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# THE AAU-CUBESAT STUDENT SATELLITE PROJECT: ARCHITECTURAL OVERVIEW AND LESSONS LEARNED

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Abstract: In September 2001 Aalborg university started the AAU-cubesat project that reached its climax when the student built satellite was launched into space on the 30th of June 2003 on top of a former Russian ICBM.

AAU-cubesat was among the first five satellites to be launched that are built within the cubesat concept that prescribes a satellite with dimensions 10x10x10cm and mass one kilogram.

This paper will describe the overall architecture of the AAU-cubesat in order to show what a pico-satellite can be and demonstrate all the fields of engineering which must come together to build a student satellite like the AAU-cubesat.

Results from the operation phase will be stated, and recommendations on further work on pico-satellite designs will be given. In addition as the project has been carried through by students, the educational value of the project will be adressed as well. *Copyright ©2004 IFAC.*

Keywords: Satellite, Education

## 1. INTRODUCTION

In the summer of 2001 it was decided to initiate the AAU-Cubesat project at Aalborg University in Denmark. This project was made possible due to the Cubesat concept, which has been developed at Stanford University and California polytechnic institute led by professor Bob Twiggs (Twiggs and Puig-Suari, 2003). This concept allows a satellite of dimensions 10x10x10cm and mass 1kg to be launched into low Earth Orbit at a total launch cost of about \$40,000. The motivation was to let engineering students from various departments cooperate in the completion of a large project and thereby give them a unique chance to participate in a project that not only needs good engineering skills, but also the skills to solve problems that are inter-disciplinary of nature.

It was decided to fly a camera as payload without a specific scientific purpose for it, but rather use the satellite as an technology evaluation mission

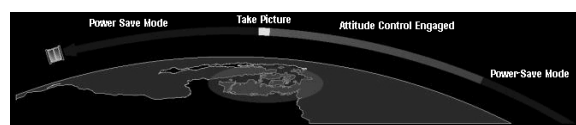


Fig. 1. Illustration of the mission concept

preparing the ground for future scientific missions using the Cubesat concept. The definition of the mission success criteria were defined in an incremental manner:

- (1) Education of engineers, practical experience with designing space system
- (2) Acquire a signal from the satellite
- (3) Acquire comprehensive housekeeping data for system evaluation
- (4) Use the camera for public outreach mission and performance evaluation.

Using this definition the project was defined such that it would still be a partial success even though no signal was ever received from the satellite.

A conceptual illustration of the nominal mission scenario is depicted in figure 1. When considering the project it is important to remember that it was constrained by:

- Short project, <2 years from idea to launch
- Very limited limited budget
- Limited mass and power
- Built by students with no prior experience with spacecraft design

The satellite was completed in April 2003 and was transported to Canada to undergo environmental qualification tests together with the other satellites to be deployed from the same deployment mechanism. From Canada it was transported to Plesetsk in Russia, where it was functionally tested and the batteries were conditioned before being launched on the 30th of June 2003.

The following sections will at first describe the satellite and all its subsystems, where after launch an operational results are presented. Thereafter the educational benefits are described and finally conclusion and recommendations for future projects are given.

## 2. SATELLITE DESCRIPTION

The following paragraphs will describe the various mechanical, electrical and software subsystems of the satellite, hereby providing an overview of the architecture of a pico-satellite. As already described the satellite has dimensions 10x10x10cm and mass 1 kg.

In general for the electrical subsystems industrial graded components were used of the shelf. Some of the more critical components CPU's and MCU's have been tested to exposure of one year equivalent radiation dose. The satellite includes of 5 electrical subsystems, these are:

- PSU: Power Supply Unit
- OBC: On Board Computer
- ADCS: Attitude Determination and Control System
- COM: Communication system
- CAM: Camera - the payload

In addition to these electrical subsystems the satellite consists of the structural subsystem, OBC software system and a ground segment has also been developed for the project. The following paragraphs will describe each part in a little more detail. For more information on the technological part of the project consult the project home-page (AAU-CUBESAT, 2003).

