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SYSTEM DESIGN FOR ATTITUDE AND ORBIT CONTROL SYSTEM FOR DELFFI FORMATION FLYING MISSION

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1 Abstract

AOCS; ADCS; Requirements; Hardware System Design; Software System Design

This thesis designs system architecture for DelFFi nanosatellite. The objective of the DelFFi mission is to demonstrate autonomous formation flying between two identical CubeSats, named Delta and Phi. The thesis updates existing requirements and develops a final set of requirements for the DelFFi mission. Secondly, the thesis considers hardware problems with the Delfi-n3Xt mission and analyzes formation flying mission hardware architectures. Furthermore, it proposes new hardware architecture for DelFFi mission. Finally, the thesis analyzes software requirements and develops new software architecture for DelFFi attitude and orbit control system.

Abstrakt

Süsteemi disain; Asendi määramis ja kontrollimis süsteem; nõuded; Tarkvara arhidektuur; Riistvara arhidektuur

Antud lõputöö käigus uuriti ja täiustati satelliidi asendi määramise ja kontrollimise nõudeid. Esialgsed nõuded baseerusid Delfi-n3Xt nõuetel, mille missioon erines DelFFi satelliidi omast. ESTCub-1, GRACEt'i ja PRISMi formatsioonilendude ning nanosatelliitide missioonide nõuete analüüsi alusel arendati lõplikud DelFFi asendi määramis- ja kontrollimissüsteemi nõuded. Teine etapp algas Delfi-n3Xti satelliidi riistavara sobivusuuringuga DelFFi missiooni jaoks. Pärast analüüse selgus, et olemasolev riistvara ei ole sobiv formatsioonilennu testmissiooniks. Töö käigus disainiti uue riistvara arhitektuur ja valiti uus protsessor. Viimase ülesandena analüüsiti süsteemi tarkvara nõudeid ja olekuid, arendati uue tarkvara arhitektuuri ning valiti sobiv operatsioonisüsteem.

Sisukord

List of Acronyms

ADCS Attitude Determination and Control System

AOCS Attitude and Orbit Control System

TLE Two-Line Element

FPU Floating Point Unit

FF Formation Flying

AEKF Adaptive Extended Kalman Filter

PLKF Pseudo Linear Kalman Filter

LEO Low Earth Orbit

MEO Medium Earth Orbit

GEO Geostationary Earth Orbit

SSO Sun-synchronous Orbit

COTS Commercial off-the-shelf

ISL Inter-Satellite Link

MWA Microwave Assembly

FRAM Ferroelectric RAM

ISS International Space Station

GNC Guidance, Navigation and Control

IP Image Processing

CDH Command and Data Handling

GRACE Gravity Recovery And Climate Experiment

DEM Digital Elevation Model

RMS Root Mean Square

ATI Along-Track Interferometry

GPS Global Positioning System

ESA European Space Agency

PECS Plan for European Cooperating States

UKF Unscented Kalman Filter

KF Kalman Fileter

OBC On-Board Computer

CDHS Command and Data Handling System

MEMS Microelectromechanical Systems

IMU Inertial Measurement Unit

EPS Electrical Power System

COM Communication System

SAR Synthetic Aperture Radar

HAL Hardware Abstraction Layer

FFC Formation Flight Controller

BGA Ball Greed Array

SMT Surface-Mount Technology

SEE Single Event Effect

2 Introduction

Technology miniaturization and wide usage of nanosatellites in the last decade has enabled nanosatellite to evolve to a new level, where they can be used for scientific experiments and commercial applications. [1] Although technology miniaturization has increased the overall performance of nanosatellites, size and mass constraints often limit the satellite and its payload capabilities. Nanosatellite constellations address the problem by fusing data from multiple small satellites to increase accuracy, or by dividing workload between small satellites. In addition, constellations of small satellites would revolutionize those research areas which benefit from global coverage, frequent revisits and closely spaced measurement points. Work distribution between multiple satellites requires active and accurate control over all of the satellites, thus one requires accurate orbit and attitude determination and control to effectively fuse data from multiple satellites.

This thesis designs system architecture for DelFFi nanosatellite. The objective of the DelFFi mission is to demonstrate autonomous formation flying between two identical CubeSats, named Delta and Phi. The main focus of this thesis is design AOCS system architecture for the DelFFi mission. DelFFi AOCS system design will be analyzed in following sections:

- Requirements
- Hardware design
- Software design

Furthermore, this work uses real life experiences gained via the design process and lessons learned from the flight experience of Crystalspace ESTCube-1, and other relevant small or nanosatellite ADCS/AOCS.

Firstly, the thesis focuses on updating and developing final set of requirements for DelFFi mission. The preliminary requirements contained multiple inconsistencies and were unsuitable for this mission.

Secondly, the thesis analyzes hardware problems with Delfi-n3Xt mission. Analyzes Formation Flying (FF) mission hardware architectures, and proposes new hardware architecture for DelFFi mission.

Finally, the thesis analyzes software requirements and develops new software architecture for DelFFi AOCS system.

2.1 Overview of ESTCube-1 Mission

ESTCube-1 is a student satellite project lead by the University of Tartu, Estonia, and supported by the European Space Agency (ESA) via Plan for European Cooperating States (PECS). Development of ESTCube-1 has been a collaborative effort with many international partners. The main scientific mission of the satellite was to perform the first in-orbit electric solar wind sail experiment. ESTCube-1 consists of the following subsystems:

- Electrical Power System (EPS)
- Communication System (COM)
- Command and Data Handling System (CDHS)
- ADCS
- Camera system
- E-sail experiment payload

All subsystems and payloads were custom built mostly using Commercial off-the-shelf (COTS) components. [2]

To fulfil the mission requirements, an integrated ADCS was developed and tested. The system can be divided into two subsystems. First, the attitude determination system, which has three-axis Honeywell HMC5883L magnetometers; three-axis Invensense ITG- 3200 gyroscopic sensors; and two-axis Sun sensors based on two one-dimensional Hamamatsu S3931 position sensitive detectors, a Sun sensor for each side of the satellite. Attitude estimation is performed using an Unscented Kalman Filter (UKF). Second, the attitude control system, which has three electromagnetic coils. [3]

2.2 Overview of DelFFi Mission

DelFFi is the third TU Delft nanosatellite mission, also the first one that will have distributed space segment. The objective of the DelFFi mission is to demonstrate as part of QB50 the autonomous formation flying (AFF) between two identical 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. [4]

NB! DelFFi mission was paused in the end of the 2015. Due to communication issues, frequent requirement changes with QB50 program. Writing of this thesis started during my internship in Delft University Aerospace faculty. Quarter of my thesis is written after project halt. Due to that fact, verification and testing of some theories is unfinished.

2.3 Delfi-n3Xt

Delfi-n3Xt is a nanosatellite of triple-unit CubeSat dimensions (10 x 10 x 34 cm^3) which was launched in November of 2013. Delfi-n3Xt is developed as educational, research and development satellite. The main technical objectives are to demonstrate a micropropulsion system developed by TNO, an innovative radio developed by ISIS BV and a highly capable system bus platform developed by TU Delft. The active ADCS is a major advancement over its predecessor Delfi-C3, which was equipped with a passive magnetic attitude stabilization system. [5]

2.4 Formation Flying Missions Overview

Most note worthy formation flying missions are brought out in this section. It should be noted that in FF missions, the dynamic states of the satellites are coupled through a common control law, i.e. , at least one satellite must track a desired state relative to another satellite and the tracking control law must at the minimum depend upon the states of this other satellite. For example, even though specific relative positions are actively maintained, the Global Positioning System (GPS) satellites and thee a constellation since their orbit corrections only require an individual satellite's position and velocity (state). [6]

The three 1U CubeSats of the **AeroCube-4** series built by The Aerospace Corporation were launched aboard an Atlas V launch vehicle from Vandenberg Air Force Base on 13 September 2012. These satellites were each equipped with an on-board GPS receiver that provided position measurements with a precision of 20 meters and enabled the generation of ephemerides with meter-level accuracy. Each AeroCube was also equipped with two extendable wings that altered the satellite's cross-sectional area by a factor of three. In conjunction with the GPS measurements, high-precision orbit determination detected deliberate changes in the AeroCube's drag profile via wing manipulation. [7]

Launched on 30 June 2014 from Sriharikota, India on board the Polar Satellite Launch Vehicle, **CanX-4 and CanX-5** were deployed separately following launch, after which a series of drift recovery maneuverer were executed to bring the spacecrafts within communications range of each other. Subsequently, the spacecrafts used onboard propulsion, an S-band Inter-Satellite Link (ISL), and relative navigation, using carrier-phase differential GPS techniques to perform a series of precise, controlled, autonomous formations from 1 km range down to 50 m separation. [8]

