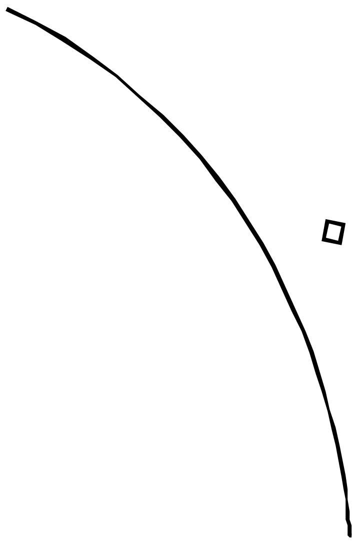
Power supply for DTU's Cubesat



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0. Contents

1. Why?

Some students at DTU have joined together to design a small satellite based on the Cubesat foundation. It has been scheduled to be launched together with probably 17 other satellites of the same size in November 2002. The size of the satellite is 10x10x10 cm and the weight is limited to 1 kg. Designing a satellite in the first place is quite challenging, but these bounds doesn't make it any easier. For instance the power made available will only be somewhere between 1 and 2 watts, and the size of the circuit boards are limited to 7x7 cm.

2. What?

This document describes some of the first small steps in designing a power supply. This includes determining what kind of solar cells, what kind of battery, and what kind of regulation is to be used.

We start with a discussion about the users of the power supply, in order to figure out what kind of voltage and current we're required to supply, and if it is at all possible. Afterwards we'll delve into a discussion about the solar panels, batteries, sensors, and a technique called Maximum Power Point Tracking. Finally we'll set up some success criteria and figure out what the next challenges are.

3. Users

We have identified the following users in the satellite:

User:	Requested voltage:	Requested power:
Main computer	2,5 - 3,3V (probably around 3,3V)	up to 100mW
Transmitter	3-5V	apx 2W
Attitude control	unknown	unknown
Payload	unknown	unknown
Solar cells	unknown	apx 1-2W

Currently the main problem in determining the user load requirements is the lack of knowledge about the users. For instance the type of payload is still to be determined, and the type of attitude control has either not been decided yet. For the latter part the current discussion suggests either a permanent magnet (which requires no power) or an active system based on inductance induced in coils - this will most likely be a greedy consumer.

As for the computer it seems like we're going to use some kind of general purpose processor that requires a lot of power compared to what most other Cubesat designs are based on, namely Microchip's PIC family or similar low-power microprocessors.

The transmitter team wants to transmit with about 1W, and expects an efficiency of about 50% requiring up to 2W. This is also a lot compared to other Cubesats. One satellite from the California Polytechnic Institute are for instance transmitting with only 300mW (requiring 1,11W). Furthermore we want to transmit a ping once every minute or so in order to track the satellite. This further stresses the battery.

