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From Single to Formation Flying CubeSats: An Update of the Delfi Programme

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ABSTRACT

This paper provides an update of the Delfi nanosatellite programme of the Delft University of Technology (TU Delft). The two completed missions, i.e. Delfi-C^3 and Delfi-n3Xt, are briefly reviewed with their up-to-date results. The lessons learned from these two missions are also presented, focusing on three aspects: people, process, and design. An innovative development strategy for university satellite projects and a systematic approach for improving reliability are introduced. These lessons are applied to the ongoing DelFFi mission, where two CubeSats will perform autonomous formation flying. An update of the status of the DelFFi project is provided, and the enabling technologies for formation flying are described.

INTRODUCTION

In the recent two decades, very small satellites, such as CubeSats, are attracting more and more attentions from academia, industries and space agencies due to their low cost, short development cycle and promising capability. Currently, most CubeSat missions are used for technology demonstrations or education, which only explore the capability of an individual satellite. However, the capability of CubeSats can be extremely enhanced by flying a cluster of satellites[1]. For example, several missions such as QB50 and OLFAR have been proposed for this purpose[2,3].

This paper provides an update of the Delfi programme of the Delft University of Technology (TU Delft). Delfi-C^3, the first CubeSat in the Delfi programme, was launched on Arpil 29, 2008 and is still operational after more than five years. Delfi-n3Xt, the second Delfi CubeSat, has been completed in January 2013 and is waiting for launch. The perspective of TU Delft on future small satellites motivated DelFFi, the third Delfi CubeSat mission, which is expected to be launched in 2015 within the QB50 framework and to demonstrate autonomous formation flying using two CubeSats named Delta and Phi.

This paper consists of three primary parts. The first part provides an overview of the Delfi-C^3 and the Delfi-n3Xt missions. The second part presents the lessons learned from the development and the mission implementations of Delfi-C^3 and Delfi-n3Xt. The third part discusses on the ongoing DelFFi formation flying mission, with a focus on the technologies that enable the autonomous formation flying. At the end of the paper, conclusions are drawn.

DELFI-C^3: THE 1^{ST} DUTCH CUBESAT MISSION

Delfi-C^3 is the first satellite of TU Delft, also the first Dutch university satellite. It's a triple-unit CubeSat with a mass of 2.2 kg and has been successfully launched on 28^{th} April 2008 with an Indian Polar Satellite Launch Vehicle (PSLV) in a Sun-synchronous orbit of 635 km altitude. The primary objective of the Delfi-C^3 mission is to provide students an opportunity to obtain hands-on experience of a real life satellite project. The secondary objective is to provide a means for fast and cheap in-orbit technology demonstration.

Delfi-C^3 Satellite

The external appearance of Delfi-C^3 satellite is illustrated in Figure 1. The key specifications are shown in Table 1.

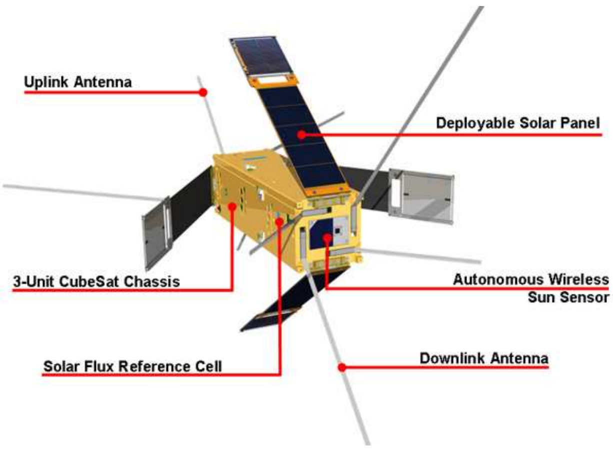

Figure 1: Delfi-C^3 satellite

Table 1: Key specifications of Delfi-C^3

Item	Specification
Dimensions	100x100x300 mm^3
Mass	2.2 kg
ADCS	Passive magnet control
CDHS	I^{2}C bus
EPS	Decentralized, each PCB protected by microcontroller
TTC	Uplink UHF @ 435 MHz, 600 bps FSK; Downlink VHF @ 145 MHz, 1200 bps BPSK
Thermal	Passive
Payload	Autonomous wireless sun sensors, thin-film solar cells, transponder

The new technologies flown on Delfi-C^3 are Autonomous Wireless Sun Sensors (AWSS) developed by the Dutch institute TNO, Thin Film Solar Cells (TFSC) developed by Dutch Space B.V. and a transponder for radio amateurs developed by TU Delft.

Since the two main payloads AWSS and TFSC only function in sunlight, Delfi-C^3 has no battery. In addition, the two payloads only require a variable orientation relative to the sun vector, which leads to a passive attitude control subsystem. The design of the satellite is Single Point Failure Free (SPFF), a characteristic that, as will be shown in the next subsection, has saved the mission in more than one aspect. For a full description of the Delfi-C^3 mission and satellite please refer to [4].

Delfi-C^3 Results

The total development time of Delfi-C^3 has been about 3 years and more than 60 MSc and BSc students have been involved in the project, which resulted in around 60 thesis. In total about four full-time equivalent staff have been involved in the project. The man-hour ratio students/staff is about 6:1. So from educational aspect Delfi-C^3 made a very good success story.

From technical point of view, Delfi-C^3 is also very successful. Two hours after being ejected into orbit at 04:40 hrs UCT on 28th April 2008, the first signal of Delfi-C^3 was received by an American radio amateur in Califonia. At 11:49:51 hrs UTC Delfi-C^3 was heard loudly and clearly by the Delft ground station at the time predicted by the pre-launch Two Line Elements (TLE). The first solar cell I-V characteristic was also seen real-time on the ground station monitors. Shortly after that, telemetry from all payloads has been received.

According to the telemetry, one of the two AWSSs carried by Delfi-C^3, i.e. the one on the +Z-axis, works properly. A typical output of the AWSS can be seen in Figure 3. For the –Z AWSS only little data was received. However, the data are still useful enough to draw conclusions about the correct functioning of the AWSS.

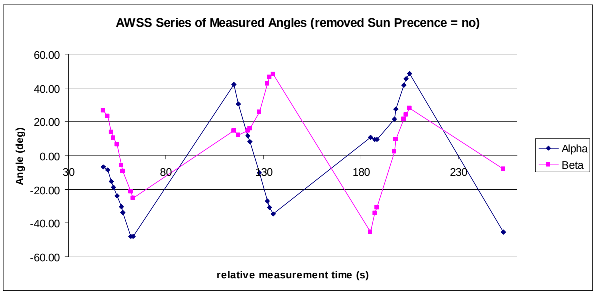

Figure 2: AWSS output

Delfi-C^3 carries a set of two TFSCs at the tip of each of the four solar panels. The cells are Copper-Indium-Gallium-diSelenide, vacuum deposited on 25 µm think Titanium foil. In the first three months of Science Mode more than 53,000 accurate I-V curves have been harvested. The top of Figure 3 shows a typical I-V curve of the TFSC at the beginning of the mission; while the bottom figure shows an I-V curve received recently with less than 1/10 of original output current. Both are at 80% influx, so an incidence angle of about 36 degrees.

