Rapid Space Mission Design, Realization and Deployment

Antti Kestilä
Rapid Space Mission Design, Realization and Deployment

Antti Kestilä

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the lecture hall AS2 of the TUAS building on the 9th of June 2017 at 12.00.

Aalto University
School of Electrical Engineering
Department of Electronics and Nanoengineering
Space Technology
Supervising professor
Professor Esa Kallio, Aalto University, Espoo, Finland

Thesis advisor
Markku Leskelä, University of Helsinki, Helsinki, Finland

Preliminary examiners
Dr. Steven Engelen, Hyperion Technologies B.V., Delft, The Netherlands
Dr. Seppo Korpela, University of Helsinki, Helsinki, Finland

Opponent
Prof. Dr. Peter Wurz, University of Bern, Space Research & Planetary Sciences, Bern, Switzerland
Abstract

Space technology has brought a range of existing possibilities for humanity, ranging from navigation, communication and remote sensing to things such as asteroid and planetary prospecting as well as colonization. Development has in part stalled due to a number of reasons. This thesis researches how to potentially accelerate a space mission from drawing board to deployment. The tool used is the fairly recent small satellite concept, which applies standardization, commercial-off-the-shelf components and decreases the satellite’s physical dimensions to improve its launch opportunities. The thesis is divided into three main chapters, which combined represent the overall development path that the research took during the thesis. It begins with the introduction of the most popular small satellite platform, the CubeSat, and describes the Aalto-1 CubeSat project. Publication 1 presents the mission of the Aalto-1 CubeSat, where the satellite’s three payloads are planned not only to perform technology demonstrations, but also a scientific campaign, giving an example of a CubeSat’s capability to perform useful and novel functions. The lessons learned from the project are presented as well as some insight into the management of a student small satellite project and an example subsystem for the CubeSat developed during the project. The project results indicate that one of the most useful applications of CubeSats, or indeed small satellites, is using them in a constellation. This leads to the research presented in the second chapter (Publication 2) which analyzes a range of constellations suitable for a fast revisit time of two hours or less in the polar regions. Some of the main problems were also studied, such as launch opportunities and construction of the constellation, as well as propulsion requirements. The conclusion drawn was that with secondary launch opportunities, in practice propulsion is needed, and that natural precession can alleviate the cost of deltaV needed in exchange for an increased time needed to construct the constellation. The chapter continues with additive manufacturing as a potential way to accelerate especially constellation mission development. This lead to the third major research topic of the thesis - manufacture of space-grade components by combining additive manufacturing and atomic layer deposition. This novel method is presented in Publication 3, in which plastic additive manufactured components are coated with a nanometer-scale uniformly conforming film. The research investigated the benefits in decreasing outgassing with the method, and the results indicate a possible improvement in outgassing, but also an improvement in the structural integrity of the printed component. This research however is just the first attempt in beginning to understand the potential of the method, as both additive manufacturing and atomic layer deposition by themselves have a very large array of applications, and so combining both could possibly realize an even larger array.

Keywords Satellites, spacecraft, Aalto-1, constellations, rapid design, rapid manufacturing, atomic layer deposition, additive manufacturing

ISSN-L 1799-4934 ISSN (printed) 1799-4934 ISSN (pdf) 1799-4942
Location of publisher Helsinki Location of printing Helsinki Year 2017
Tekijä  
Antti Kestilä

Väitöskirjan nimi  
Nopea avaruustehtävän suunnittelu, toteutus ja käyttöönotto

Julkaisija  
Sähköteknikan korkeakoulu

Yksikkö  
Elektroniikan ja nanotekniikan laitos

Sarja  
Aalto University publication series DOCTORAL DISSERTATIONS 111/2017

Tutkimusala  
Avaruustekniikka

Käsikirjoituksen pvm 16.03.2017  
Väitöspäivä 09.06.2017

Julkaisuluvan myöntämispäivä 12.05.2017  
Kieli  
Englanti

Monografia  
Artikkeliväitöskirja  
Esseeväitöskirja

Tiivistelmä


Avainsanat  
Satelliitti, avaruusalus, Aalto-1, konstellaatiot, nopea suunnittelu, nopea valmistus, atomikerrosastus, 3D-tulostus

ISBN (painettu) 978-952-60-7477-1  
ISBN (pdf) 978-952-60-7476-4

ISSN-L 1799-4934  
ISSN (painettu) 1799-4934  
ISSN (pdf) 1799-4942

Julkaisupaikka Helsinki  
Painopaikka Helsinki  
Vuosi 2017

Sivumäärä 145  
Preface

This thesis work was carried out at the Department of Electronics and Nanoengineering at the Aalto University School of Electrical Engineering, Espoo, Finland, and funded primarily by it. The work was funded initially through Aalto-1 project funding coming from the Aalto MIDE-programme as well as later on by Aalto School of Electrical engineering graduate school. Additional funding support was provided by Finnish Academy of Science and Letters, as well as the Finnish Society of Science and Letters.

First I'd like to thank Professors Esa Kallio and Martti Hallikainen for the excellent supervision and guidance during this work and while completing it. They gave me the space to forge the ideas that made this work possible in these wide ranging, yet interconnected and important topics of the thesis, and actively supported by sound advice on directions to take, necessary steps to completion and careful review of the various levels of my PhD work.

I am grateful to the pre-examiners of this thesis, Dr. Steven Engelen and Dr. Seppo Korpela, for their helpful suggestions and comments on the work. I would also like to thank Prof. Peter Wurz for accepting to be my opponent.

