Unmanned Solar Powered Airship Concept Evaluation

Critical Design Report

Document Reference No.: USPACE-CDR-00

Document Status: DRAFT

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September 3, 2012
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Acronyms

BCR Battery Charge Regulator

BJT Bipolar Junction Transistor

CC Constant Current

CDR Critical Design Review

CM Current Mode

COTS Commercial Of-The-Shelf

DCM Discontinuous Conduction Mode

DM Development Model

DSP Digital Signal Processor

ECSS European Cooperation for Space Standardization

EGSE Electrical Ground Support Equipment

EKF Extended Kalman Filter

EMC Electromagnetic Compatibility

EMI Electromagnetic Interference

EPS Electrical Power System

ESR Equivalent Series Resistor

FM Flight Model

FRR Flight Readiness Review

GPS Global Positioning System

IC Integrated Circuit

IRF Swedish Institute of Space Physics

ITPU Imaging and Tracking Payload Unit

ITU International Telecommunication Union

LDO Low-dropout

LiPo Lithium-Polymer

LTU Luleå University of Technology

MCC Motor Control and Communication

MCU Micro-Controller Unit

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

PTC Positive Temperature Coefficient

PWM Pulse Width Modulation

RHPZ Right Half Plane Zero

SAR Solar Array Regulator

SMD Surface-Mount Device

SPA Solar Powered Airship

SSC Swedish Space Corporation

TBD To Be Decided

U-SPACE Unmanned Solar Powered Airship Concept Evaluation

UAS Unmanned Aircraft System

UAV Unmanned Aerial Vehicle

UVLO Under-Voltage Lock-Out

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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, 9]. 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]. In Scandinavia there have been several studies on using airships for transport of windmill structures[9, 10] and the big windmill company Vestas has filed a patent on this method[11]. 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.

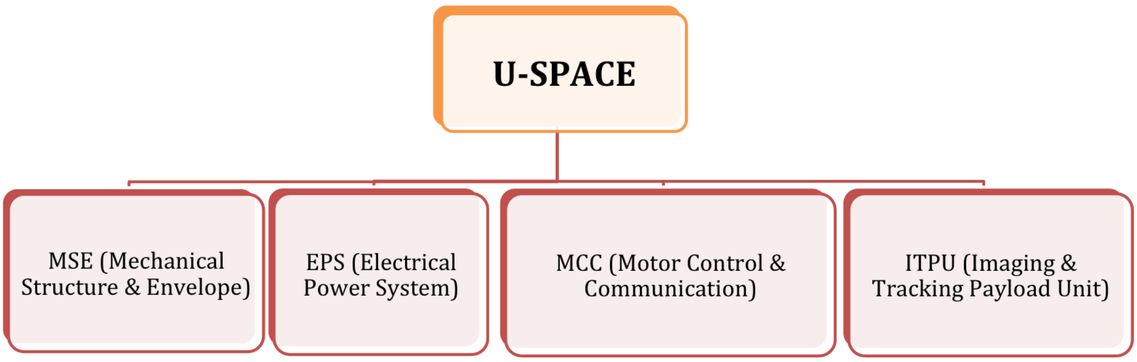

Figure 1.1 – *Hardware block diagram of the U-SPACE project*

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.

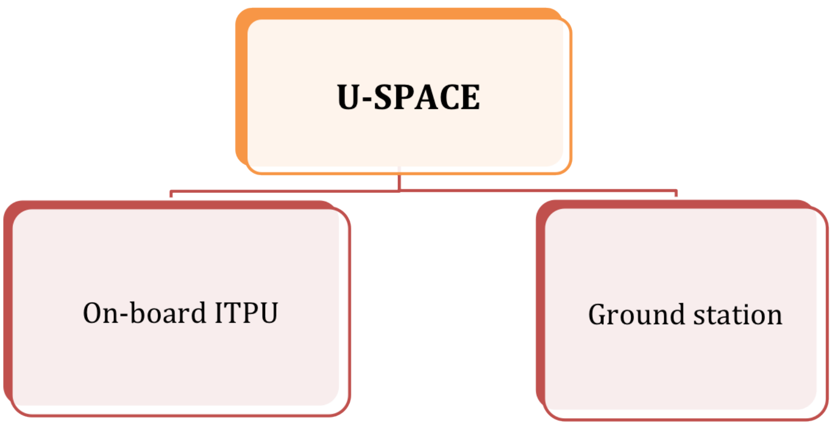

Figure 1.2 – *Software block diagram of the U-SPACE project*

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	-	$40\,W$
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. The cost of this student project is limited by its approved budget, a

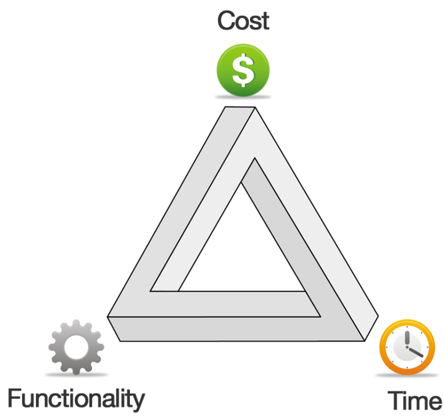

Figure 2.1 – *Project management triangle [12].*

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 for the months May-September[13].

Table 2.2 – *Environmental conditions*

Parameter	Lower boundary	Upper boundary	Remarks
Temperature	$-7° C$	$22° C$	Worst-case $10-90$ percentile bands.
Wind speed	1 (3) m/s	6 (9) m/s	Daily averages (worst-case $10-90$ percentile bands).
Probability of precipitation	61%	63%	Daily average. Mostly light rain/snow to moderate rain/snow.
Cloud cover	83%	85%	Median cloud cover (mostly cloudy).
Solar incidence angle	46°	57°	See Section 4.2.3.

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 [14] when using wireless connections. Secondly, when flying the SPA, the Swedish Transport Agency's regulations on Unmanned Aircraft System (UAS) [15] 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 11.

2.5 Materials

With the limited time and funding inherent to this student-driven project great care needs to be 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 (refer to the Preliminary Design Review (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 Critical Design

As was mentioned in the 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.

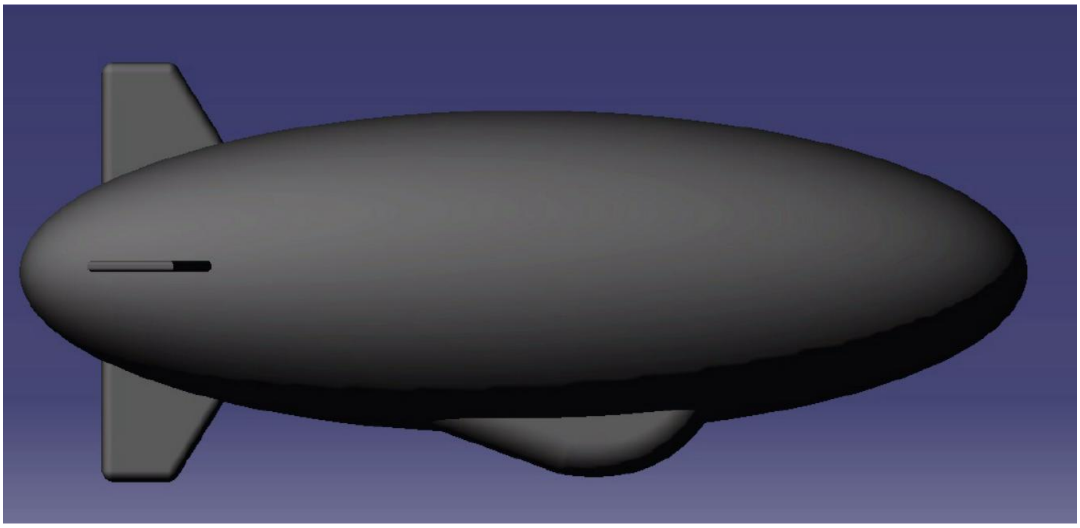

Figure 3.1 – *Initial 3D sketch of the airship*

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.

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.

Figure 3.2 – *TIF - 250 Blimp*

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 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

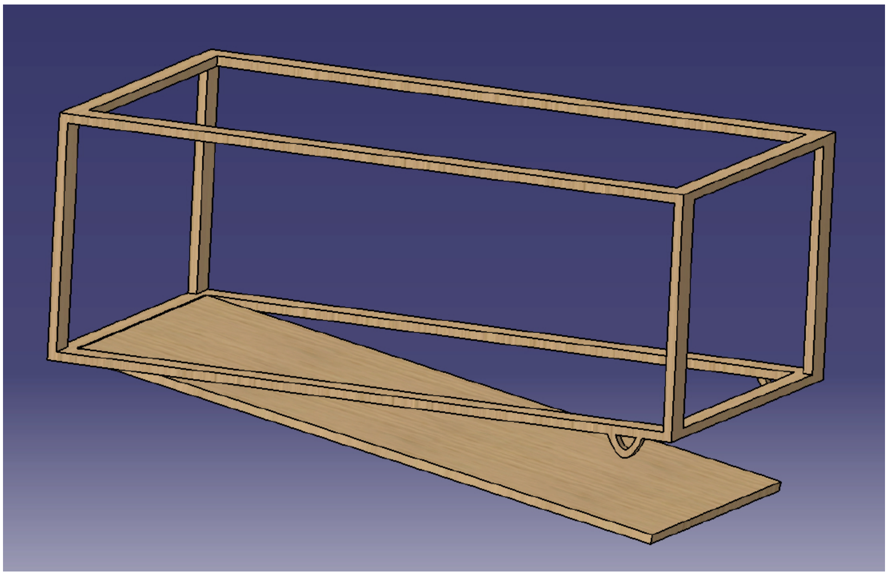

Figure 3.3 – *3D sketch of the cargo bay*

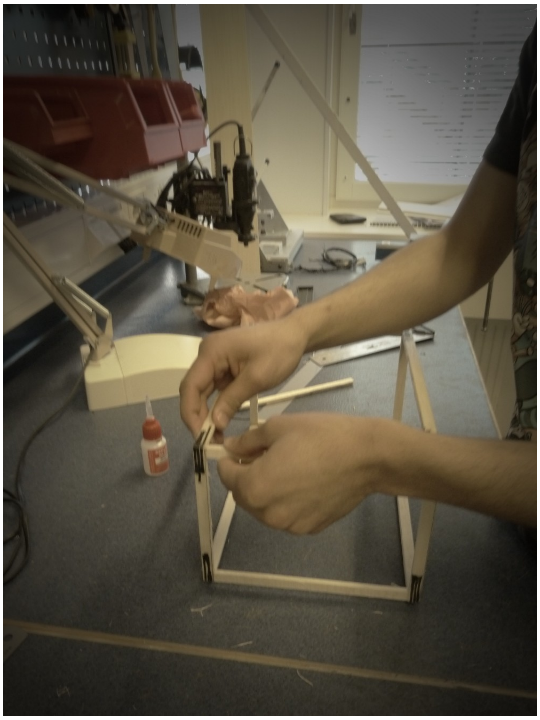

Figure 3.4 – *Initial construction phase of the cargo bay*

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.