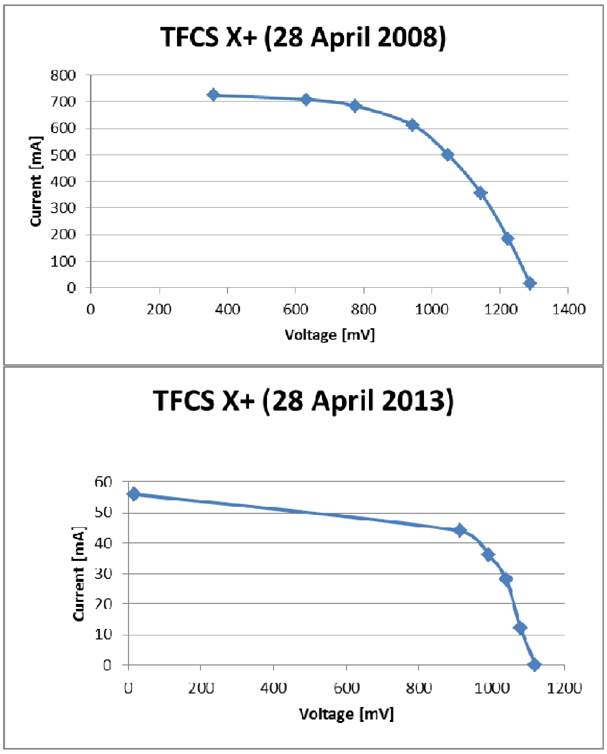

Figure 3: TFSC I-V curve

The third payload of Delfi-C[3], i.e. the transponder, worked in a good manner until the end of September 2008. After that complains about the bad quality of the transponder function were received and diagnostic tests were performed. The conclusion is that somewhere in the chain between antenna and power splitter a short circuit or open connection is present. The transponder was then declared dead and the satellite continues full operations using the redundant transceiver.

For the platform of Delfi-C[3], in general all subsystems were fully operational from the beginning of the mission. All the four solar panels and eight Rx/Tx antennas were deployed successfully. The rotation rate of the satellite was decreased from 5.2 °/s after injection down to 0-0.7°/s. However, the Command and Data Handling Subsystem (CDHS) suffer from non-nominal performance. The CDHS design has an inherent flaw that quite often prevents data transmission on the Inter-Integrated-Circuits (I^2C) bus, leading to either insertion of zeros in the telemetry, arbitrary switch off of subsystems, a reset of the computer or even a fall back to a very limited back-up mode. The reboot of Onboard Computer (OBC) is usually completed within a few seconds, but in worst case could after next eclipse. This bus issue also caused the relatively low yield of payload data. More details of the Delfi-C[3] flight results can be found in [5].

Although aforementioned issues present, Delfi-C[3] is still in operations after more than 5 years in orbit. Therefore it can be claimed as a full mission success, from both educational and technical aspects.

DELFI-N3XT: AN ADVANCED CUBESAT

Delfi-n3Xt is the second Dutch university satellite and successor to the Delfi-C[3] as part of the Delfi nanosatellite development program[6]. Same as Delfi-C[3], Delfi-n3Xt is also a triple-unit CubeSat developed by students and staff of TU Delft in cooperation with industrial and institutional partners within The Netherlands. Its main objectives are to provide hands-on training and research for students, demonstrate novel small space technologies and act as robust and versatile nanosatellite platform. The satellite development is finished and now waiting for launch before the end of 2013.

This section provides an overview of the Delfi-n3Xt satellite platform and payloads. For details please refer to [7].

Delfi-n3Xt Satellite Platform

The artist impression of Delfi-n3Xt is shown in Figure 4. Its key specifications are listed in Table 2.

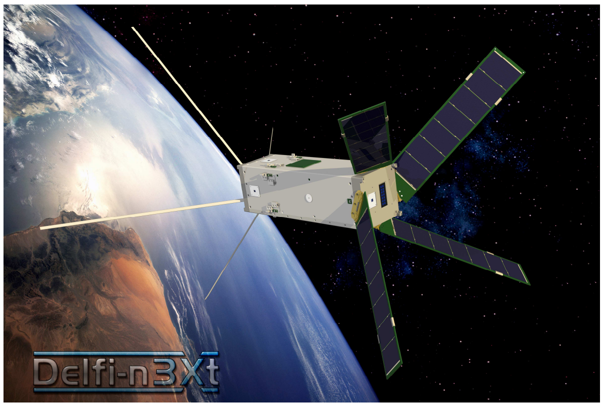

Figure 4: Delfi-n3Xt artist impression

Table 2: Key specifications of Delfi-n3Xt

Item	Specification
Dimensions	100x100x300 mm^3
Mass	3 kg
ADCS	Active 3-axis stabilized using reaction wheels
CDHS	Delfi Standard System Bus (DSSB)
EPS	Decentralized, each PCB protected by microcontroller
TTC	Uplink UHF @ 435 MHz, 600 bps FSK; Downlink VHF @ 145 MHz, 1200 bps BPSK
Thermal	Passive
Payload	T3μPS, Solar cell experiment, ISIS Transceiver

The design of Delfi-n3Xt started early 2008 when Delfi-C[3] was awaiting launch. Later the lessons learned from the design and in-orbit data are applied to Delfi-n3Xt. The main technical lesson from Delfi-C[3] was that power and data interfaces are prone to errors and (temporary) failures. In Delfi-n3Xt this is dealt with by the introduction of the Delfi Standard System Bus (DSSB).

The DSSB is hardware and software which standardizes the power and data interfaces between the subsystems and provides failure tolerance to these interfaces. The wiring harness consists of a flex-rigid printed circuit board and 20-pins Harwin Datamate M80 connectors for connection with each board in the internal stack, as shown in Figure 5. All wiring interfaces are redundant for failure tolerance to wire or pin breaks. Each board in the stack contains standard circuitry which protects the main power and data bus from misbehaving subsystems.

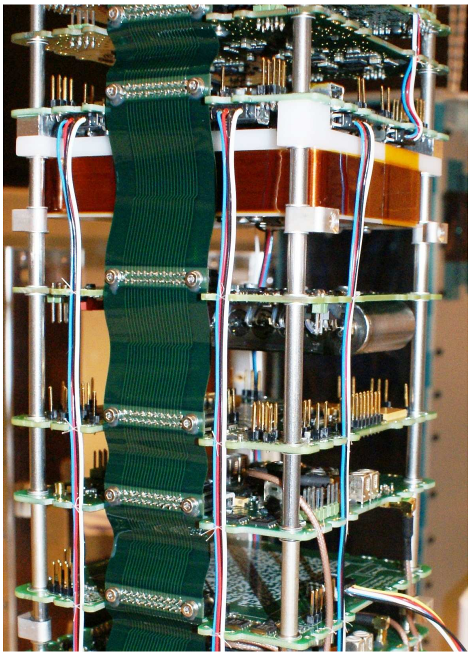

Figure 5: DSSB flex-rigid wiring harness

Delfi-n3Xt uses the I^2C serial interface as data bus. Many data busses have been compared, with its closest competitor being the Controller Area Network (CAN) bus which is also used in some nanosatellites[8]. The reasons to choose I^2C over CAN, despite the fact that CAN has better inherent reliability, are power consumption, the availability of peripherals, standard support in microcontrollers and the flight heritage of Delfi-C^3. It has to be noted however that using I^2C for a high intensive bus traffic with many devices connected has been difficult because many commercial devices have a slightly different implementation of the standard. In the Delfi-C^3 project, it has been discovered that microcontrollers can have failure modes in which they pull one or both of the I^2C lines down indefinitely[9].