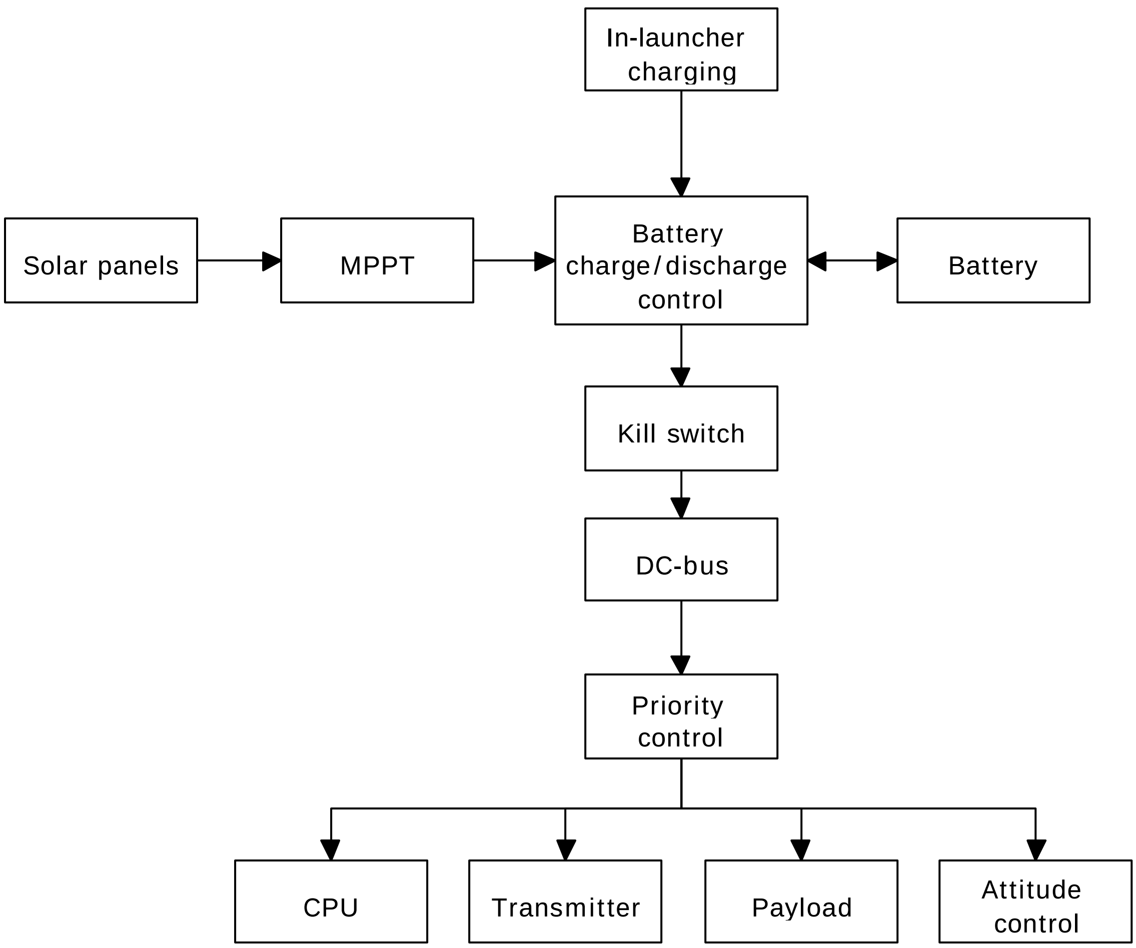
4. The basic layout of the power supply

The main goals in designing this power supply are simplicity and modularity. We want to keep it as simple as possible as simple systems generally have a better change for *not* breaking down. The desire to create a modular design is twofold. First of all it will make it easier to develop the design for a next generation satellite. Secondly it will allow us to get the vital parts done first, and if time allows we can later on try to increase the efficiency and the like.

When the satellite is in orbit it only has one source of power, namely the sun. Unfortunately we don't know what kind of orbit we're going to get. The Cubesats launched in November 2001 will be put in a helious synchronous orbit. Whether this is a tendency or not is hard to say, but it would make our life a hole lot easier if it was. For now we're going to design for an average orbit with about 33% solar eclipse.

During the solar eclipse we'll have to depend on an onboard battery. This will also be needed if we're launched to a helious synchronous orbit since the transmitter will most likely require more power than we can produce from our solar cells.

For now the layout looks like this. See the description of each box on the following page:



Solar panel
Each of the 6 solar panels consist of 6 solar cells. The solar panels can be instrumented with voltage, current and temperature sensors, so that the solar panels provide an analog sun sensor for attitude control. This is not shown on the diagram.

MPPT
Maximum Power point Tracking is an electronic DC to DC converter that optimizes the match between the solar panels and the battery/ DC-Bus. This is not a primary goal.

Battery Charge/Discharge Control
Makes sure that the battery doesn't overcharge and that the battery doesn't discharge through the solar panels.

Battery
Stores electrical energy.

Kill switch
The kill switch turns off the Cubesat while it is in the P-POD. In reality this switch consists of several switches connected in parallel for redundancy. This is done since it would be a disaster if the satellite didn't turn on due to a broken switch.

In-launcher Charging
Makes it possible to charge the battery while the Cubesat is in the P-POD when the kill switch is turned off.

DC-BUS
Provide the subsystems with power.