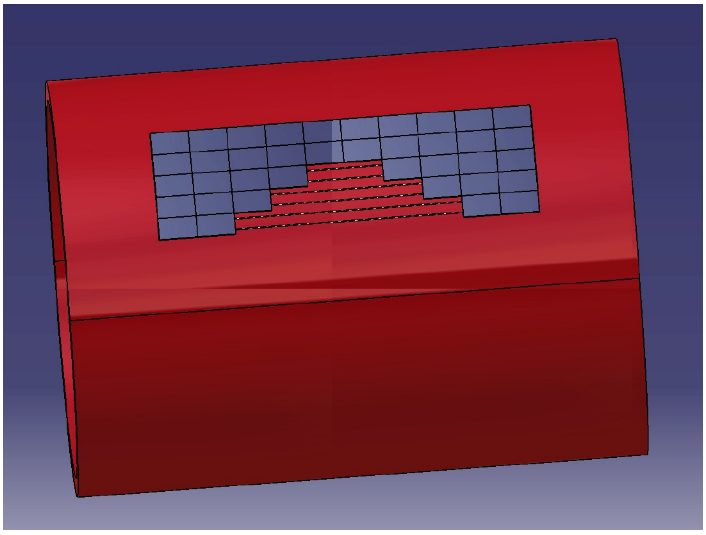

Figure 3.5 – *3D sketch of the integration of the power system*

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

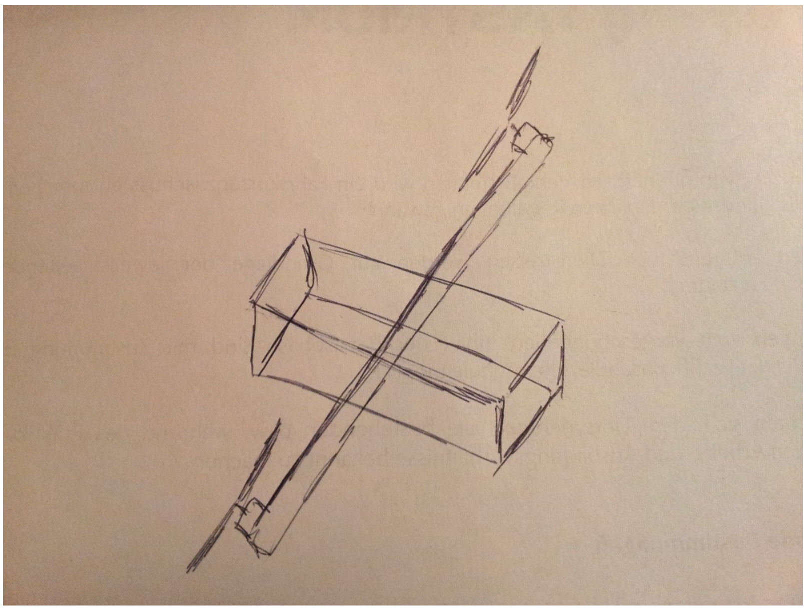

Figure 3.6 – *Hand sketch of the integration of the propelling system*

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.

Chapter 4

Electrical Power System

4.1 Introduction

The EPS provides power to motors, the on-board computer, communication system and payloads. Power is mainly supplied from solar cells but can also be supplied from a battery, when solar power is not available or insufficient.

4.1.1 Changes from PDR to CDR

Table 4.1 lists major design changes from the EPS PDR report.

Table 4.1 – *Design changes from PDR to CDR*

Area of change	Change	Argumentation for change
Total power budget	Increased to $> 40\,W$	Airship total mass and size are increased thus requiring much more power for the motors.
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 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).
Battery	New part	A battery that supports much higher discharge currents has been selected which simplifies current limiting circuitry and improves battery efficiency.

4.2 Functional and Technical Requirements

This section describes the functional and technical EPS requirements along with the expected EPS performance.

4.2.1 Functional Requirements

The primary functional EPS requirements are:

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

Additional desired requirements are:

- Scalable and flexible system architecture allowing the EPS to be upgraded to higher power levels or re-used in different applications (rover, Unmanned Aerial Vehicle (UAV) etc.)
- Robust design allowing flight in more extreme conditions (altitude, weather etc.)
- Provide adequate protection circuits for battery and loads to prevent any major failure and damage to other subsystem components.
- Optimal design and high performance to increase power capability and minimize system mass

4.2.2 Technical Requirements and Power Budget

The EPS power budget is listed in Table 4.2 and the technical requirements are listed in Table 4.3.

Table 4.2 – *EPS Power Budget*

Part/subsystem	**Peak load**	**Average load**
2 x MCC motors	$120\,W$	$\sim 35\,W?$
ITPU MCU + sensors	$3\,W?$	$3\,W?$
MCC ETag	?	?

Table 4.3 – *EPS Technical requirements*

Description	Symbol	Value
Minimum power output	$P_{out,min}$	$40\,W$[1]
Maximum mass	$W_{EPS,max}$	$1000\,g$ including solar arrays
Maximum cost	-	$4000\,SEK$[2]
Output voltages	$V_{mainbus}$, V_{5V}	$6.0 - 9.5\,V$ un-regulated and $5\,V$ regulated
Operational temperature	T_{min}, T_{max}	$-20°C\,to + 45°C$
Battery capacity	C_{bat}	$> 5\,Wh$

4.2.3 Mission and Environmental Constraints

This section discusses the system challenges imposed by the operation environment.

Solar Array Temperature

As was discussed in [16], the optimal operating voltage of the solar cells change with temperature. The EPS must be able to generate optimal power from the solar cells in the full expected temperature range of the environment. This can be achieved using a Maximum Power Point Tracking Unit (MPPTU) which will be discussed in Section 4.3.3

Solar Incidence Angle

The flight location of U-SPACE is near Kiruna in Sweden. Figure 4.1 shows the average solar incidence angles in Kiruna for the months June and September[17], considering a flat solar panel facing straight up. The solar cell output current drops with the Kelly cosine function as shown in figure 4.2. To minimize power losses due to inclined solar incidence, MSE design must consider the optimal mounting position and angle of the solar panels. The most optimal flight conditions are at noon in June, with a solar incidence angle of around 46°, however that still reduces the solar array output by about 30%. If the solar array output should not drop by more than 50%, the maximum solar incidence angle is about 57°. This is only an approximation from the assumption that the solar array is mounted flat on top of the airship envelope, which will not be the exact case in practical.

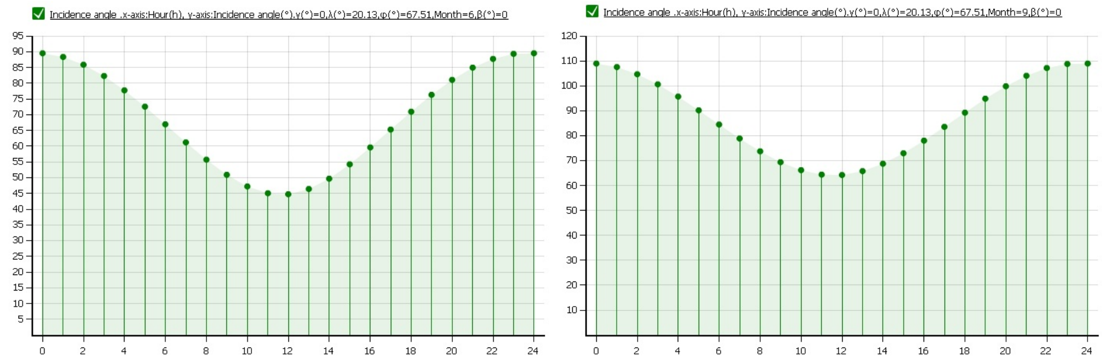

Figure 4.1 – *Monthly average solar incidence angles for June(left) and September(right) for each hour of the day. Solar panel is facing straight up*

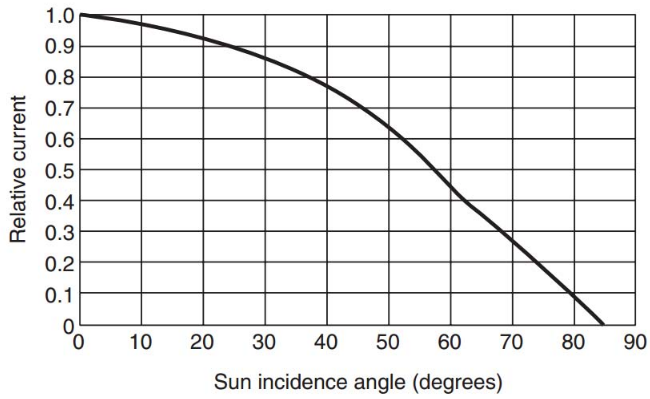

Figure 4.2 – *Kelly cosine function showing how solar cell photo current depends on sun incidence angle[18, Fig 9.12]*

Solar Array Shading

Shading on the solar panels, for example caused by airship stabilizer structures or objects in the landscape, can cause a significant drop in the cell output voltage, as described in [19, p. 165]. Bypass diodes can be used to partly mitigate this issue. However, since the airship is only expected to fly at altitudes above terrain and buildings the only shading possibly expected is from the airship structure hence the MSE design must consider this restriction.

Battery Temperature

One of the most temperature critical EPS components is the battery which must stay within its safety temperature limits. In the proposed design, only temperature monitoring is offered therefore, flight is only allowed when outdoors temperatures are well within the allowed battery temperature range. Otherwise a battery heater and more sophisticated thermal design may be necessary.

4.2.4 Expected Performance

The expected EPS performance values are listed in Table 4.4.

Table 4.4 – *Expected performance*

Description	Symbol	Value
Power conversion efficiency(SAR)	-	$> 90\%$
Power output(SAR)	P_{out}	$\sim 45\,W$ [a]
Battery capacity	C_{bat}	$7.3\,Wh$
Mass	W_{EPS}	$\sim 980\,g$
Total cost	-	$\sim 12000\,SEK$ [b]

[a]For ideal weather conditions, i.e. no clouds and best expected solar incidence angle

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

4.3 Critical Design

The basic EPS diagram is shown in Figure 4.3. A SAR controls the operating voltage of the solar array and supplies an unregulated mainbus. The mainbus voltage is mainly controlled by the battery voltage. A DC-DC regulator provides a regulated $5\,V$ supply to subsystems and payloads. Motors are supplied from the unregulated mainbus.

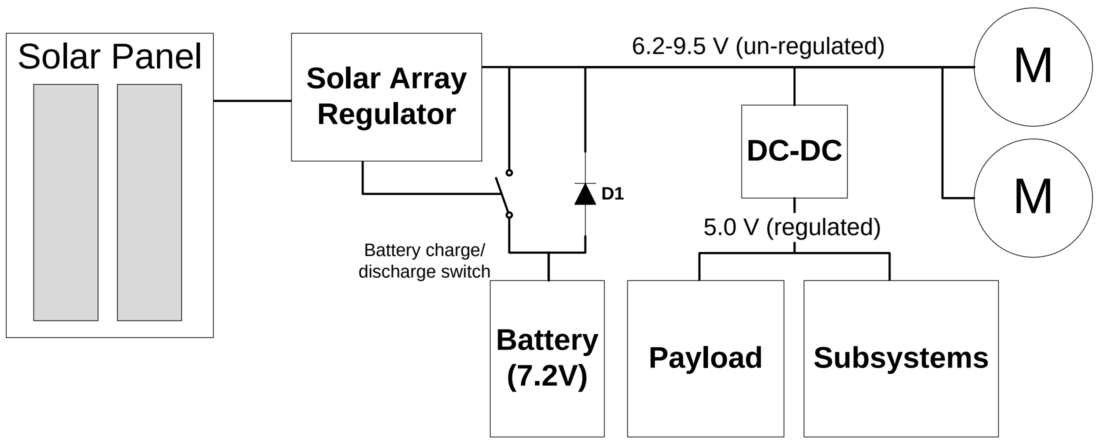

Figure 4.3 – *EPS simple block diagram*

4.3.1 Battery Design

In [16] it was decided that a Li-ion type battery was suitable for the EPS. An *Ansmann Lithium-Polymer (LiPo) Racing Pack 2S1P 30C* battery is selected with the specifications as listed in Table 4.5.

Table 4.5 – *Specification of chosen battery*

Description	Symbol	Value
Chemistry	-	Li-Polymer
Nominal voltage	V_{bat}	$7.4\,V$
Capacity	C_{bat}	$2.1\,Ah$ / $15.54\,Wh$
Weight	W_{bat}	$122\,g$
Dimensions	-	$105\,mm \times 35.2\,mm \times 17\,mm$
Maximum fast charge current	$I_{charge,max}$	$3\,A$
Maximum discharge current (continuous)	$I_{discharge,max}$	$63\,A$

Battery Charge Regulator

The Battery Charge Regulator (BCR) must control the charge rate of the battery such that the charge current limit is not exceeded and cut off the charge current when the battery is fully charged. Temperature monitoring is usually also required to inhibit charging if the battery temperature is outside its safety limits.
An *MCP73842* Li-ion battery charge regulator Integrated Circuit (IC) is selected. It employs three different charge modes: low-charge for deeply discharged batteries, Constant Current (CC) charge and trickle charging as well as inputs for temperature monitoring. The battery maximum charge current was in Table 4.5 given as $3\,A$. From the *MCP73842* datasheet, the minimum current sense resistor value is calculated as

$$R_{sense} = \frac{V_{FCS}}{I_{REG}} = \frac{120\,mV}{3\,A} = 40\,m\Omega \tag{4.1}$$

A $50\,m\Omega$ current sense resistor is selected leading to a charge current of $2.4\,A$. The worst-case thermal dissipation in the MOSFET happens when the battery is charged from its minimum charge state

$$\begin{aligned} P_{max,MOSFET} =&(V_{in,max} - V_F - V_{bat,min}) \cdot I_{charge} \\ =&(9.5\,V - 0.3\,V - 5.5\,V) \cdot 2.4\,A = 8.88\,W \end{aligned} \tag{4.2}$$

where $V_{in,max}$ is the maximum mainbus voltage, V_F the expected Schottky diode forward voltage drop and $V_{bat,min}$ is the preconditioning threshold voltage of the BCR IC. An *SUP75P03-07-E3* P-channel MOSFET is selected which is rated for a peak power dissipation of $187\,W$, well above the minimum requirement provided that suitable thermal design is applied, most likely also including a heat sink.