The DSSB circuit is schematically shown in Figure 6. Subsystems are switched on/off through command by the onboard computer according to the operational mode and available power. This is done by a low power microcontroller in the DSSB circuit which is safely connected to the main bus through a series resistor and regulator. An is detected by a monitoring circuit and the subsystem is immediately switched off and disconnected. This can be undone through the DSSB microcontroller. Buffers protect the I^2C lines and can be switched to high impedance state in case of malfunctioning of the subsystem.

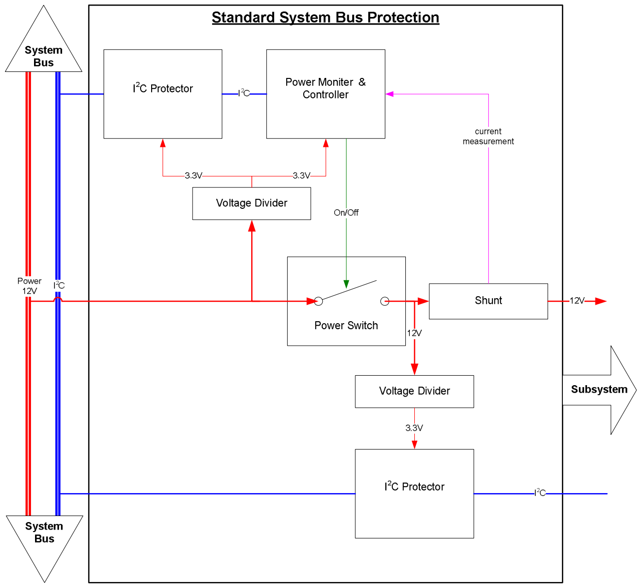

Figure 6: DSSB schematic overview

Another significant improvement of Delfi-n3Xt is an active Attitude Determination and Control Subsystem (ADCS) to stabilize the satellite and demonstrate triple-axis pointing and tracking capabilities. Separate operating modes are implemented for detumbling, coarse- and fine sun pointing, thruster pointing and ground station tracking. The ADCS comprises six sun sensors, two magnetometers, three magnetorquers, three reaction wheels and a main board. The main board is equipped with a fast Atmel ARM9 microprocessor running at 400 MHz and a Texas Instruments XMega A1 microcontroller for backup (only detumbling).

Figure 7 shows the integrated ADCS (excluding sun sensors), which has a mass of 330 g, volume of 90×90×34.6 mm^3, and a peak power consumption of 1600 mW.

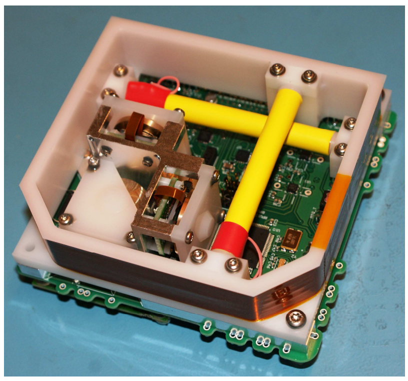

Figure 7: Integrated ADCS

Payloads Onboard Delfi-n3Xt

Delfi-n3Xt will demonstrate novel space technologies such as a micropropulsion system, silicon solar cells, a VHF-UHF transceiver, and an S-band transmitter.

A solid cool gas micro-propulsion system ($T^3\mu PS$) has been developed jointly by TNO, TU Delft and University of Twente[10]. The core of the system is the Cool Gas Generator (CGG) where pure gas at ambient temperature is produced by self-sustained decomposition of a solid propellant charge in which the gas is chemically stored. When ignited, the gas is released and the residuals of the decomposition stay in the generator as a slack material. The compact storage allows the design of the propulsion system to be simplified as no high pressure components are needed. One advantage of CGGs arises from the fact that the system remains unpressurized until operation in space, which simplifies integration and launch preparation and reduces safety issues to an absolute minimum. Due to the long storage lifetime a CGG propulsion system can be integrated with the satellite, be in storage for a few years, does not need filling or other pre-launch operations. As shown in Figure 8, this system consists of eight CGGs mounted inside a buffer volume, a pressure transducer and a filter that are integrated using micro-system technology. Due to the innovative approach of integration, the mass of the system, including mechanical and electrical interfaces, is below 100 grams and the volume is below 100 ml.

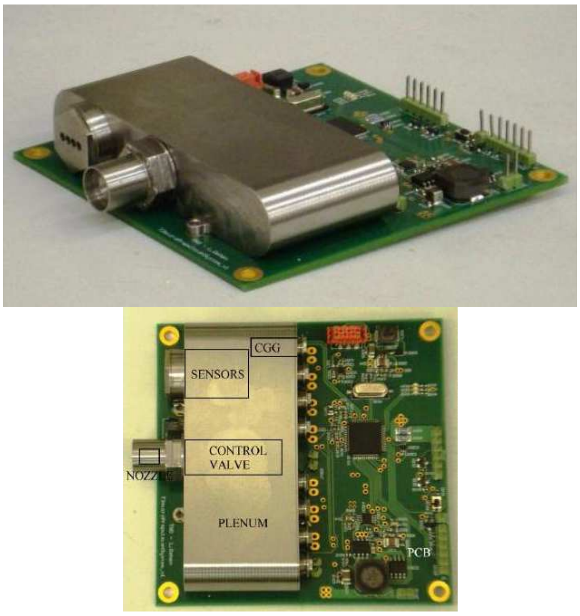

Figure 8: The $T^3\mu PS$ onboard Delfi-n3Xt

The solar cell experiment payload was developed by TU Delft. In this experiment 14 small amorphous silicon (a-Si:H) solar cells (Figure 9) will be monitored during the mission by measuring the current-voltage characteristics under illumination and the temperature of the solar cell assembly. These a-Si:H solar cells have a higher radiation tolerance, better annealing properties, and higher power-versus-weight ratio when no cover glass is used. The objective of the experiment is to monitor the solar cells and compare the results to a degradation model developed in lab research[11].

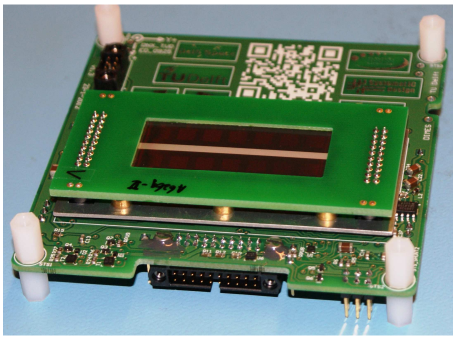

Figure 9: The solar cell experiment payload onboard Delfi-n3Xt

The ISIS Transceiver (ITRX) payload is to demonstrate a new type of versatile CubeSat radio transceiver which is an improvement of the commercially available TRXUV transceiver from ISIS BV. The key specifications of ITRX are shown in Table 3.