I am also deeply grateful to Professor Markku Leskelä from the Laboratory of Inorganic Chemistry in University of Helsinki for his support as my thesis advisor, as well as the world-class atomic layer deposition experts Prof. Mikko Ritala, Dr. Ville Miikkulainen and MSc. Mikko Kaipio, propulsion 91specialist MSc. Kalle Nordling as well as additive manufacturing expert Dr. Mika Salmi for support and interest in the combination of additive manufacturing and atomic layer deposition.

I'd also like to thank all colleagues, but especially MSc. Tuomas Tikka and Asst. Prof. Jaan Praks, and students working with the Aalto-1 Cube-
Sat and its payloads - together we made this satellite and its successor projects possible.

Last and most important, I’d like to thank my fiancée Riikka and my mother Dora for supporting me during all these years. Your love and endless support is what made this work possible.

May 23, 2017,

Antti Kestilä
Contents

Preface i

Contents iii

List of Publications v

Author's Contribution vii

List of Abbreviations xi

1. Introduction 1
   1.1 Background and context 1
   1.2 Aim and scope 2
   1.3 Thesis structure 4

2. The Small Satellite Concept 5
   2.1 The CubeSat as a case study 5
      2.1.1 The lessons learned 8
      2.1.2 New project and technical management aspects beneficial for rapid space missions 10

3. Constellation Missions 13
   3.1 The importance of orbits 13
   3.2 Constellation benefits 14
   3.3 Constellation requirements 15
      3.3.1 Launch opportunities 15
      3.3.2 Propulsion 17
      3.3.3 Ground segment 17
      3.3.4 Repeatable manufacturing process 18

4. Small satellite rapid development and manufacturing 19
4.1 Additive manufacturing as part of a new approach to space technology ........................................ 19
  4.1.1 The challenge of space as an environment .......... 20
  4.1.2 Atomic layer deposition .............................. 21
  4.1.3 Combination of ALD and AM ...................... 23

5. Summary of Publications 25
  5.1 Publication I: Aalto-1 nanosatellite - technical description and mission objectives ....................... 25
  5.2 Publication II: Small Satellite Remote Sensing Constellation for Fast Polar Coverage ...................... 26
  5.3 Publication III: Towards space-grade 3D-printed, ALD-coated small satellite propulsion components for fluidics .......... 27
  5.4 Publication IV: Aalto-1 Earth Observation CubeSat Mission - Educational outcomes ......................... 27
  5.5 Publication V: The Aalto-1 nanosatellite navigation subsystem: development results and planned operations ....... 28
  5.6 Publication VI: Online documentation approach for assisted system engineering and assessment in student projects. . . . 28
  5.7 Publication VII: Particle Swarm Optimization with Rotation Axis Fitting for Magnetometer Calibration ............ 29

6. Concluding remarks 31

References 35

Publications 41
This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.


V Leppinen Hannu, Kestilä Antti, Tikka Tuomas, Praks Jaan. The Aalto-


Author’s Contribution

Publication I: “Aalto-1 nanosatellite - technical description and mission objectives”

The present author is the co-founder of the Aalto-1 project, in addition to being the project mission designer and system engineer. The present author was the main contributor and writer of the article, with other authors contributing specific sections and material. The Aalto-1 project involved throughout its length almost 100 people all of which contributed to varying levels during it.


The original idea resulted from collaboration with all authors. The present author is the main designer of the constellation design in the publication, as well as the original co-founder and responsible leader of the ICEYE-project in Aalto University that worked as a use-case for the publication. The present author wrote the article and performed all the simulations and calculations in the publication.

Publication III: “Towards space-grade 3D-printed, ALD-coated small satellite propulsion components for fluidics”

The present author wrote the article and designed the experiments in it in collaboration with Nordling, Miikkulainen and Kaipio. The present author designed and built the flow setup together with Nordling and the test pieces together with Salmi and Auer. Atomic layer deposition and
mass spectrometry was performed by Miikkulainen and Kaipio.

**Publication IV: “Aalto-1 Earth Observation CubeSat Mission - Educational outcomes”**

The present author is the co-founder of the Aalto-1 project, as well as the project mission designer and system engineer. Together with the first author, the present author was responsible for the educational activity in the project, supervising the technological and project development by the different teams during the project. The present author with a contribution from Leppinen, Tikka and Praks developed the first version of the critical system engineering online documentation and tracking system necessary for the Aalto-1 project.

**Publication V: “The Aalto-1 nanosatellite navigation subsystem: development results and planned operations”**

The present author is the co-founder of the Aalto-1 project, in addition to being as the project mission designer and system engineer. The present author contributed to the part of the publication describing the mission and operation plan of the navigation system. He also approached the manufacturer of the GPS receiver for help and hardware during the feasibility phase of the project. The author also performed together with Leppinen and Tikka all engineering and flight model tests of the navigation subsystem.

**Publication VI: “Online documentation approach for assisted system engineering and assessment in student projects”**

The present author is the co-founder of the Aalto-1 project, as well as the project mission designer and system engineer. The present author in collaboration with the other authors developed and actively used the online documentation approach - that eventually formed the later more mature system - iteratively throughout the duration of the project.
Publication VII: “Particle Swarm Optimization with Rotation Axis Fitting for Magnetometer Calibration”

The present author is the co-founder of the Aalto-1 project, in addition to being the project mission designer and system engineer. The author’s contribution to the publication included designing and performing the test setup as well as the actual tests jointly with Riwanto and Tikka. The author, together with Tikka, also contributed to the design of the test procedures used during the Aalto-1 project.
Author's Contribution

x
List of Abbreviations

ABS Acrylonitrile butadiene styrene
ALD Atomic layer deposition
AM Additive manufacturing
COTS Commercial-off-the-shelf
LEO Low-earth orbit
PEEK Polyether ether ether ketone
PEKK Polyether ether ketone ketone
PSO Particle swarm optimization
UV Ultraviolet
1. Introduction

1.1 Background and context

The aerospace sector is seeking new directions for future development through which to solve its current challenges. The main bottleneck, launches, have created a difficult set of parameters that all space applications and technology has to survive and operate under [38]. Space as an environment also poses unique challenges to all human-made objects that need to survive there, especially in the case of long-term operations. At the same time the potentials offered by space remain tantalizingly on the horizon. Applications ranging from remote sensing which has become more familiar, communications and navigation to an almost endless array of more exotic examples (such as novel deep-space science, asteroid and planetary exploration and resource exploitation up to colonization) create a pull for new generations of scientists and engineers to try push our space capabilities further.

