A Comparative Analysis of Project Management and Systems Engineering Techniques in CubeSat Projects

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Abstract. In the year 2000, California Polytechnic State University and Stanford University issued a new standard for small satellites: The CubeSat standard. This standard allowed universities to design, build, test and operate affordable, small, satellites within a time span of two to three years. Both Delft University of Technology (DUT) and Aalborg University (AAU) have used the CubeSat standard to develop a student satellite. In Delft, the Delfi-C^3 and in Aalborg AAUSAT-II satellites were developed. This paper evaluates the different techniques that are used in the Project Management and Systems Engineering of CubeSats. The satellite projects of DUT and AAU, which are highly different in setup, will be used as reference points for this evaluation. AAU has a strong pragmatic approach, while DUT uses a structured industrial standard approach.

1. Introduction

In 2000, the CubeSat standard was introduced to enable universities to design, build, test and operate affordable, small, satellites. Usually a time span of two to three years is considered for CubeSat projects. Delft University of Technology (DUT) in The Netherlands and Aalborg University (AAU) in Denmark have used the CubeSat standard to develop student satellites. DUT has developed Delfi-C^3 satellite and AAU CubeSat and its successor, AAUSAT-II, were developed in AAU. Both Delfi-C^3 and AAUSAT-II satellites were scheduled to launch with an Indian Polar Satellite Launch vehicle (PSLV) in late 2007 or early 2008. Besides the fact that both projects use the CubeSat standard, they also operate in an educational environment. Next to these similarities there are also differences between the two projects. Since each satellite has its own specific mission objectives, therefore the size, configuration and complexity of each CubeSat differs. Furthermore the ways in which the project has implemented Project Management and Systems Engineering (PMSE) differs as each project tailors the different standards available to fit its own needs.

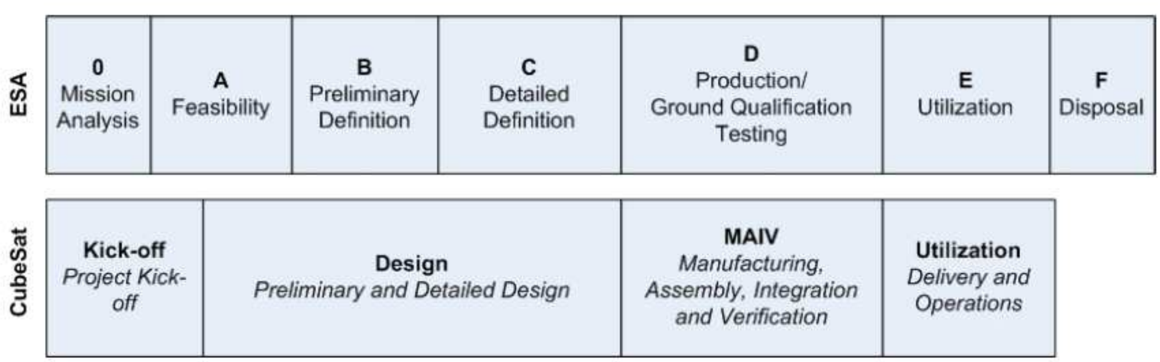

Figure 1. Comparing the CubeSat lifecycle in our work to the ESA lifecycle

In space systems engineering the lifecycle of a satellite is often modeled according to the standards defined by European Space Agency (ESA), National Aeronautics and Space Administration (NASA) or the Department of Defence (DoD). These lifecycles are defined for conventional satellite projects. This paper uses a tailored version of the ESA lifecycle (Wertz, 1999) that is more representative for the phases in CubeSat projects, as illustrated in Figure 1. The Kick-off phase is the start-up phase in which the project is set up and preliminary design is started. The design phase is the phase in which the first full team of students start working on the satellite. After the preliminary and detailed design the project makes a transition into the Manufacturing, Assembly, Integration and Verification (MAIV) phase in which the satellite is produced and tested. After this the satellite is launched and operated in the utilization phase.

In this paper we evaluate the PMSE activities within these CubeSat projects and will identify the key drivers behind CubeSat successes and failures. The Delfi-C^3 and AAUSAT-II projects function as reference projects for this evaluation. The paper does not focus on the theoretical design process of a satellite but rather will look back on two projects and draw lessons learned from practice. We focus on treating the design and MAIV phases of the project since these are the phases in which most student activities take place. Since the author has been involved in the MAIV phase of both projects most focus will lie on this phase.

In Section 2, we give some additional background information on the projects and compare the complexity of the two projects. Section 3 treats the CubeSat teams and project structures. Section 4 discusses the design phase of a CubeSat, followed by the integration phase which is treated in Section 5. Section 6 will analyze some complexity issues surrounding CubeSat projects. In this section phasing, scheduling, information management, requirement management, change control and interface control will be discussed. Section 7 lists some lessons learned from the projects. The paper ends with conclusion and some recommendations.

2. Background

The CubeSat Standard

A standard CubeSat is a nano-satellite with dimensions of 10×10×10 centimeters, weighing no more than one kilogram. Also a double (10×10×20 cm) and a triple (10×10×30 cm) version of the CubeSat exist. This new standard literally opened the heavens for universities. It allowed them to build affordable student satellites that perform scientific experiments within this framework. Universities use the satellite projects as learning environment for their students who use the CubeSat as a project environment.

