and execute basic telecommands such as image capture start/stop.
- Send basic telemetry data such as position.
- Combine single image captures to a large area map.
- Operate in open air environment up to 500 m over ground. In U-Space the module will only fly to a height of a few 10s of meters. However it should be used in higher altitudes for later applications.
- Operate at 5 V unstabilized input voltage at a maximum power consumption of 2.5 W.
- Store at least 1000 medium-resolution images.

6.2 Electronic components

- Board computer
- Accelerometer
- Magnetometer
- Gyroscope
- GPS-receiver
- Transmitter/Receiver
- Camera

Board computer

For reading the sensors, communicating with the ground station and saving images from the camera an embedded system which provides all necessary interfaces and enough computing power to handle comparably large data streams from the camera was needed. It was chosen to use the BeagleBone, but only the BeagleBoard was delivered which is a related predecessor and lacks some features.

The BeagleBoard is a microcontroller board running a TI OMAP3530 ARM Cortex-A8 system on a chip (SoC). It provides 256 MB RAM and several high and low level interfaces. For this project the main interfaces used are the I2C and UART for communication with the sensors (gyroscope, magnetometer, accelerometer) and the GPS-receiver and radio-transmitter module (E-TAG) respectively. The camera The used high level interface is the USB-host adapter to connect the camera to. The operating system with the control program as well as the image files are stored onto an 8 GB class 10 sd-card. The needed supply voltage for the BeagleBoard is 5 V. The voltage of the pins on the expansion header is 1.8 V.

Sensors

For determining the position and attitude the LSM303DLM [17] combined magnetometer and accelerometer and the ITG-3200 triple-axis gyroscope [18] from sparkfun were used. Both sensors have been used during the CanSat-project in Würzburg with decent results. They communicate via an I2C interface with the main board at 3.3 V. For receiving GPS information an E-TAG device developed by Esrange was used. It is connected via a serial line interface with the main board. It also provides a transmitter module for communicating with the ground station.

Camera

As high quality embedded industrial cameras are very high priced, a consumer webcam with a resolution of several megapixels will be connected to the USB-port of the main board. It is intended to buy a camera which is supported by the Linux operating system running on the main board.

6.3 Software environment

The BeagleBoard is equipped with an 8 GB sd-card. A debian based Linux operation system is installed onto the card providing the environment, libraries and drivers for the program to run. As compared to the BeagleBone the BeagleBoard lacks pull-up resistors on its I2C interface which produced problems with Linux kernel the standard kernel for this board came without the possibility to enable the I2C controller. Therefore an own version of the Linux kernel had to be compiled for the BeagleBoard in order activate the I2C device on the expansion header.

The program is divided into several threads. One thread is responsible to get the newest sensor data from the accelerometer, magnetometer and gyroscope from the I2C interface and fuse them to accurate position and attitude representations. It is running at a comparably high frequency (>50 Hz, the final frequency is not defined yet). More about the algorithm for sensor fusing is explained in section ????. A second thread is polling for new GPS data from the E-TAG via serial line. As the GPS-chip only updates the positional data around once per second this thread can run at a much lower frequency. A third thread is responsible to control the camera. If it is active it will shoot a picture every second and save it to the sd-card. And finally two threads will be handling sending telemetry data to and receiving basic commands from the groundstation.

Due to lack of time a standard kernel was used which is not hard real-time capable. Nevertheless it still has the possibility to use preemptive scheduling which should give a high enough accuracy, but it should be noted that in future developments it could be beneficial to use a real-time Linux kernel.

6.4 Image processing

Will be included in the final version...

6.5 Attitude Determination System

The Attitude Determination System (ADS) measures and estimates position and pointing direction of the payload system. This is crucial for the further use of recordet images, as it provides the reference system and relative alignment of the taken images towards each other.

In order to produce high-accuracy attitude estimates and compensate for disadvantages of certain sensor types such as drift and noise, we chose to use a variety of sensors and fuse their information to a combined information. The facilitated sensors will be (see figure 6.1):