Calculations on heat sink requirements still remain to be done.

Future Improvements

As was calculated above, significant power may be lost in the BCR MOSFET. This is due to the selected BCR IC which requires an input voltage of around $9.5\,V$ (including a Schottky diode forward voltage drop and some design margin). In future, the BCR could be designed to allow operation with an input voltage only slightly above the battery voltage thus minimizing the charge losses and the thermal requirements of the MOSFET.

Battery Temperature Monitoring

The selected LiPo battery is rated, in charge-mode, for the temperature interval 0 to $+45°C$. For temperature measuring, a $4.7\,k\Omega$ *NTCLE203E3472GB0* thermistor is selected which has a Beta Value, $B = 3977\,K$. Since the battery temperature is measured using an external thermistor, thus the temperature response is likely to be somewhat slower, an extra $5°C$ thermal design margin is added. The required resistance values of the BCR temperature control resistors are determined from the *MCP73842* datasheet as

$$\begin{aligned}
R_{cold} &= R_{25}\, e^{B(\frac{1}{T}-\frac{1}{T_0})} = 4.7\,k\Omega\, e^{3977\,K(\frac{1}{278\,K}-\frac{1}{298\,K})} = 12.28\,k\Omega \\
R_{hot} &= 4.7\,k\Omega\, e^{3977\,K(\frac{1}{313\,K}-\frac{1}{298\,K})} = 2.48\,k\Omega \\
R_{T1} &= 2\frac{R_{cold}R_{hot}}{R_{cold}-R_{hot}} = 6.2\,k\Omega \\
R_{T2} &= 2\frac{R_{cold}R_{hot}}{R_{cold}-3R_{hot}} = 12.6\,k\Omega
\end{aligned} \tag{4.3}$$

where R_{25}, R_{cold} and R_{hot} are the thermistor resistance values at room temperature, the low and high temperature limits respectively. R_{T1} and R_{T2} are the required BCR temperature control resistors setting the required temperature interval.

If the sensed battery temperature falls outside the +5 to $+40°\,C$ region, battery charging will be inhibited. The technical requirements from Table 4.3 requires the EPS to operate down to $-20°\,C$. Hence some insulation and/or heating of the battery may be necessary or flight must be disallowed at outdoors temperatures much below $+5°\,C$.

Battery Under-Voltage Lock-Out

To prevent over-discharge of the battery, a battery Under-Voltage Lock-Out (UVLO) circuit is added as shown in Figure 4.6. An *TL431* precision shunt regulator IC is selected. The lock-out voltage is given as

$$V_{UVLO} = V_{ref}(1+\frac{R_1}{R_2}) = 2.5\,V(1+\frac{29\,k\Omega}{20\,k\Omega}) = 6.125\,V \tag{4.4}$$

where V_{ref} is the *TL431* build-in voltage reference. If the battery voltage drops below this value, the gate voltage to the P-type MOSFET is pulled high thus opening the switch. The $1\,M\Omega$ resistor adds about $200\,mV$ hysteresis.

The UVLO circuit only cuts out the motor power line. Thus payloads remain supplied and the battery is still slowly drained. This design has been chosen to allow telemetry and telecommand capability during a heavy battery discharge event. In this case, it is expected that all payloads and on-board computers enter a low power consumption mode, to extend the remaining battery supply time. If the battery voltage drops below $5.62\,V$, the $5\,V$ payload power supply shuts down and all telemetry and telecommand capabilities will be lost.

4.3.2 Solar Array Design

The main driver for selecting the solar cell is to choose a part which is very light-weight and easy to mount on the SPA. A *PowerFilm RC7.2-75(PSA)* solar cell is selected as shown in Figure 4.4. This is a very light-weight flexible solar cell with a PSA backside for mounting. Table 4.6 lists the solar cell specifications.

Table 4.6 – *Specifications of chosen solar cell*

Description	**Symbol**	**Value**
Nominal output current	I_{cell}	$100\,mA$
Nominal output voltage	V_{cell}	$7.2V$
Nominal output power	P_{cell}	$0.72\,W$
Dimensions	-	$270\,mm \times 90\,mm \times 0.2\,mm$
Weight	W_{cell}	$7.6\,g$
No. of required cells	N_{cells}	100[a]
Total solar array area	A_{array}	$2.43\,m^2$ (assuming 100 % fill factor)

[a] [20] offers good discount for +100 units order

The solar array is an array of 50 parallel connected strings of two series solar cells as shown in Figure 4.4. The nominal output voltage and current are given as

$$\begin{aligned} V_{array} &= 2 \cdot V_{cell} = 14.4\,V \\ I_{array} &= 50 \cdot I_{cell} = 5\,A \end{aligned} \tag{4.5}$$

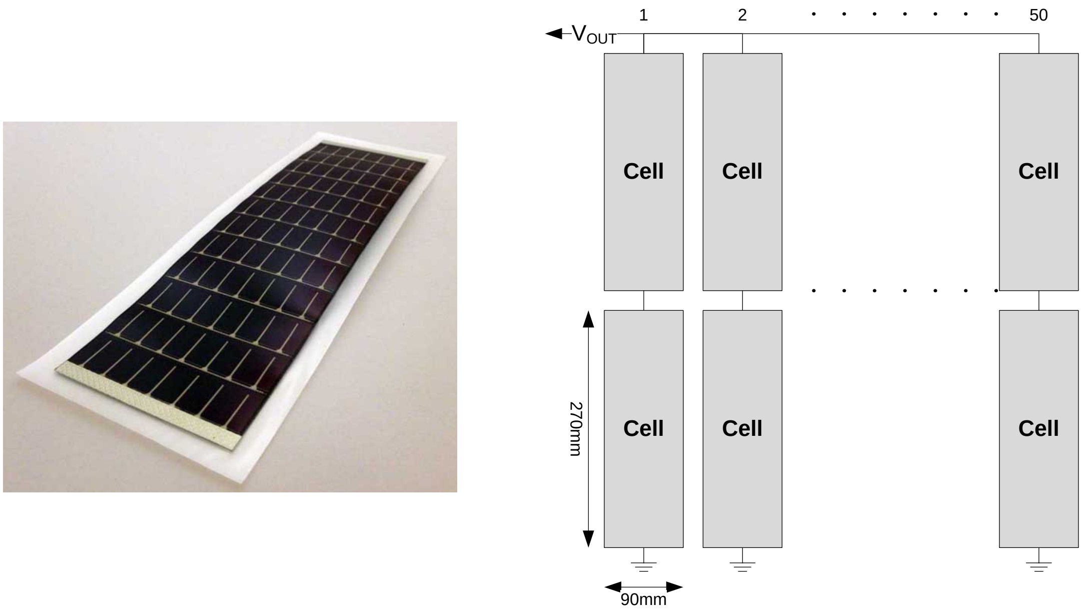

Figure 4.4 – *PowerFilm solar cell (left) and solar array configuration (right)*

Since only two cells are in series, it is estimated that bypass diodes are not very beneficial for mitigating shading issues, as was discussed in Section 4.2.3, and hence are not included in the design.

4.3.3 Solar Array Regulator

The SAR must control the optimal the solar array operating voltage as well as limit the output mainbus voltage. A simple step-down buck converter topology is preferred for a number of reasons:

- simple circuit analysis and low components count
- no inherent Right Half Plane Zero (RHPZ) in contrary to the standard boost topology
- step-down topology calls for a high input voltage which leads to low input current thus minimizing ohmic losses and the relative forward voltage drop loss from the reverse protection diode

Buck Converter Circuit Design

The ideal transfer function for the buck converter shown in Figure 4.6 is given as

$$V_{out} = D\,V_{in} \tag{4.6}$$

where D is the duty cycle of the MOSFET switch, V_{in} the solar array voltage and V_{out} the mainbus voltage. The duty cycle is controlled by a Pulse Width Modulation (PWM) controller which provides input to a high-side MOSFET driver. A Main Error Amplifier (MEA) measures the mainbus output voltage to generate a control signal for the PWM controller. An *LM3477* chip is selected which combines PWM controller, MEA and gate driver in one IC.

The Current Mode (CM) control scheme is adopted due to its excellent dynamic abilities[21, sec. 12-3-6] and simplified feedback regulator design. A low resistance $10\,m\Omega$ precision sense resistor measures the inductor current slope. The *LM3477* has build-in slope compensation to avoid current mode instabilities[21, sec. 12-1].

The converter switching frequency, f_{switch}, is chosen relatively high to $500\,kHz$. The increased switching losses are expected to by out-weighted by the fact that the low operating voltage limits switching losses and high frequency allows the inductor and filter components to be made smaller thus limiting system mass and the resistive losses in the inductor copper wires which are expected to dominate converter losses due to the relatively high currents.
The inductor current ripple, ΔI_L, can be calculated as

$$\Delta I_L = \frac{V_{in} - V_{out}}{L\, f_{switch}} D \tag{4.7}$$

where L is the inductance and f_{switch} the converter switching frequency. The inductor current ripple is usually limited to about $10\,\%$ of the maximum converter output current leading to a minimum required inductance of

$$L = \frac{V_{in} - V_{out}}{\Delta I_L\, f_{switch}} D = \frac{14.4\,V - 7.4\,V}{10\% \cdot 10.83\,A \cdot 500\,kHz} \cdot 0.514 = 6.7\,uH \tag{4.8}$$

where $10.83\,A$ is the maximum converter output current calculated as

$$I_{SAR,max} = \frac{P_{out,max}}{V_{out,min}} = \frac{65\,W}{6.0\,V} = 10.83\,A \tag{4.9}$$

A $10\,uH$ inductor is chosen giving a current ripple of about $0.72\,A$. If the load current drops below $0.36\,A$, which is unlikely to happen in most operating modes, the converter will enter Discontinuous Conduction Mode (DCM).

For the converter output capacitor, a component is chosen which has very low Equivalent Series Resistor (ESR) and high capacitance to limit the output voltage ripples.

Current Sense Amplifier

With an inductor current ripple of $0.72\,A$ the current sense voltage slope is only

$$v_{sense} = \Delta I_L \cdot R_{sense} = 0.72\,A \cdot 10\,m\Omega = 7.2\,mV \tag{4.10}$$

It is recommended that the slope compensation is equal to or the double of the sense slope[21, sec. 12-1], however the minimum compensation slope is limited to $103\,mV$ by the *LM3477* chip. Thus the sensed slope signal must be amplified with a gain of around 20 being suitable. This also has the advantage of eliminating some of the typical noise susceptibility in the current sense signal. The current sense circuit in Figure 4.6 consists of two differential OpAmps which amplifies the current sense slope. Resistive voltage dividers are placed on the OpAmp inputs to scale down the input voltage signals to always be below the $5\,V$ OpAmp supply voltage.

Since a closed-loop OpAmp gain of 20 is needed at an operating frequency of $500\,kHz$, the gain-bandwidth specification of the OpAmps must be more than $10\,MHz$. The *LTC6362CMS8PBF* OpAmp is chosen. One limitation of this OpAmp is its temperature range which only goes down to $0°\,C$. This might be solved by thermally connecting it to the transistor heat sinks or ensure that the internal EPS temperature does not go below $0°\,C$.

Input Filter

An input filter is placed in front of the buck converter, mainly to draw a continuous current from the solar array. It also reduces the converter Electromagnetic Compatibility (EMC) issues. One challenge with the input filter is that it effects the dynamic properties of the converter and if not properly designed, it can degrade the control feedback loop performance. A damping network in the filter is also necessary to avoid instabilities[21, sec. 10-3].

A usable filter has been designed based on PSpice simulations. However thorough analysis still remains to be done to optimize the filter design.