AAUSAT-II Project

In the summer of 2003 the AAUSAT-II project was started at AAU. Figure 2 shows the layout of this small satellite. AAUSAT-II is the second CubeSat developed at AAU. As with most CubeSat projects the primary goal of the AAUSAT-II project is education. The primary mission of the project is the education of students in the complicated process of building a complex system like a satellite. Next to this, AAUSAT-II also has technical goals:

- Establish one-way and two-way communications
- Perform science experiment 1: Attitude Determination and Control System (ADCS) system
- Perform science experiment 2: Gamma ray detector

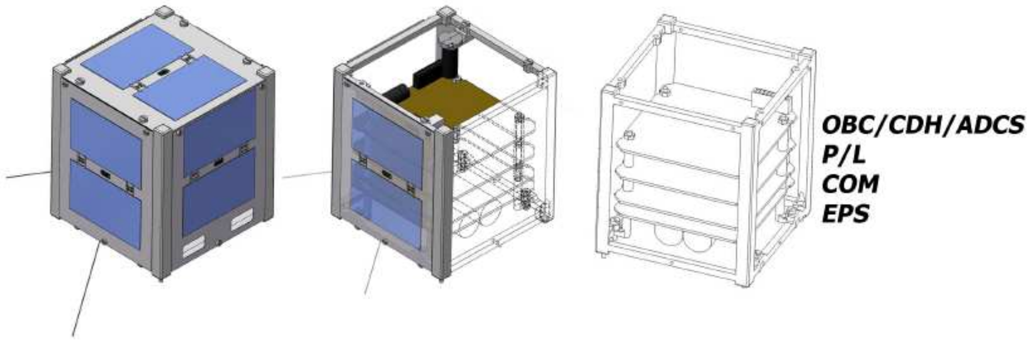

Figure 2. AAUSAT-II satellite is a 10x10x10cm CubeSat

Delfi-C^3 Project

Delfi-C^3 project was started in DUT in November 2004. Figure 3(a) and 3(b) shows the satellite configuration and stack with the Printed Circuit Boards (PCBs). The objectives of the Delfi-C^3 mission are twofold. Firstly, the project serves an educational objective meaning that it provides students with an opportunity to gain interdisciplinary hands-on engineering experience. Second, the Delfi-C^3 satellite serves as a technology demonstration platform which will demonstrate a number of new techniques in-orbit:

- In-orbit performance test of a new type of Thin Film Solar cells developed by *DutchSpace.*
- In-orbit functional and performance test of an Autonomous Wireless Sun Sensor (AWSS) developed by *"Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek" (TNO).*
- In-orbit demonstration of a Radio Amateur Platform (RAP)

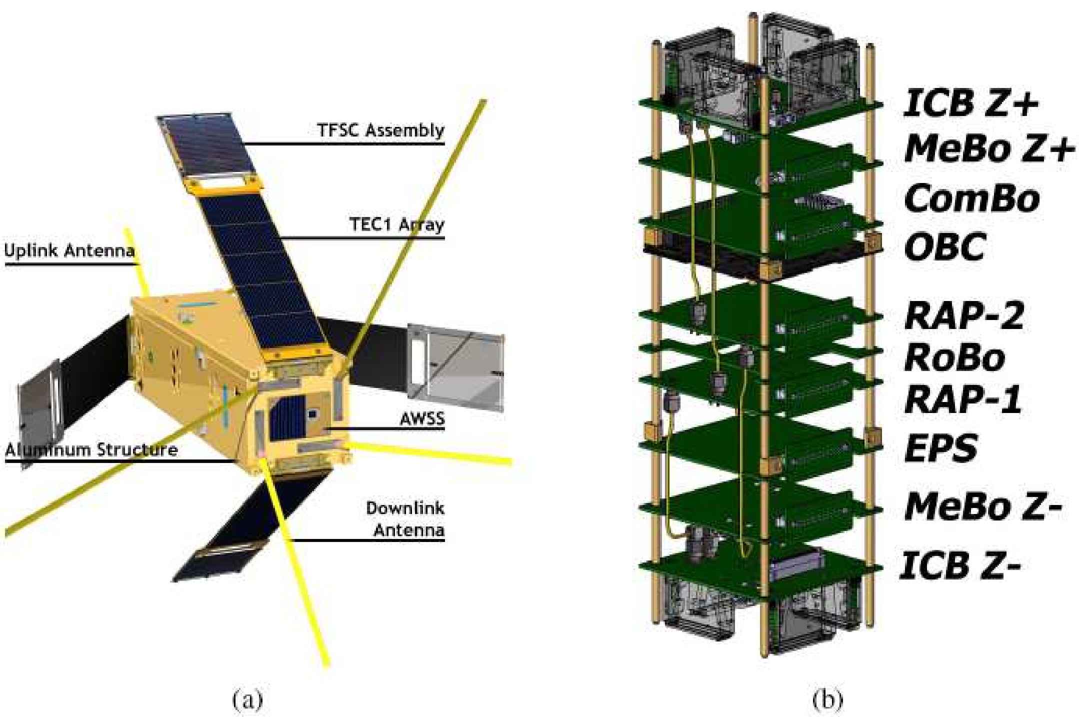

Figure 3. Delfi-C^3 external (a) and internal (b) configuration as a 10x10x30cm CubeSat