### 2.1 Power Supply Unit

The main purpose of the PSU is to take power from the solar cells on the sides of the satellite

and store it in the batteries as well as deliver it to the other subsystems of the satellite on a 5V power-bus and protect these users from latch-ups caused by radiation. The PSU consists of solar panels, electronics and batteries.

A conservative estimate of average input power is about 1.4 W. This power estimate constitutes one of the major constraints in the design and has been the driving force behind many design decisions.

The acquired energy is either consumed by the other subsystems or stored in the battery pack. The batteries are 4 Lithium-Ion polymer cells with a capacity of 940mAh each, giving a total capacity of almost 4Ah.

### 2.2 On Board Computer

The On-Board Computer (OBC) is the brain of the satellite and it features a Siemens C161 micro controller which combines low power consumption with great performance. The hardware interfaces are: the power line and boot-selector from the PSU, I2C connections from PSU and ADCS, a combined DMA and I2C interface to the camera and a parallel interface to the COM-unit.

The OBC has the option of booting either on a PROM with the original software the satellite was launched with or on FLASH-ROM which contains new software uploaded to the satellite from the ground station.

An RS-232 UART interface on the OBC is used as an alternative communication entry to the OBC for on ground check out operations and debugging.

### 2.3 Attitude Determination and Control System

In order to be able to take pictures of specific locations on the Earth the AAU-Cubesat features an ADCS system. To control the satellites attitude in orbit three coils are used, which are mounted on three of the satellites sides perpendicular on each other. These will generate magnetic fields, which interact with the Earth's magnetic field, and hereby change the attitude of the satellite. To determine the attitude, two types of sensors are used: A three axis magnetometer and sun sensors.

The satellite has two controller modes: B-dot and inertial. The B-dot controller is used when the system boots. At this point the satellite does not have any orbital parameters it can use for attitude determination. The B-dot controller then simply works by reducing the kinetic energy of the satellite by providing negative feedback from the derivative of the measured magnetic field.

When ground contact has been established and orbital parameters uploaded to the satellite the Kalman filter begins to converge on the correct attitude and the inertial (wrt. to the sun) control mode can be employed. This controller is a constant gain controller for the linear time varying plant model.

## 2.4 Communication System

The communication system is controlled from the OBC and it consists of an MX909 packet modem and an SX-450 telemetry radio. In addition the AX25 protocol for amateur packet radio is implemented on the OBC.

The radio transmits with a power of 0.5 W and the modem outputs a GMSK modulated signal at 9600 Baud. The radio output is transmitted using two dipole antennas and the frequency used is 437.450 MHz. This frequency has been obtained through the Amateur satellite association AMSAT. The worst case link margin has been calculated to 10.7dB.

Given the bandwidth provided by the COM system it was expected that it would be possible to acquire a new picture taken by the camera every second day, while still leaving bandwidth to acquire housekeeping information and command the satellite.

The radio design was conceived very late in the process due to an initial subcontractors<sup>1</sup> failure to deliver a usable product. This means that the subsystem has not been tested as extensively as it ought to.

## 2.5 Camera

The camera is based around a Kodak CMOS image sensor that provides a resolution of 1280x1024 pixels in 24bit colours. The lens systems for the camera has been custom built for this project and it will provide an on ground resolution of approximately 150x120 meter from a 900 km orbit. An exploded view of the lens and camera system can be seen on figure 2. The camera is only turned on while taking the picture. Pictures are always taken in full resolution, but it is possible to down link a thumbnail version of the picture before beginning to download the complete picture. It is possible to configure various camera parameters in orbit, e.g. integration time and colour gains.