The **CubeSat Proximity Operations Demonstration (CPOD)** mission led by Tyvak Nano-Satellite Systems leverages several formation flying techniques to enable rendezvous, proximity operations, and docking with two identical 3U CubeSats. Inertial reference module includes both ADCS and Command and Data Handling (CDH) functionality. It houses three reaction wheels, two star cameras, Microelectromechanical Systems (MEMS) Inertial Measurement Unit (IMU) (3-axis gyroscope and 3-axis accelerometer), three torque coils, and both the ADCS and CDH processors. The propulsion system includes a liquid fuel tank, gas plenum, control/management circuitry, and 8 nozzles to support full 3-axis translational control. The rendezvous & proximity operations, docking module includes two visible and two infrared cameras, the ISL patch antenna, docking electro-magnet, fiducial LEDs, docking mechanism, and the Guidance, Navigation and Control (GNC) and Image Processing (IP) processors. Satellites should be lauched in 2017 with Minotaur-C-3210 [9]. [10]

GRACE was the first formation-flying occurring at an altitude below 500 km. The twin spacecrafts were successfully launched on March 17th 2002 by a Russian Rockot launcher. The main scientific goal of the mission was to collect data for creating both static and time-varying Earth gravity field models of unprecedented accuracy. This was done by measuring relative variations in satellites separation down to 1 μm/sec, using a microwave link between the two spacecrafts that are flying on a polar orbit at an altitude of about 500 km and that are kept at a distance of 170 - 270 km. [7]

The TerraSAR-X mission provides high-resolution Synthetic Aperture Radar (SAR) data to both science and commercial users. The TerraSAR-X satellite was launched on 15 June 2007 and has been operated in a 505 km high, sun-synchronous, 11-day repeat orbit. On 21 June 2010 an almost identical satellite, TanDEM-X, was launched in order to form the first configurable SAR interferometer employing formation flying with TerraSAR-X. The main objective of the common TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) mission is to generate a global Digital Elevation Model (DEM) with unprecedented accuracy as the basis for a wide range of scientific research as well as for commercial applications. In contrast to the coarse 200 m along-track accuracy required for routine across-track interferometric DEM acquisition, the along-track separation desired for Along-Track Interferometry (ATI) oceanography is only 50 m $\pm$ 710 m. This is quite challenging for ground control with typically 30 m Root Mean Square (RMS) along- track control accuracy and a maximum control deviation of 100 m. Satellites use thrusters and GPS for formation flying. S-band is used for ISL. [11]

3 Attitude and Orbit Control System Requirements

In this thesis analysis of AOCS requirements is divided into three groups:

- Environmental requirements
- Determination and control requirements
- Mission and satellite configuration related requirements

Section analyzes the preliminary DelFFi requirements, compares them with relevant mission requirements and where necessary, updates for the requirements are proposed.

3.1 Environmental Requirements

Environmental requirements are stated such that spacecraft shall withstand harsh environments during launch and estimated operation time. Underestimation of environmental requirements may lead to mission failures and overestimation unnecessarily increases system complexity and price. Environmental requirements are influenced by following factors:

- Launcher characteristics (solid-fuel rockets have harsher vibration conditions than liquid-propellant rockets). Nanosatellites should be designed to withstand all of the most used launchers vibration characteristics. Previous decision guarantees the highest number of possible launch opportunities
- Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Earth Orbit (GEO), Moon etc. Orbit decision influences the satellite temperature and radiation environment and ground access time. Due to the fact that most of the nanosatellites use LEO, their orbit related requirements are similar. Only difference is in satellite temperature characteristics and available power on Sun-synchronous Orbit (SSO)
- Mission length determines total radiation dose. Most of the nanosatellite missions are planned with mission length under 3 years. Thus radiation dosages are similarly low and primarily COTS components can be used

The preliminary environmental requirements of DelFFi are described in Table 1 and ESTCube-1 in Table 2.

Tabel 1: DelFFi environmental requirements [12]

Type	Requirement
Constraint	All satellite systems shall be able to withstand the launch environment
Constraint	All satellite systems shall be able to withstand the space environment
Constraint	All satellite systems shall comply with the thermal budget and to vacuum conditions without significant outgassing or structural degradation
Constraint	The satellite shall not use any material that has the potential to degrade in an ambient environment during storage after assembly, which could be as long as approximately 2 years
Constraint	The satellite shall withstand a total contamination of $3.1\ \mathrm{mg/m^2}$ at all phases of the launch vehicle ground operation and in flight
Constraint	The satellite shall withstand a maximum pressure drop rate of 3.92 kPa/s
Functional	CubeSat shall pass the acceleration (quasi-static) test
Functional	The CubeSat shall pass a resonance survey test. The lowest natural frequency of the FM of the CubeSat shall be $>$ 90 Hz
Functional	The CubeSat shall pass the sinusoidal vibration tests
Functional	The CubeSat shall pass the random vibration tests
Functional	The CubeSat shall pass the shock tests
Functional	The CubeSat shall pass the Thermal Cycling tests
Functional	The CubeSat shall pass the Thermal Vacuum tests
Functional	The CubeSat shall pass the EMC / ESD tests

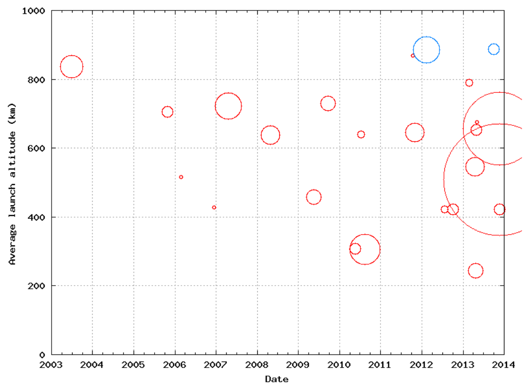
Tabel 2: ESTCube-1 environmental requirements [13]

Type	Requirement
Constraint	System shall withstand operating temperature range $-20 \ldots 60\ ^\circ$ C
Constraint	System shall withstand Vega launcher characteristics
Constraint	Mission lifetime 1 year
Constraint	System shall pass vibration, temperature & vacuum testing
Constraint	System shall be designed to minimize the probability of destructive SEE

Tabel 3: Comparison of ESTCube-1 & DelFFi environmental requirements

Requirement	ESTCube-1	DelFFi
Launcher	ESTCube-1 used Vega VV02 rocket (solid-fuel rocket) [14]. Decision was made 9 moths before the launch date	DelFFi satellites (part of QB50 project) rocket type was unknown in the beginning of the project. Latest news of QB50 suggest that satellites will be deployed from ISS [15]
Orbit	ESTCube-1 was deployed into SSO with an altitude of 665 km and the inclination of 98° . orbit was not known until 9 moths before launch (**LEO**)	Initial plan of QB50 was to study the variations of a number of key constituents and parameters in the lower thermosphere (90-320 km). Satellites would have been launched to near circular orbit at altitude of 320 [16]. Final information suggest that now satellites will be launched to 3 different orbits SSO 475 km, SSO 550 km and 415 km ISS orbit (**LEO**)
Mission Length	Planned mission length for ESTCube-1 was 1 year. [13] Actual operation time was approximately 2 years	Preliminary planned mission length was approximately 3 months due to satellite rapid orbital decay at altitude of 300km . [16] After multiple launch changes possible lifetime of the satellite has increased up to 1 or 2 years.

On Figures 1 & 2 common choices for satellite orbits and inclinations are described. Circle size shows the number of satellites launched to this specific orbit. Except few special mission, all of the CubeSats are launched to orbit under 900 km where satellites are protected by Earth magnetic field, which on lower orbits lowers yearly radiation dosage significantly. On average, mission actual length is a little bit over 10 months. Planned mission length is usually between 6-12 months, however in reality, successful missions tend be prolonged into many years. [17]



Joonis 1: CubeSats launch attitudes [17]

Joonis 2: CubeSat launch inclinations [17]

Requirements of ESTCube-1 and DelFFi are compared in Table 3. From gathered information following conclusions can be made:

1. CubeSats orbit altitude is in average unknown during the development phase. Even if orbit altitude is known, there is high chance for orbit change. In general one rule exists, almost all CubeSats are launched to orbit under 900 km where satellites are protected by Earth magnetic field
2. Orbit inclination is often changed and continues to changes during mission time due to perturbations. Thus AOCS should be designed operate in any inclination specific orbital conditions, such as SSO temperature conditions
3. Launcher type (solid-fuel, liquid-fuel) is not known until the late phase of nanosatellite development. AOCS should be designed to withstand all common rockets launch environment
4. There is no significant difference in environmental requirements between AOCS with or without formation flying capabilities
5. Postponing the launch and mission delays are common in satellite business. For example QB50 and Alto-1

Finally, updated DelFFi requirements can be generated from conclusions, ESTCube-1 and Delfi-n3Xt requirement. DelFFi final environmental requirements are in Tale 4.