Maximum Power Point Tracker Unit

In [16] it was decided to use a MPPTU with the SAR to increase solar array efficiency during changing environment conditions. The SAR with Maximum Power Point Tracking (MPPT) can operate in three different operation regions:

- Battery discharge - 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. The MPPTU controls the input solar array voltage.
- Battery charge - when the solar array input is greater than the load power, excessive power is used to recharge the battery. The MPPTU controls the input solar array voltage.
- 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 at a maximum limit. The extra potential input power is dissipated as heat externally on the solar arrays.

It is preferred to implement an analog MPPTU mainly since this makes the circuit independent on a control signal from a more complicated external Micro-Controller Unit (MCU) or Digital Signal Processor (DSP) thus allowing a flexible plug'n-play system to be implemented. One challenge with an analog MPPTU is the typical need for expensive analog multipliers[22]. Since the required multiplier only needs to be a 1st quadrant type (only two positive inputs), it is believed that a low-cost multiplier can be build using standard discrete components[23].

The MPPTU design still remains to be completed.

Mode Transitions

As was discussed in Section 4.3.3, the SAR can operate in three different main modes. The transition between the modes is controlled by the mainbus output voltage as shown in Figure 4.5. If the SAR input power is lower than the load power, the battery will discharge and the mainbus voltage will follow the battery voltage. Once the input power is larger than the load power, the mainbus capacitor will quickly be charged to a voltage higher than the battery voltage. Once the mainbus capacitor voltage crosses the $9.2\,V$ charge threshold, the BCR starts to charge the battery. If the input power is still higher than the combined battery charge power and load power, the mainbus capacitor voltage continues to rise until reaching $9.5\,V$ where the SAR enters the input power limitation mode. The battery may still be charging in this mode. Since the battery is charged with constant current, the input power may be lower than the combined charge and load power but higher than the load power alone. Hence an oscillatory state between battery charge and discharge mode may rise whose frequency depends on the mainbus capacitance which should therefore be large.

The $9.20\,V$ battery charge threshold voltage is calculated from

$$V_{charge,threshold} = V_{UVLO,BCR} + V_F = 8.90\,V + 0.3\,V = 9.20\,V \tag{4.11}$$

where $V_{UVLO,BCR}$ is the worst-case UVLO threshold voltage of the BCR IC and V_F is the reverse protection diode forward voltage drop.

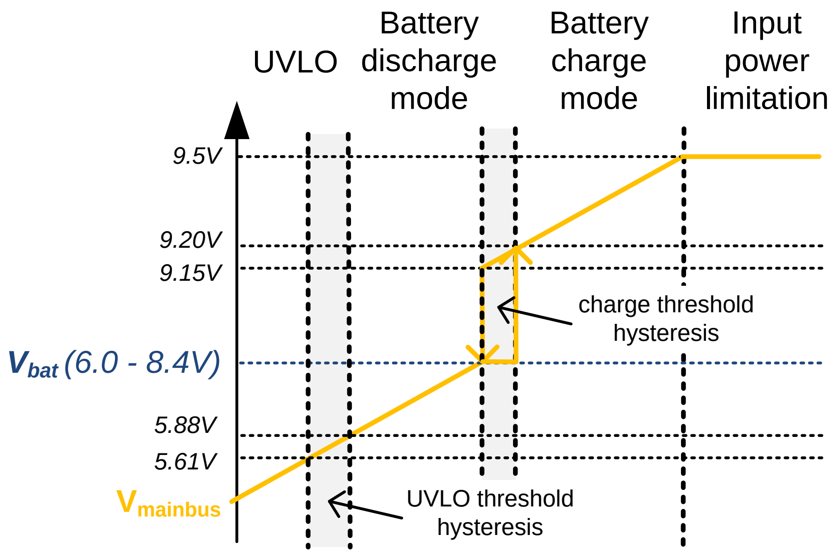

Figure 4.5 – *Different SAR operation modes as function of mainbus voltage*

4.3.4 5V Regulator

To provide a regulated 5 V supply for the on-board computer and payloads, a *MIC29300-5* Low-dropout (LDO) regulator is selected. A 2 A resettable Positive Temperature Coefficient (PTC) fuse is added to protect the loads from excessive currents and to protect the battery in case of a payload short-circuit failure.

4.3.5 Complete Electrical Power System Diagram

The complete EPS diagram is shown in Figure 4.6. Two 17 A fuses are added in front of the motors, to protect the battery from a motor short-circuit failure.

4.3.6 External Interfaces

The interfaces of the EPS external are listed in table 4.7.

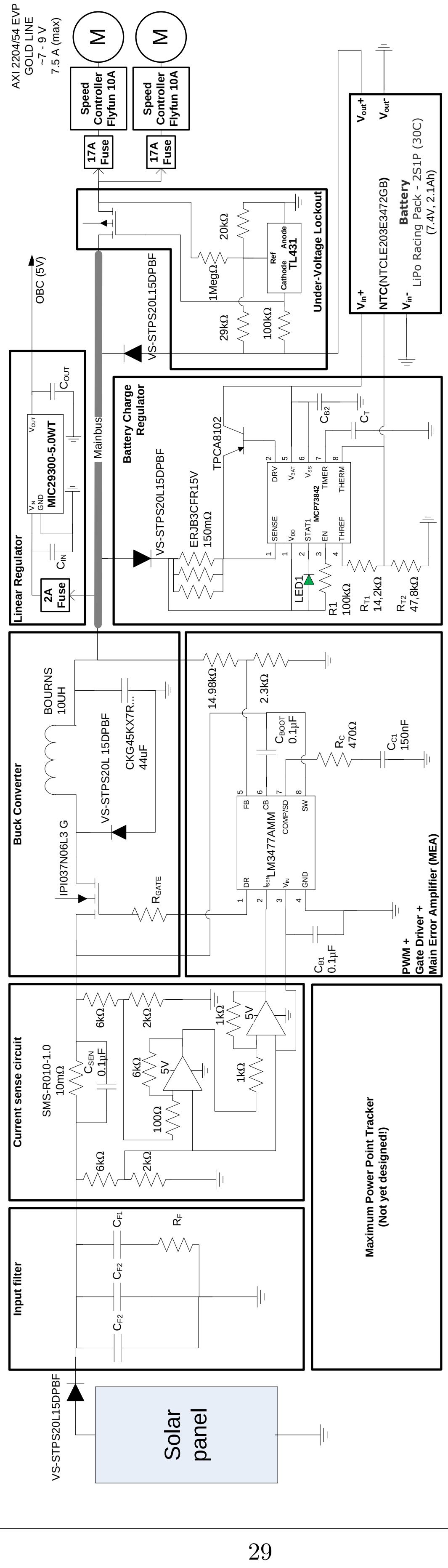

Figure 4.6 – *EPS detailed block diagram*

Table 4.7 – *External interfaces*

External interface	Type	Implementation
Solar cells mounting	Mechanical	Possibly using PSA - To Be Decided (TBD).
Power electronics mounting	Mechanical	Mounted on a Printed Circuit Board (PCB) which sits in the cargo bay, attached with screws.
Battery mounting	Mechanical	Mounted in cargo bay with strips or Velcro. Thermal insulation with Styrofoam or similar material should be added to protect against cold temperatures.
EPS telemetry	Electrical	Analog signals to Microcontroller. Electrical connector interface still remains TBD.
EPS telecommands	Electrical	TBD
Output voltages	Electrical	$6.0 - 9.5\,V$ (unregulated) and $5.0\,V$(regulated).

4.3.7 Telemetry and Telecommands

The suggested EPS telemetries are listed in Table 4.8 and the suggest telecommands in Table 4.9. Not all telemetries or the telecommands are part of the initial EPS design and will only be implemented if time and resources allow it.

The exact electrical configuration and interface connectors still remains to be designed.

Table 4.8 – *Telemetry*

Telemetry	Data rate	Data size	Data range
Battery voltage	Every 5 sec	2 bytes	TBD
Battery temperature	Every 5 sec	2 bytes	TBD
BCR status	Every 5 sec	1 byte	High($5\,V$), low($0\,V$) and $1\,Hz$ 50% duty cycle ripple[3]
UVLO status	Every 5 sec	1 byte	$0\,V$(nominal operation), $5\,V$(under-voltage lock-out)
Mainbus voltage	Every 5 sec	2 bytes	TBD
Solar array temperature	Every 5 sec	2 bytes	TBD
Solar array voltage	Every 1 sec	2 bytes	TBD

Table 4.9 – *Telecommands*

Telecommand	Command format	Description
Battery charge inhibit	TBD	Battery charging can be remotely terminated in case of battery anomalies.
Solar array voltage set	TBD	When MPPT is running, the solar array operating voltage can manually be set to mitigate any malfunction in the MPPT algorithm.

4.4 Test and Verification of Design

This section describes the various design models used to develop the EPS along with the expected functional test to be executed.

4.4.1 EPS Design Models

EPS PSpice Simulations

A transient PSpice simulation model of the whole EPS is currently being implemented. The completed PSpice models are shown in Appendix A.1. These will help in the design and testing of the regulator performance and system stability during transient loading as well as the interactions between the different circuits.

In future, it is desired also to implement transient PSpice models for the solar array[24], MPPTU, battery[25], motors and BCR.

EPS Development Model

An EPS Development Model (DM) is currently being build as seen in Figure 4.7. The prototype PCB is realized using self-made "mini-mount" PCB pads as shown in Appendix A.2. These pads are attached, using a simple glue roller, on a complete copper ground plane. This design approach allows a compact layout which reduces parasitic effects. Also any IC package can be supported and parts can easily be moved around if the design changes.

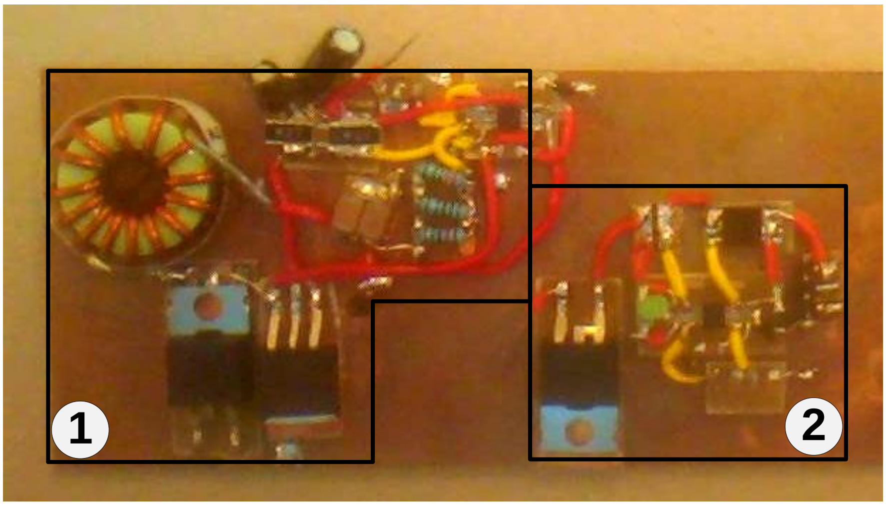

Figure 4.7 – *EPS prototype - 1: SAR, 2: BCR*

Development Model Status

The SAR is working but shows signs of CM instability which is expected to be caused by the missing current sense amplifier circuit and input filter. Development progress is currently awaiting delivery of components.

The BCR is also working however excessive heating of the MOSFET was experienced. A new part rated for higher power dissipation has been selected and is currently awaiting delivery.

EPS Flight Model

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

4.4.2 EPS Test Program

Table 4.10 lists all necessary and desired test of the EPS. Priority "1" tests are all required while priority "2" tests will only be realized if time and resources allow it.