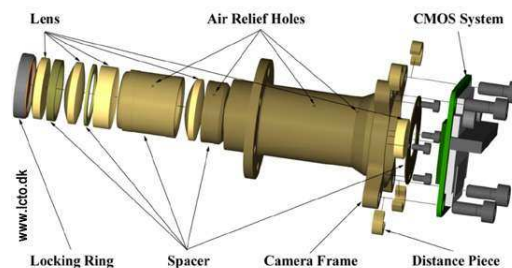


Fig. 2. Exploded view of the camera subsystem

## 2.6 Software

On the OBC the software controlling the satellite is executed. It has the following main functionality:

- Transmits beacon signals with an interval depending on power status
- Controls the actions of the satellite based on a flight plan uploaded from the ground station
- Reacts to subsystem alarms, e.g. low power signalled from the PSU
- Collects and store housekeeping information from all subsystems
- Calculates the attitude of the satellite with regards to the sun based on sensor data from the ADCS subsystem
- Manages communication with the ground station using the AX25 protocol
- Logs everything that goes on on the satellite to a central satellite log

The software is developed using the Keil  $\mu$ -vision IDE and it runs on top of the Keil RTX-166 real-time kernel. The functionality is implemented in a number of independent tasks that communicates using mailboxes.

The software consists of a task associated to each electrical subsystem, in charge of the communication and data handling for the subsystem. Besides this there is a Flight Plan task keeping track of what the satellite must do in general, e.g. collect house keeping or take a picture. Then there is a Log task receiving the house keeping and debug information and collects it into a linked list that can be downloaded to the ground segment. There is also a Beacon task transmitting crucial house keeping at a given interval depending on the battery level.

## 2.7 Mechanical Structure

The structural system consists of a frame cut from one piece of aluminium and side panels made in carbon fibres to conserve mass. Also in order to conserve mass the electro-magnetic coils are implemented as part of the structure.

<sup>1</sup> Initial it was decided to purchase the radio from an external supplier

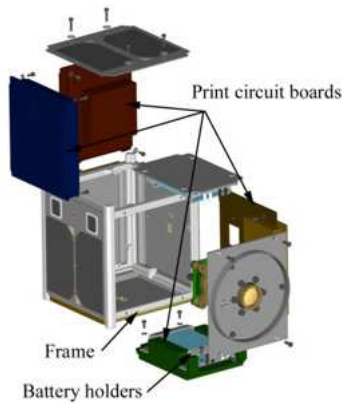


Fig. 3. The satellite structure, exploded view

The internal structural composition is such that the camera lens-systems is mounted on the middle of one side of the satellite with the lens occupying the centre of the satellite. On the remaining five sides print boards are positioned. An exploded view of the satellite main structures can be seen on figure 3. High requirements have been set regarding the structure of the satellite and its integrity, as it has to withstand high temperature variations, vibrations and shocks, radiation, and the vacuum in space.

Simplified thermal characteristic simulations have been carried out for the mechanical structure including the print circuit boards in order to evaluate what the temperatures will be within the structure where the electronics are placed. These simulations have indicated temperatures between 0 to 40° C. Depending on solar influx (eclipse time).

### 2.8 Ground Segment

The ground segment that has been developed for the project consists of a tracking antenna, an off-the-shelf amateur radio, a modem similar to that on the satellite and a PC. The software on the PC is capable of controlling the satellite autonomously, i.e. acquire signal, download house-keeping data and upload new flight plans, or it can be operated by an operator. All downloaded data are stored in a central database.

## 3. LAUNCH AND OPERATION RESULTS

The satellite was launched on the 30th of June 2003 from the Plesetsk Cosmodrome in northern Russia. The launch vehicle was the Rocket, operated by Eurockot. The launch was shared with 6 other satellites: The MOST satellite from the Canadian Space Agency, The MIMOSA from the Czech Republic, Quakesat from the Quakefinder company and the Cubesats: DTU sat

(Danish Technical University), CanX-1 (university of Toronto), Cute-1 (Tokyo Institute of Technology) and XI-IV (university of Tokyo). The satellites were launched into a near sun-synchronous orbit (inclination 98.73°), the orbit is near circular with mean altitude above the geoid of 820km.

In the first days following launch it took a lot of coordinated effort of all the involved operation teams, together with the NORAD tracking radars, to locate and identify all the satellites separated from the launch vehicle.