Tabel 4: Updated DelFFi environmental requirements

Type	Requirement
Constraint	Satellite must withstand launch characteristics of most common launchers
Constraint	Satellite must survive space environment at orbit under 900 km at least 1 year. This allows system repairs in the beginning of the mission
Constraint	Systems shall comply with the thermal budget and to vacuum conditions without significant outgassing or structural degradation
Constraint	System design shall allow storage of satellite for 2 years without degradation. Exceptions are are batteries and similar components etc
Constraint	The satellite shall withstand a total contamination of 3.1 mg/m^2 at all phases of the launch vehicle ground operation and in flight
Constraint	The CubeSat shall withstand most common orbit inclinations thermal environment, including sun synchronous

3.2 Determination & Control Requirements (Functional Requirements)

Determination & Control requirements main purpose is to define system sensor measurements and actuators control accuracies for successful mission. Those characteristics are mostly defined by satellite mission, payload and camera system. ESTCube-1 attitude determination & control requirements (Table 5) can be used as baseline for DelFFi updated requirements (Table 6).

Tabel 5: ESTCube-1 attitude determination & control requirements [13] [18]

Type	Requirement
Functional	Satellite supports following mission modes: • Detumbling mode • Pointing mode for camera • Spin-up for tether deployment • Safe mode
Functional	Determine the rotation of spacecraft and measure change in angular speed caused by E-sail effect $\approx$ 0.4 deg/s (initial plan 0.1° /s)
Functional	**Reach angular velocity of 360 degrees around z-axes with pointing accuracy of 1° [18]. Unique satellite mission related requirement, part of the electric solar wind sail experiment**
Functional	**Pointing accuracy of 5 deg for taking pictures of the Earth**
Functional	Orbit determination at TLE accuracy. Required for communication, experiment timing and coil usage

Updated determination & control requirements for DelFFi mission are defined in Table 6.

Tabel 6: Updated DelFFi Attitude and Orbit control requirements

Type	Requirement
Attitude Determination and Control	The ADCS shall be equipped with coarse attitude sensors for coarse onboard attitude determination around three spacecraft body axis

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Type	**Requirement**
Attitude Determination and Control	The CubeSat shall be able to detumble from speeds up to 50 ° /s
Attitude Determination and Control	The ADCS shall be able to determine attitude information with no worse than 2° accuracy and control attitude with a minimum pointing accuracy of 5° . Main driver is ISL & orbital maneuvers
Attitude Determination and Control	The ADCS shall provide a pointing stability better than 0.5 ° /s. Required during thrusting
Orbit determination & control	Satellite separation determination accuracy of 1 km [4]
Orbit determination & control	Satellite separation control accuracy of 10 km [4]
Orbit determination & control	Formation along/track separation is 1000 km with control window size of 100 km [4]
Sensors & Actuators	Sensors & Actuators shall support 3 axis attitude control
Sensors	Sensors shall be mechanically isolated from reaction wheels noise
Sensors	Sensors shall be duplicated for system robustness and data analysis
Sensors	Accelerometer shall be able to measure thrust Δ V
Actuators	Magnetorqures shall be able to desaturate reaction wheels & control satellite attitude
Actuators	Reaction wheels are required for attitude stability during thrusting
Reaction Wheel System	The Reaction Wheel System shall be able to control the angular momentum about each individual axis with a minimum accuracy of 2.0×10^{-7} N × m × s [12]
Reaction Wheel System	The Reaction Wheel System shall be able to determine the angular momentum about each individual axis with a minimum accuracy of 2.0×10^{-8} N × m × s [12]
Actuators	Thrusters will be able to provide 40 m/s ΔV for formation accusation and holding formation. It is increased 2x since initial planning due to increased mission length [12]

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Type	**Requirement**
Mode	Satellite supports following mission modes: • Detumbling mode • Pointing mode for ISL and mission • Orbit change/ Thrust vector control mode • Safe mode (Used only in cases of system failure)

3.3 External Interface Requirements

Final object with this section was to determine AOCS external interfaces and weather other subsystems influence AOCS. Requirements are in Table 7.

Tabel 7: External interface requirements

Source	**Requirement**
Budget	AOCS mass shall be lower than 350g (including reaction wheels and coils)
Budget	AOCS average power consumption shall be under 300 mW
Budget	AOCS shall fit into CubeSat form factor
Interface	AOCS will communicate with reaction wheels, OBC and thrusters over I2C. This is heritage of Delfi-n3Xt. Thrusters are controlled through OBC

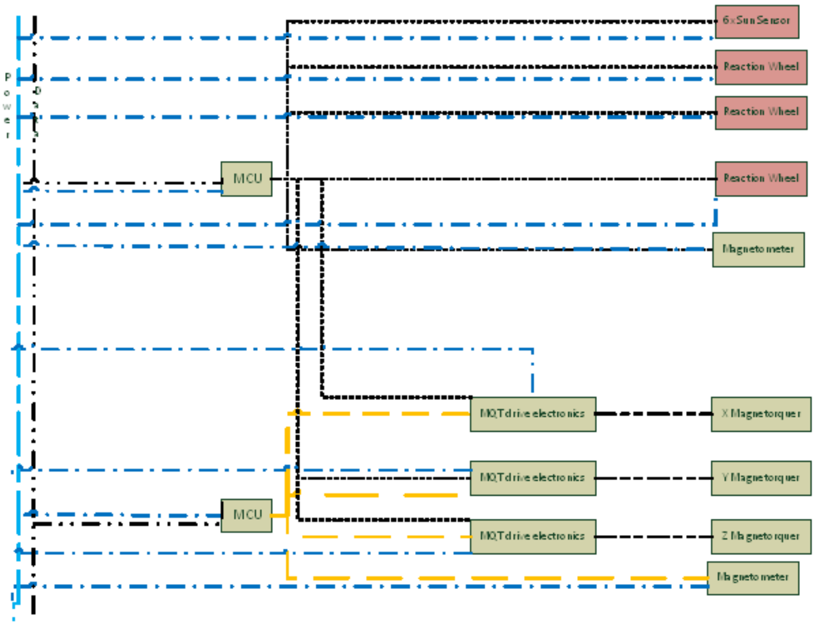
4 System Design of DelFFi Hardware

Second goal of the thesis was to create hardware system design for DelFFi mission. Work was divided into 3 phases:

- Analyze Delfi-n3Xt hardware design and the mistakes that were made
- Research other missions hardware system design
- Develop suitable hardware design for DelFFi mission

4.1 Analyze Delfi-n3Xt Hardware Design

Analyzing Delfi-n3Xt hardware design was the first step towards DelFFi hardware design. The initial plan was to use Delfi-n3Xt ADCS with minor updates in DelFFi mission. Due to problems with Delfi-n3Xt mission and unsuitability for DelFFi mission, new hardware architecture was designed. Delfi-n3Xt hardware problematic areas are described in Table 8.



Joonis 3: Delfi-n3Xt hardware layout [19]

Delfi-n3Xt was equipped with an active ADCS, which was a major advancement over Delfi-C3 that used passive magnetic control. The ADCS supports several modes: detumble, coarse and fine Sun pointing, thruster alignment and ground station tracking. It comprises custom developed sun sensors, magnetorquers and reaction wheels as well as commercial magnetometers. The main ADCS uses a 400 MHz ARM9 based module for all operational modes. An XMega controller was used for backup and can only perform detumbling with a redundant magnetometer. The main objectives of the ADCS where to demonstrate and characterize all sensors and actuators as well as the different operational modes. [4] Delfi-n3Xt hardware architecture is on Figure 3.

Tabel 8: Delfi-n3Xt Hardware Problems

Name	Problem	Comments & Analysis
1	ARM9 AT91SAM9G45B high power consumption (1W)	Due to overestimating calculation requirements, a too powerful processor was chosen. Due to complex processor installation process, module with unnecessary extra RAM was used (ICnova SAM9G45 SODIMM). This limited the usage time of ADCS.
2	Processor comes only with BGA package	BGA is important technology to provide higher pin counts, but in the same time it comes with multiple drawbacks for space applications. BGA solder joints cannot be inspected and reworked using conventional methods and are not well characterized for multiple double side assembly process methods. In ultra low and low volume SMT assembly applications, e.g. space and defense, the ability to inspect the solder joints visually has been standard and has been a key factor for providing confidence in solder joint reliability. [20] Furthermore, BGA packages do not perform well with thermal cycles. Solder joints get severely deformed and connections broken. [21]