This continually prompts searches for new ways to advance activities in space quicker and cheaper. Activities with small satellites is one such direction.

While having been around since the 60’s [21], the most recent wave of small satellite missions utilize the new technological developments in digital electronics miniaturization and radiation tolerance, small satellite bus, and launch vehicle technology [61], and are thus able to fit into a smaller form factor as particular digital electronics in themselves can be fit into progressively smaller volumes. Small satellites in this work are defined to be all satellites of 500 kg or less mass. In some cases however, less than 1000 or even 500 kg satellites have been described as "small", with [45] explaining some common definitions. Below this upper limit are
several in-between categories, such as microsatellites in the 10 - 200 kg
range and nanosatellites generally in the 1 - 10 kg. The scale continues
with pico (1 kg or less) and even femto (some hundred of grams), but from
experience generally no firmly established convention in naming these
categories exists.

These small satellites also take advantage of standards (in most cases
fairly loose ones), and are able to thus ease their development process, as
their form factor is set and COTS components and subsystems are avail-
able to be added into the satellite in a (ideally) "plug-and-play" fashion.
CalPoly's CubeSat is the most popular standard, with universities mak-
ing up around half of CubeSat missions by 2013, with 2014 showing a
larger share in commercial missions mainly due to Planet Labs Inc. Flock-
CubeSats [51]. As the name suggests, the standard's outer form factor is
based on a cube and so can utilize a protective (mostly the main payload
against the CubeSat breaking up during launch) deployment pod system,
the theory being that this helps in finding faster launches. The Cube-
Sat's popularity has also created a large COTS manufacturer base (see
e.g. [59] for an example selection of companies) from which is possible
to acquire the technology that cannot be currently produced in-house, as
well as other teams with which to share experiences.

1.2 Aim and scope

The goal of this work is to evaluate the possibilities of speeding up space
missions and make them cheaper, and in such a way to optimize those
missions. The number of possible approaches that can be taken are ex-
haustingly large, and so the work will concentrate on a few of the more
major topics found during the course of research, consisting of:

- The CubeSat mission Aalto-1 which works a test case of small satellite
technology and its technological bottlenecks and benefits. The author of
this work was a co-founder, mission designer and system engineer of the
mission.

- As a result of the Aalto-1 mission, the expansion and study of the small
satellite concept to that of constellations and the orbits that enable those
constellations.
• As a result of the demands of a constellation, studying the combination of additive manufacturing and atomic layer deposition as a new rapid manufacturing method.

The work studies and evaluates how is it possible to design, deploy and operate a space mission that can contribute a meaningful output with greatly decreased costs and time periods. With this understanding the aim is to maximize the benefits gained from new technology, as well as to concentrate on some of the specific perceived problems and bottlenecks that currently defines how space missions are designed and performed. It is then hoped that the understanding gained with small satellites can one day beneficially translate to larger satellite designs.

The thesis research questions can be formulated as:

• Is it possible to decrease a space mission development timeline using lower mass, standardized space technology (small satellites), and is the mission able to then produce novel results?

• What are the main bottlenecks and benefits associated with small satellite technology?

• How influential is orbit design for small satellite space missions?

• Is the combination of additive manufacturing and atomic layer deposition effective technology for a space mission?

In all publications the centrepiece was the concept of the small satellite - not only the compact volume and mass that they typically hold, but also standardization and the different approach to launch opportunities. It should be noted here already, that in the case of launch opportunities small satellites do not necessarily have an easier time in getting them. Each publication was also a continuation of research that went into the previous publication, creating a path in this large scientific and technical field which requires further research.
1.3 Thesis structure

The structure of this work is divided into three major sections - (i) the Small satellite concept and Aalto-1 CubeSat, (ii) constellations as a result of the research into Aalto-1, (iii) and enhanced additive manufacturing as a consequence of constellations manufacturing requirements. Each research topics is a continuation and consequence of the previous. The thesis is finally closed with a discussion and iteration of the main research points and their benefits and limitations, as well as suggestions for future work. The publications themselves are finally included as appendices.
2. The Small Satellite Concept

This section begins by tackling the research questions posed earlier from the concept of a single small satellite, the Aalto-1 CubeSat. Publication 1, on which this section is based on, concentrates on explaining the mission and its goals, as well as its technical details from satellite to ground segment. However, the project that created the Aalto-1 CubeSat worked as a test bed for many relevant issues for this thesis, such as an example technical development (with Aalto-1 navigation subsystem as an example) and small satellite project management, which will also be discussed here.

2.1 The CubeSat as a case study

The most common type of small satellite is CalPoly’s [54] CubeSat standard conforming type. The CubeSat’s defining feature is it’s Cube-conforming volume enveloped. It also consists of PC104 computer boards from the computer industry and their specific stack connectors. The boards and their stack connectors enable ideally a plug-n-play style construction of the CubeSat according to selected one or multiple cube configurations, such as the popular three cube stack.