For the first 24 hours no distinct signal was heard from AAU-Cubesat, but hereafter the operation team was able to detect the beacon signal with increasing confidence. After about 4 days it was clear that the satellite had been successfully located, but the transmitted signal strength was far below expected. Therefore the ground station was relocated 200 km to make use of an 8m dish antenna.

When the new ground station was finally fitted for operations in the correct frequency (1 month after launch) signal was received with enough strength to decode some of them, but at this point the beacon intervals and the decoded signals started to indicate massive loss of battery capacity leading to frequent returns to the contingency charge mode of operation, which does not supply power to the OBC.

Unfortunately the degraded battery condition made it impossible to establish a real data link connection and download extensive house keeping data, but simple two-way communication was established (pinging) demonstrating that the complete data path from ground station to OBC and back was functional.

In addition to battery voltages, temperatures of the OBC processor were received and decoded from the advanced beacon signal. These indicated a temperature of an average of 28°C consistent with the values predicted with the thermal model (orbit entirely in sun).

On figure 4 an example of a received signal is plotted. Specifically it is a basic beacon, which is a special beacon signal transmitted prior to OBC boot, when leaving the battery contingency charge mode. The signal contains an identifier and battery voltage as a simple Morse signal.

## 4. LESSONS LEARNED

### 4.1 Educational Value

The project has from its start been controlled by the students involved in the project. Each student

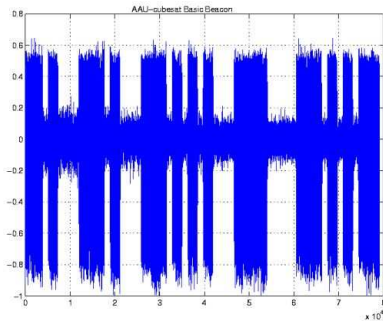


Fig. 4. The basic beacon signal as received on the 20th of August

has been part of a group of about 5 students that have had the responsibility for one single subsystem of the satellite. This approach has not only given the students a profound insight into the specific subsystem that he/she has been working on, but due to the highly integrated architecture of a pico-satellite it has also been necessary for each student to have a good overview of the other satellite subsystems in order to be successful. To be a part of a project like this is very motivating and the problems to be solved on a pico-satellite are very technically challenging.

The project has therefore provided the student with a very beneficial educational opportunity that has both focused on a single technical design while also teaching the student to coordinate work within a group and coordinate work between groups working on different parts of the satellite. In addition it is something one can be proud to be a part of.

The project included engineering students from the following departments of the natural science faculty at the university:

- Mechanical engineering
- Control engineering
- Electrical engineering
- Power systems
- Computer science

The period following launch also showed itself to be very educating for the students participating in the operation of the satellite. The challenge of locating the satellite, understand the problems and try and recover the mission was a good and educating exercise for all involved.

The project has also received a lot of attention from the media and younger (prospective) students at the university. And it is clear that a lot of students are interested in continuing building student satellites. To that end the development of a new pico-satellite has started. And parts from this satellite and some from the AAU-Cubesat will be used in SSETI Express. Also the OBC for the new project will be used in a Russian satellite, Baumanetz. For further information

on the educational benefits from the project see (Alminde, 2003).

#### 4.2 Lessons Learned from the Design of the Individual Subsystems

A lot of lessons were learned throughout the design, integration, test and of course after launch. The most important ones were about the COM unit because of the weak signal and because of the failure of the external supplier. Other important lessons were about the PSU and the MECH subsystems which will be described in the following.

*4.2.1. PSU* While the received telemetry indicated that the PSU in overall did function correctly. The batteries, however, lost their capacity after a month in vacuum. The batteries were tested in vacuum and they quickly lost their capacity. The problem seemed solved when pressing the batteries together with two aluminium plates so that the battery could not expand. It was however only tested for a week and it seems that the Lithium-Ion polymer batteries is a bad choice for batteries. Furthermore it seems that MPPT is not necessary for a satellite of this size.