Table 3: Key specifications of ITRX

Characteristic	Specification
Transmitter Frequency	145.870MHz (VHF band)
Receiver Frequency	435 MHz (UHF band)
Transponder Frequencies	From: 435.530 - 435.570 MHz To: 145.880 - 145.920 MHz
Transmitter Data Rate	1200-9600 bit/s (set @ 2400 bit/s)
Receiver Data Rate	1200 bit/s
Transmitter Output Power	0.2 W
Transmitter Power Consumption	1.285 W
Receiver Power Consumption	0.222 W
Transponder Power Consumption	0.637 W
Transmitter Modulation	Binary Phase Shift Keying (BPSK)
Receiver Modulation	AFSK
Communication Protocol	AX.25 & CW

The last payload of Delfi-n3Xt is an S-band Transmitter (STX) which can achieve relatively high data rates compared to the primary downlink. The key specifications of STX are shown in Table 4. It comprises of a directional patch antenna which is directly mounted on the outer structure of the satellite. All functional electronics are directly placed on the back of the patch antenna. This minimizes losses and makes it possible to provide future CubeSats with multiple STXs on the satellite, such that its use can be decoupled from attitude control. In the internal Delfi-n3Xt stack, an STX interface board is placed which connects to the system bus. All telemetry frames sent by the primary transceiver or ITRX will also be stored on the STX in local flash memory and being sent in a beacon mode in small bursts at 50 kbit/s. The STX will be turned switched to full transmit mode by telecommand and will sent part of the stored content to the ground station with the intention to fill in gaps of data reception on the continuous low data rate transmission.

Table 4: Key specifications of STX

Parameter	Input
Frequency	2405.0 MHz (S-band)
Data rate	2.4 to 250 kbit/s
Transmitter Output Power	0.12 W
Modulation	MSK
Data Storage	16 GB (~2 years of data)
Power Consumption Store Only	75 mW
Power Consumption Beacon Mode	122 mW (average)
Power Consumption Transmit Mode	846 mW

LESSONS LEARNED

Through the development (and operation) of Delfi-C3 and Delfi-n3Xt, many lessons have been learned, which are mainly from three aspects: people, process, and design.

People

The key for a successfully space project (also true for all other projects) is the people. For university satellite projects, the most important objective is to provide hands-on experience to future space engineers. Therefore, significant involvement of students is essential. These students as well as other young and dynamic engineers are most motivated for innovations, but they are lacking of experiences. In order to make sure they are on track and to reduce the possible risks, having experienced engineers in the team to supervise young engineers is critical. The ideal satellite team shall consist of both of them.

It came into attention that some universities under-estimate the importance of having experienced engineers. They either totally ignore the involvement of experienced engineers, or only have them in the role of review board. However, according to TU Delft's experience and lessons, the only way to effectively utilize the knowledge of experienced engineers is to have them really integrated in the team and provide supervision and support on a daily (or at least regular) basis.

Process

In this subsection "process" refers to systems engineering processes, e.g. documentation management, scheduling, requirement engineering, etc. Some of these processes have been addressed[12], and in this paper the focus is on design phases.

Most university-class satellite projects likely have to deal with fluctuating availability, continuity and quality of human resources. Within the Delfi-n3Xt mission for example, the amount of students have fluctuated between 10 and 25 students. They remain on the project for 0.5 to 1.5 years and their role on project is driven by their interests and learning objectives rather than their proven knowledge, experience or other qualities. Only a few staff members are working on the entire project. This environment is better suited for technologies which are pushed (incremental, bottom-up development) rather than pulled (top-down derivation of fixed mission objectives and strict planning). Knowledge transfer becomes more important than the experience and the quality of individual people and project planning should allow for unexpected events.

Another problem caused by the discontinuous human resources is: the duration of 0.5 to 1.5 years for students to work in the project does not match the development lifecycle which is typically 2 to 3 years. In other words, the students can participate in only part of the design lifecycle without a proper overview of the whole project. This is not desirable from educational point of view since the students did not get an opportunity to complete an end-to-end systems engineering. For example, students who worked on Delfi-n3Xt when the project just kicked off usually graduated before the Critical Design Review (CDR). Therefore they did not participate in the product verification and validation. From technical perspective, this is also dangerous. It was observed several times within the Delfi-n3Xt project that the preliminary design made by one student cannot be realized by his/her follower in a later project phase since the preliminary design was made by an inexperienced engineer and was verified only through incomplete simulation rather than prototyping.

The aforementioned lessons learned by TU Delft have led to a new design approach which is different with the traditional phase-based approach. As shown in Figure 10, the new approach is well-suited within the current university environment. Instead of starting each mission from a concept, Delfi-n3Xt acts as a consolidated baseline. A development cycle of a new component will follow the following outline:

- Analyze using real hardware and test equipment the functionality, performance and reliability of existing systems and/or components in order to get acquainted with the baseline.
- Propose a concept for an innovation, extension or addition of components or subsystems of the new satellite. The proposal will be discussed in a review.
- Work out the design (alone or with a small existing team) directly in one flow from preliminary design to the detailed level.
- Test the new component and/or subsystem on compatibility with the existing subsystem and/or satellite baseline. Compare the performance and reliability with the existing baseline if applicable.
- Integrate a successful new component and/or subsystem in the satellite. A new satellite baseline design is created once fully tested and proven to function well.

The duration of the development cycle should be compatible with the human resources involved. If a student plans to work on it for e.g. 8 months, the innovation level should be kept limited in order to be able to complete the full cycle. An example: improvement of the reaction wheel design to limit the amount of generated vibration noise. This noise currently prohibits the use of MicroElectroMechanical System (MEMS) gyroscopes. Once a new noise-limited reaction wheel is consolidated in the new baseline, this opens a possibility for another student or staff member to start a similar development cycle to implement a MEMS gyroscope. The latter is probably relatively simple and can e.g. be done within 4 months.

- While this design approach enhances flexibility and freedom in the design while reducing project risk, there are also some limiting constraints in this new design approach which need to be considered.