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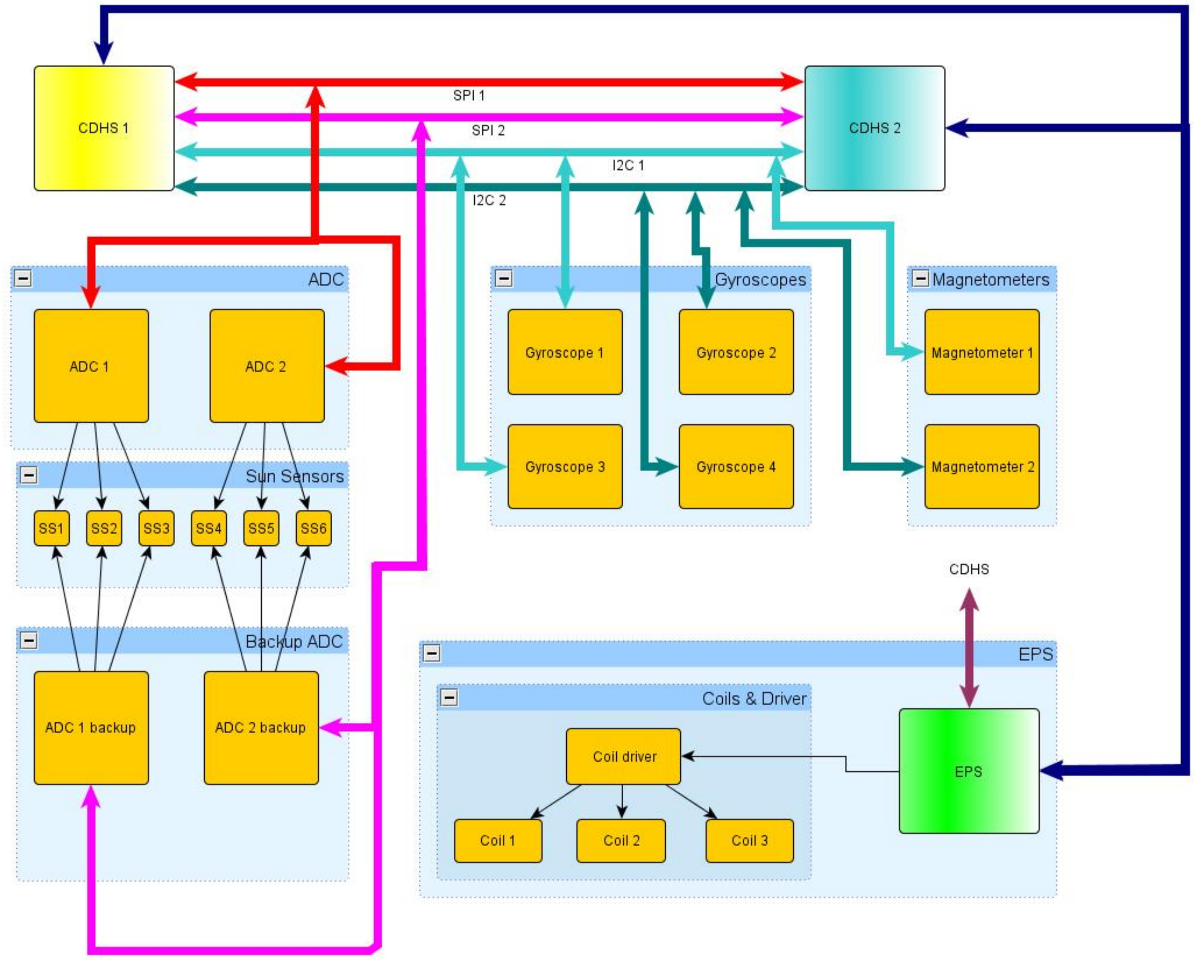
Name	**Problem**	**Comments & Analysis**
3	Two different processor architectures were used (ARM9 AT91SAM9G45B & XMega)	On Delfi-n3Xt the idea was to use two processors, one for low accuracy (detumble) and other for high accuracy movements. In real life they both failed due to increase hardware and software complexity.
4	I2C communication problems	I2C bus lockups have occurred in-orbit, as was already anticipated during on ground measurements. The protection circuit has successfully determined this event 6 times during periods in which data was gathered. It is estimated that I2C lockups occurs about 5 times a day. Due to single events and external noise on the I2C bus, a slave or master device may misinterpret the intended communication. For time critical communication in the future, it is advised to implement an inherently more reliable bus (e.g. CAN) or to have a dedicated I2C line between the onboard computer and the specific subsystems such that it becomes feasible to fully debug that specific data link. [4] Furthermore, usage of one vendor processors on OBC AOCS would reduce vendor to vendor I2C mismatch errors.
5	Sensor noise issues	Only 2 magnetometer and 6 sun sensors where used in the design. [5] Magnetometers where attached to different processors and system had limited noise reduction capabilities.

4.2 Overview of Satellites ADCS & AOCS Hardware System Design

4.2.1 ESTCube-1

ESTCube-1 ADCS architecture is described in Figure 4. ESTCube-1 uses two CDHS processors and redundant buses, to increase system radiation and error tolerance. All sensor are at least duplicated for data filtering and reducing single point failure locations.



Joonis 4: ESTCube-1 hardware layout [18]

ESTCube-1 uses common set of active ADCS sensors and actuators. Following set is used: [18]:

- Magnetometers - The expanded uncertainty for an angle of the magnetic field direction measured by the magnetometer is 3.2° . The value is estimated by taking into account such major contributors as the temperature (1.4°), the statistical error (0.8°) and the precision of the test set- up (0.3°). [3]

- Sun Sensors - The expanded uncertainty for an angle of incident light measured by the Sun sensor is 2.5° . The value is estimated by taking into account such major contributors as the Earth's albedo influence (1°), the temperature drift (0.76°) and the solar irradiance uncertainty (0.25°). [3]
- Gyroscopic sensors - The expanded uncertainty for an angular velocity measured by the gyroscopic sensor is 3.6° /s. The value is estimated by taking into account such major contributors as the temperature (1.5° /s), the statistical error (0.9° /s) and the vacuum (0.2° /s). [3] Gyroscopic sensor selection was one of the mistake of ESTCube-1 mission and thus can be easily replaced with more accurate sensor.
- Three orthogonal coils - Two coils with magnetic moment of 0.094 Am^2 and one with 0.091 Am^2. [3]

4.2.2 ESEO

European Space Agency European Student Earth Orbiter mission uses following set of sensors and actuators:

- 2 MWs in cold redundancy
- 6 magnetic actuator in cold redundancy (2 for each axis)
- 1 cold-gas micropropulsion system

4.2.3 GRACE

GRACE formation flying used following set of sensors & actuators: [22]:

- Coarse earth (∼5-10° accuracy) & sun sensors (∼3-6° accuracy). Accuracies are influenced by orbital position
- Magnetometer - Used for Safe Mode and commanding torque rods
- Optical gyro. High accuracy rotation speed data
- Accelerometer

- Microwave Assembly (MWA) - Measures the distance between satellites
- 2 star cameras providing data with 1 Hz. High accuracy pointing information
- GPS receiver
- Three magnetic torquer rods - LEO mission with altitude of 500km. Limitation - at four places in the orbit field lines are parallel and one axis can not be controlled (roll axis (near equator), yaw axis (near poles)).
- 2x6 GN2 cold gas thrusters - Attitude control
- Orbit control thrusters

4.2.4 PRISMA

If formation flying at meter level is required real time relative orbit control is advisable. This also changes sensor selection. For PRISMA mission following set of senors was used to increase formation determination [23]:

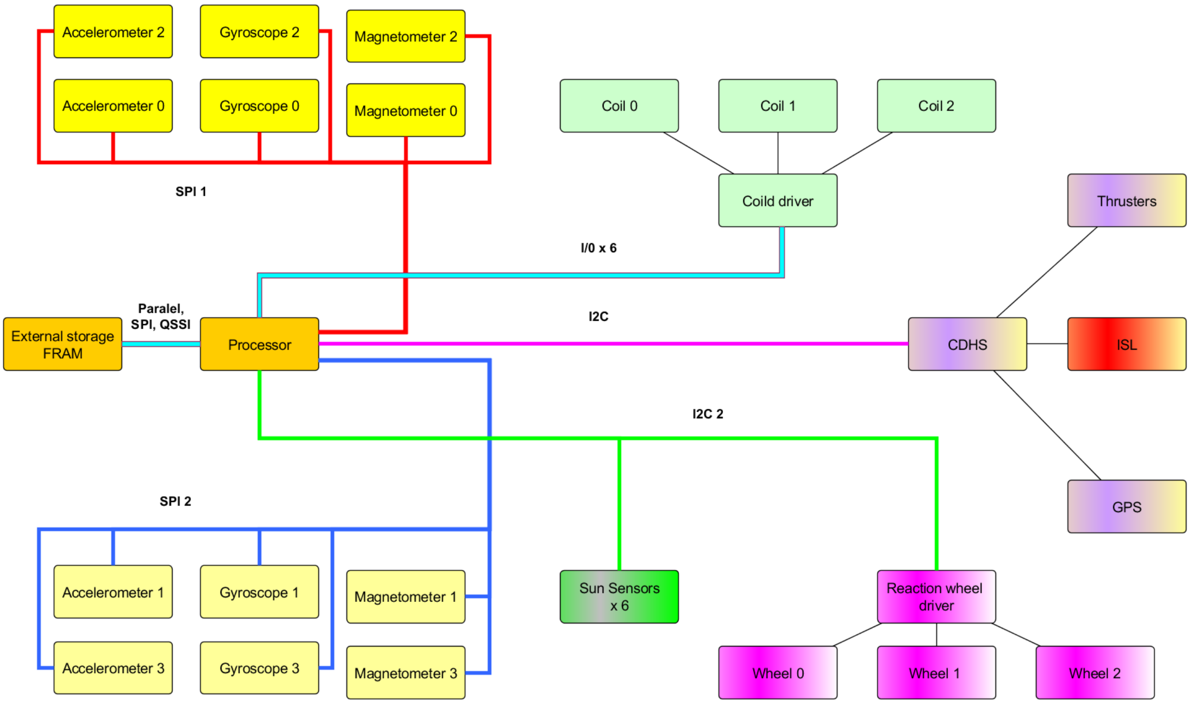
- Phonix-S GPS
- Vision-Based sensor
- Formation Flying Radio-Frequency sensor