Table 4.10 – *Test program*

Subsystem	Condition/Mode	Test Description	Pri.
SAR	Mainbus voltage limitation	With more input power than load power, SAR must be able to maintain a stable 9.5 V output voltage also during transient loading.	1

-	Maximum power handling	With an input and load power slightly above the maximum expected solar array power, no SAR components must overheat or otherwise malfunction.	1
-	MPPT	TBD.	2
-	Mode transitions	SAR must be able to change between MPPT, battery charge and discharge mode without loosing mainbus voltage regulation or causing other malfunctions.	2
-	Feedback loop stability	Regulator bandwidth, gain- and phase margins should be measured with a Network Analyzer.	2
-	EMC	Electromagnetic emissions should be measured with a Spectrum Analyzer, especially with concerns to the telecommunication systems.	2
BCR	CC and trickle charging	CC charge at $2.4\,A$ and trickle charge mode entered when battery voltage reaches $8.4\,V$ should be verified.	1
-	Charge inhibit at high/low temperatures	While battery is charging, battery thermistor is heated/cooled in thermal oven/fridge to slightly above/below the specified temperature limits and charging should be terminated.	1
UVLO	Power cut-off and recovery	Reducing input voltage below calculated threshold voltage should open switch and switch should close again when input voltage is increased above the threshold.	1
Battery	Dynamic model	Test approach is described in [26].	2
Solar cell	I-V specifications	Short-circuit current, open-circuit voltage, current and voltage at the Maximum Power Point (MPP) should be determined from an irradiance test.	2

-	Temperature coefficients	Solar cell temperature coefficients should be determined be measuring the I-V characteristics at different temperatures within the expected temperature interval.	2
Fuses	Temperature variation	The PTC resettable fuses should be tested at nominal, minimum and maximum expected temperatures to verify acceptable functionality.	1

4.5 Resources and Scheduling

4.5.1 Main Tasks

TBD...

4.5.2 Parts List and Costs

Table 4.11 lists all ordered EPS parts (including one order which is expected to be placed in the near future). The calculated costs does not including invoicing or shipping costs.

Table 4.11 – *Parts list*

Part	Part Name	Supplier	Cost[1]	Qty.
SAR current sense resistor	FCSL110R010FER	Farnell(US)	31.52	2
SAR power diode	MBR3050CT	Farnell	9.24	3
SAR power MOSFET	IPI037N06L3 G	Farnell	19.32	4
SAR mainbus capacitor	CKG45NX5R1C226M	Farnell	38.72	4
PWM, MEA and MOSFET driver	LM3477AMM	Farnell	16.37	5
SAR inductor	2101-H-RC	Farnell(US)	25.13	2
PCBs	CIF - AA15	Farnell	67.42	4
Battery(obsolete)	PA-L60	Farnell	294.28	2
Battery	LiPo Racing Pack 2S1P	Ansmann	N/A[2]	1
Reverse protection diode	VS-STPS20L15DPBF	Farnell	24.56	6
BCR	MCP73842-840I/UN	Farnell	13.61	2
BCR Transistor(obsolete)	TPCA8102(TE12L,Q)	Farnell	28.5	2

Table 4.11 – *Parts list*

Part	Part Name	Supplier	Cost[1]	Qty.
Current limit Bipolar Junction Transistor (BJT) (obsolete)	2STN2540	Farnell	7.84	5
Current limit MOSFET (obsolete)	IRLML6401PBF	Farnell	6.41	2
BCR current sense resistor	ERJB3CFR15V	Farnell	1.97	5
Current limit sense resistor (obsolete)	ERJB2BFR33V	Farnell	4.83	5
Current limit sense resistor 2 (obsolete)	ERJA1BJR27U	Farnell	5.30	5
Power limit BJT (obsolete)	STN888	Farnell	5.49	5
Solar cell	RC7.2-75(PSA)	Eco Power Shop	230.08	2
Solar cell (obsolete)	MC-SP0.8-NF-GCS	Farnell	66.51	2
LDO regulator	MIC29300-5.0WT	Farnell	74.85	2
Current sense OpAmp	LTC6362CMS8#PBF	Farnell	32.31	2
Thermistor	NTCLE203E3472GB0	Farnell	8.64	5
Motor fuses	RGEF1000	Farnell	6.46	5
LDO regulator fuses	MC36248	Farnell	1.41	5
BCR MOSFET	SUP75P03-07-E3	Farnell	31.51	2
UVLO linear shunt regulator	TL431AILPME3	Farnell	1.36	5
UVLO MOSFET	SUP75P03-07-E3	Farnell	31.51	2
Total cost			2707.6	

4.5.3 Electrical Ground Support Equipment

The Electrical Ground Support Equipment (EGSE) in Table 4.12 is mainly required for testing of the EPS.

Table 4.12 – *Required EGSE*

Instrument	**Required Specifications**
Network Analyzer	Up to about $\sim 1\,MHz$
Spectrum Analyzer	TBD
Power supply	$75\,W$ output power at $\sim 15\,V$
Heating and cooling chamber(s)	$-20°C$ to $+45°C$ and allow small wires to be pulled through chamber

4.5.4 Mechanical Ground Support Equipment

The required Mechanical Ground Support Equipment (MGSE) is mainly for PCB manufacturing, i.e. UV light source, photo developing facility, etching facility, drills, cutters etc.

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

- 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 Critical Design

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.

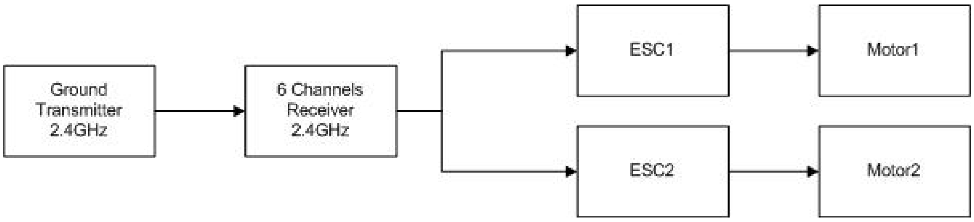

Figure 5.2 – *Block diagram of the MCC Subsystem*

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 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 the 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 off-line 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 tens 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 [27] combined magnetometer and accelerometer and the ITG-3200 triple-axis gyroscope [28] 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). 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 ground station.

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 pre-emptive 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 recorded images, as it provides the reference system and relative alignment of the taken images towards each other.

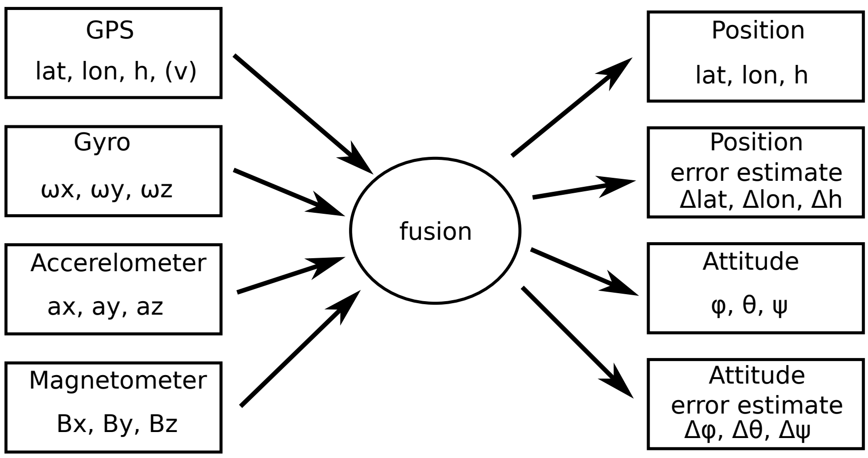

Figure 6.1 – *Attitude Determination System overview*

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):

- GPS receiver: Provides absolute position values, but has much high-frequency noise
- Gyroscope: Provides accurate relative pointing direction, but has drift.
- Accelerometer: Provides absolute 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.

6.5.1 Attitude Determination System Development

The attitude determination system was not only developed on the final hardware itself. For continuation of the development during the semester break a recently released Raspberry Pi minicomputer was privately purchased, which has properties very similar to the Beagle Board and runs a derivative of the Debian operating system. We created a board to attach a complete set of sensors to the system, which is gyroscope (ITG-3200 from Sparkfun), magnetometer+accelerometer (LSM303 from Sparkfun) and GPS receiver (Venus 6 GPS Module ST22 from SkyTraq). All sensors are pluggable and the complete system is shown in Figure 6.2. The bottom side of the board with wiring cables is shown in Figure 6.3. This testing system does not yet contain a camera, but it will be added in the future.

In this configuration the whole unit consumes 3W of power and weighs 71g (30g for sensors and shield and 41g for the computer).

6.5.2 Attitude Determination Algorithms

The attitude of the sensing unit could in principle be determined by simply integrating the gyroscope rates up from an initial alignment. This however will degrade with time because of significant low-frequency drifts, sensor offsets and measurement inaccuracies.

To solve the problem more robustly we use a set of 3D gyro-, magnetometer and accelerometer sensors which are fused with our C++ program that runs on the board computer. Main technique is the Extended Kalman Filter (EKF) which offers a near-optimal estimation with fixed memory usage. Attitudes are represented as quaternions, which is

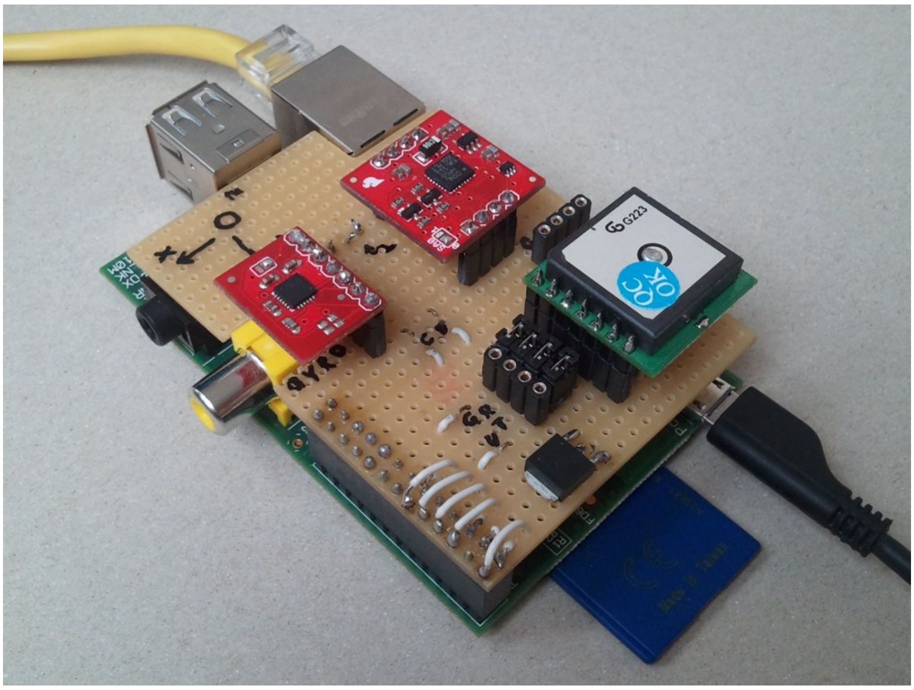

Figure 6.2 – *Raspberry Pi computer with self-constructed pluggable sensor shield. Mounted on the shield are gyroscope (red, left), magnetometer + accelerometer (red, top) and a GPS receiver (green, right). Also I2C and UART 4-pin sockets are visible as well as a small voltage regulator (bottom) that connects the 3.3V GPS module to the 5V high-current source.*

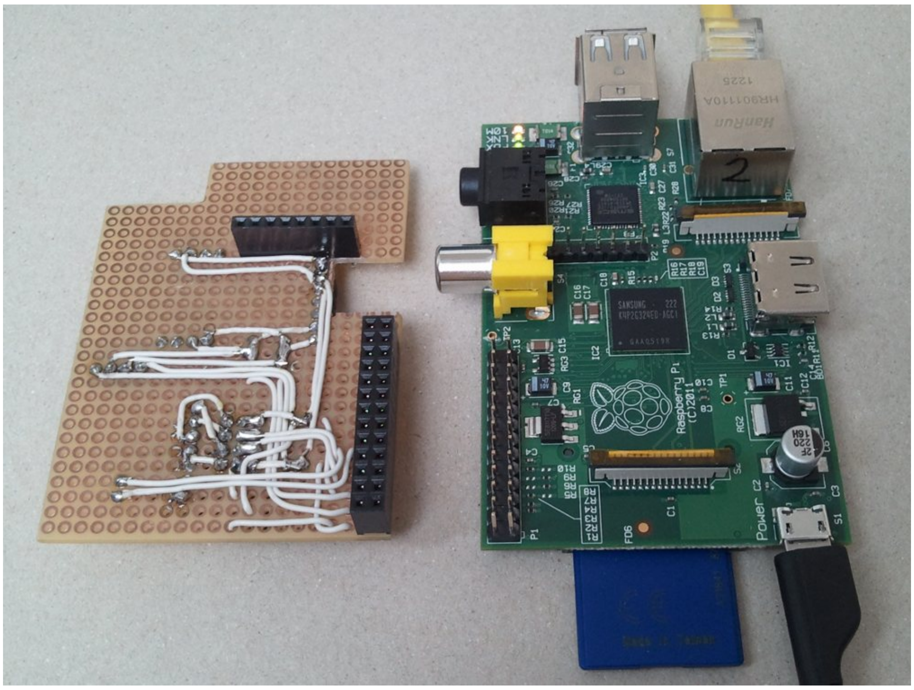

Figure 6.3 – *Raspberry Pi computer with self-constructed pluggable sensor shield. Wiring from the Raspberry Pi 26pin P1 header to individual sensors can be seen on the bottom side of the shield.*

an elegant and cpu-effective solution.