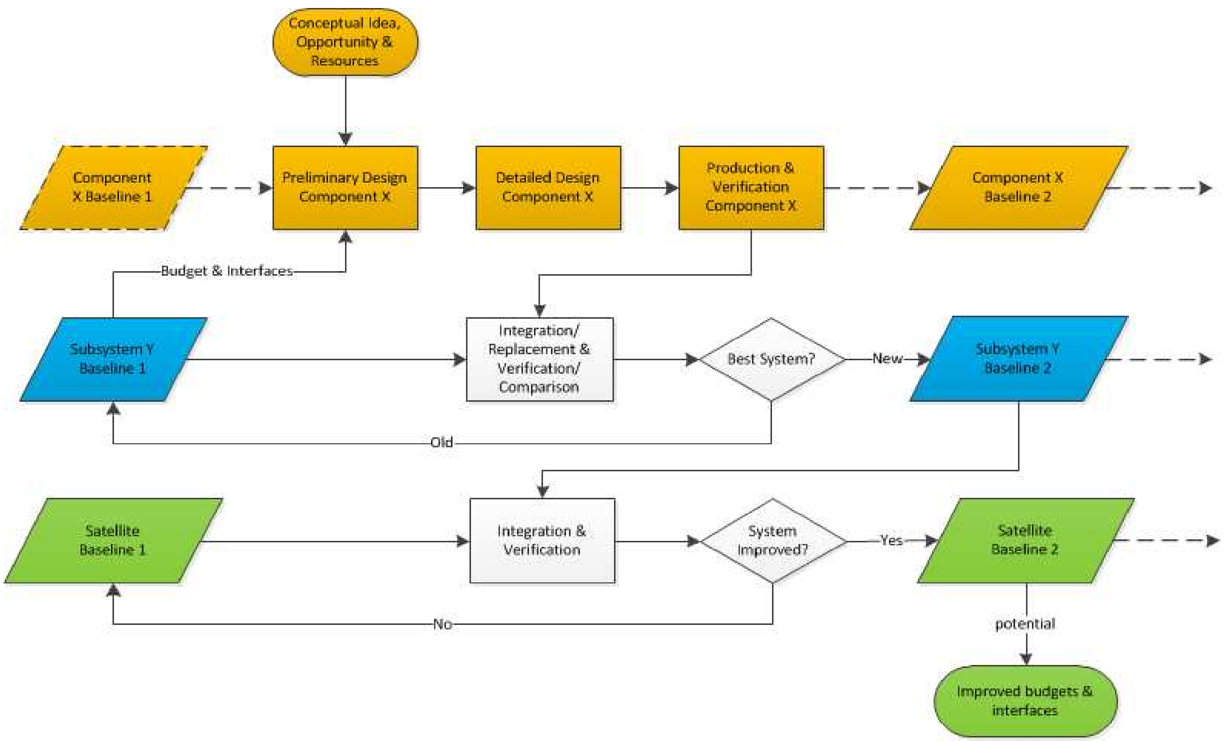

Figure 10: The stepwise baseline approach

- The main interfaces of the satellite should in principle remain fixed as this has impact on the whole satellite and therefore not compatible with a stepwise baseline approach.
- Disruptive innovation is more difficult to achieve as especially student resources are limited in duration of stay. Evolutionary innovation however is not exciting enough for everybody.
- The design approach is conservative with respect to technical budgets. Interdependent system level innovations should be avoided, e.g. an improved radio requiring more power which can be provided by an improved Electrical Power System (EPS). The alternative is to develop innovations in parallel, but only allow increase in the satellite baseline if the right sequence of integration is performed. The risk is that a certain innovation will not be implemented at all in the end.

Design

The lessons learn on the design aspect are closely linked with the reliability. Although university satellite missions are usually at low cost, a certain level of reliability still shall be achieved. Through Delfi-C^3 and Delfi-n3Xt missions, it has been fully recognized that the reliability should be achieved by functional or software redundancy with some hardware redundancy. The usage of rad-hard or high level components shall be avoided due to cost and resource limitations.

An important approach that was utilized by the Delfi satellites to increase the reliability is to guarantee Single-Point Failure Free (SPFF) for critical subsystems, which include e.g. ADCS for de-tumbling mode, Radio Frequency (RF) receiver and EPS (excluding batteries). In some sense SPFF means redundancy is unavoidable. Some developers might state that redundancy in a pico- or nanosatellite is not desired due to size of those satellites, and single-point of failures is a risk which is allowable. It has to be stated however that the overall risk of a satellite increases to the square of the amount of single-point-of-failures.

Note that a malfunctioning subsystem might be able to draw too much current from the power bus or cause malfunctioning or a lock-up of the data bus. In the Delfi-C^3 project, it has been discovered that microcontrollers can have failure modes in which they pull one or both of the I^2C lines down indefinitely. Internal watchdog timers, cleared on I^2C events, did only partially mitigate this problem. Next to this, many microcontrollers short their I^2C ports to the ground when there is no supply power. This means that switching a subsystem off can yield an I^2C lock-up. This is not prevented by the redundancy of the wiring and/or subsystems. Therefore additional protection circuitry is implemented on each node on the Delfi-n3Xt standard system bus, i.e. DSSB, as already detailed before in this paper.

From Delfi-C^3, Delfi-n3Xt as well as other CubeSat projects implemented by other parties, it has been well recognized that a new bus standard shall be established to replace the current I^2C bus. The DSSB is an improvement, but its availability is very limited. Currently there is no any Commercial-Off-The-Shelf (COTS) component with DSSB interface; therefore every component has to be specifically developed for DSSB, which resulted in high development efforts and costs. Some CubeSat teams used CAN as a replacement, but CAN is still heavy for CubeSats. The definition of a new standard is therefore an urgent issue to be discussed by the CubeSat community.

Another lesson learned is about testing, which has significant relevance with reliability. Through the Delfi missions and a research on the in-orbit failures of very small satellites, it has been discovered that although testing under flight representative environmental and operational conditions is expensive, cost should never be the single reason to ignore such tests. In case of Delfi-C^3, too little attention has been paid to end-to-end testing. If the more time and cost were allocated to testing, it might have led to early discovery of the missing AWSS data, the TFSC temperature measurement problem, and better insight in the content of the CDHS problems. However, a positive example is also from the Delfi-C^3 project, which is about the deployable antenna. This innovative antenna was developed by students without enough experiences. Extensive tests have been implemented on the ground as well as on the parabolic flight to verify the design. The successful deployment of all eight antennas onboard Delfi-C^3 and their commercialized version on other satellites shows how much the testing can contribute to the high reliability with relatively low cost.

DELFFI: FORMATION FLYING OF CUBESATS

DelFFi is the third Delfi nanosatellite mission, also the first one that will have distributed space segment, as illustrated in Figure 11. The objective of the DelFFi mission is to demonstrate as part of QB50 the autonomous formation flying between two CubeSats, named Delta and Phi. This will be achieved using innovative concepts, methodologies and technologies to be introduced in this and next sections. The other satellites of QB50 form a network with permanently changing relative positions and velocities. In contrast, DelFFi enables to autonomously control the relative dynamics of Delta and Phi using various guidance, navigation and control technologies, which could enhance the scientific objectives of the QB50 fundamentally[13].

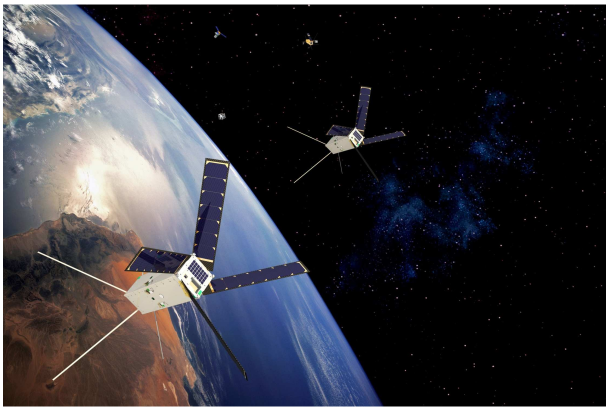

Figure 11: Artist impression of the DelFFi mission

The operations architecture of DelFFi comprises the space segment, the control segment and the ground segment. The space segment is composed of the Delta and Phi satellites which both will have independent telecommand and telemetry capabilities to the ground segment. In addition, for some scenarios an inter-satellite link (ISL) is used based on the AFF payload, described below. The ground segment comprises two ground stations at TU Delft both with UHF/VHF uplink and downlink capabilities. Telecommands to Delta and Phi will be uplinked through these two ground station. Telemetry of Delta and Phi, comprising housekeeping and science data, will be received through the network of ground stations provided by QB50, including the Delft ground stations.