Delfi-C^3 and AAUSAT-II Characteristics		
	AAUSAT-II	**Delfi-C^3**
Mass	650 grams	2500 grams
Dimensions	10x10x10 cm	10x10x34 cm
Power	2 Watts	3 Watts
Subsystems	4 PCBs + MECH	9 PCBs + MECH
Subsystem complexity	Student developed OBC Large amounts of interfaces on PCBs	COTS OBC Some interfaces on PCBs
Complexity locations	Mostly electronical	Spread throughout satellite design
Mechanical aspects	Standard CubeSat design Mechanical design done at AAU Deployable antennas (2x)	Triple CubeSat body Modified COTS body Deployable panels (4x) and antennas (8x)
Electrical aspects	CAN bus architecture Batteries	I2C architecture Battery free design
Thermal control	Passive thermal control	Passive thermal control
Attitude control	Active ADCS: Momentum wheels and coils	Passive ADCS: Permanent magnet and hysteresis rods
Robustness	Satellite modes	Satellite modes Single point failure free design
Stakeholders	Mostly internally in AAU	DUT, industry and government
Development standards	Custom/university	Industrial

Table 1. Comparing AAUSAT-II and Delfi-C^3 project

Comparing Delfi-C^3 and AAUSAT-II complexities

There is no clear standard by which satellite projects can be compared when it comes to complexity. Table 1 shows a comparison between the two projects. AAU develops most things in-house and builds a technically relatively simple satellite that focuses on electrical challenges. DUT uses a variety of self developed and Commercial Of The Shelf (COTS) products and combines these to a complex satellite. The fact that the COTS products are implemented also adds complexity since the rest of the satellite needs to interface with these COTS products. The design is furthermore very robust, failure proof and up to industry standards, which adds a lot of complexity to the system. For these reasons and the fact that the Delfi-C^3 project has more stakeholders that are actively taking part in the project the Delfi-C^3 satellite is considered to be more complex than the AAUSAT-II satellite.

3. CubeSat Project Teams and Organisation

Project teams are the cornerstone of any project. Furthermore the way in which the CubeSat projects are positioned in the curriculum, the university and the industry are keys to understand the directions of a university CubeSat project. While the CubeSat standard forms the technical boundary for the satellite itself, the CubeSat project team and university form the organizational boundary for the CubeSat project. Due to the different setup of the projects, the teams differ as size, experience, qualities, availability and involvement of the teams vary greatly. A CubeSat project has to deal with different disciplines and technical skills. Therefore the team should have a good mix of a variety of competences. Usually, the group should be dividable in three subgroups which are usually Mechanical, Electrical and Project Management and Systems Engineering (PMSE). The mechanical group is responsible for the correct design of the satellite physical structure and its mechanisms. The electrical group is responsible for the functionality of the satellite. The PMSE group is responsible for the project overhead and interfaces. They define what the satellite should do and ensure that the requirements are met throughout the development. The division presented here is strict and there is overlap between the disciplines. This division does however shed some light on the way in which the AAUSAT-II and Delfi-C^3 project are organized. Tables 2 and 3 show the characteristics of the project teams and the project organization respectively.

The AAUSAT-II project is a collaboration of four departments of AAU and one department of Copenhagen University College of Engineering. The department of control engineering houses most of the satellite activities. The project is coordinated by a steering committee which consists of staff, AAU CubeSat veterans and a student from every subsystem group. This committee oversees the development of AAUSAT-II during weekly meetings in which the progress of the project is discussed with representatives from all subsystem groups. Each subsystem group is formed of students who are working on a semester assignment (between 5th to 10th semesters). This means that the satellite project is split into several smaller assignments. Each group works on the assignment for a semester. The education at AAU is designed as a Problem Based Learning (PBL) system. It is very pragmatic in nature and the assignments reflect this as well, since they often deal with real hardware. One staff member functions as project leader and manager and coordinates the project, other staff members function as group supervisors and advisers.

Delfi-C^3 and AAUSAT-II Project Teams		
Item	**AAUSAT-II**	**Delfi-C^3**
Students	>80 students from semester 3 to 10 Students in project groups	>30 MSc students, >35 BEng students Student have individual assignments for their thesis or internship
Staff tasks	Project leaders (financial) Project Manager Systems Engineers Project group supervisors Project Advisors Not active project members	Project leaders (financial) Internship and thesis supervisors Actively involved in project PMSE Actively involved in HW/SW development
Workforce flowthrough	Small core team of students participate every semester Large group of students participates during 1 semester Stable amount of student available during design	Dedicated teams for design and integration phase Handover in mid-project Fluctuating amount of students involved
Workforce availability	Design: Fulltime MAIV: Voluntary base	Fulltime
Workforce competences	Strong teamworking skills Strong electrical engineering skills	Strong PMSE skills Strong mechanical engineering skills Practical space engineering knowledge and skills through staff

Table 2. Overview of AAUSAT-II and Delfi-C^3 project teams

Delfi-C^3 and AAUSAT-II Project Organisation		
Item	**AAUSAT-II**	**Delfi-C^3**
PMSE	Implicit part of project No top level definition No philosophy	Explicit part of project Top level defined and flowdown Defined by students in collaboration with staff
Electrical Engineering	Project focal point, done purely by students	Done by students with staff assistance
Mechanical Engineering	All HW designed and build by students	Done by students with staff assistance
Facilities	Clean Room Workshop Project rooms PCB population facility Ground station	Clean Room Workshop Project rooms PCB population facility Ground station
Management	Part of steering group No dedicated project hours	Dedicated project manager Dedicated hours
Partners	One partner: - Supplied payload - Assisted in solar panel laydown	Multiple partners: - Usage of facilities - Supplied payloads - Supplied expertice - Dedicated workforce hours
Non-student activities	Solar panel laydown PCB production HW production	Solar panel laydown PCB design, production and population HW production

Table 3. Comparing AAUSAT-II and Delfi-C^3 project organization

The AAUSAT-II project is almost completely developed at AAU itself. Only the scientific payloads were delivered by an external source. This means that AAU has most of the knowledge it needs in-house and that they are almost independent of others. However they are missing knowledge when it comes to the use of standards and PMSE in space engineering. The cause of this is that the education more focused on the electronics students being educated to be control engineers.