Offset filtering for the magnetometer and accelerometer is done independently. We set up an EKF that estimates x- y- and z-offset and total radius along with each new measurement. The measurements are available readily at system start-up without calibration, but the accuracy will only improve as soon as measurements from different attitudes are available. The EKF also accounts for slow offset drifts and similar effects.

Estimation of the gyro offsets and rate scaling is done with combination of acceleration and magnetometer absolute attitude estimations and the gyro-integrated attitude. This outputs a gyro error value at each measurement step that is used by the Kalman algorithm to estimate the system parameters and calculate a best-estimate attitude.

Finally the position is determined independently from the GPS receiver. This is much simpler than fusing position values from the inertial measurement of the previously described sensors with the absolute GPS position. With the tight time constraints of the project we choose this simpler method. However in continuation of the project we want to test the fusion algorithm described in the book "Stochastic Models – Estimation and Control" chapter 6.4.

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. Thus additionally to the external pull-up resistors on the I2C interface also voltage level converters have to be used.

Chapter 7

Thermal Interfaces

This chapter describes the U-SPACE thermal requirements and design.

7.1 Thermal Requirements

The U-SPACE systems are required to operate in the temperature range $-20^\circ\,C$ to $+45^\circ\,C$. The limits are based on weather data from Table 2.2 including appropriate design margins. The high temperature limit also considers heat contribution from direct external sun exposure and internal power dissipation from the EPS. Table 7.1 lists temperature critical parts that are not rated for the full temperature range as given above.

Table 7.1 – *Temperature critical parts*

Part	Rating	Monitoring	Control	Protection
BeagleBoard MCU	$0^\circ\,C$ to $+85^\circ\,C$	-	-	?
EPS Battery	$+5^\circ\,C$ to $+40^\circ\,C$[a]	External thermistor	-	Charge inhibit at low temperature.
Current sense OpAmp	$0^\circ\,C$ to $+70^\circ\,C$	-	-	-

[a]Including $5^\circ\,C$ design safety margin

7.2 Thermal Design

From Table 7.1 it is mainly the lower temperature limit which is of concern. Currently the U-SPACE thermal design does not include temperature monitoring, except the battery, nor any temperature control. It will therefore not be possible to fly when the outdoor temperature falls much below $+5^\circ\,C$. This issue may be solved by insulating the cargo bay with Styrofoam or similar material. Internal dissipation from the EPS and payloads will then increase the internal cargo bay temperature with respect to the outdoor temperature. Additional heaters may also be included in the design, however this will complicate the system and consume power which is already limited.

Complete thermal analysis, insulation requirements and possible heater design still remains to be done.

Chapter 8

Electromagnetic Compatibility

This chapter describes the U-SPACE EMC, Electromagnetic Interference (EMI) susceptible parts and mitigation methods.

For the U-SPACE EMC we have defined one mission critical circuit which is the motor control of the MCC subsystem. Loss of motor control due to EMC issues, could in the extreme case result in equipment damage. Two non-critical circuits have been identified: The ITPU sensors and the telemetry communication system.

8.1 Electromagnetic Interference Sources

The identified main EMI sources are:

- The EPS SAR - Radiated EMI from power inductor and high AC-current loops. Conducted EMI from power switches.
- The two MCC DC-motors - DC H-field from permanent magnet rotor and radiated EMI when motors are running.
- The MCC motor power leads - Radiated EMI from large AC-current loops (up to $\sim 7.5\,A$ per motor).

8.2 Electromagnetic Interference Susceptibility

Table 8.1 lists the EMI sensible parts which have been identified along with the applied mitigation method.

Table 8.1 – *EMI susceptible parts and mitigation methods*

Susceptible part	Susceptibility type	Mitigation method
ITPU Magnetometer	DC H-fields	Must be kept at minimum distance from DC-motors. Calibration might be necessary after ITPU integration in complete U-SPACE system.
ITPU Sensors	Radiated and conducted EMI	Must be kept at minimum distance from EMI radiation sources.
MCC motor communication	Radiated EMI	Must be kept at minimum distance from EMI radiation sources.
MCC telemetry communication	Radiated EMI	Must be kept at minimum distance from EMI radiation sources.

8.3 Electromagnetic Interference Mitigation Methods

In U-SPACE, the primary applied method for reducing EMI related issues is to separate EMI sources from EMI susceptible parts be appropriate distances. It is also important to minimize the area of high AC-current loops. This can be achieved by proper PCB layout of the SAR and by keeping together and twisting the forward and return power leads to the DC-motors. A secondary method of mitigating radiated EMI from the SAR will be to apply shielding either around the complete circuit or only the power inductor. This will however increase the system mass and is therefore only a last-resort option.

8.4 Electromagnetic Interference Tests

EMI tests for the EPS were defined in Section 4.4.2. In general, susceptibility tests should be applied to the sensible parts defined in Table 8.1. When the EPS SAR and DC-motors are running at full power, no performance/communication degradation or glitches should be noticed, due to EMI. Guides for EMI emission measurements and susceptibility tests along with accepted limits are provided in [29].

Chapter 9

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.

Chapter 10

Test and Verification of Design

10.1 Design Verification Plan

In order to verify that the goals of the U-SPACE project (as set forth in chapter 2) are truly satisfied after the realization of a prototype, it is very important to perform a series of design verification procedures with this prototype. Both verification by analysis and verification by test exist.

10.1.1 Objectives and Responsibilities

A complete design verification plan is an essential element of a successful project. The first main objective of having such a plan is the availability of a structure that allows to systematically verify the quality of the work delivered during the project. It is also important because it makes it possible to check exactly where problems occur and to find clues towards the solution of these problems.

The responsibility of defining and performing the appropriate design verification procedures for each subsystem lies with the team members responsible for that subsystem. They report to the quality manager and the project manager, who can then define test verification procedures for combinations of subsystems, possibly testing each combination individually. When satisfactory results are achieved the entire prototype can be verified by a final series of procedures.

10.1.2 Verification By Analysis

A first verification method is verification by analysis. This method uses theoretical calculations and simulations to check if the goals of the subsystem and/or project can be realized with the current hardware and software combination [30]. For the U-SPACE project these calculations could for example consist of a theoretical analysis of the maximum payload weight based on the characteristics of the SPA structure or a comparison of the forces on the structure to evaluate the maximum forward velocities caused by the motors. Simulations could also be performed for the EPS to check the stability of the provided power or the power consumption of each subsystem. Comparing the prototype with previously used solution concepts (verification by similarity) can be considered as a subset of this verification method. However, since there are very few examples of a SPA of this type, this specific subset is not used during the project verification phase.

Although calculations and simulations are used extensively during the design phase of the project they are not an essential means to verify the final quality of the subsystem and/or prototype. This type of calculations is very difficult and requires a clear insight in the underlying principles. Since the experience in the team is limited in this respect, the principal verification method is verification by test, which is treated below.

10.1.3 Verification By Test

The second and most important verification method during the U-SPACE project is verification by test. As the name implies this method consists of monitoring the performance and functionality of the subsystem and/or prototype in a simulated test environment [30]. Detailed test procedures and test matrices have to be defined for each subsystem, including such topics as stable basic performance, compliance with other subsystems and extreme conditions. The subsystem or prototype has to achieve satisfactory results in all test procedures to be considered as a successful realization of the project goals.

10.1.4 Verification By Inspection

The final verification method is verification by inspection. It is defined as the visual inspection of hardware and software for good workmanship and compliance to industry or design standards [30]. This method is a very simple method that can give the first clues regarding the successful design of a subsystem, but which always has to be corroborated by means of test procedures. It is therefore only a minor element in the complete design verification plan.

10.2 Subsystem Test Matrices

The design verification plan of the U-SPACE project includes test matrices for each subsystem, presenting all tests and their (future) results. These matrices can be used to check the progress of the test procedures and are also useful to identify problems with the subsystem. More details regarding the test procedures for each subsystem can be found in the dedicated sections of the specific chapters.

Chapter 11

Ground Support Equipment

11.1 Electrical Ground Support Equipment (EGSE)

The design, construction and test of a SPA requires the use of extensive EGSE, specifically during test flights. This EGSE can be divided into the ground station, the controller and supplementary material.

11.1.1 Concept

The ground station of the U-SPACE project is responsible for receiving data from the scientific payload and combining this data with images taken by the camera. This combination is then used to form aerial maps of the environment (see chapter 6). It can also be used to track the airship with the help of the GPS module and to visualize all data received from the airborne vehicle.

The controller is used to control the SPA during flight testing. It consists of a basic commercial transmitter/receiver that allows a human ground-based pilot to remotely control the motors of the airship. More information can be found in chapter 5.

The supplementary material of the EGSE consists of a single power supply to charge the battery before flight. This allows the airship to start flying even without the presence of sunlight.

11.1.2 Hardware Description

For the ground station, the hardware is a desktop computer or laptop connected to a receiver. The receiver is described in chapter 6. The pictures taken by the camera can be downloaded after flight (requiring a connection between this camera and the computer) or can be sent to the ground station when the SPA is still airborne (via the same wireless connection as the scientific payload data). The user is presented with visualizations of the scientific data as well as with aerial maps constructed from the camera images and the scientific data.

The hardware of the controller is basically a commercial remote controller capable of transmitting and receiving. By adjusting the controls the pilot is able to give more or less power to the motors mounted onto the airship. This is the principal means of forward propulsion. This controller is described in more detail in chapter 5.

Finally, the supplementary material consists of a commercial power supply that is able to charge the batteries of the EPS. The characteristics of this power supply are discussed in chapter 4.

11.1.3 Software Description

The supplementary power supply and the controller do not require any additional software. Only for the ground station additional software has to be developed, capable of reading the scientific payload data received via the wireless connection and visualizing this data. In order to combine the aerial camera images and the scientific data a custom algorithm has to be written. This software is further described in chapter 6.

11.1.4 Compliance

Both the ground station receiver and the controller transmitter/receiver have to comply with the Radio Regulations of the ITU [14]. As both hardware devices are commercial, no problems are expected in this respect.

11.2 Mechanical Ground Support Equipment (MGSE)

Apart from the EGSE, also a certain amount of MGSE is required for the success of the U-SPACE project. First of all facilities at LTU Rymdcampus, IRF or Esrange have to be available during flight tests to enable on-site fuelling of the envelope with a suitable gas (see chapter 3). These facilities include a large gas tank, valves and tubes to connect the tank to the envelope and also safety equipment to ensure that the entire procedure does not harm the persons involved.

Secondly an extensive safety system is necessary to prevent the airship from flying beyond the flight test perimeter in case of failures or unexpected weather conditions. This system should nevertheless allow the SPA to move freely about during all flight test procedures, without interfering with the normal operation of the airship. Possible implementations include a long rope tied to a fixed point or a cable firmly anchored to a movable object.

Chapter 12

Project Management

12.1 Organisation and Responsibilities

A project of the extent of the U-SPACE project, even though it is a student project, requires clear agreements between the team members with with respect to responsibilities, work load and communication. Also the available support facilities and other practical issues have to be investigated beforehand.

12.1.1 Key Personnel and Responsibilities

Two important team members in the U-SPACE project are the quality manager and the project manager. These managers were elected by the entire team. The quality manager, Morten Olsen, takes care of the technical side of the project. He is responsible for topics such as technical consistency between the different subsystems, follow-up of the progress of each subsystem and finally for guaranteeing the general technical quality of the project. The quality manager therefore gathers updated information from each subsystem, synthesizes this information and informs the project manager when problems arise. Currently Morten Olsen has also taken over the responsibilities of Dries Agten as project manager of the U-SPACE project.