As shown in Figure 12, the concept of operations foresees a separation of the two spacecraft from the orbital deployer, followed by a deployment of the spacecraft antennas and solar arrays. Both spacecraft will then undergo a check-out phase. The natural drift of the spacecraft will allow a precise characterization of the relative positions and their drift and help building-up the targeted separation. Once this separation has been achieved, a drift stop maneuver will be conducted followed by the acquisition phase of the formation and the active control of the two spacecraft in a formation flying mode. Depending on the mission sequence and the needs from science and technology stakeholders, various formation flying configurations and baselines can be demonstrated. A key limitation of QB50, and thus of DelFFi, is the low altitude orbit which constraints the mission lifetime to several weeks. Together with uncertainties and risks associated with all elements of the system and a lack of experience from students involved in operations, this poses a tremendous challenge. To cope with that challenge, the design of the entire system will strive for maximum simplicity wherever possible, intentionally disregarding complex options which may be demonstrated towards the end of the mission, if the schedule allows.

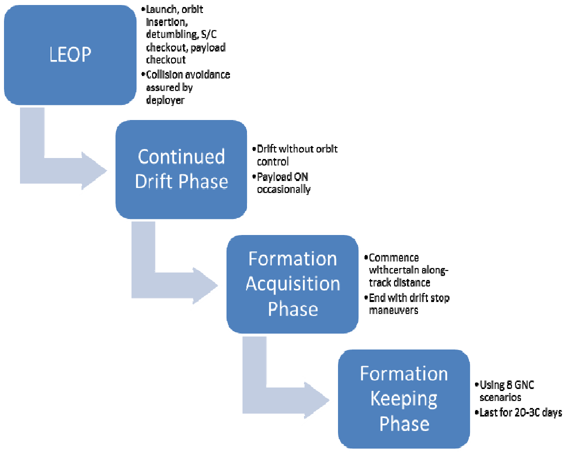

Figure 12: Mission phases of DelFFi

Launch and Early Operation Phase

The Launch and Early Operations Phase (LEOP) consists out of the launch, orbit insertion, detumbling, and checkout of the Delta and Phi spacecraft. According to the QB50 mission, the Delta and Phi spacecraft will be launched together with other 48 Cubesats on a launcher into an orbit of around 350 km altitude. The two spacecraft are not mated during launch. Collision of spacecraft is avoided through the design of the orbital deployer. After the separation, the two spacecraft will perform a series of check-out activities for both the platforms and the payloads.

Continued Drift Phase

During LEOP, the satellites will drift apart (mainly) due to differential aerodynamic drag. Depending on the differential ballistic coefficient and on the duration of LEOP, the along-track separation of the Delta and Phi spacecraft can be several hundreds of kilometers. Since it might be too early to implement the formation acquisition immediately after LEOP, the two spacecraft will keep natural drift for several days. During this period, the QB50 scientific payloads will be switched on regularly to gather scientific data. Therefore, this phase is a scientific observation phase without orbit control, like for all other satellites within the QB50 space segment.

Formation Acquisition Phase

The formation acquisition phase will commence when the two spacecraft achieve a certain along-track distance. This phase is expected to last for a minimum of 10 days. During this period, the relative position and drift will be determined and this phase ends with drift stop maneuvers. The final along-track distance of this phase will be around 1000 km.

Formation Keeping Phase

After the formation acquisition phase, the two spacecraft will have an inter-satellite distance of around 1000 km. Then the formation keeping phase will start. In the formation keeping phase, Delta and Phi will demonstrate the ability to autonomously maintain an along track separation of 1000±10 km for a period of 20-30 days. A suitable control window size in this case would be 100 km which is kept with a control accuracy of 10 km. The relative navigation accuracy required for such a scenario is about 1 km which is easily achievable, e.g. using differential TLE.

During the formation keeping phase, scientific observations will still be performed. This is of interest for scientists since this enables unique collection of thermosphere data from spacecraft with fixed baselines. As the other CubeSats realize continuously changing baselines, the fixed-baseline geometry of DelFFi is expected to provide valuable additional data which enhance the science case of QB50.

TECHNOLOGIES ENABLING FORMATION FLYING

After a comprehensive trade-off between performance, development risk, cost and schedule, it has been decided that the two CubeSats of the DelFFi mission, i.e. Delta and Phi, will be identical satellites and their design will be based on an adapted Delfi-n3Xt platform. Therefore, the two satellites will benefit from the flight heritage of Delfi-n3Xt.

Each of the two satellites is broken down in seven subsystems and two payloads. One of the two payloads is a standard QB50 science payload unit, which will be identical for the two satellites for extra benefit from cross calibration. The other payload is the Autonomous Formation Flying (AFF) payload, or called In-Orbit Demonstration (IOD) payload. Although the satellite platform will be enhanced for the DelFFi mission, the most challenging part is the AFF payload unit, which provides technologies enabling the formation flying.

According to the requirements identified by the mission, the AFF payload unit shall have the functionalities of relative Guidance, Navigation and Control (GNC) without human interactions. Various technologies have been studied on their feasibilities and availabilities. In Phase-A study, four instruments were considered as part of the AFF payload unit, including a relative navigation and communication device (called SPARCS), a cool-gas micropropulsion system ($T^3\mu PS$), a micro-resistojet propulsion system, and a multi-agent based formation flying controller[13]. During Phase-B study, further investigations on the availability of these four instruments were implemented. The following major changes on the AFF payload unit have been proposed:

- The SPARCS will not be available for the DelFFi mission due to severe delay on development; therefore a new relative navigation and communication device, i.e. the GAMALINK, will be used.
- Neither the $T^3\mu PS$ nor the micro-resistojet can provide required orbit control capability on its own; therefore a new design, called $\mu PS+$, combining these two has been proposed and investigated.
- In order to reduce the volume as well as the complexity of the satellite, the formation flying controller function will be implemented on main ADCS controller with the software Formation Flying Package (FFP); however the formation flying algorithms will be put into a separated formation flying package and still treated as part of the AFF payload unit.
- The assessment and the development of the multi-agent based formation flying controller will be continued in parallel with and independent to the development of FFP; the final decision on whether use it will be made before the end of 2013.

In the following subsections the components of the AFF payload unit are described.

GAMALINK

The GAMALINK is an advanced communications platform relying on the flexibility of Software-Defined Radio (SDR)[14]. It empowers the formation of mobile wireless ad hoc networks in space, benefitting from technology that has already been vastly tested to provide connectivity in the most demanding environments on the ground. GAMALINK also delivers accurate position determination based on GPS, which provides absolute position and timing information that may be used to achieve synchronization between satellites.

The GAMALINK device for the space segment includes the ad hoc networking capability for Inter-Satellite Link (ISL), a GPS receiver and, optionally, a radio-based attitude determination algorithm that will not be used by Delta and Phi. It has a Real-Time Clock (RTC) on-board and makes use of spread spectrum techniques. It also includes a set of antennas, which varies depending on the attitude control capability of each CubeSat. Figure 13 shows the space GAMALINK functional block diagram[14], and the technical specifications are presented in Table 5, based on its configuration on Delta and Phi.