Two satellites of PRISMA mission have considerably different hardware architecture and actuators set, as following: [23]:

1. Mango is equipped with three propulsion systems
    - High-performance green propellant thrusters
    - Cold-gas Micro-thrusters
    - Hydrazine propulsion system
2. Tango has simplified 3-axis attitude control with magnetic torquers without orbit maneuver capability.

4.3 DelFFi Hardware Architecture Design

DelFFi hardware architecture is designed to solve problems with which were present in Delfi-n3Xt system design. New system design into takes account changes in satellite mission and functionality added to AOCS. Good system design practices and lessons learned from ESTCube-1, Gravity Recovery And Climate Experiment (GRACE), PRISMA and TerraSAR-X/TanDEM-X missions are used. DelFFi final hardware system design is presented on Figure 5.



Joonis 5: DelFFi hardware layout

Justifications for sensor and actuators type selection are described in Table 9 & 10. Compared to average CubeSat mission, formation flying mission requires orbit control thrusters and reaction wheels, for stabilizing satellite during orbital maneuvers. All the sensors have two levels of redundancy. One due to allocating two SPI buses for sensors, second one due to duplicating sensors on both bus. Due to redundancy and robustness issues I2C usage was limited where possible. Systems that use I2C have been already developed during Delffi-n3Xt mission.

Tabel 9: DelFFi actuators

Actuator	**Justification**
Magnetic torquers	Main attitude control actuators. Chosen due to easy manufacturability and simple control algorithms. Furthermore, magnetic torquers have proven as one of the best options for the nanosatellite mission due to low mass and low error rate
μPS+ Micro-propulsion system	In house propulsion system that is developed for orbit control
Reaction wheels	In house developed for attitude control during orbital maneuvers

Tabel 10: DelFFi sensors

Sensor type	**Amount**	**Justification**
Magnetometer	2 x 2	Magnetometers will be used to determine magnetic vector. This information can be used for detumbling algorithm, controlling magnetic torquers and coarse pointing information. Magnetometers provide 3-4 deg accuracy, but can be offset by satellite magnetization
Gyroscope	2 x 2	Are used for accurate rotational information. Enables easy interpolation of attitude vectors. COTS sensors can provide accuracies up to 0.1° /s. Gyroscopes have to be mechanically isolated from reaction wheels
Accelerometer	2 x 2	Used for measuring acceleration during thrusting.
Sun Sensors	6	Sun sensors are used as main attitude sensors. Sun sensors provide 2-3 deg accuracy
GPS	1	Used to determine satellite position and orbital information. Allows orbit determination during and after orbital maneuver when TLE data is obsolete until new update.

. . . continued

Sensor type	**Amount**	**Justification**
System status monitoring sensors. Such as temperature sensors etc.	NA	Used for satellite health monitoring.

4.4 Processor Selection

Processor selection is central part of the system design. In DelFFi case selection of processor was complicated due to problems with Delfi-n3Xt, interactions with other subsystems, unknowns due to formation flying and the political wish not to change hardware. Selection processes was divided into following parts:

- Pin & port analysis
- Analyzing software computational complexity
- RAM, Code Memory & Non-Volatile Memory Usage
- Compatibility with CDHS

4.4.1 Pin & port Analysis

Tabel 11: Delfi processor pin count

BUS type	**Required amount**	**Justification**
I2C	2	• CDHS communication (x 1) • Reaction wheels & sun sensors (x 1)
SPI/QSSI	3	SPI is preferred over I2C due to robustness. • External FRAM (x 1) • Sensor (x 2), two lines for backup

. . . continued

Name	Problem	Comments & Analysis
General I/O	39	• Sensor I/Os, such as trigger sensor etc. (x 10) • Coil driving (x 6) • SPI chip selects (x 13) • Debugging & Safety margin (x 10)
ADC inputs	8	Used for current and voltage measurement. External temperature measurements. Error detection
UART	1	Uploading code without debugger. Debug communication output
USB	1	Optional. Good for testing

4.4.2 Computational Complexity

Computational complexity was analyzed using two approaches = experience from other missions and calculations done on existing Delfi-n3Xt software. Estimated cycle usage with a safety margin was calculated. High safety margin was used due to number of unknowns. Calculations were done with an assumption that processor with Floating Point Unit (FPU) is used. A Processor with FPU is preferred as most calculations on AOCS are done with floats.

Tabel 12: Code Profiling

Algorithm	Explanation	Complexity in cycles	With 100% safety margin
AEKF, PLKF	Heavily dependent on sensors count, and if sensors are grouped before insertion to KF. Furthermore, uncertainty was increased by the fact that at that point preferred KF was not chosen. [24] [25]	1-20M	40 M cycles

...continued

Algorithm	**Explanation**	**Complexity in cycles**	**With 100% safety margin**
Detumbling	Detumbling uses open loop controller. First data is gathered from magnetometers, then filtered and inserted into the controller. It should be noted that time complexity of the algorithm is bigger due to time it takes to get sensor data	10k	20k
Thrust Vector & Thrust Vector Control& Velocity pointing	TLE data with propagator SGP4 will be used to determine satellite position. KF output will be used to get satellite orientation. Finally all of this data will be fed into PD controller, which controls reaction wheels and torquers	100k	200k
FF algorithms	At this stage purely theoretical and uncertain. First simulations show that they should take approximately 5-10M cycles	5-10M	20M
SUM		≈ 30M	≈ 60M
Overhead	This section includes housekeeping, communication, logging etc overhead. It is approximately 15%	≈ 3M	≈ 6M
TOTAL SUM		≈ 33M	≈ 66M

4.4.3 RAM, Code Memory & Non-Volatile Memory Usage

Delffi-n3Xt SRAM usage was 23 KB. DelFFi add features, look-up tables, formation flying code and the operating system. Thus 256 KB of RAM would be required for DelFFi mission.

Delffi-n3Xt code size was $\approx$ 200 KB. ESTCube-1 code size was $\approx$ 500 KB (result of optimization). Taking account of formation flying code size, the required internal flash should be at least 1 MB. External Ferroelectric RAM (FRAM) should be used for logs and backup firmware images to increase system redundancy. FRAM should be preferred due to its radiation tolerance.

4.4.4 Compatibility with CDHS Processor

CDHS uses TI processor thus if AOCS uses same vendor processor there is lower chance of communication errors due to more similar peripheral design (hardware and software) and internal testing. Furthermore, using same vendor products enables usage of same development environment and tools, this reduces learning curve and increases the development speed.

4.4.5 Result

Following processors were included in the selection process - SAM9G series (one used in Delfi-n3Xt), Ti TIVA series and STM32F4 series. The Delfi-n3Xt processor was eliminated in early phase from the trade off, due to BGA package, and high power consumption. Secondly, only cortex-M family processors where focused in the trade off. Main reasons where:

- Low power consumption
- Suitable computational power
- Cortex-M4 processors where targeted due to built in FPU. As ADCS calculations are done with floats FPU allows to lower processors frequency to lower power consumption

Finally Ti processor TM4C1294NCPDT was selected. Following list describes the main decision points:

- Fulfilled all basic requirements including environmental
- Best compatibility with CDHS
- Shortest learning curve for developers who have used Ti products
- Recourse sharing with CDHS team
- Ti has one of the best development environments

- Good availability and high quality development board

5 Software

The final goal of the was to develop suitable software architecture and develop new Hardware Abstraction Layer (HAL) for the DelFFi mission.