The project manager, Dries Agten, has responsibilities ranging from practical organisation over general communication to project documentation. The practical organisation includes the call for a weekly meeting, chairing this meeting, checking meeting reports, etc. With regards to communication the project manager is responsible both for internal and external communication. Therefore the project manager is in contact with the supervisors, Kjell Lundin (IRF) and Alf Wikström (LTU), to communicate the progress of the project and to have regular meetings to discuss this progress. The internal communication topics range from calls for meetings to the passing-on of important information gained from the contact with the supervisors. Taking care of the project documentation means that the project manager is responsible for the design reviews, the meeting reports and other documentation that may be generated over the course of the project.

12.1.2 Functional Organigram

A functional organigram presenting the different subsystems (as defined in chapter 1) and the associated team members is shown in figure reffig:obs. This organigram is based on the background and expertise of the different team members (see table 12.1), such that each team member is assigned a responsibility which he is able to handle.

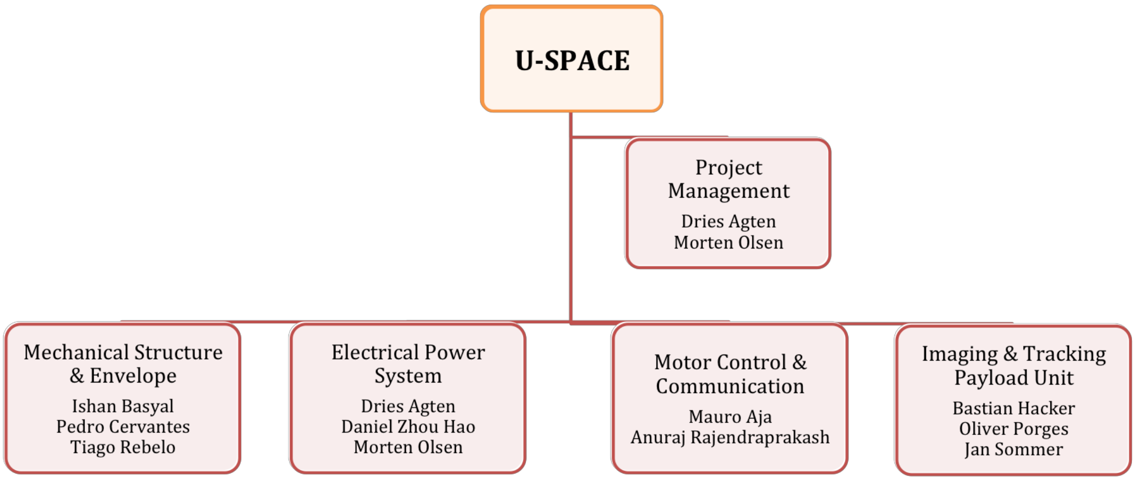

Figure 12.1 – *Functional organigram*

Table 12.1 – *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

12.1.3 Support Facilities

The support facilities of the U-SPACE project are the responsibility of three organisations, each with a focus on a specific part of the project. The first organisation is LTU, represented by Alf Wikström. As all team members are students from LTU, this university is the principal support facility during the U-SPACE project. Its responsibility is the practical, financial and also technical support of the team members. The practical support consists of providing tools and specific work spaces, such as mechanical workshops or electronics laboratories. Some other aspects are discussed in more detail in section 12.2.

The two other supporting organisations are IRF and Esrange. IRF is represented by Kjell Lundin, while the contacts with Esrange are the responsibility of Alf Wikström. These two support facilities provide technical assistance during the course of the project, consisting of guidance regarding the selection of the components, support during the fabrication procedures and recommendations regarding the test set-up.

12.1.4 Transport

The transportation of the prototype SPA is an important topic in this project. Since the prototype will be built at the Rymdcampus of LTU and since the test flight will most probably take place at Esrange, a secure transport procedure has to be developed. As the envelope is the property of Esrange (see chapter 3), the complete assembly of the airship will only take place at this location, which relieves the transport constraints. Most subsystem are limited in size and can easily be transported in a normal passenger car. The only exception is the solar array and supporting mechanical structure which might be difficult to fit inside a car. A closed trailer or small truck might be needed for transportation of this.

12.2 Relation With Support Facilities

The support facilities mentioned in the previous section play an important role in the course of the U-SPACE project. Their responsibilities are wide, ranging from reports over components to finances.

12.2.1 Reporting and Monitoring

During the entire project the team is monitored by the supervisors Kjell Lundin (IRF) and Alf Wikström (LTU). This monitoring task consists of controlling the budget, approving the ordering of components and evaluating the (technical) progress of the team at strategical points in time. Weekly meetings between the two supervisors and the two team managers are scheduled to identify, discuss and solve all issues that have come up since the last meeting. Apart from these weekly meetings, communication via email and telephone is used to keep the supervisors updated about the status of the project and to ask for assistance when needed.

12.2.2 Reviews

Three main reviews are planned for the U-SPACE project:

- Preliminary Design Review
- Critical Design Review
- Flight Readiness Review

The first two reviews are also the points in time when grades are connected to the work executed up to those points. Each review is briefly described below.

Preliminary Design Review

The PDR was held and approved in early April 2012. With the help of five separate documents, the general project and the different subsystems were introduced to the supervisors, with a focus on the preliminary design concepts. The supervisors approval of the PDR made the project budget available and allowed the first components to be ordered.

Critical Design Review

In the Critical Design Review (CDR), which is the current document, the final designs of the subsystems are presented, together with some early verification and prototype results. An oral team presentation was held already in the middle of June 2012, before many team members had to leave Kiruna. The outcome of the CDR is to ensure that the complete system design will meet the functional requirements from Section 2 and the technical requirements stated for each subsystem. It must also show that all the system interfaces between different subsystems or the environment are compatible.

Flight Readiness Review

A third optional Flight Readiness Review (FRR) is also planned. This is to be held prior to flight, to ensure that all systems are fully functional and inter-compatible with each other and that all support equipment needed for a successful flight are available. This review is important since flight events at Esrange are expensive and the availability of the Esrange facilities and help from the staff is limited.

12.2.3 Component Ordering

The ordering of the components is the responsibility of LTU, the organization that is also responsible for the project financing (see section 12.3). The members of the subsystems select the appropriate components and pass the order on to the project manager. He consults with the project supervisors and after approval the components are ordered, usually by Lars Jakobsson(LTU). Components are preferably ordered from inside Sweden, but international orders have also been possible.

12.3 Financing

The U-SPACE project is financed by LTU, the principal support facility. For each European team member, the team receives 2,000 SEK, amounting for a total budget of 14,000 SEK. This budget has to be used for the ordering of all components and for any other expenses that might arise during the course of the project (e.g. tools). An increase in the budget can be realized after an application procedure and approval by LTU. As of this writing, the U-SPACE project still has 4,824 SEK left of its initial budget. As was mentioned in Table 4.4, a request for more funds for EPS is under preparation.

12.4 Schedule and Milestones

Since the U-SPACE project is a student project that has to be realized within a limited amount of time a tight schedule and a clear definition of important milestones are vital for the success of the project. The schedule has to updated regularly to reflect the current progress and/or delays of the project. The most recent schedule is shown in figure **??** below. All important milestones and test programs are indicated as well.

12.5 Configuration Control

Although the U-SPACE project is limited in size, configuration control remains an important element of the success of the project. With four different subsystems and many different team members it is essential to have a common platform where design changes are listed, tracked and discussed. This is necessary to guarantee technical consistency and to avoid misunderstandings that may endanger the outcome of the project.

The main component of the U-SPACE configuration control is a weekly meeting of all team members. An agenda is composed beforehand by the meeting chair, listing all important issues, both practical and technical, that have to be discussed during the meeting. A meeting secretary is responsible for producing minutes of the meeting. These min-

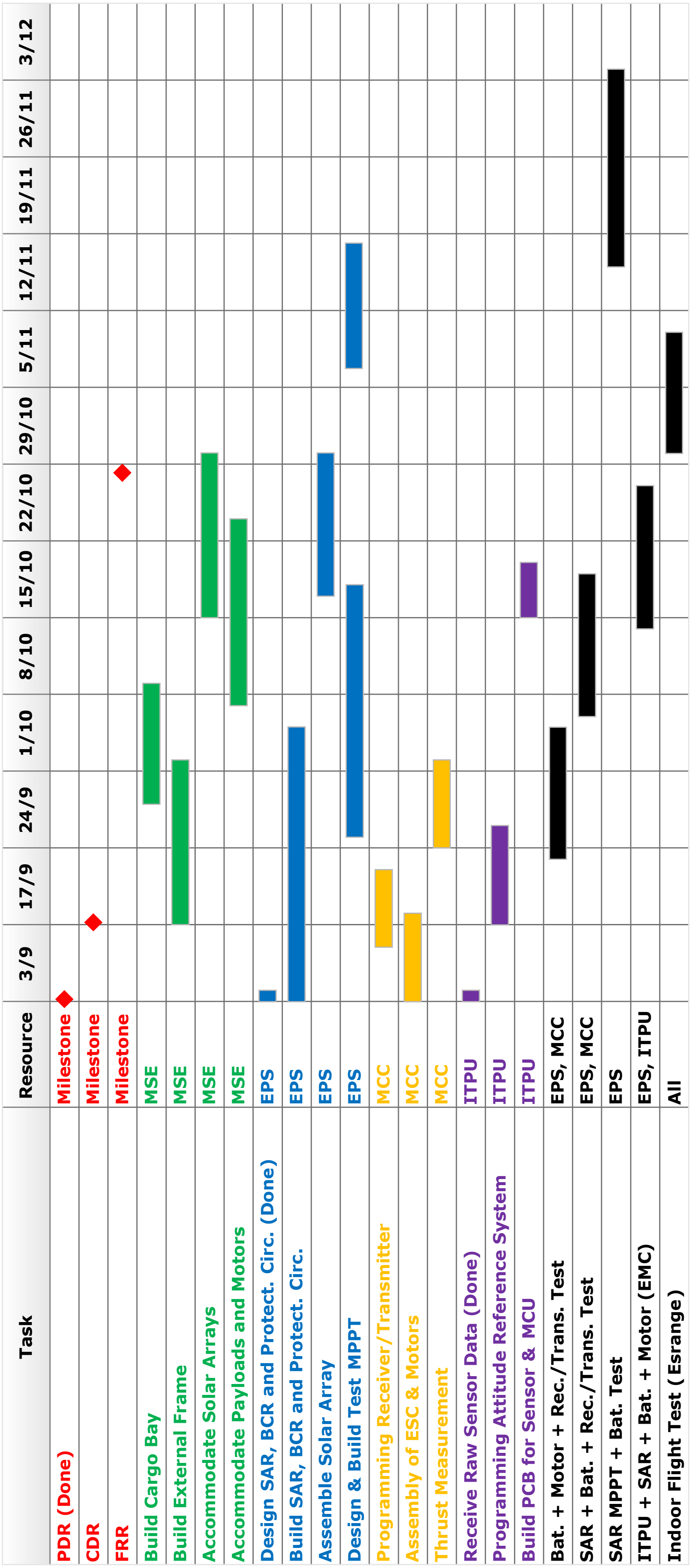

Figure 12.2 – *Project Plan*

utes, together with the agendas, are accessible for the entire team by the use of Google Docs. Another minor component of the configuration control is the revision control system GitHub, which is mainly used to share the documents that make up the design review. It is also the place where the developed ITPU code is made available to the relevant team members. For minor issues, emails to a common team email address are used.

12.6 Deliverables

The ultimate goal of the U-SPACE project is to realize a functioning prototype of a SPA capable of forward propulsion while supporting a scientific payload. Since this project is a student project under the supervision of LTU, the final phases of the project also require the handing in of several deliverables.

12.6.1 Hardware and Software

The main deliverable is a functioning prototype of an SPA, consisting of several separately developed subsystems (see chapters 3 through 6). Each subsystem should function on its own as well as in concurrence with the other subsystems. All necessary components have to be included when the subsystem is delivered.

Also the ground station is a deliverable, although it is mainly software-based. All code has to be delivered at the end of the project, together with comments that explain the code (see the following subsection). Also the code written for the airborne part of the ITPU has to be included.

12.6.2 Documentation

The deliverable documentation first of all consists of both design reviews (PDR and CDR), which are documents that provide details on the functioning of each subsystem and on the general elements of the project. When available, all documents that were used during the development of a subsystem should be classified and stored for future use. This allows future team members to easily pick up the work where it was left by their predecessors.

Apart from these hardware-related documents, documentation regarding the developed software should also be delivered. This documentation mainly consists of comments on the code such that it may be understood and further developed by future team members.