A CubeSat conforms this way into a so-called deployment pod, which is essentially a closed-wall container for the CubeSat. This then enables the one-off verification of withstanding launch conditions of the deployment pod as well as new, more relaxed verification procedures for the satellite inside it. If something unexpected would occur, for example the satellite would break up during launch, the deployment pod would protect the rest of the launcher’s payloads from harm. Several versions of the deployment pods have been made (see [8], [20] or [24] for examples).

In addition to physical standards, the CubeSat standard defines several
The Small Satellite Concept

Figure 2.1. Aalto-1 was integrated in a QuadPack. The QuadPack is made out of four three-unit deployment pods, in one combined structure.

operational rules and limitations, such as antenna deployment after 45 minutes of main deployment, again to mostly make the CubeSats acceptable onboard a launcher or another satellite. See [8] for details on the CalPoly standard. The CubeSats thus follow a fairly comprehensive standard in most of their design and development process, which is an important factor in speeding up its development.

In order to gain a better picture of the CubeSat standard and what it entails, the most important requirements for a CubeSat are summarized:

- The most obvious design requirement is to fit the satellite inside the deployment pod specified by the standard. This means the satellite has to adopt roughly 10x10x10 cm Cube-shape, and can stack these shapes according to the availability of qualified deployment pods (one to three cubes long satellites, and more recently two by three unit satellites). The pods themselves can also be stacked together as in the case of the QuadPack into which Aalto-1 was placed, see Figure 2.1.

- The subsystems inside the satellite have to conform their form factor according to the PC/104 pc standard.

- The satellite bus electrical interface main conduit throughout the structure is the stack connector of the PC/104.
• Operational requirements demand that the satellite starts its operation ("powers up") and deploys its deployables (such as antennas) half an hour after release from the deployment pod. The satellite’s communication system should not start transmitting anything until 45 minutes after release.

The CubeSat popularity has been led by mainly smaller public entities, such as universities (indeed as the CubeSat was developed by CalPoly) and research institutes. The popularity growth has been high with a hockey stick-like curve forming, see Figure 2.2. [53] points out that their applications tend to be limited - during past years most missions have in fact been technology demonstration by Universities and other research entities with a goal to space-grade their technology for more credible development in space use, as well as for education. A few commercial entities dominate currently most of the commercially targeted small satellite launches, and the newest application of them has been as credible scientific missions, most recently (and prominently) NASA’s CYGNSS constellation [1] (not CubeSat), the 6U TEMPEST [43] and the planned TROP-ICS mission [29] (12 three-unit CubeSats). A list of various other scientific missions can be found in the work of [40], as well as a comprehensive review in [14].

Aalto-1 is a research effort in understanding how to speed up space mission development and realization, keeping related costs down. The Cube-
Sat standard was adopted early on during the project, and influenced the satellite by simplifying many of the design decisions that need to be done, which can be an especially difficult task for a (mostly) student team with little prior experience. The rising popularity of the CubeSat and the availability of COTS parts and even complete subsystems made for an attractive option. Other research teams around the world experiencing the same challenges created a community with which to exchange helpful experiences.

The project’s goals were also in line with what CubeSats have been used for by other missions, namely as technology demonstration “space-grading” the payload and the in-house built technology of the satellite. The goal was also to learn and understand the complete technology and process chains needed for a space mission. Indeed the Aalto-1 project aimed at not only building (and launching) a satellite, but also constructing the ground segment, support equipment as well as training personnel for all steps of designing, building and operating the space mission.

The adoption of the standard and its "ready" design solutions also helped with the payload development. Much hard work and detailed design went into the payloads, but their interfacing with the bus and platform structure in principle was to be more straightforward thanks to a largely fixed design set offered by the CubeSat standard.

### 2.1.1 The lessons learned

While publication 1 concentrates and explains in detail the technical and mission details of Aalto-1, this and the next subsection will describe the essential lessons learned during the project and the main managerial developments achieved. Aalto-1’s development process was greatly assisted by the ready standards provided by the CubeSat standard. While not complete, they nonetheless in the end either provided a ready design to start from or at least the direction from which to look for answers.

The actual COTS level of the subsystems purchased from outside manufacturers was lacking in many respects, and had several flaws, non-existent or patchy software and sub-standard quality. In many respects the satellite’s development was hampered by COTS subsystems arriving late or patching them up after arrival. The quality of some of the ground segment equipment, mainly developed based on the radio amateur community, was also sub-standard.

Overall, subsystems of Aalto-1 built in-house fared better - all in-house
The Small Satellite Concept

Built subsystems were designed so as to employ COTS components, with the main consideration for their endurance in the space environment (such as radiation) being their past references (for example, whether the component had been used in previous CubeSat or otherwise missions). Publication 5 describes the navigation subsystem, which was based on Fastrax’s GPS receiver and a COTS antenna, which was developed into its Aalto-1 form mainly with the effort and help of the students and staff of the project. Help was also received from the original developers and outside partners during development and testing. The result was a subsystem designed and tested both stand-alone as well as together with the satellite engineering and flight models.

Generally concerning CubeSats, Aalto-1 payloads, while of good quality are of course of lesser performance than their larger cousins. This indicates probably one of the main lessons about small satellites: whether it be with passive or active payload instruments, they all suffer from decreased performance. Their usefulness then can come out of their development price, such that many more could potentially be deployed instead of one large satellite. This led to the consideration of what a space mission with many more of these satellites looks like, and led to the idea that temporality is what these satellites improve in the end. Thus, theoretically, in applications where many “quick and dirty” images of short in-between times are needed, many cubesats can be applied and so their inherent performance limitations are compensated by offering - essentially, increased temporal resolution for decreased spatial resolution.