On the other hand, The Delfi-C^3 project is ran by the faculties of Aerospace Engineering (AE) and Electrical Engineering, Mathematics and Computer Science (EEMCS) of the DUT. The project is done in close collaboration with Dutch Space and TNO, who both fly a payload on the satellite.

The Delfi-C^3 project is set up as graduate project. Students are involved in the project for their MSc thesis for about a year. Next to these students the team also consists of Bachelor of Engineering and international students who perform an internship or do a Beng of MSc thesis assignment on the project. This means that there is a great diversity within the team. Within the project there is a split up between different disciplines. Specific people are responsible for the software, hardware, systems engineering, project management, verification etc. Allthough there are overlaps between their functions, there are more distinctions between the different engineering disciplines than AAUSAT-II project. This results from the fact that the Delfi-C^3 project is more complex than the AAUSAT-II project. Next to their role as advisers and tutors both the staff members and the industry partners actively take part in the project and have dedicated hours on the project. There is a clear structure in the project in which the role of project manager and systems engineer are given to specific persons. The whole project is structured and ran as an industry standard space project. This is a result of the fact that the industry has stakes in the project. Furthermore the staff members, who are mostly veteran space engineers, have a large amount of practical knowledge about satellite engineering that is invaluable in deciding how to design the satellite right and tackle problems during the integration and testing.

In comparison to Delfi-C^3, AAUSAT-II has focused most effort on the electrical part of the project. The PMSE part was done, but a top level PMSE definition and space engineering standards were lacking. The main focus within the project was on getting a working stack inside of the satellite. But Delfi-C^3 project has a strong focus on the PMSE. This is done since the education is focused on this and the fact that the complexity of the satellite forces more PMSE into the project in order to keep the overview within the project. Practical electronics knowledge is lacking in Delfi-C^3 project since relatively few students from Electrical Engineering, Mathematics and Computer Science (EEMCS) actually take part in the project. This means that he Aerospace Engineering (AE) students do a lot of the electrical work under supervision of EEMCS staff.

4. CubeSat Design

During the design phase the satellite project is defined to a component level after which production, integration and verification starts. A solid definition of the design and the PMSE procedures is the base of every properly defined project. However it must be accepted that certain errors can only be found in integration and not all problems can be mitigated in paper design. Table 4 shows an overview of the characteristics for the design process of both projects.

The design of AAUSAT-II started in the summer of 2003. Different groups started working on the subsystems of the satellite supported by the staff. After several months the design process was disturbed by the start of the ESA's SSETI Express project. AAU was playing a major role in this project and several students involved in AAUSAT-II started working on this project as well (Alminde, 2005). This caused a major delay in the development of AAUSAT-II. The effect of this can be seen when the development of the mechanical subsystem is compared to that of the rest of the satellite subsystems.

Delfi-C^3 and AAUSAT-II Design Characteristics		
Item	**AAUSAT-II**	**Delfi-C^3**
Assignments	Project groups	Individual assignments
Design approach	Integrated, each assignment: HW/SW	Specific assignments: HW or SW
Design characteristics	Practical satellite engineering Focus on working HW Early prototypes KISS design Modular design Inhouse development	The process of building a satellite Focus on 'paper' design Detailed definition of functions, requirements, trade-offs and procedures KISS design Modular design COTS/SHOTS approach
PM	Parttime PM Scheduling Semester Project Definition	Dedicated Fulltime PM Phasing/Scheduling Organisation and Work Breakdown Design Data and Documentation Management
SE	Implicitly done in project Requirements definition Budgets (mass, power, data, link)	Explicit workpackages Functional analysis Requirements definition Configuration/hardware items Interface control Budgets (mass, power, data, link)
Maturity growth	OBC developed earlier, other subsystems have equal maturity growth	Differential, some subsystems mature faster than others
Student involvement	+/- 60	+/- 40

Table 4. Comparison of design characteristics of AAUSAT-II and Delfi-C^3 projects

The mechanical subsystem group was not involved in SSETI Express and delivered their hardware, ready for integration, at the end of the first semester of 2005. Most other subsystems would require over a year extra to obtain the same level of maturity as the mechanical subsystem. During the development of AAUSAT-II the focus was already strongly on the complete design and the implementation, both hardware and software. The groups working in the detailed design phase deliver a report that concerns hardware, software and often a prototype of the board and simulations of operations. This highly integrated approach is good for the project and ensures gradual maturity growth. After the detailed design was finished a small group of students proceeded to make the actual first Engineering Model (EM) during the summer. This was done on a voluntary basis. As the result, there was hardware in an early stage of the project. The fact that both hardware and software design are done simultaneously means that there is an evenly spread in maturity growth throughout the project. It furthermore allows early prototyping since basic software and hardware are available in an early stage. During the design of AAUSAT-II there was a lack of top level hierarchy when it came to PMSE. The subsystems were built according to the requirements that were stated and all worked well on subsystem level. The project, however, used little standards when it came to risk management, cleanliness, interface control and documentation control. The main reason for this was the lack of real system level project management and systems engineering functions in the project. This was caused by the fact that the departments in which the project is performed lack PMSE in their curriculum. Furthermore the staff members functioned as advisers and project leaders that performed some of the PMSE tasks, but had limited time on the project. The students were doing PMSE on subsystem level and since they did not get any PMSE education they often did this as an integrated task within their project in stead of separating it and giving it a real place in the project. Since no overall philosophy is present each group used its own vision on PMSE and these are not always compatible.