FF mission is a set of more than one spacecraft, in which any of the spacecraft dynamic states are coupled through a common control law. In particular, at least one member of the set must (i) track a desired state profile relative to another member, and (ii) the associated tracking control law must at the minimum depend upon the state of this other member. The second point is critical. For example, even though prescribed relative positions are actively maintained, GPS satellites constitute a constellation since their orbit corrections only require an individual satellite's position and velocity. [26] [27]

Formation Flight Controller (FFC) architectures are divided into 5 categories: [27]

- Multiple-Input Multiple-Output, in which the formation is treated as a single multiple-input, multiple-output plant
- Leader/Follower, in which individual spacecraft controllers are connected hierarchically
- Virtual Structure, in which spacecraft are treated as rigid bodies embedded in an overall virtual rigid body
- Cyclic, in which individual spacecraft controllers are connected non-hierarchically, and
- Behavioral, in which multiple controllers for achieving different (and possibly competing) objectives are combined

DelFFi mission contains increased number of modes compared to ESTCube-1 and Delfi-n3Xt. In addition of attitude control modes DelFFi mission includes orbital control functionality. DelFFi mission available modes are described in Table 13. DelFFi satellite uses modified Leader/Follower architecture. Major difference is that with telecommand allows to interchange leader and follower satellites. This is due to following reasons:

- Robustness - when communication fails with one satellite, it is possible to change the lead and continue communication with other satellite over ISL
- Fuel consumption - Follower does more thrusting than leader. Interchanging them allows to use the same software on both of the satellite and equalize fuel consumption

Tabel 13: DelFFi actuators

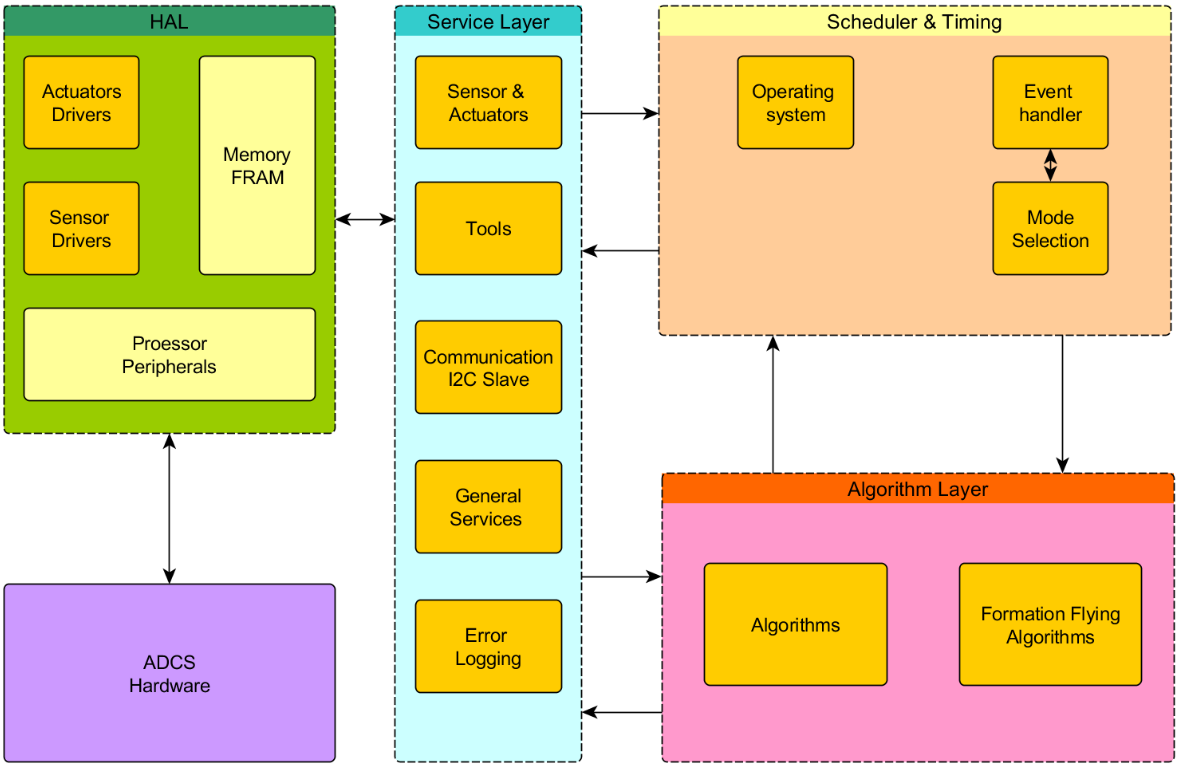
Mode	Sensors & Actuators used	Comments
Safe Mode	Only sensors are used. Magnetometer and Gyroscopes	There are 2 ways that the system can enter safe mode. If an error occurs or telecommand is sent
Detumbling mode	Magnetometers, gyroscopes and coils	Simple B-dot algorithm is ran when the satellite rotation speed gets to high. Also used in the beginning of mission for detumbling
Velocity pointing mode	Magnetometers, gyroscopes, GPS and coils	System vector is aligned with velocity vector. In this case 2 satellites can communicate and data from QB50 mission can be gathered. Communication between 2 satellites has a higher priority than velocity pointing i.e. when velocity pointing does not provide communication link, then velocity pointing is changed to satellite pointing
Thrust vector control mode	All sensors and actuators	During thrust vector control, orbital maneuvers are done by follower satellite. Final start command always comes from ground

5.1 Software Architecture

Main goals for architecture design:

- Reuse Delfi-n3Xt code where possible
- Modular architecture, makes changes in the future easier, such as uncertainties with the algorithms to be used

- Suitable operating system shall be used to provide core feature set



Joonis 6: DelFFi software architecture

Final DelFFi software architecture is on Figure 6. DelFFi AOCS software is divided into four groups:

- HAL - Contains sensors, actuators, devices & peripherals drivers. Layer purpose is to remove service layer processor dependency which allows to use Delfi-n3Xt code. Peripheral drivers are coming with the operating system (TI-RTOS)
- Service layer - Provides services, libraries and communication handlers. Such as OBC communication handler, KF and SGP4.
- Scheduler & Timing - The core system scheduler is here. Contains operating system, system event handler and mode selection. Specific processor task timing is dependent on mode.
- Algorithm layer - Attitude and orbit control algorithms. A specific layer to separate core control algorithms. Algorithms to use at given time, is decided by mode and scheduler.

Architecture was developed with multilevel abstraction due to following reasons. Creating HAL allows to use most of Delfi-n3Xt services. Delfi-n3Xt used limited hardware abstraction to allow usage of some functions on both processor. New architecture with fully implemented HAL and allows to port both processors existing services.

Scheduler & timing is new abstraction compared to Delfi-n3Xt. This separates system timing and mode control from rest of the software which clarifies architecture by separating system states, timing and function callers from rest of the system. Finally, algorithm layer was created. Algorithms were separated from service layer, as algorithms are actively using services and thus do not ideologically fit under services. Furthermore, separation enables modularity and changing of algorithms. In future this architecture supports live updates of services, drivers and algorithms.

5.1.1 Scheduler & Timing

The main features that scheduler and timing part proves are event and error handling, mode selection, and operating system with its core features. Part of the architecture design process was to decide which operating system to use. As the DelFFi project uses TI processor TM4C1294NCPDT (selection process described under hardware section) operating system selection was limited to FreeRTOS & TI-RTOS. Limitation has 2 main factors, (i) FreeRTOS & TI-RTOS have good support for Tiva series, (ii) FreeRTOS & TI-RTOS are free to use which for student project is important feature.

After analyzing both operating systems positive and negative sides TI-RTOS was chosen over FreeRTOS. The main reasons where:

- Beside SYS/BIOS, TI-RTOS also comes with tested device drivers. Thus reducing the software development time
- There is better support for TI-RTOS on TM4C129 processors
- More examples available for TI processors
- Most of the developers had used TI & TI-RTOS
- Negatively, TI-RTOS has larger footprint
- FreeRTOS has safety critical version (SafeRTOS). This was out of this project scope

6 Results

The gaol of this thesis was to develop system design for DelFFi satellite. The work was divided into 3 parts:

- System requirements
- Hardware design
- Software design

As a result of this thesis DelFFi attitude and orbit control system architecture was developed.

First goal in the thesis was to update DelFFi system requirements. Existing ones where mix of multiple missions and thus had multiple inconsistencies. Final requirements where divided into three groups: environmental, determination & control requirements aka. functional requirements and finally external interface requirements. Overviews of final requirements are described in Tables 14, 15, 16.

Tabel 14: DelFFi Environmental requirements

Requirement	**Justification**
Satellite shall withstand launch environment of most common launchers	Launcher name or type(Solid-fuel, liquid-fuel) is not known until the late phase of nanosatellite development. AOCS should be designed to withstand all common rockets launch environment
Satellite shall survive space environment at orbit under 900 km at least 1 year	CubeSats orbit altitude is in average unknown during the development phase. Even if orbit altitude is known, there is high chance for orbit change. In general one rule exists, almost all CubeSats are launched to orbit under 900 km where satellites are protected by Van Allan belt
Satellite shall withstand most common orbit inclinations thermal environment including sun synchronous	Orbit inclination is often changed and continues to changes during mission time due to perturbations. Thus AOCS should be designed operate in any inclination specific orbital conditions, such as SSO temperature conditions

Tabel 15: Determination & control requirements aka. functional requirements

Requirement	**Justification**
FF determination & control accuracy	Separation determination accuracy 1 km, satellite separation control accuracy 10 km. Formation separation of 1000 km with 100 km control window. **Those are the mission goals.** [4]
Attitude determination accuracy no worse than 2 ° accuracy and pointing accuracy of 5 °	Main drivers are ISL field of view and orbital maneuvers efficiency.
Pointing stability better than 0.5 ° /s	Requirement drivers are ISL field of view and orbital maneuvers efficiency (attitude control during thrusting).