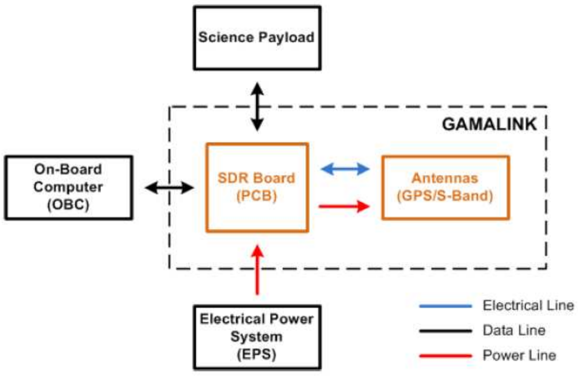

Figure 13: GAMALINK functional block diagram

Table 5: GAMALINK technical specifications

Parameter	Value
Frequency	2.45 GHz (S-band)
Bandwidth	40 MHz
Positioning precision	5 m
PCB size	$80\times80\times10$ mm^3
PCB mass	< 100 g
Number of antennas	4 (3 S-band + 1 GPS)
Antenna size	~ 15×15 mm^2 (S-band) ~ 20×20 mm^2 (GPS)
Data interface	I^2C, UART
Supply voltage	3.3 V
Power consumption	< 1.5 W (transmitting) < 200 mW (S-band receiving) < 50 mW (GPS receiving)

GAMALINK has a power interface with the satellite EPS for power provision. The antennas and any coupled electronics are powered from the SDR. There is a bidirectional data link with the OBC for housekeeping data exchange and also a direct data link to the science payload, which can be used as a backup communication subsystem if necessary.

On Delta and Phi, the GAMALINK will be used to provide ISL as well as absolute GPS positioning information (backup for TLE). The relative positioning information can be obtained by exchanging and differencing absolute GPS positioning information via different communication architectures.

μPS+

The μPS+, i.e. the micro-propulsion system to be used on Delta and Phi, is an enhanced version of the T^3μPS that was used on Delfi-n3Xt. The current version of T^3μPS has a major limitation: its specific impulse is very low (69 s). In order to provide required ΔV (20 m/s) around 88 grams gas shall be generated, which results in a T^3μPS-like system with a volume of 1.5 unit of CubeSat.

To increase the specific impulse and mean while comply with safety regulations, a simple way of improvement is to increase the temperature of the gas. Therefore μPS+ incorporates a micro-resistojet with the solid cool gas system[15]. With a resistojet, the gas temperature is increased just before the nozzle. The gas produced by the CGG at ambient temperature will flow through the valve (also at ambient temperature) and after the valve it will enter the resistojet which increases its temperature. The resistojet propulsion system uses electricity passing through a resistive conductor to increase the gas temperature. The heated gas is expanded through a nozzle to a higher speed than the cold gas. A higher exit velocity means a higher specific impulse. Figure 14 shows a typical resistojet configuration.

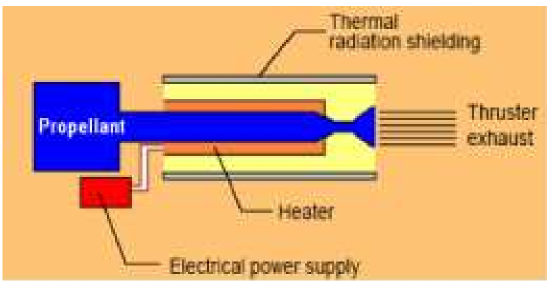

Figure 14: A typical resistojet

A micro resistojet thruster (Figure 15) has been developed by TU Delft, which has an integrated thin-film heater, capable of delivering thrusts in the microNewton-milliNewton range[16]. Its small size

(25mm×5mm×1mm), low mass (162 mg), low power and propellant consumption make it very attractive candidate to be integrated with the solid cool gas system.

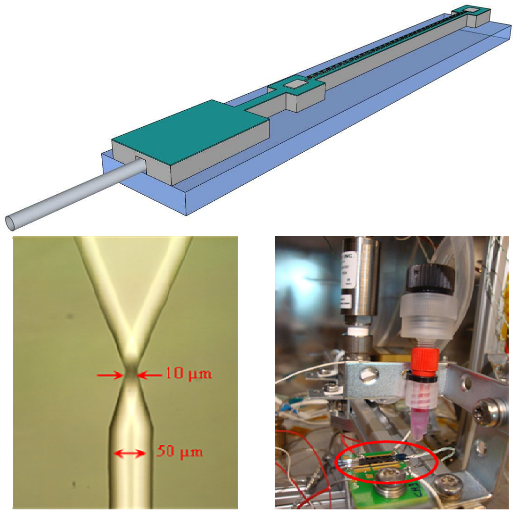

Figure 15: The micro-resistojet of TU Delft

With the integrated micro-resistojet, the design of the µPS+ is shown in Figure 16. There are 16 CGGs, one more than the 15 estimated to reach 20 m/s of ΔV; this choice has been taken to better design the system with 4 rows of CGGs each composed by 4 CGGs. They occupy all the surface of the plenum and they are connected to the electronic through the PCB. The electronic will be all set on this other side of the PCB. The nozzle assembly and the sensor assembly are exactly the same as the previous design and their pins will also be connected to the other side of the PCB; a resistojet will be incorporated before the nozzle (not yet visible in the drawings). The key specifications of the µPS+ are provided in Table 6.

Table 6: Key specifications of µPS+

Section	Parameter	Input
General	Dimensions	90 mm x 90 mm x 80 mm
	Mass	459 g
	Power Consumption	0.063W (idle), 10 W (ignition or heating)
	Data Interface	I^2C, 100 kbit/s
Propellant	Type of Gas	Nitrogen
	Number of CGG	16
	Total mass of propellant	61 g
	Gas temperature	573 K
	Chamber pressure	7.6 bar
Performance	Thrust Level	9.5×10^{-3} N (max)
	Specific Impulse (I_{sp})	100 s (average)

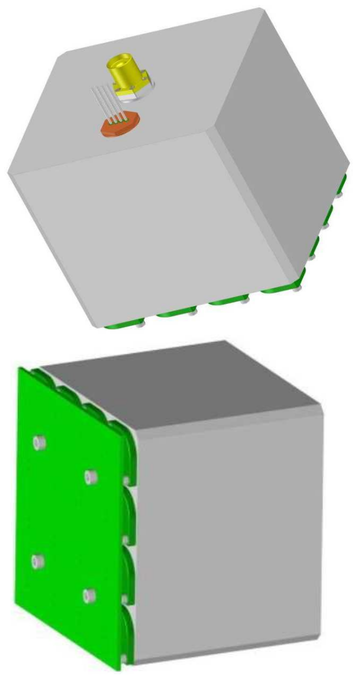

Figure 16: The design of µPS+

Formation Flying Package

The Formation Flying Package (FFP) is a software AFF payload that runs within the ADCS main controller in order to perform autonomous formation flying experiments. A high-level block diagram of the FFP is shown in Figure 17. The same software resides on both Delta and Phi but may be implemented differently according to different GNC scenarios.