Priority Control
Turns off the subsystems if they are using to much current or if the power system cannot provide enough power to all of the subsystems at any given time. Priority control makes sure that the most important subsystems (for the survival of the satellite) get the power needed.

CPU, Attitude Control, Transmitter, and Payload
These are the subsystems.

The discussion of what kind of solar cells and batteries to choose is up next.

5. Solar panels

Solar panels are currently made of Silicium (Si) or Gallium-Arsenide (GaAs). The conversion efficiency for commercially available cells are apx 16% for Si cells, 18% for GaAs cells and about 24% for GaAs triple-junction cells. The latter ones are basically 3 GaAs cells stacked on top of each other in order to trap more of the solar energy. In addition to the higher efficiency of the GaAs triple-junction cells they also provides a higher output voltage, namely 2,1 V instead of the typical

0,6 V for Si cells. This is an important improvement since we can only have a limited number of cells on the satellite.

The price for Si cells made for space is about 175000 kr/m2, whereas the price for the multi junction GaAs cells is about 1,2 mill kr/m2. Even for our tiny satellite this amounts to a lot: 0,10m · 0,08m · 6 · 1,2 mill kr/m2 = 57600 kr. But then again: We probably won't need the space-approved label on the box.

The efficiency of solar cells is reduced over time by radiation and dust. Depending on the length of our mission this might become an issue. Usually a reduction of about 20% is expected over the life of a satellite (several years).

If the satellite is put in a helious synchronous orbit the sun is always shining on the solar panels and therefore a battery is only needed if some circuits requires more power than the solar panels can provide at a given time. For instance the radiotransmitter may require 2W while the panels only provide 1,5W. This, of course, implies that the transmitter can only be operated at a limited interval during each orbit.

If the satellite is not put in a helious synchronous orbit the battery is also needed when the satellite is in the night area - typically about 33% of each orbit. Another problem is that the temperature change between night and day can reach from -100 °C to +100 °C which stresses the construction. One advantage of the cool nights is that solar cells are more efficient when they are cold. Therefore more power is available for charging the batteries in the beginning of each day - just when it is needed.

If more power is required one option is to unfold the solar panels on 1 to 4 sides of the satellite, making the total power available up to 5 times that of a single side. This rises a few problems, though. First of all a mechanism for unfolding the panels that is fool- (or rather space-) proof must be invented. Secondly - and more challenging - the satellite must have some pretty accurate attitude control system onboard in order to keep the panels facing the sun at all times.

If the sun points directly on one side of the satellite the available effect can be calculated like this: $P = 1350\frac{\mathrm{W}}{\mathrm{m}^2}\cdot(10\cdot 8)\ \mathrm{cm}^2\cdot\frac{1\ \mathrm{m}^2}{10000\ \mathrm{cm}^2}\cdot \mathit{efficiency}$. This scenario happens to be the worst-case too, and we need this value in order to calculate the minimum expectable power.

Since it would be stupid to point the satellite in the worst case position it is useful to know what the best case power provided is. This scenario happens when one corner of the satellite points towards the sun, illuminating 3 sides of the satellite. Unfortunately the power won't increase by a factor 3, though: $P = 1350\frac{\mathrm{W}}{\mathrm{m}^2}\cdot(10\cdot 8)\ \mathrm{cm}^2\cdot\frac{1\ \mathrm{m}^2}{10000\ \mathrm{cm}^2}\cdot \mathit{efficiency}\cdot\sin 135°\cdot 3$

Please note that the values in the table are the raw power. We will loose power when the cells are connected together, when we do the power conversion, and unless we use maximum power tracking (see a later section) we'll loose even more power. We'll probably end up with an overall efficiency of about 50%.

	Efficiency	Worst case	Best case
Si	16%	1,72W	3,66W
GaAs	18%	1,94W	4,12W
GaAs multi junction (3)	24%	2,59W	5,50W

6. Getting the solar cells

It has turned out that getting the cells may become quite an issue. The company Spectrolab (California) has come up quite a few times in our search for a supplier of solar panels. Both Flemming Hansen, DSRI, and Peter Davidsen, Terma, recommend their products. So does one of the Japanese Cubesat projects, but in the end they couldn't use them and had to purchase some cells from a Japanese supplier instead. The reason is some very annoying export restrictions from the US State Department. According to Flemming Hansen it usually takes at least 6 months to get a license.