The temporality benefits potentially offered by small satellites have to be weighed for their pros vs. cons. On one hand the possibility of getting more images from one particular target is certainly tempting and seen as useful, and might find different applications; on the other hand, this is achieved with smaller satellites which results in smaller apertures, more difficult power budgets as well as storage and downlink of the payload data, which increases along with the increase in temporal resolution. For active imaging instruments CubeSats become infeasible, and depending on the instrument, even significantly larger bus platforms might not be sufficient. A review of applications and challenges is given by [47]. More ground stations are thus needed to handle the larger downflux of data coming from the expected constellations.

For communications, small satellite constellations face similar problems as remote sensing, and are limited again mainly by aperture, power and
Concrete examples of systems using small satellites for communication and data relay planned or implemented are rarer, with OneWeb reportedly planning to use less than 200 kg satellites [19]. More exotic communication solution technology demonstrations with CubeSats include inter-satellite link constellations [34]. The Aalto-1 CubeSat project also gave valuable lessons on the launch issues facing small satellites. If small satellites in this context are grouped as satellites requiring piggyback ride to an orbit (parameters of which are chosen by the primary payload of the launch, with generally little if at all influence by the secondaries [12]), then in theory launch opportunities are abundant as often launchers tend to have spare mass. In practice however, things fall short of this, as the piggybacking satellites are going to space only when their primary is going, and do not have more than a few suitable launch opportunities per year. Also less urgent primary payloads due to crowded launch rosters tend to lose their position in the queue. Aalto-1 is a good example, as it had to endure more than a year and a half of launch delays, as the satellite’s launcher SpaceX suffered failures and prioritized down the primary satellite with which Aalto-1 was supposed piggyback (this happened several times). An alternative to piggyback launches is a custom launch with a dedicated small launcher system where the small satellite is the primary. This won’t decrease financial launch costs (on the contrary), and from a technical point of view such a launch system is less efficient.

2.1.2 New project and technical management aspects beneficial for rapid space missions

The project management and organizational structure around the satellite and associated ground segment was under constant development throughout the project. Publications 4 and 6 describe this. Early on many common industry practices were discovered to be unsuitable for the task of building a CubeSat with a student force. Throughout the project, more than a hundred people were involved (with only a few staff) and at any given time during the project there were 5 - 10 people actively engaged. The most influential force on the change of practices was the student team in flux, with new students constantly arriving at the project and old ones graduating from the university, often taking the knowledge and experience gained during the project with them. This put stress on how issues such as documentation and in-team communication was to be handled, as
well as between the external payload and subsystem manufacturers.

A rigid release version system, with paper-based documentation, was initially tried along with a wiki-based community approach for day-to-day communication. However, as outdated documentation was constantly being used by the teams (internal and external manufacturers), critical information was not always reaching the right persons. As a solution to this, all satellite and ground segment relevant interfaces, mission goals and requirements (mission and technical) and system technical budgets were all transferred to an online cloud-based service (mainly Google Drive excel sheets) so as to be found and editable by the relevant team members. Generally all relevant information and documentation used and created in the project was uploaded to the Google Drive for easy sharing. In the continuation Aalto-2 project this system was developed further to include direct derivation from the mission statement and goal, the mission and technical requirements all to be contained in the same online document.

The verification and testing process of the Aalto-1 satellite was also significantly different from larger traditional space missions. The normally rigorous test campaigns were alleviated thanks to partly relying on some COTS subsystems, and new testing approaches could be more readily applied. Though the satellite was built and tested with a separate engineering model and flight model approach, there was no clear cut starting time for a test phase during the project but rather each subsystem was iteratively tested by itself, as part of the engineering model and, finally, in acceptance tests as the flight model. The satellite due to its standard form factor and small size was from a practical point of view easier to test, as it could be readily transferred to the test site and associated test equipment. As an example, Publication 7 depicts the magnetic overview of the complete engineering model CubeSat in a magnetometer cage using an improved algorithmic approach in the test data processing.

The CubeSat onboard computer is running a Linux-forked operating system. This introduced both challenges and opportunities - the satellite’s software development was initially made slightly easier thanks to it, and during late-development a direct ssh-connection to the satellite helped in “last-minute” development. Overall, however, no significant development advantages came from using Linux in the satellite’s onboard computer.
3. Constellation Missions

As was the case with Aalto-1, smaller satellites tend to have a poorer performance due to their smaller size, especially when aperture sizes and power production matters, and so their most useful application boils down to using several of them in a concerted effort to improve either remote sensing temporal resolution or planetary coverage. This led to the consideration that the small satellites should be viewed as pieces of a larger system, and so the question arose of how effective small satellites can be in a constellation. If each satellite in the constellation would have an identical payload and bus, its function and performance would be the same, thus creating the situation where one satellite would appear to be in many locations at the same time. It would also be easier and less expensive to manufacture.

The constellation concept in turn created several interesting questions with which to evaluate the feasibility and benefits of the concept. The most important of these was the effect of the orbits chosen, and whether concentrating on a certain area on the planet would be beneficial, leading to Publication 2. The chosen application in this publication was remote sensing.

3.1 The importance of orbits

Arguably the most important element of a constellation is the orbits of its constituent satellites keeping in mind its intended application target. Whether it be communication or remote sensing, the orbit of each satellite should be chosen carefully with respect to the whole, considering also that all the constellation’s orbits evolve in time. Publication 2 concentrates on a remote sensing constellation in Earth’s polar regions and lays in detail the requirements and choices leading to a certain type of constellation or-
bit configuration in terms of maximizing revisit time at the target regions. The constellation orbit parameters need to be finetuned in the end to achieve a certain set of goals, such as better revisit time for remote sensing applications. As an example, the constellation often needs to be either symmetric for global coverage or in some cases concentrates into a certain area by utilizing, for example elliptic orbits [57], or in the case of a communication constellation, needs to have essentially global coverage and good line-of-sight between the element satellites.