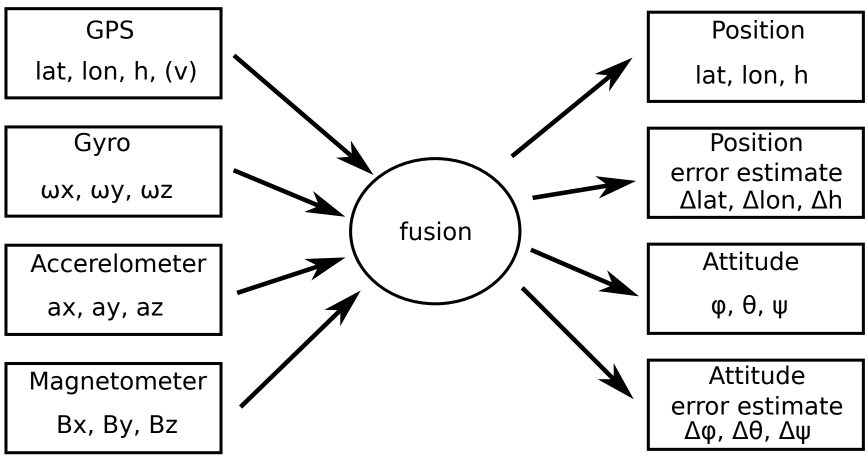

Figure 6.1 – *Attitude Determination System overview*

- GPS receiver: Provides absolute position values, but has much high-frequency noise
- Gyroscope: Provides accurate relative pointing direction, but has drift.
- Accerelometer: Provides absoulte pointing relative to the horizon (gravity) and linear acceleration.
- Magnetometer: Provides absolute pointing relative to the earth's magnetic field.

Combined all together, these sensors provide complete information about the module's attitude. As a fusion method we will use well-understood algorithms, such as the extended Kalman filter.

The fused information will be updated in real-time and stored together with each image snapshot.

For development of the software, a simulation module is being written that feeds simulated measurement data into the fusion algorithm. By this the performance can be quantified and development gets much faster than with waiting for actual measurement data.

The fusion algorithm being developed and implemented in C++ will use a Kalman-like approach with least-square estimators for an optimized estimation of position and attitude combined. In a first simpler appoach, we treat position and attitude independetly, which is less accurate but more robust as the system is being developed.

6.6 Electrical Circuits

As compared to the BeagleBone the delivered BeagleBoard's voltage at the pins of the expansion header is only between 0 V and 1.8 V but the expected voltage at the supply and the I2C interface for the sensors is 3.3 V additionally to the external pull-up resistors on the I2C interface also voltage level converters have to be used.

More information will be included in the final version...

Chapter 7

Thermal Interfaces, Pyrotechnics and Electromagnetic Compatibility

7.1 Thermal Interfaces

The topic of thermal interfaces is irrelevant for the U-SPACE project. All subsystems, both for the airborne structure and the ground-based structures, will have roughly the same temperature during the entire operation period of the SPA. Also the expected ambient temperature is uniform and not extremely high or low (see section 2.2 in chapter 2). For these reasons it is not necessary to investigate the issues related to thermal interfaces (e.g. thermal mismatch).

7.2 Pyrotechnics Interface

In order to achieve the functionality described in chapter 2 there is no need for any form of pyrotechnics. The project does not require the release or deployment of other structures which could make use of pyrotechnics. Therefore pyrotechnics particulars are not discussed in this respect.

7.3 Electromagnetic Compatibility

With regards to Electromagnetic Compatibility (EMC), no problems are expected during the U-SPACE project. The frequencies employed in the subsystems are compatible with each other and with the regulations from the ITU [11]. More information regarding the selection of the relevant frequencies and their use in the U-SPACE project can be found in chapters 5 and 6.

The possible issues related to grounding are briefly discussed in chapter 4. Once again the requirements are not very stringent, meaning that few issues are expected related to this topic.

Chapter 8

Test and Verification of Design

This chapter describes the test procedures of the U-SPACE project. Objectives and responsibilities are introduced in section 8.1,together with the main test procedures. Section 8.2 describes the different test matrices of the subsystems.

8.1 Design Verification Plan

8.1.1 Objectives and Responsibilities

Will be included in the final version...

8.1.2 Verification By Test

To test and verify the proposed design concepts throughout the project, four methods are considered [19], as listed in table 8.1.

Table 8.1 – *Design verification methods*

Method	Description
Testing	Monitoring of system performance and functionality in a simulated test environment.
Analysis/Simulation	Theoretical calculations and simulations. Also includes verification by similarity, i.e. previously used solution concepts.
Review of Design	Using records, drawings, schematics, etc. that unambiguously show fulfilment of the system requirements
Inspection	Visual inspection of hardware/software for good workmanship as well as compliance to industry/design standards

To test the complete SPA, a DM will be built and subjected to flight testing. A 3-4 week launch campaign is scheduled for the start of autumn. The planned launch site is the old balloon launch site at IRF near the LTU Rymdcampus or a location at the Esrange Space Center (in cooperation with the Swedish Space Corporation (SSC)).

8.2 Subsystem Test Matrices

Will be included in the final version...

Chapter 9

Ground Support Equipment

This chapter describes the required electrical ground support equipment and mechanical ground support equipment for the U-SPACE project.

9.1 Electrical Ground Support Equipment (EGSE)

During flight testing of the DM, the following Electrical Ground Support Equipment (EGSE) are required:

- A power supply to charge the EPS batteries before flight.
- A ground station (depending on the final design of the communication system and requirements for telemetry/telecommand).

More information will be included in the final version...