Therefore it would be natural to get the cells from a European supplier. The only one is the Italian company CISE. They made the solar cells for the Danish satellite Ørsted. Unfortunately their website is gone, but we're trying to contact them by email.

A third possibility mentioned by Flemming Hansen is that Bob Twiggs (for unknown reasons) had some triple-junction GaAs cells stored in his garage. The rumors are that the quality is too poor for commercial satellites, but they should be suitable for a Cubesat. The thing is that the garage sale is located in the US, which again leads to a license.

7. Batteries

The solar cells provide power to the DC-bus during daylight, but during solar eclipse the solar cells cannot provide power and therefore we need to have batteries. The batteries also provide power during peak situations, for example during communication with the ground station.

Today there are to types of rechargeable batteries that dominate in space. It is NiCd (Nickel Cadmium) and NiH_2 (Nickel Hydrogen) but Li-Ion batteries are becoming more and more common in space applications. Therefore it is necessary first to look at the advantages and disadvantages for the three kinds of batteries and then make the choice of which kind to use.

NiCd Batteries

+ Well known for space applications
- Low output voltage (1,2 V)
- Low energy density (apx 40 Wh/kg)
- Suffers from memory effects, that is: The discharge capacity of the battery is reduced when it is repetitively discharged incompletely and then recharged

NiH_2 Batteries

+ Well known for space applications
+ No memory effect
- Low output voltage (1,2 V)

The NiH_2 batteries have a higher energy density than do NiCd batteries, namely apx 60 Wh/kg.

Li-Ion Batteries

- \+ Have higher energy density than NiCd or NiH_2 batteries (well over 100 Wh/kg)
- \+ Produce approximately three times the voltage of rechargeable NiCd or NiH_2 batteries (3,7 V)
- \+ No memory effect
- \+ Have an extremely flat discharge profile
- \+ Wider operating temperature interval than NiCd or NiH_2 batteries
- \- Suffers from overcharging which may cause the battery to explode. This is only a problem if several cells are connected to form a battery.

Since we're most likely only going to use one cell for the battery we won't see the problem of overcharging. It therefore seems like Li-ion batteries are the best suited for the job. The next question that arise is which Li-ion battery to use. We have chosen three preliminary types that can do the job. When we choose the final batteries for the Cubesat, we must use some additional criteria. These includes:

- dimension of individual cells - do we prefer a flat or a circular one?
- Longevity (maximum cycle life)
- Voltage output
- Capacity
- Mass
- Test for space applications

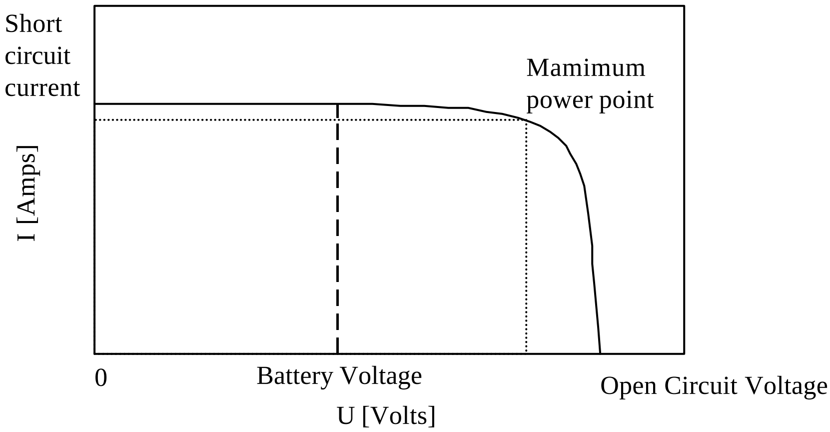
The specifications for the three types of Li-ion are shown in the following table:

	Sony US18650	Danionics DLP443573	Panasonic CGP345010
Nominal Capacity	**1500mAh**	**700mAh**	**1500mAh**
Nominal Voltage	**3.6V**	**3.7V**	**3.7V**
Charge Voltage	**4.2V±0.05V**	**4.2V**	**4.2V**
Charge Time	**3h**	**?**	**2h**
Energy Density	**135Wh/kg**	**120Wh/kg**	**130Wh/kg**
Cycle Life	**>500 times**	**>500 times**	**>500 times**
Temperature Charge	**0° ~ +45°**	**0° ~ +60°**	**0° ~ +45°**
Temperature Discharge	**-20° ~ +60°**	**?**	**?**
Temperature Storage	**-20° ~ +45°**	**?**	**?**
Weight	**41g**	**22g**	**43g**
Dimensions	**64.9mm , Ø18.3mm**	**73 x 35 x 4.4 mm^3**	**34 x 49.8 x 10.3 mm^3**

It could be exciting to use Danish batteries in the Cubesat so from that point of view we should use the batteries from Danionics. But otherwise the main difference between the batteries is the dimensions. Furthermore we might need two of the batteries from Danionics since their capacity is a little low. On the other hand: If we don't need the extra capacity we can save about 20 g.

8. Maximum Power Point Tracker - MPPT

One problem in connecting a solar panel to a rechargeable battery is that they don't work at maximum efficiency at the same voltage - they don't match. The most efficient voltage is not even constant due to temperature differences and the change in battery voltage due to it's load condition. It is, of course, possible to design a power supply without matching the two, but the efficiency is usually very low. A Maximum Power Point Tracker solves the problem. On the following figure the maximum power point is calculated as the largest possible area of the dotted square. The voltage and current are the values supplied by the solar panels.



One major problem is that the MPPT system itself draws some power, and it gets more difficult to get a good performance when the required power gets low. This is actually quite obvious since the power the MPPT uses itself becomes a larger fraction of the total power flow in the system. We'll therefore have to verify whether it is at all useful to use an MPPT in such a small satellite.

An MPPT system is most useful when the panels are cold or the battery is discharged. When the panels are cold they produce more power, but without MPPT most of the extra power will be lost. Therefore an MPPT system will be most useful if we're *not* launched to a helious synchronous orbit. An MPPT system is also useful when the battery is discharged, which is exactly one of the times that the extra power is needed the most. In fact the battery will be drained the most when the satellite leaves the shadow of the earth, which is exactly when the solar panels are cold, making the use for an MPPT system twofold.

9. Sensors

One of the attitude control proposal groups has requested a measurement of the voltage and current supplied by each of the solar panels (one on each side of the satellite), in order to get a rough estimate of the attitude. Even though the attitude control group might decide they don't need such a sensor it is probably a good idea to include it anyway since it will make it possible to get some health status communicated to the earth.

Other sensors we are considering includes: Battery voltage and temperature.

10. Redundancy

Many satellites include redundancy for some of the most critical subsystems. As for the power supply almost everything is vital - if anything goes wrong the power will be lost. Redundancy is of course expensive - both in designing and our case in extra weight and space needed.

One place where we're definitely going to use redundancy, however, is for the kill-switch.

11. Success criteria

We have made the following success criteria for this part of the satellite:

1. Learn how to build a power supply suitable for space
2. Create a foundation that can be improved for a next generation spacecraft
3. Get it to work - in space

12. What's next

The upcoming things to take care of are:

- Figure out whether MPPT is useful or not
- Figure out how - and where - to get the solar cells
- Get some batteries - Danionics or Sony

13. References

We've got the price information for the solar cells from this document:

Flemming Hansen, DSRI: Byg din egen satellite, Draft 1, 2001:
http://www.cubesat.auc.dk/documents/Byg_din_egen_satellit_2_Draft_1.pdf

and we've used the following datasheets:

Panasonic CGP345010 battery:
www.panasonic.com/industrial/battery/oem/images/pdf/li-ioncgp345010.pdf

Danionics DLP443573 battery:
http://www.danionics.com/products/pdf/dlp443573.pdf

GaAs triple-junction solar cells
http://www.spectrolab.com/DataSheets/TJCell/tj.pdf