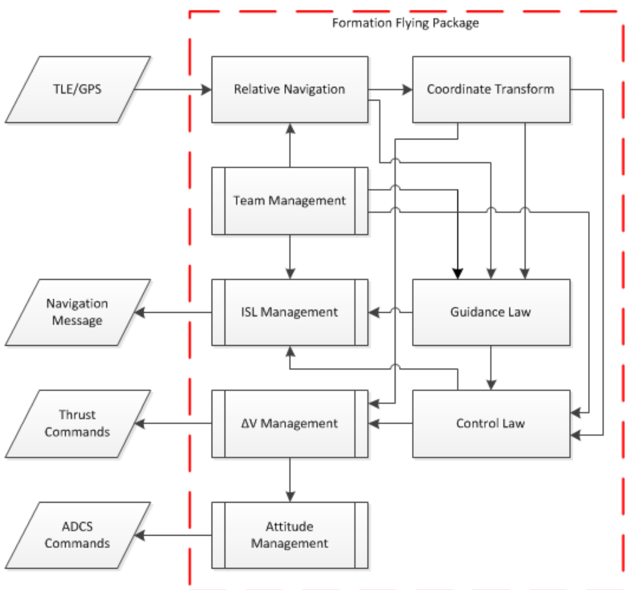

Figure 17: Block diagram of Formation Flying Package (FFP)

The FFP consists of 8 software modules, which are implemented as separate, single-threaded tasks that communicate with one another through an efficient messaging system. This can facilitate a more direct transition from MATLAB to C++. The arrows connecting the modules indicate the flow of messages within the system. The primary functions of each module are summarized below.

- Relative Navigation: Interfaces with OBC to get TLE or GPS data of the spacecraft itself and the other spacecraft; Estimates the formation state.
- Coordinate Transformation: Transforms the state estimate from the Relative Navigation module into appropriate coordinate frames as required by the formation flying algorithms.
- Team Management: Receives commands from the ground station and forwards them to the appropriate module(s); Provides autonomous team formation and autonomous reference rollover capabilities.
- Guidance Law: Determines the desired relative trajectory of the spacecraft based upon the desired geometry of the team.
- Control Law: Plans impulsive maneuvers to achieve the desired relative trajectory.
- ISL Management: Interfaces with the ISL to enables navigation messages to be sent to and received from the other spacecraft.
- ΔV Management: Interfaces with the micro-propulsion system (part of AFF payload) on the spacecraft. Receives ΔV commands from the Control Law module. Sends commands to fire thruster at the appropriate times to achieve the desired ΔV.
- Attitude Management: Interfaces with the ADCS of the spacecraft. Computes the required attitude that the spacecraft must have for each thruster firing.

According to [13], the Delta and Phi allow various GNC architectures for autonomous formation flying; therefore the functions of some modules in Figure 17 may be replaced by on-ground software.

Multi-Agent Based Formation Flying Controller

Delta and Phi will both host a multi-agent based formation flying controller. Different with any other formation flying controller, this controller is developed based on the smartphone technology.

The smartphone is now the most widely used telecommunication product in the market. A typical smartphone has a mass of less than 200 grams, costs 200-400 Euros, and has the standby time around 400 hours. It runs on the ARM architecture processor with a mobile operating system such as Android or Windows Mobile, which makes the smartphone powerful and capable of complex tasks[17]. For example, a high-end smartphone typically combines the functions of high-speed data access via Wi-Fi, mobile broadband, portable media players, compact digital cameras, and GPS navigation units. More important, the speed of technologies emerging allows the releases of more powerful smartphones in a monthly basis or even shorter.

On the other side, the utilization of innovative technologies in space community is relatively slow, and cannot share the ever-changing progress of terrestrial technologies. This is mainly due to the reliability considerations in space environment. In order to promote the spin-in of terrestrial technologies and reduce the complexity and costs of space systems, recently several projects have been kicked-off to test smartphones onboard CubeSats[18,19].

The DelFFi mission will further extend the utilization of smartphone technology to distributed space systems, with a focus on the onboard autonomy of formation flying. The controller that is under development in TU Delft is based on an ARM-9 processor, with Android 2.3 operation system. The reason of choosing this processor is on its expected flight onboard Delfi-n3Xt. The onboard autonomous formation flying functionality is achieved by means of multi-agent system (MAS) technology[20]. The uniqueness of this architecture is that it is implemented on an ARM processor with the Android system. In order to realize MAS on Android, the open-source MAS development environment JADE (Java Agent Development Framework) is utilized[21]. Preliminary experiments of implementing this onboard autonomy architecture are ongoing at TU Delft. The hardware-in-loop test on a formation flying testbed is ongoing.

The architecture of ADSS is based on MAS and smartphone technology. An ARM processor is selected as the onboard computer; Android is chosen as the onboard OS; the spacecraft is modelled as an agent and the MAS run-time is incorporated into the data handing service layer; and applications in the application layer are implemented as behaviours of the spacecraft agent. It should be pointed out that the MAS architecture is intrinsically peer to peer, as any agent is able to sponsor communication with any other agent or be the receiver of an incoming communication at any time. It should be also mentioned that not only the spacecraft but also applications in the application layer can be modelled as agents. Figure 18 presents top level building blocks of software onboard each spacecraft agent. Figure 19 shows an autonomous distributed space system composed by multiple (for the DelFFi case it is 2) spacecraft agents. In the ADSS, the abstract high-level goals are decomposed autonomously into sequences of cooperative tasks by following certain rules, which is performed by the mission planner. And then there is a distributed allocator algorithm to allocate those cooperative tasks to each spacecraft agent by virtue of sharing knowledge. In the end the local controller onboard each agent makes the spacecraft to achieve the allocated tasks cooperatively. The mission planner, allocator and local controller belong to the high-level layer, the middleware and the layer underneath of a distributed system, respectively.

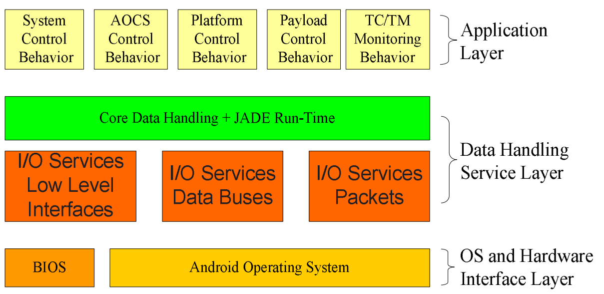

Figure 18: Top level building blocks of software onboard spacecraft agent

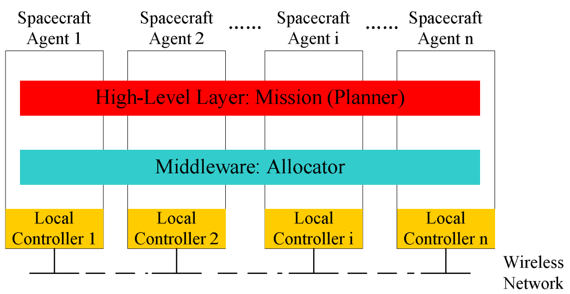

Figure 19: An autonomous distributed space system

CONCLUSIONS

This paper provides an update of the Delfi nanosatellite programme of the Delft University of Technology (TU Delft). The two completed missions, i.e. Delfi-C3 and Delfi-n3Xt, are briefly reviewed with their up-to-date results. The lessons learned from these two missions are presented, focusing on three aspects: people, process, and design. An innovative development strategy for university satellite projects and a systematic approach for improving reliability are introduced. These lessons are applied into the ongoing DelFFi mission, where two CubeSats will perform formation flying. An update of the status of the DelFFi project is provided, and the enabling technologies for formation flying are described.

Acknowledgments

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