9.1.1 Concept

9.1.2 Hardware Description

9.1.3 Software Description

9.2 Mechanical Ground Support Equipment (MGSE)

Developing, building and testing the SPA will require the following Mechanical Ground Support Equipment (MGSE):

- During flight test a safety system is required to prevent the airship from flying beyond the flight test perimeters in case of failing attitude control. This could be implemented using a simple cable/rope or a similar system.
- Facilities at test locations for on-site fuelling of the envelope gas, i.e. gas tanks, valves, tubes etc.

- Storage facility at IRF/LTU Rymdcampus, for the SPA DM, components and materials. This storage facility should be large enough to accommodate and transport the large SPA structure.

Chapter 10

Project Management

This chapter describes the different aspects of the project management.

10.1 Organisation and Responsibilities

10.1.1 Key Personnel and Responsibilities

Will be included in the final version...

10.1.2 Functional Organigram

Based on the expertise of the team members a functional organigram was defined. This structure is shown in figure 10.1.

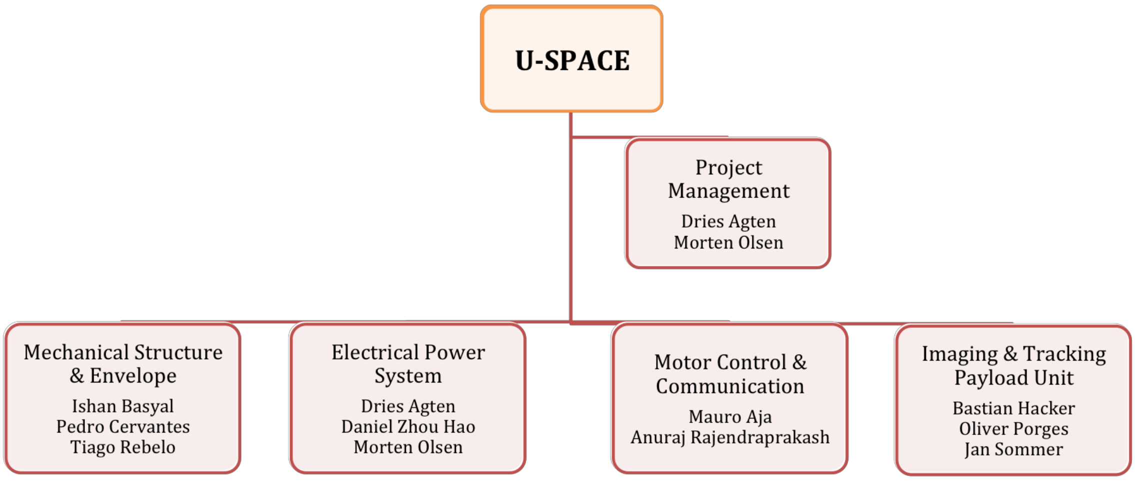

Figure 10.1 – *Functional organigram*

The background of each team member can be found in table 10.1 below.

Table 10.1 – *Background of team members*

Name	Background
Dries Agten	M.Sc. Eng. - Nanoscience & Nanotechnology
Mauro Aja	B.Sc. Eng. - Electronic and Computer Engineering
Ishan Basyal	B.Sc. Earth and Space Sciences
Pedro Cervantes	B.Sc. Eng. - Aeronautical Engineering
Bastian Hacker	B.Sc. Physics
Daniel Zhou Hao	B.Sc. Eng. - Aerospace Engineering
Morten Olsen	B.Sc. Eng. - Electrical Engineering
Oliver Porges	B.Sc. Cybernetics and Measurement
Anuraj Rajendraprakash	B.Tech. Electronics Engineering
Tiago Rebelo	B.Sc. Eng. - Aeronautical Engineering
Jan Sommer	B.Sc. Computational Science

10.1.3 Support Facilities

The U-SPACE project is supported practically, financially and technically by LTU. IRF and Esrange both provide technical assistance. The practical support from LTU consists of the availability of tools and specific rooms (e.g. mechanical workshop or electronics laboratory). Also component orderning (see section 10.2.3) is the responsability of LTU. The financial support is discussed in section 10.3.

The technical help of all three support entities consists of guidance regarding the components, support during the fabrication and assistance with the future testing procedures.

10.2 Relation With Support Facilities

10.2.1 Reporting and Monitoring

During the entire project, the team is monitored by Kjell Lundin (IRF) and Alf Wikström (Esrange). The team and the supervisors have weekly status meetings, in which all current issues are identified, discussed and solved. Reports to the supervisors are discussed in the next subsection.

10.2.2 Reviews

Will be included in the final version...

10.2.3 Component Ordering

LTU helps the team with the ordering of all components, both national and international. The procedure include component selection by the team, followed by approval of the supervisors and then the final ordering of the components by LTU.

10.3 Financing

Will be included in the final version...

10.4 Schedule and Milestones

Will be included in the final version...

10.5 Configuration Control

Will be included in the final version...

10.6 Deliverables

Will be included in the final version...

10.6.1 Hardware and Software

10.6.2 Documentation

10.6.3 Deliverable Items and Build Standard

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