On the other hand, Delfi-C^3 was designed by the first group of students that worked on the project in November 2004 (Bonnema, 2005). Each one was responsible for part of the project. The work of the first group was gradually handed over to their successors who finished the design and started with the production, integration and testing. Most of the design work was done at the AE faculty with assistance of the EEMCS staff. The EEMCS faculty was primarily responsible for the development of the Radio Amateur Platform (RAP) subsystem and *SystematIC Design*, a small electronics firm in Delft, was responsible for the EPS. During the preliminary and detailed design PMSE techniques were used. The downside was that actual hardware and prototyping started late in the project life cycle. The first electronic boards arrived less than six months before the initial delivery of the satellite was planned. Apparently more focus on hardware and less on paperwork should be adopted. In later stages it was felt that some of the PMSE work was not very useful for later phases. One of the reasons for this was that most documents were not seen as living documents and new students wrote new documents on existing items instead of updating the old documents. During the integration a more flexible attitude towards documentation and procedures should be adopted in order to make the rapidly changing integration process more efficient. If more living documents were maintained this could have been achieved.

5. CubeSat Integration

During the integration phase the satellite is lifted from the paper design, produced and assembled. This process is often called the MAIV phase. When a commitment is made to build a CubeSat all phases should have equal academic potential to ensure that the overall satellite quality is maintained. The manufacturing and verification process of a complex subsystem design requires similar academic accreditation as the system design, although the academic skills used in both parts of the lifecycle might be different. Table 5 shows a comparison of the integration characteristics of both projects.

For AAUSAT-II the MAIV phase is left outside of the curriculum. The project ends with detailed designs of the subsystems and several prototypes. The project is then dependent on students finishing the satellite in their own leisure time. This causes a major unbalance in the project and it causes an structural shortage of

Delfi-C^3 and AAUSAT-II Integration Characteristics		
Item	**AAUSAT-II**	**Delfi-C^3**
Team availability	<10 persons	>20 persons
Team composition	Staff, PhD and MSc students	Staff and MSc students
Project commitment	Voluntary base/PhD hours	Contract based/thesis work
Academic accreditation	No	Mostly
Design approach	EM/FM	Protoflight
PM	Scheduling	Phasing/Scheduling Organisation and Work Breakdown Design Data and Documentation Management
SE	Interface control	MAIV management Operations planning Interface control Configuration management
Integration issues	CDHS SW architecture (CAN problems) Ill structured SW development Bad software protocol version control Late integrated testing	SW development Rework on flight PCBs Late production of PCBs Late integrated testing

Table 5. Comparison of integration characteristics of AAUSAT-II and Delfi-C^3 CubSats

man-hours. After the official semester is done students have other educational obligations and are hardly available for the satellite project. This causes the project to be delayed. PhD students that have graduated on AAUSAT-II or AAU CubeSat are often asked to dedicate part of their time to finalizing the remaining of the project and helping the verification process. Also compromises need to be made in order to deliver on time. This results in a loss of satellite quality. For example, the initial design incorporated a deployable solar panel that had to be canceled due to lack of development and integration time. A big advantage was gained by the fact that the EM stack was ready several months prior to the launch. This allowed debugging of the software and proper integrated functional testing. Unfortunately, the software formed a major bottleneck in the MAIV phase. When the stack was integrated there were severe interface problems between the software on the subsystems. One of the reasons for this was the fact that the satellite uses a Controller Area Network (CAN) driver for communication. The implementation of this system took longer than what was anticipated. A solution to cope with this problem can be trying to incorporate the integration phase in the curriculum or alternatively creating an environment in which students are hired to finish the project. This would drastically reduce the integration time.

Also new, mission critical items should be tested as early in the integration phase as possible to allow for proper troubleshooting and enough time for integrated testing. A good thing is the fact that there is both an EM and an Flight Model (FM). This forces the project to get integrated hardware early on in the integration phase.

In Delfi-C^3 case, the project encountered similar problems in the MAIV phase. However, the curriculum is more tolerant with respect to the demands on thesis work. Even though the workforce on the project is available full time there were still problems in making deadlines. The faculty has hired several Delfi-C^3 graduates to finish the project. This solves most of the problems but is not the preferred solution. In Delfi-C^3 project the ProtoFlight approach was chosen as the MAIV philosophy. This meant that only one satellite would be build and tested. Although this approach has the advantage of saving time and resources over an EM/FM approach a negative consequence was that the MAIV phase was delayed due delays in electrical and software development. Production of initial hardware and electronics started late in the project and issues that could have easily been detected in an EM. A large amount of rework and testing was necessary to get the subsystems up to flight status. The integrated electrical tests are scheduled only weeks before delivery. This makes these tests crucial for the success of the project. Most of these problems can be found