*4.2.2. COM* The COM unit turned out to be a problematic subsystems and an important lesson learned is to keep track of contracted hardware, and not to be afraid off cutting your losses when the contracted company seems unable to fulfill the contract. As it was the time from the ordering of the COM unit from the external company to the time it was decided they could not deliver, was far too long. This was in part due to the fact that no single person or group followed the contract from start to end.

In the environmental test phase it was discovered that the communication protocol was very difficult to test because of its complexity. The chosen AX.25 protocol is a very large and complex protocol which enables both connection less and connection oriented communication utilised through a series of buffers and communicating tasks. Almost all communication to the AAU-Cubesat was implemented connection oriented in order to avoid data loss.

Because of its complexity two different back doors were implemented in the protocol in order to allow the ground segment to either restart the communication protocol, OBC or the entire satellite. For a future communication protocol it is recommended to either use a different and very simple protocol or to only use a minimum implementation of the AX.25 protocol. After launch disadvantages of the connection oriented communication was also

discovered. With a connection oriented communication it is necessary first to establish a connection before a command can be sent from the ground segment to the satellite. This is a problem when the link is poor because several consecutive packets must be sent successfully for a command to be sent connection oriented whereas only one is needed to send it connection less.

Another lesson learned was after launch, when only the basic beacon was received. Because of a too weak signal the advanced beacon could not be decoded in the modem. It was experienced that all important house keeping as for example charging current into the batteries should be sent in both the advanced and basic beacon. If the beacon is all you have it is important to be able to identify why this is all you have and maybe it is possible this way to take remedial actions in order to improve the situation on the satellite.

*4.2.3. MECH* In the integration phase it was experienced that it was very difficult to debug the electronics when the PCB had been integrated into the satellite. Mainly because it was impossible to access the side of the PCB turning against the sides of the satellite – these sides were glued to the structural frame in order to save weight. Another issue was that if a PCB should be removed from the frame several other PCB's needed to be removed because of space limitations – the subsystems for the satellite should be inserted/removed in a certain order. The advice is therefore that the sides of the satellite shall be mounted as the last part in order to be able to access the PCBs from all sides when testing it after integration. Besides this it should be noticed that the satellite is assembled and disassembled many times which means that it must be assembled with plastic screws in order not to break the threads.

#### *4.3 Overall Design Recommendations*

For the future design of student built pico-satellites a few important recommendations can be made:

The launch should not be fixed when the project is initiated; it is better to have the satellite standing on a shelf for half a year than launching a half finished satellite. It is difficult to predict the development time of the satellite, specially when the work is performed by students with little experience

Keep the designs simple; design conservatively and make sure to consider how the satellite operates under the presence of faults and make sure to implement simple and robust initial operating modes. More advanced operation should then be

enabled incrementally when ground contact has been established.

When selecting parts for use on the satellite with regard to the space environment there exists two options; one can buy components that are guaranteed to withstand the environment or one can buy commercial parts and test them vigorously. The latter option is cheaper and more educating and therefore the most suitable for this type of satellite.

The mechanical design must include simple ways to assemble and disassemble the satellite and making it possible to access all prints from both sides when integrated. For the electrical subsystems it is about avoiding long wires by routing the signals through the prints and position the connectors at strategic places.

## 5. CONCLUSION

Concluding from the flight results from AAU-Cubesat it can be said that the platform is not yet mature enough to be reliably used for scientific experiments, but it must be seen as a first step within pico-satellite design. Out of the 5 Cubesats launched together on the Rockot two failed to make any contact with their ground station, one (AAU-Cubesat) did make contact, but operations were severely limited. Finally both Japanese satellites are operating nominally.

In conclusion the AAU-project has achieved two major results: Primarily a large group of students will leave the university with a great deal of "Hands-on experience" within satellite design and experience with working with a large project that requires cooperation between everybody that are involved. Secondly, while post-launch operations have not yet fulfilled all mission objectives, it has provided enough feedback to provide a sound starting point for the next pico-satellite project at Aalborg university, which will utilise all the experience gained from the AAU-Cubesat project.

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