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Appendix A

EPS

A.1 PSpice Simulations

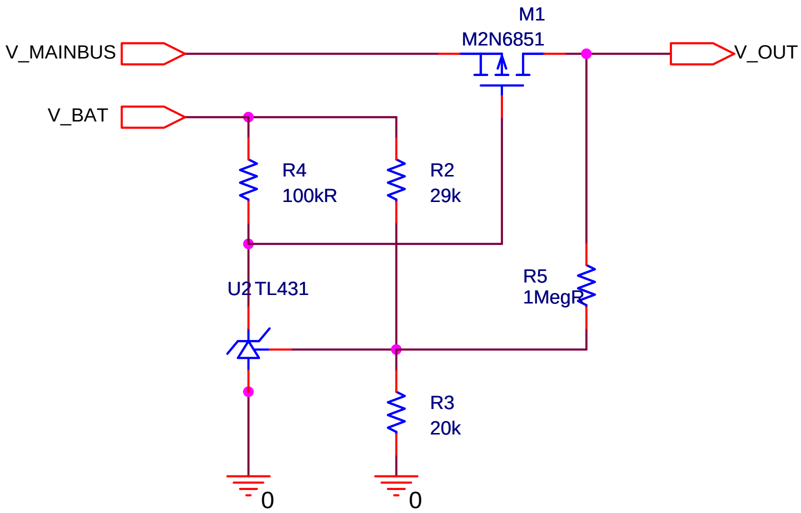

Figure A.1 – *EPS UVLO circuit PSpice simulation*

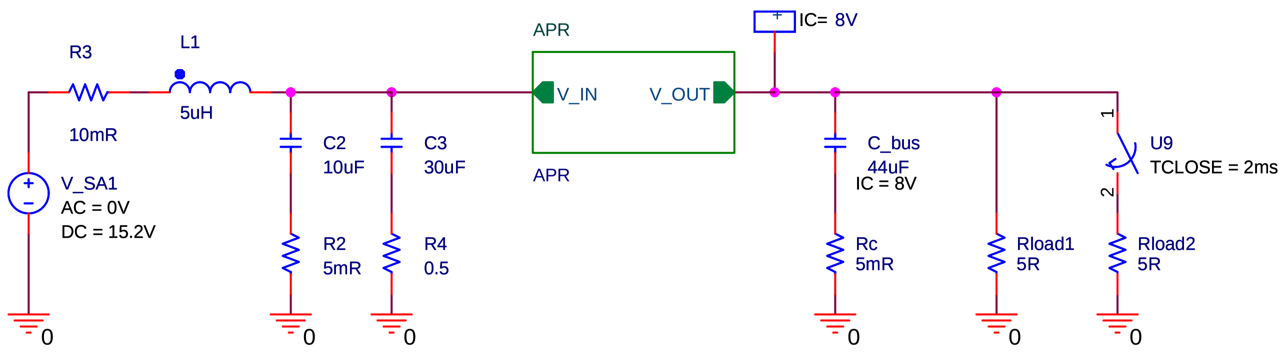

Figure A.2 – *EPS mainbus PSpice simulation*

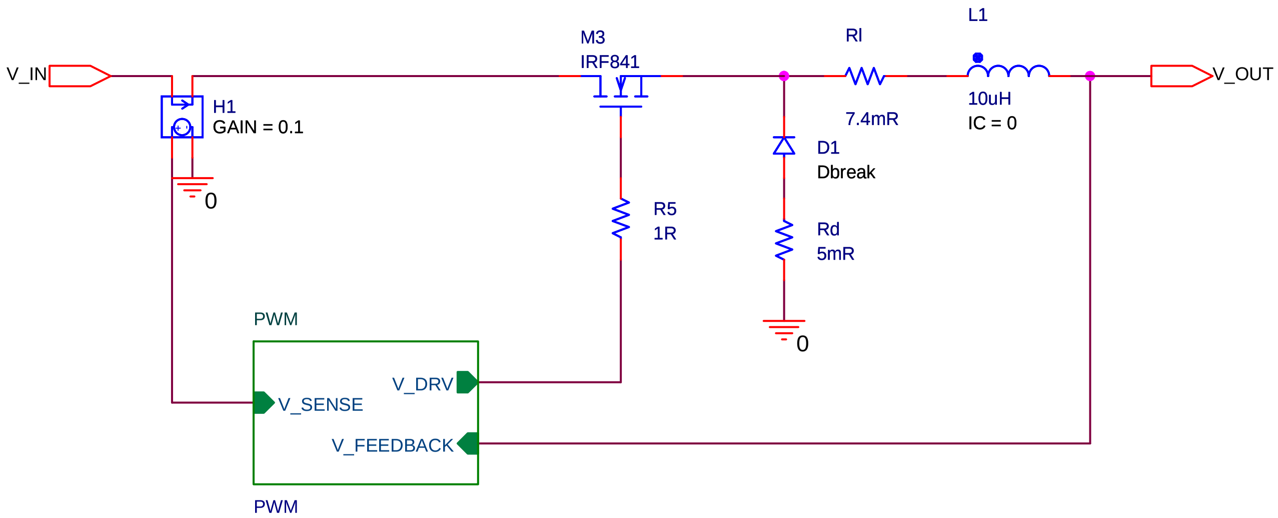

Figure A.3 – *EPS SAR PSpice simulation*

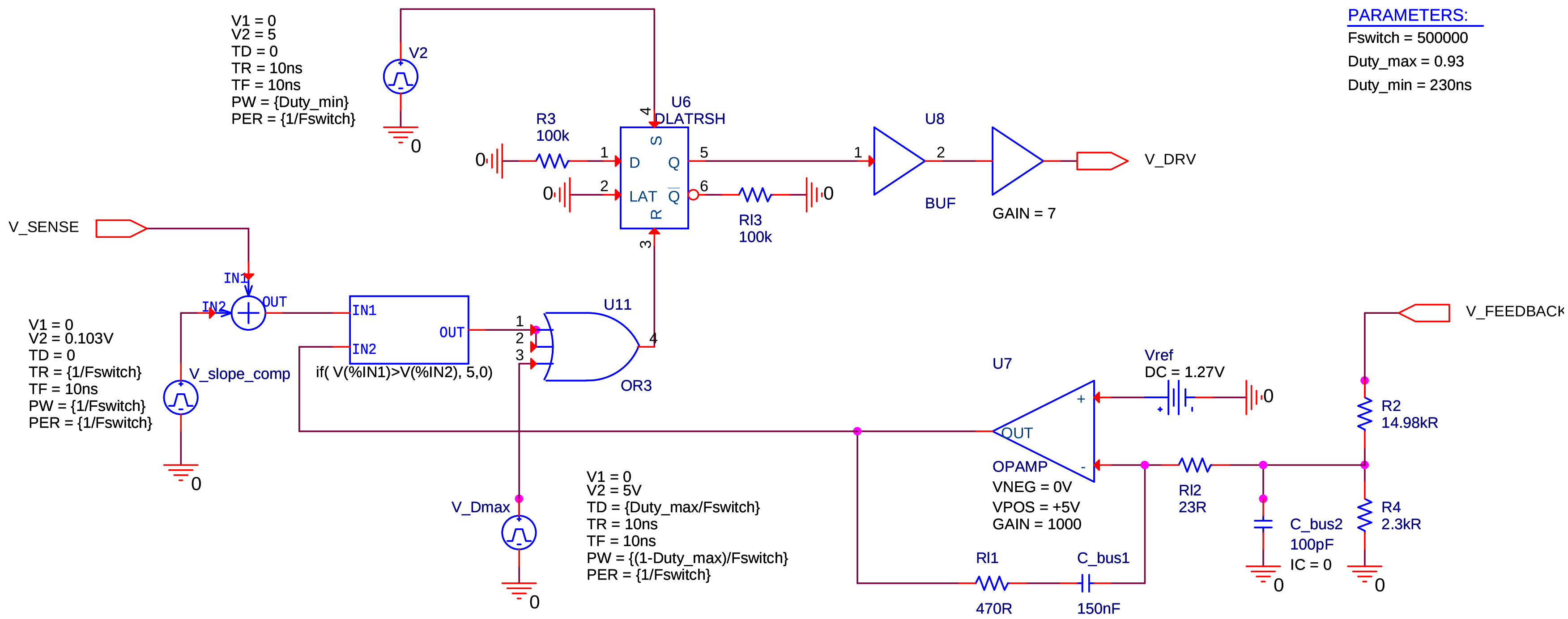

Figure A.4 – *EPS PWM controller PSpice simulation*

A.2 Mini-Mount Image

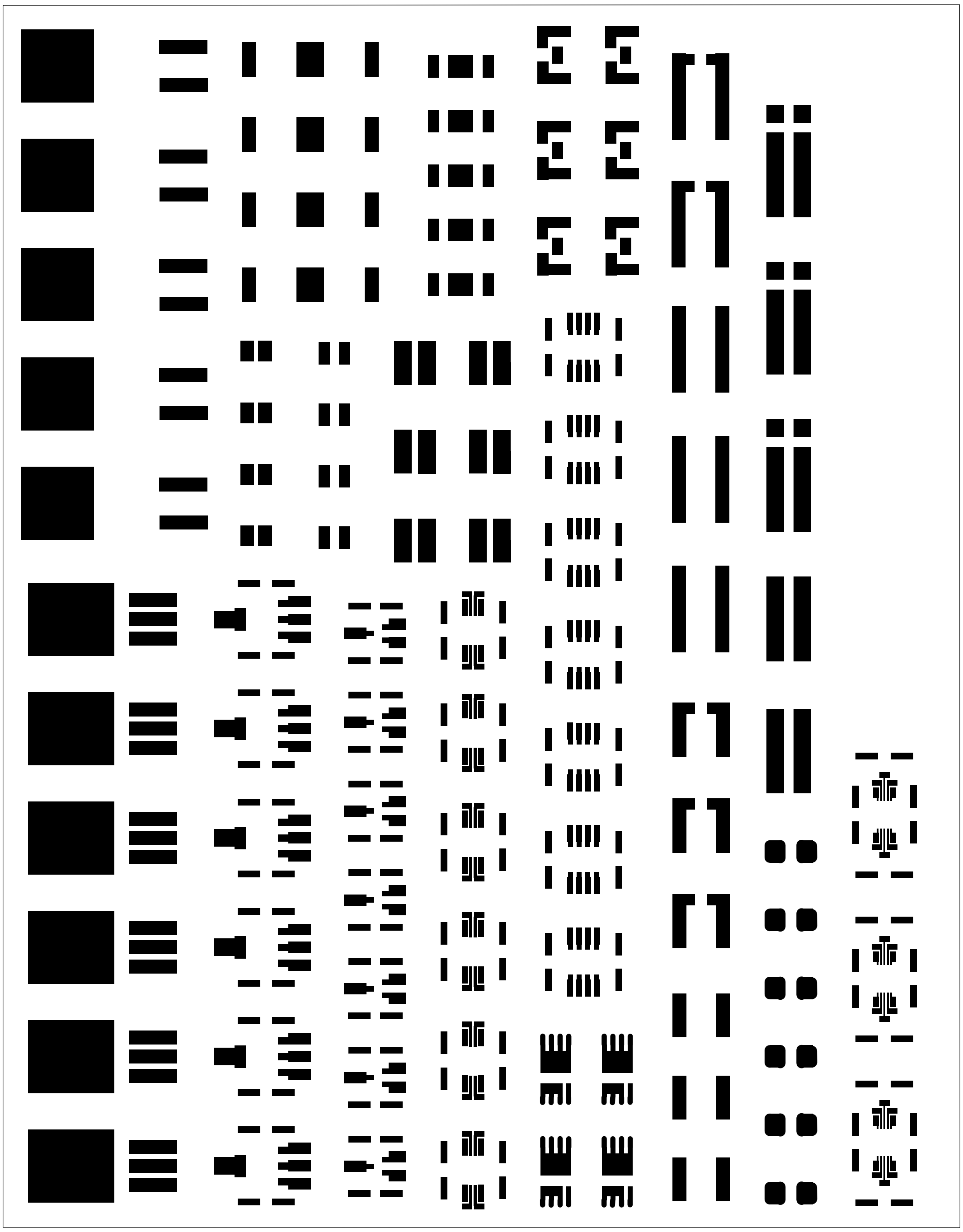

Figure A.5 – *Mini-mount prototype patches*