3.2 Constellation benefits

The main benefits for a constellation considered during the study performed in Publication 2 were for imaging applications the possibility of "quick and dirty" imagery (irrespective of imaging instrument) either for some specific locations, or with a larger constellation, eventually anywhere on Earth. While such imagery has a certain demand, as coarser and more frequent satellite imagery can be used to identify areas of concern and then dynamically “zoom in” on the critical regions by using high-spatial-resolution image data [60], the imagery will be by definition (thanks to smaller satellites having smaller apertures) of poorer quality. Also important factors such as how much each satellite needs to recharge its available power and how much data it needs to downlink per image taken. This makes the constellation’s true capabilities being limited, as now each satellite has to wait either to recharge enough or for a suitable data downlink opportunity, both functions not being in the small satellite areas of strength either.

While not covered by publication 2, another often envisioned application for small satellites is in a communication constellation. The argument of size vs. performance applies here as well - smaller antenna apertures and solar panels make for a weaker signal and less bits transferred. Most of a communication constellation aims for global seamless coverage and so requires a significant number of satellites (notable examples being Iridium, and more recently the wireless internet plans of OneWeb with their thousands of satellites [19]). Thus if a standardized small satellite is able to satisfy the requirements of a communication constellation, then the overall constellation price tag will drop due to the inherently smaller size and standard manufacturing of each satellite.

The inherent limitations of smaller satellites also force looking into other
benefits that the space environment can offer. One example is the proposed "quantum internet” or quantum communication satellite constellation enabling theoretically unbreakable encryption [6], which uses the lack of atmosphere (or any other obstruction) between the constellation satellites to avoid decoherence of their quantum entangled signal [58].

3.3 Constellation requirements

When considering the benefits a constellation can bring to a certain application, a few main requirements that drive the cost, complexity and capabilities of a small satellite (or in fact any) constellation were identified: getting the satellites to their exact orbits, as well as downlinking produced/transferred data down through the bottleneck the ground segment forms. In addition, the need for a repeatable manufacturing process for complex parts and systems was also identified as an element, that although not absolutely essential (and not discussed in Publication 2), might in practice be necessary to keep costs down.

3.3.1 Launch opportunities

In practice, the small satellite concept has only to a certain degree sped up and made access to space easier. Chronic launch delays and even individual launch failures (such as that by Orbital Science’s Antares, and two SpaceX Falcon 9 failures) affect the amount of small satellites launched per year, as seen in the dip of launched CubeSats in the period 2014-2016, causing a large backlog and a record expected launch year for 2017, see Figure 3.1. Piggybacking spacecraft are lower in priority for launchers, and are more likely to be fit as an additional ballast rather than the value they offer as customers. The launch services providers have few incentives and no clear business case to provide secondary payload services even if their customers were to allow it [30]. In the case of Aalto-1 CubeSat piggybacking with more than 80 other small satellite onboard the SHERPA dispenser system [18], the primary payload of the launch - a Taiwanese weather satellite - was constantly delayed and put back down the launch queue and along with it went the CubeSats. The orbits offered by piggyback launches are chosen based on the need of the primary payload. Secondary payloads have to then live with this orbit. If it's a more popular orbit such as, for example, a sun-synchronous
low-Earth orbit, then many small satellites performing simple technology demonstrations (or other mission in which an exact orbit is not critical) accept it and jump aboard. If a secondary payload (often small) satellite wants to get to a specific orbit which is different from a primary's target orbit, as is the case with constellations, then what remains is some situation-specific deployment strategy or propulsion onboard the satellites themselves [11]. The satellite has to carry its own propulsion, either as an integrated part of it and the mission, or as a last-stage temporary attachment. Then additional mass needs to be added as a payload from the launcher's perspective. The satellites can also simply ignore finalizing their orbits with respect to the remaining constellation and form "ad hoc" constellations with non-optimal performance as suggested by [27].

Another approach is to use individual, more tailored launches, which launch fewer or just one small satellite payload, but have a more frequent launch rate. In practice, this means smaller space launchers. Although several different small launcher systems targeting the small satellite market have been developed or are in development (ranging from air launches to converted ICBM submarine missiles) their "per kilogram to LEO orbit" for a maximum LEO capacity prices are generally even higher than that available for larger, more collective launches [7]. While technologically these types of launcher systems might be able to get their payload small satellite to a LEO orbit close to its wishes, such as inclination and node, higher than LEO orbits remain out of reach. This inherent inef-
efficiency narrows down the applications of these small launchers, making the whole concept useful only for a niche of missions to LEO which have high relative but low absolute launch costs, rather than a long-term solution for space applications and development.

In addition, if the target orbit of the small satellite is low enough, it will need propulsion after deployment to compensate and maintain this orbit due mainly to atmospheric drag [26].

### 3.3.2 Propulsion

As mentioned earlier, low enough orbits require propulsion for long-term missions. Propulsion is also needed to reach the target orbit after the launcher has deployed the satellite, so that the constellation satellites are correctly placed with respect to each other. The total impulse requirements for this can be quite high as discussed in Publication 2 and can make the resulting requirements for an onboard propulsion system demanding. Such a system will be necessary for a constellation that uses piggyback launches, adding to the power demands and complexity of the satellite (especially in the case of electric propulsion)(for a good overview see [4]). For satellites using smaller custom launches, the target orbit and the perturbing forces in that orbit determine the level of propulsion required.

### 3.3.3 Ground segment

Publication 2 did not cover in detail the ground segment, but with research into this area, it became clear that the demands on the ground segment also increase with a constellation of satellites. For example, if the constellation aims for speedy imaging, the ground segment coverage can become a bottleneck, as the satellite has to wait to be in view of the ground station to downlink the images it has taken.