CubeSat Model Approach			
	Prototypes	Basic Model	Protoflight Model
Purpose	Proof of subsystem functions	Achieve an integrated and functional architecture	Fully functional satellite
Functionality	Subsystem subfunctions Subsystem functionality Proof of concept	Comparable to EM boards EPS architecture functional CHDS architecture functional	Flight Model Fully integrated Upgraded Basic Model
Verification	Verify functions	Qualification testing	Acceptance testing
Examples	Battery conditioning board Power distribution board	Basic EPS in stack	Flight EPS in stack

Table 6. Definition of CubeSat models

to lead to the same source: a lagging electrical and software maturity in the project due to a lack of EEMCS students on the project. In the Delfi-C^3 project the satellite designs remained on paper for a long time. Once the production was started the schedule pressure and workload were very high. There was little margin for error and not enough time for elaborating the integrated testing. Another area of improvement is the project status awareness. Within the team only few people know the actual project status. Having weekly meetings or status mailings could improve this awareness.

Model Philosophy

Both AAU and DUT use different approaches for the models of the satellite produced for MAIV. At DUT a ProtoFlight Model (PFM) is made and AAU uses an EM/FM approach. Both projects recognize the need for prototypes and bread-boarding before these complete models are produces. Table 6 shows the characteristics of the different models used in this approach. The Basic model is used for initial subsystem and architecture testing. Furthermore it can be used to perform initial coarse environmental tests. The final design is updated during the MAIV. Then, the updated design is used to produce the Flight Model design. This approach ensures that (integrated) testing will start in time. Section 6 will illustrate how this new approach is to be implemented in the phasing and scheduling.

Both projects are dependent on spacecraft launch delays in order to get their satellite integrated and tested in time. When a Basic Model is used and the launch is booked at the end of the MAIV phase of this model the launch can be booked with more confidence since fewer delays are expected during FM integration. After this milestone the project can generally be finished in four to eight months, when proper attention is given to the MAIV of the FM. Furthermore if time is left the team can work on thesis reports and general documentation. A detailed and elaborated design process can only be verified and validated in an elaborate integration phase. Doing a short integration phase after an elaborate design phase compromises the satellite quality since the design features can not all be verified to the degree in which they were defined. It is unrealistic to expect that in a two year satellite project the integration can be done in 4 months while the design has taken twenty months.

6. Managing CubeSat Complexity

Next to the project teams and lifecycle, there are also some general PMSE aspects that are of importance in a CubeSat project.

As the project transcends through its lifecycle it is important to keep track of the status of the project. It should be always considered that CubeSat projects have a much shorter lifecycle, are educational in setup, are less complex than conventional space projects and have great overlap between the different phases. Within the AAUSAT-II project there is no detailed phasing within the project. Since the education is based on Problem Based Learning (PBL) the project has natural phases of six months. One of the advantages of this is that the project progress is uniform for all the subsystems since the workload for each group is

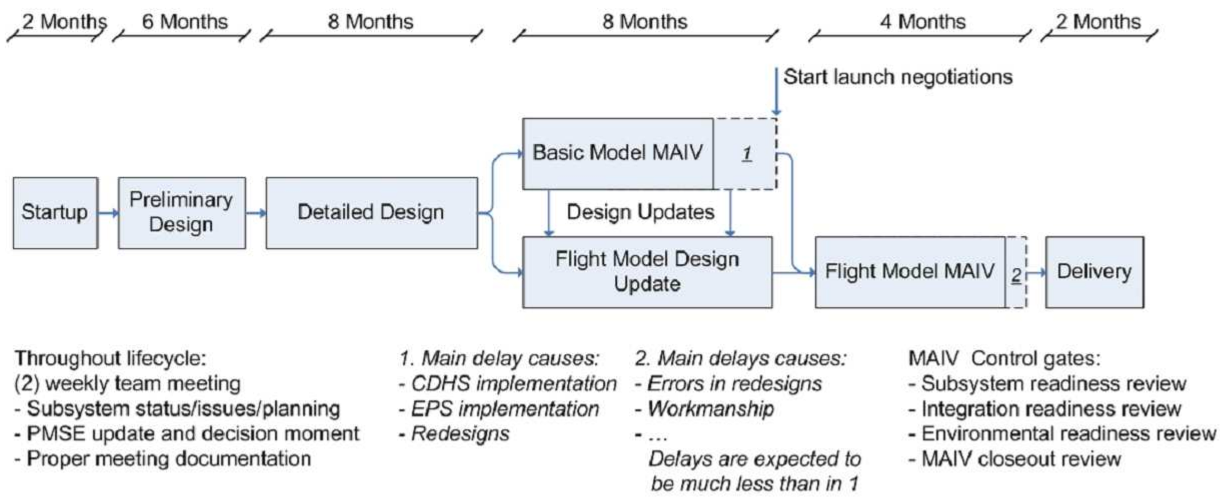

Figure 4. Proposed CubeSat phasing

similar. The down side is that no real control mechanism was defined in the development process to make sure that the project evolves to the next stage.

The Delfi-C^3 project has incorporated phasing in the development process. Since Delfi-C^3 does not use a PBL structure it is more dependent on the availability of students for certain subsystems. Because of this the maturity of these subsystems are not necessarily similar. Tailoring has been done in order to account for these inconsistencies in the CubeSat project. So called “delta-sessions” have been implemented. Delta-sessions are implemented for reviewing those subsystems that do not have the desired design maturity at the time of system review. These sessions allow the subsystems to pass the review at a later time and not to delay the entire development process. Extra attention should be given to those subsystems which make use of delta-sessions since they lag behind the rest of the development process. Delfi-C^3 had implemented these sessions but due to a lack of manpower, the critical subsystems could not catch up with the rest of the system.