Tabel 16: External interface requirements

Requirement
AOCS mass shall be lower than 350g (including reaction wheels and coils)
AOCS average power consumption shall be under 300 mW
AOCS shall fit into CubeSat form factor.
AOCS will communicate with reaction wheels, OBC and thrusters over **I2C!**. This is heritage of Delfi-n3Xt. Thrusters are controlled through OBC

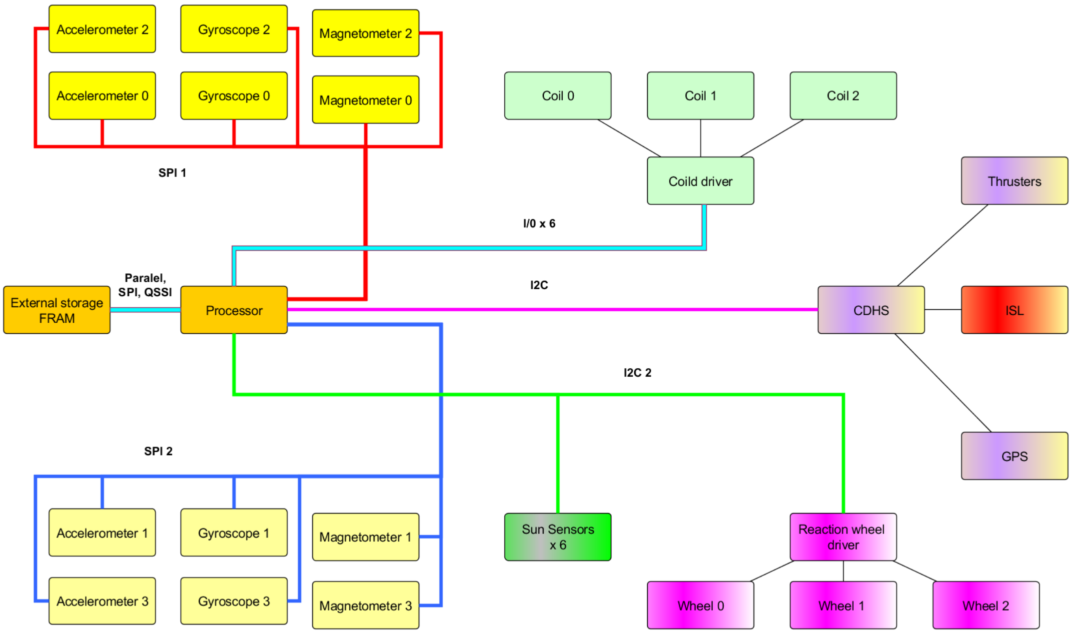
The Second goal was to analyze Delfi-n3Xt hardware and its suitability for DelFFi mission. During the analysis following problems came out, (i) unsuitable main processor with module was chosen, which would jeopardize DelFFi mission, (ii) system had two processors with different architecture, that overcomplicated software design, (iii) I2C problems, (iv) sensor noise issues.

To solve those issues this thesis analyzed multiple satellites missions hardware architecture. In the end this thesis found suitable new processor, sensor types and hardware architecture for DelFFi mission. Ti processor TM4C1294NCPDT was selected due to following reasons:

- Fulfilled all basic requirements

- Best compatibility with CDHS/OBC
- Shortest learning curve for developers who have used Ti products
- Recourse sharing with CDHS team
- Ti has one of the best development environments
- High quality development board with good availability

Final hardware architecture is shown on Figure 7, actuators type selection in Table 19 and sensor type justification is in Table 18.



Joonis 7: DelFFi hardware layout

Tabel 18: DelFFi sensors

Sensor type	**Amount**	**Justification**
Magnetometer	2 x 2	Magnetometers will be used to determine magnetic vector. This information can be used for detumbling algorithm, controlling magnetic torquers and coarse pointing information.
Gyroscope	2 x 2	Are used for accurate rotational information. Enables easy interpolation of attitude vectors

. . . continued

Sensor type	**Amount**	**Justification**
Accelerometer	2 x 2	Used for measuring acceleration during thrusting. Also used for data in
Sun Sensors	6	
GPS	1	Used to determine satellite position and orbital information. Allows orbit determination during and after orbital maneuver when TLE data is obsolete until new update.
System status monitoring sensors. Such as temperature sensors etc.	NA	Used for satellite health monitoring.

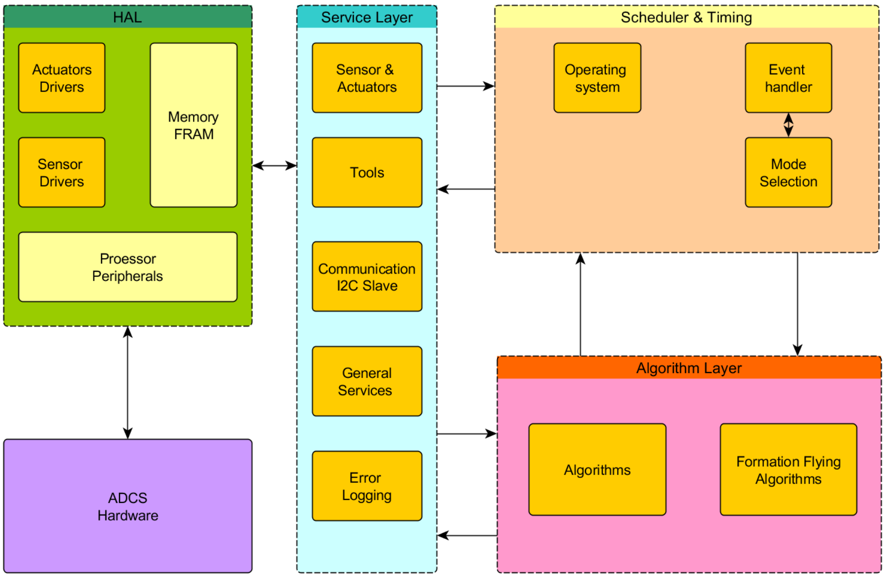
Tabel 19: DelFFi actuators

Actuator	**Justification**
Magnetic torquers	Main attitude control actuators. Chosen due to easy manufacturability and simple control algorithms. Furthermore, magnetic torquers have proven as one of the best options for the nanosatellite mission due to low mass and low error rate
μPS+ Micro-propulsion system	In house propulsion system that is developed for orbit control
Reaction wheels	In house developed for attitude control during orbital maneuvers

Third and final goal was to develop new software architecture for DelFFi formation flying mission. As a result of this thesis new software architecture was developed and operating system was selected. Final software architecture is on Figure 8.

DelFFi AOCS software is divided into four groups:

- HAL - Contains sensors, actuators, devices & peripherals drivers. Layer purpose is to



Joonis 8: DelFFi software architecture

remove service layer processor dependency, which enables to use Delfi-n3Xt code. Peripheral drivers are coming with the operating system (TI-RTOS)

- Service layer - Provides services, libraries and communication handlers. Such as OBC communication handler, KF and SGP4.
- Scheduler & Timing - The core system scheduler is here. Contains operating system, system event handler and mode selection.
- Algorithm layer - Attitude and orbit control algorithms. Specific layer to separate core control algorithms. Specif algorithms to use at given time is decided by mode and scheduler.

Operating system for DelFFi mission is used to provide support for core functionalities. TI-RTOS was chosen due to folling reasons: The main reasons where:

- Beside SYS/BIOS, TI-RTOS also comes with tested device drivers. Thus reducing the software development time
- Better support for TI-RTOS on TM4C129 processors and extensive testing
- TI-RTOS has more examples available for TIVA processors

7 Summary

DelFFi attitude and orbit control system final requirements were created and system architecture was developed. Existing requirements where analyzed, inconsistencies where found and new requirements where proposed. Successful relevant missions requirements were analyzed to increase quality of the requirements.

Secondly, Delfi-n3Xt mission ADCS hardware was analyzed to find systematic errors that caused erratic behavior. ESTCub-1, GRACE and PRISM mission architecture were analyzed to find best configuration for DelFFi formation flying mission. New hardware architecture was developed and new processor was chosen.