[49] describes well the major points that make the ground segment coverage such a complex topic in itself - as an example of the myriad parameters that matter, satellite inclination, altitude, ground segment latitude and amount of ground stations significantly affect the percentage of ground segment coverage and daily access times [50]. [33] shows a few higher throughput constellation examples. The situation tends to be worse for communication constellations as their application works by offering, ideally, seamless communication. Inter-satellite communication
Constellation Missions

links have been proposed as a possible solution, see [42] for a review of some systems studied.

3.3.4 Repeatable manufacturing process

Each satellite should have (at least roughly) similar properties in order for a constellation to have a fast revisit time or a large coverage, or at least similar properties when in a dedicated subsection of a constellation. If each satellite has its own bus configuration or payload, each satellite will create a differing product and thus application. Besides the process of design (discussed with a CubeSat as an example earlier in Chapter 2), the manufacturing process and standardization play an important role in being able to manufacture several small satellites with identical (or at least similar) designs. This requirement of having the capability of manufacturing complex systems with repeatable quality led to the consideration of additive manufacturing during this work, as it has been studied in the past as a potential method for cheap and fast complex parts suitable and revolutionary for space technology. The next chapter deals with the results of research into combining additive manufacturing and another revolutionary manufacturing method, atomic layer deposition.
4. Small satellite rapid development and manufacturing

4.1 Additive manufacturing as part of a new approach to space technology

Additive manufacturing (AM) has been considered widely in the recent past to be able to produce customized and complex systems (or in the long-term possibly even complete spacecraft) relatively cheaper and faster than more traditional manufacturing methods [10] especially in the aerospace sector [46], and is capable of manufacturing these complex systems with a steady and often better design quality (no joints between different parts for example). [39] and [35] give a range of example use-cases, from organ printing to aircraft. AM thus represents an interesting approach to answering the requirement of repeatable manufacturing for small satellite constellations. As most components in aerospace tend to be complex and with low manufacturing volumes, typical manufacturing times in the aerospace industry can take from weeks to even months. With additive manufacturing, on the other hand, the amount of time needed can be decreased to days. An extensive review of the benefits (and costs) of additive manufacturing can be found in [55]. With good planning, parallel development and testing, a satellite can be reliably built and deployed from these components. Small satellite development times drop, in theory at least, as the size and complexity of the mission lessens (but not necessarily that of the satellite), with typical development times from conception to launch of around 3 to 5 years according to [17] for 3-50 kg satellites, for CubeSats 1.7 to 3.8 years according to [44], while according to [48] "single-sensor" small satellite platforms have a development time of 24 to 36 months. If, for the sake of argument, a CubeSat is taken as a reference size again and three years is taken as a reference time for "from the design board to
launch” development, the quick prototyping of complex parts in a satellite (as well as manufacturing their flight versions) with additive manufacturing could shave off a significant amount of time and cost from prototyping and manufacture of those satellite systems that are applicable to additive manufacturing. The same logic applies to any sized missions. When comparing the different methods and selection of materials within AM, plastic AM is still the most popular and affordable. While metal AM has obvious benefits for high-temperature and force applications such as rocket nozzles (see e.g.[28]), for other components plastic is sufficient, being more lightweight, faster and cheaper to produce. Materials like polyether ether ketone (PEEK) and polyether ether ketone ketone (PEKK) are rising in popularity specifically for aerospace applications, but the most commonly used material in the general plastic AM community is still acrylonitrile butadiene styrene (ABS) [37]. All of these plastics however tend to have a limited endurance to the challenges of the space environment. These ideas formed the basis for publication 3, where the aim was to study a novel method of potentially improving for space-use cheap AM plastic, such as ABS, using atomic layer deposition. Other interesting materials for AM aerospace applications include:

- Metal, including aluminum, titanium, brass, bronze, steel, silver, gold and platinum. Ceramics are also possible.

- Combinations of plastic and other materials, such as magnetic and conducting materials.

- Flame-retardant polyamides [36].

- Self-assembling "4D printing" materials [56].

### 4.1.1 The challenge of space as an environment

Space as an environment is very challenging for plastics. Threats like ultraviolet (UV), high vacuum, atomic oxygen (and other species) and high launch loads damage the material throughout the mission. UV and atomic species degrade the material gradually, outgassing due to vacuum can cause problems to payload lenses, solar panels and other sensitive sur-
faces, and forces endured by the material during launch can break it. A good review is done by [16].

4.1.2 Atomic layer deposition

The aim of this subsection is to introduce Atomic layer deposition (ALD) to the reader as Publication 3 contains less details about the actual process. ALD is a vapor phase technique that is able to deposit a uniform thin film over an object, in such a way that the coating is of very similar quality throughout the entire surface of the object. ALD film thickness can also be controlled down to the Angstrom level. The different layers in the film can also be controlled, so that even several different material layers can be used to compose the coating film. The phases of the technique with which the film is built are described in Figure 4.1. A good review of ALD is done by [15]. Essentially, each layer is built by a satu-

![Figure 4.1](image)

Figure 4.1. (a) The process begins from the bare substance, which has either natural functionalization or treated to have such. (b) Next, a reactant, precursor A, is released in a pulse into the chamber and starts to react with the surface substrate, until (c) the surface is covered, reaction stops and reaction by-products and excess precursors are purged with inert gas (such as N2 or argon). (d) Precursor B is released in a pulse and reacts with the surface made out of precursor A, after which (e) again the excess precursor B and by-products are purged. In (f), (a)-(e) are repeated until the coating is of a desired thickness. Adopted from [23].
rating, cyclical and self-limiting procedure of great precision. Compared to other coating methods, ALD also operates often at significantly lower temperatures. This is beneficial for additive manufactured plastic materials, as they typically have glass temperatures less than 200°. When combining AM and ALD, the question of process temperature is critical, as ALD becomes more efficient and more coating materials become available at higher temperatures. However, for plastic AM the opposite occurs and materials availability shrinks. If the process happens serially, wherein the AM is first produced and then coated, ALD at higher temperatures risks melting the AM plastic being coated. This balance is essential in this method and requires the designer to carefully choose the materials used, as they are to a certain extent dependent on each other.