A new model for phasing is presented in Figure 4 in combination with the Basic Model that was suggested. In this model the main point is that a basic model is made to prove that all subsystems have enough maturity and the subsystems have EPS and CDHS basic architecture. Once these requirements have been met the launch can be negotiated and production of the FM (updated from the basic model) can be started.

Scheduling

In conventional space projects the development time is long while CubeSat projects generally take no more than 3 years. What CubeSats do have in common with conventional projects is the fact that they both use space grade materials that have longer lead-times than commercial products. The scheduling needs to take these things into account and structure the project in time. Since CubeSat projects have a short lifecycle, project phases are short and small disturbances in the project can cause relatively large delays. Furthermore due to scope of CubeSat projects it is also important to keep the scheduling at a usable level for the project.

In our study cases, both projects suffered from extensive delays that pushed back the schedule over a year with respect to the launch windows that were identified at the initiation of the project. AAUSAT-II simply did not have the manpower to finish the tasks in time. For Delfi-C^3 one of the causes of the delays was the fact that there was an increase in workload in the transition from detailed design to production and testing phases due to the large amount of parallel activities. During this time there were not enough students to perform all the parallel activities.

The two project schedules have been compared at several moments in the project lifecycle: The start of the project, the halfway point (January 2006) and the current planning (June 2007). The results can be seen in Figure 5. The project lifecycle is divided up in five phases. The first and last phase indicates the semester in which the project was initiated and should be delivered for launch. The more interesting phases are the middle three. What can clearly be seen is the optimism that is present in both project plannings. Initially the projects are expected to be finished in two to three years. At the second measuring point both projects conclude that the phases they have went through have taken longer than expected (except preliminary design) but they still expect the phases to come to be as short as initially defined. At the last measuring point this is also found to be inconsistent. There are obviously overlaps between the phases and project complexity and starting maturity also play a role.

The authors believe that AAUSAT-II could have been finished in 2.5 years if the SSETI Express mission did not interrupt the progress and the MAIV phase was defined inside of the curriculum. When looking at the Delfi-C^3 schedule one can see that the MAIV phase had to be compressed in order to make the delivery date, else the satellite would have been finished later. Proper scheduling in CubeSat project is updated frequently and is realistic. A general result from both projects is that the production and verification of the satellite is structurally underestimated.