Finally, software requirements and system modes where analyzed. Suitable DelFFi software architecture was created which enables to port most of the Delfi-n3Xt code. Operating system for DelFFi mission was chosen. **Work with hardware abstraction layer was not finished due to fact that project was halted.**

8 Acknowledgments

I would like to thank Mart Noorma, who took me on the Studient Satellite project on my first day in university. I would also thank Andris Slavinskis for time we worked together on ESTCUbe-1 attitude and control system and for the times he, as the supervisor, has tolerated me . I would like to thank all of the Student Satellite team members for making my time in university interesting.

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9 Kokkuvõte

Lõputöö "System Design for Attitude and Orbit Control System for DelFFI Formation Flying Mission"põhineb minu üheksakuusel praktikal Delfti Tehnoloogiaülikooli satelliidimeeskonnas ajaperioodil septembrist 2014 kuni maini 2015. Praktika jooksul oli peaülesandeks DelFFi satelliidi asendi määramise ja kontrollimise süsteemi arendamine. DelFFi satelliit on omapärane, kuna oli üks esimesi nanosatelliite, mille eesmärgiks oli teostada formatsioonilend. Lõputöö käigus uurisin ja parandasin satelliidi asendi määramise ja kontrollimise nõudeid. Esialgsed nõuded baseerusid Delfi-n3Xt nõuetel, mille missioon erines DelFFi satelliidi omast. ESTCub-1, GRACE'i and PRISMi formatsioonilendude ja nanosatelliitide missioonide nõuete analüüsi alusel genereerisin lõplikud DelFFi asendi määramis- ja kontrollimissüsteemi nõuded. Teine etapp algas Delfi-n3Xti satelliidi riistavara sobivusuuringuga DelFFi missiooni jaoks. Pärast analüüse selgus, et olemasolev riistvara ei ole sobiv formatsioonilennu testmissioonile. Töö käigus disainisin uue riistvara arhitektuuri ja valisin uue protsessori. Viimase ülesandena analüüsisin süsteemi tarkvara nõudeid ja olekuid. Arendasin uue tarkvara arhitektuuri ning valisin operatsioonisüsteemi.

Viited

[1] S.-J. Chung, S. Bandyopadhyay, R. Foust, G. P. Subramanian, and F. Y. Hadaegh, “Review of Formation Flying and Constellation Missions Using Nanosatellites,” *JOURNAL OF SPACECRAFT AND ROCKETS*, vol. 53, no. No. 3, MayâĂŞJune, pp. 567–578, 2016.

[2] A. Slavinskis, M. Pajusalu, H. Kuuste, E. Ilbis, T. Eenmae, I. Sünter, K. Laizans, H. Ehrpais, P. Liias, E. Kulu, J. Viru, J. Kalde, U. Kvell, J. Kutt, K. Zalite, K. Kahn, S. Latt, J. Envall, P. Toivanen, J. Polkko, P. Janhunen, R. Rosta, T. Kalvas, R. Vendt, V. Allik, and M. Noorma, “ESTCube-1 in-orbit experience and lessons learned,” *IEEE Aerospace and Electronic Systems Magazine*, vol. 30, pp. 12–22, aug 2015.

[3] A. Slavinskis, E. Kulu, J. Viru, R. Valner, H. Ehrpais, T. Uiboupin, M. Järve, E.Šoolo, J. Envall, T. Scheffler, I. Sünter, H. Kuuste, U. Kvell, J. Kalde, K. Laizans, E. Ilbis, T. Eenmäe, R. Vendt, K. Voormansik, I. Ansko, V. Allik, S. Lätt, and M. Noorma, “Attitude determination and control for centrifugal tether deployment on the ESTCube-1 nanosatellite,” *Proceedings of the Estonian Academy of Sciences*, vol. 63, pp. 2–242, 2014.

[4] J. Guo, J. Bouwmeester, and E. Gill, “In-orbit results of Delfi-n3Xt: Lessons learned and move forward,” *Acta Astronautica*, vol. 121, pp. 39–50, 2016.

[5] J. Bouwmeester, J. Reijneveld, T. Hoevenaars, and D. Choukroun, “Design and Verification of a Very Compact and Versatile Attitude Determination and Control System for the Deflt-n3Xt nanosatellite,” no. 1, pp. 1–15, 2012.

[6] S. Bandyopadhyay, G. P. Subramanian, R. Foust, D. Morgan, S.-J. Chung, and F. Hadaegh, “A Review of Impending Small Satellite Formation Flying Missions,” in *53rd AIAA Aerospace Sciences Meeting*, (Reston, Virginia), American Institute of Aeronautics and Astronautics, jan 2015.

[7] J. W. Gangestad, B.Š. Hardy, and D. A. Hinkley, “Operations, Orbit Determination, and Formation Control of the AeroCube-4 CubeSats,” in *Conference on Small Satellites*, 27th AIAA/USU.

[8] G. Bonin, N. Roth, S. Armitage, J. Newman, B. Risi, and R. Zee, “CanX-4 and CanX-5 Precision Formation Flight: Mission Accomplished!,” *AIAA/USU Conference on Small Satellites*, pp. 1–3, 2015.

[9] GunterSpacePAge, “CPOD A, B (PONSFD A, B) - Gunter’s Space Page.”

[10] J. Bowen, M. Villa, and A. Williams, “CubeSat based Rendezvous, Proximity Operations, and Docking in the CPOD Mission,” *29th Annual AIAA/USU Small Satellite*, no. 949, pp.ŠSC15–III–5, 2015.

[11] R. Kahle, H. Runge, J. Ardaens, S. Suchandt, and R. Romeiser, “Formation flying for along-track interferometric oceanography - First in-flight demonstration with TanDEM-X,” *Acta Astronautica*, vol. 99, no. 1, pp. 130–142, 2014.

[12] J. Guo, “DelFFi System Overview,” Tech. Rep. 0.1, 2014.

[13] J. Viru, “Jaan Viru Design and Testing of Attitude Determination Sensors for ESTCube-1 Bachelor ’ s Thesis,” 2013.

[14] A. Slavinskis, H. Ehrpais, H. Kuuste, E. Kulu, J. Viru, I. Sünter, J. Kütt, and M. Noorma, “ESTCube-1 attitude determination: in-flight experience,”

[15] C. Henry, “QB50 Launch Switches from Alcantara Cyclone Space to NanoRacks and Kosmotras,” 2016.

[16] E. Gill, P. Sundaramoorthy, J. Bouwmeester, B. Zandbergen, and R. Reinhard, “Formation flying within a constellation of nano-satellites: The QB50 mission,” *Acta Astronautica*, vol. 82, no. 1, pp. 110–117, 2013.

[17] I. Ploom, “Analysis of variations in orbital parameters of CubeSats,” 2014.

[18] A. Slavinskis, E. Kulu, J. Viru, R. Valner, H. Ehrpais, T. Uiboupin, M. Järve, E.Šoolo, J. Envall, T. Scheffler, I. Sünter, H. Kuuste, U. Kvell, J. Kalde, K. Laizans, E. Ilbis, T. Eenmäea, R. Vendt, K. Voormansik, I. Ansko, V. Allik, S. Lätt, and M. Noorma, “Attitude determination and control for centrifugal tether deployment on the ESTCube-1 nanosatellite,” *Proceedings of the Estonian Academy of Sciences*, 2014.

[19] J. Guo, “DelFFi System Overview,” Tech. Rep. 0.1, Delft University of Technology, Delft, 2014.

[20] R. Ghaffarian, “Accelerated Thermal Cycling and Failure Mechanisms For BGA and CSP Assemblies,”

[21] B. D. Dunn and P.-E. Tegehall, “Assessment of the Reliability of Solder Joints to Ball and Column Grid Array Packages for Space Applications,” tech. rep., ESA, 2001.

[22] J. Herman, D. Presti, A. Codazzi, and C. Belief, “Attitude control for GRACE the first low-flying satellite formation,” *European Space Agency, (Special Publication) ESA SP*, no. 548, pp. 27–32, 2004.

[23] S. D’Amico, J. Ardaens, S. De Florio, and S. Damico, “Autonomous formation flying based on GPS - PRISMA flight results,” *Acta Astronautica*, vol. 82, no. 1, pp. 69–79, 2013.

[24] S. A. Hoseini and M. R. Ashraf, “Computational Complexity Comparison of Multi-Sensor Single Target Data Dusion Methods by Matlab,” *International Journal of Chaos, Control, Modelling and Simulation (IJCCMS)*, vol. 2, no. 2, 2013.

[25] V. Bonato, E. Marques, and G. A. Constantinides, “A Floating-Point Extended Kalman Filter Implementation for Auronomous Mobile Robots,”

[26] D. Scharf, F. Hadaegh, and S. Ploen, “A survey of spacecraft formation flying guidance and control (Part I): guidance,” in *Proceedings of the 2003 American Control Conference, 2003.*, vol. 2, pp. 1733–1739, IEEE, 2003.

[27] D. P. Scharf, F. Y. Hadaegh, and S. R. Ploen, “A Survey of Spacecraft Formation Flying Guidance and Control (Part II): Control,” in *American Control Conference, 2004*, 2004.

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