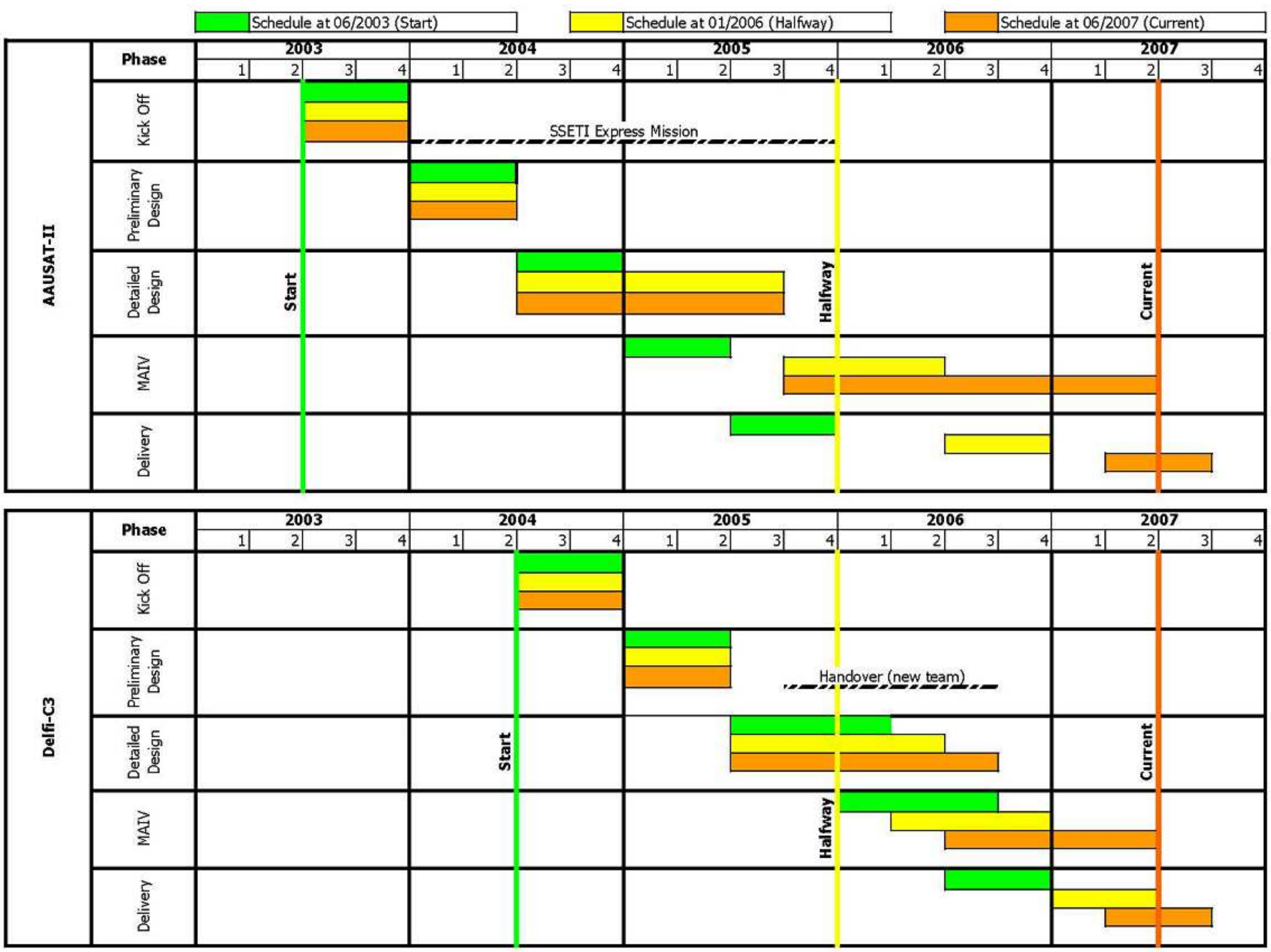

Figure 5. Project schedules of AAUSAT-II and Delfi-C^3 at three points in the lifecycle.

Requirements Management

Requirements form the red line that runs through each project. They are derived from the functions that the product should have and flow through the design process where they are reviewed, implemented and verified (Fortescue, 1999). First of all the CubeSat standard requirements dictate the physical properties and environmental performance of the satellite. Next to this there is a set of mission and payload requirements that further specify the demands on the satellite project.

Within the AAUSAT-II project also mission requirements were formulated. The general satellite requirements were put into a requirements document. However the subsystem requirements were not stored centrally and a standard for requirement tracing was not present. Furthermore in later phases of the development the documentation was not kept up to date. This caused confusion on which requirements were to be verified. In AAUSAT-II project the interfaces are defined in the weekly meetings. Furthermore each individual subsystem keeps a very basic list of its electrical interfaces and commands.

In Delfi-C^3 project requirements are explicitly stated in a requirement specification document. This document contains all requirements for the Delfi-C^3 system categorized and numbered. The requirements originate from the requirement analysis which was done at the start of the project. They are used later in the lifecycle during the verification process. Interface Control Documents are used in which the interfaces between the different configuration items are defined. Because of the large amount of interfaces there is a need to track them thoroughly. Different kinds of interface types are identified and charts are made in which these are related to the configuration items.

Both projects use a modular design to simplify and concentrate the interfaces between the modules. In interface control it is important to tailor the standards to the system needs. If AAU wants to upscale the complexity of their satellites a better interface control will be needed in order to cope with the increasing amount of interfaces.

6. Lessons Learned

There is no doubt that CubeSat projects are great educational practices. Many students take part in the project in the form of internships or graduation assignments. Vaartjes (2008) has analyzed the CubeSat project at Delft University of Technology and has identified a number of areas which will need attention for next similar projects:

- Experienced staff with broad knowledge outside their field of expertise and with experience not limited to the academic community is required. University recruiting rules should allow hiring such staff.
- Evaluation of an MS thesis executed within a project should, in addition to the classic aspects of quality of the research and written and oral presentation of the results, take the specifics of that project into account. In the case of Delfi-C3 that is at least the student’s role(s) in the team, in development and verification activities and external (customer) contacts. Well-structured evaluation criteria and a regular peer evaluation may provide valuable inputs to that process.
- Student supervision should put the interests of the student above that of the project and should therefore be independent of the project.
- Hierarchy is often lacking among students, which is particularly difficult for systems engineers whose tasks are often misunderstood. New team members should be informed about the different roles within a project and the purpose, methods and tools of systems engineering.

- The workforce discontinuity when the old student group is replaced with the next generation students is the hardest to deal with. Documentation needs to be complete and accessible. Having the predecessor supervise the successor to teach him the ropes is ideal, and sufficient time should be allocated to do this.
- Co-location of the different disciplines within the team is highly desirable. This promotes the communication between disciplines and increases the visibility of all aspects of the project.
- Establishment and maintenance of a well-structure documentation (change) system is essential, also for a relatively "informal" student satellite project.
- Co-operation with industry, which has a direct stake in the success of the project, has a very positive influence on the project and promotes knowledge exchange between university and industry. It seems natural that such an initiative is rewarded in the academic environment.

Observing the results and conclusions of AAUSAT-II project also shows that similar lessons learned are applicable for the CubeSat project at Aalborg University.

7. Conclusions

Student CubeSat projects are a challenge in many ways. These projects are characterized by short development time and complexity of both the project and the satellite. Multidisciplinary teams are of key importance in getting the job done. With increasing complexity of the project, the need for PMSE increases. The Delfi-C^3 project is a more complex and hence there is more need for PMSE. Furthermore the educational background of the students is filled with PMSE courses and projects. Within the AAUSAT-II project PMSE is used, but in a more implicit way. The great challenge in PMSE control is that some subjects that are dealt with are unpredictable by nature. Both projects introduce interesting features which can be used in the other project. AAUSAT-II could use more structure, standardization, organization and documentation. This can be achieved by implementing more courses on PMSE and being more thorough in the design phase. AAU could cut back their development time by enhancing their educational definition of the MAIV phase.

The Delfi-C^3 project would benefit from the more pragmatic approach of AAUSAT-II and start working on prototypes, and software in a much earlier phase.

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BIOGRAPHY

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