A wide range of materials suitable for ALD exist such as can be seen in [31]. The ALD coating study in Publication 3 was performed with aluminum oxide as it is relatively well understood and has a low process temperature, but examples of other interesting ALD applications for space technology include:

- Titanium oxide in combination with aluminum oxide, opaquing the film for UV light and thus mitigating its effects in Space [32].

- New developments in fuel cell technology, such as by [22].

- ALD has long been considered and used in microelectronics and nanotechnology, where fairly intricate nanoscale designs could be produced with it [25]. With a careful design, this could potentially be developed into better radiation protection for electronics onboard space missions.

- ALD is used already in a large variety of photovoltaics applications, ranging from improving their conversion efficiency significantly [5] to transparent conducting oxide [3] usable as e.g. an environmental protection. Space missions have throughout its history heavily depended on photovoltaics as a primary power production method, and so as ALD enables new improvement in photovoltaics it is also natural that it should contribute to space technology development.
Many of the materials that can be used in ALD can in principle be combined in order to be able to create composite films with other useful properties [23].

### 4.1.3 Combination of ALD and AM

This section is concerned with summarizing the results in Publication 3 and the perceived benefits in combining AM and ALD, with an emphasis on space technology.

The benefits found during the study were indications of structural integrity and possible decreased outgassing for increased temperatures of the test pieces. The fluidics test piece also seemed to have improved flow properties. With further research and development, this can then present the possibility of a practical method for relatively fast "space grading" of additive manufactured parts, speeding the manufacturing process of (small or otherwise) satellites.

If AM can speed up development and manufacturing of space systems, then the choice of material can be a limiting factor if the material is vulnerable to the space environment. If ALD in turn can effectively broaden the choice of materials, then the development and manufacturing process will accelerate even further by using the technically simplest application of ALD, a gas diffusion barrier. Faster ALD methods, such as ultrafast ALD [41] (or more specific methods such as [9]), can further this.

Furthermore, it is not far fetched to expect that in the longer run it would be possible to combine, respectively, the micro and nanometer-level precision of AM and ALD as one process, and in so doing open a whole new range of opportunities and applications, many of which might be beneficial for space technology.
Small satellite rapid development and manufacturing
5. Summary of Publications

This chapter summarizes the publications in this work.

5.1 Publication I: Aalto-1 nanosatellite - technical description and mission objectives

The aim of the publication was to describe in detail the satellite’s goals, mission and technical specifications. The publication was the first comprehensive peer-reviewed publication on the Aalto-1 CubeSat. Another publication will be written by the author of the mission first results once the satellite has been launched and operations begin.

The satellite was primarily a research and educational tool, but also aimed for real-world results by demonstrating the technology of the three payloads of the satellite. The Finnish Technical Research Center’s hyperspectral imager is relatively advanced in technological terms compared to its peers, and enables multi-channel spectral imagery in the 500-900 nm range while still being able to easily fit into a CubeSat. Another payload was the CubeSat-fitting radiation monitor jointly developed by the universities of Helsinki and Turku. This monitor is based on the technology developed during BepiColombo, and measures a range of radiation in orbit, concentrating especially on interesting radiation phenomena such as the South Atlantic Anomaly. The third payload was a plasma brake, developed by and based on the Finnish Meteorological Institute’s e-sail technology. The payload seeks to demonstrate that the technology behind the e-sail is capable of deorbiting a satellite.

All of these payloads had their own requirements especially with attitude control, and so the mission was planned to be performed in steps. After commissioning, the satellite will run the spectral imager and radiation monitor 6 to 12 months with an attitude pose pointing the imager...
towards nadir. After that, the plasma brake operations begin, with a period of careful untethering and spinning up the satellite around with a rotation axis through the transferred common center of mass when the brake’s reel is out. The plasma brake then slows down the satellite’s velocity with the Coulomb drag it aims to generate when operational.

The satellite communicates will be performed using two channels, UHF and S-band, the latter used primarily as a one-way downlink of collected payload data during the mission. The satellite communicates with Aalto University’s own ground segment, which was also built by the Aalto-1 project during the course of the project. The satellite is capable of performing its missions in a variety of low-earth orbits from 500 - 900 km altitude, with basically a polar orbit being the only requirement.

As a result, the study outlined how the CubeSat Aalto-1 will be capable of not only a technology demonstration of three very different payloads, but also of running a comprehensive science campaign with those different payloads.

5.2 Publication II: Small Satellite Remote Sensing Constellation for Fast Polar Coverage

The goal of this publication was to study suitable orbit configurations for constellations making possible fast coverage of the polar regions with two hours or less revisit time. The constellation was designed to concentrate on the 60 to 85° latitude, and considered several orbit configurations with a number of satellites in each. The results indicated that a Walker Delta configuration performs best. The number of satellites needed depends on the altitude of the constellation: at a 1000 km altitude, four satellites are needed; at 725 km, six satellites; and at 450 km, eight. It was found that the altitude choice depends on the requirements of the imaging instrument. When using secondary payload opportunities, the satellite needs an onboard propulsion system capable of delivering relatively high \( \Delta V \) in order to get the constellation satellites to their intended orbit parameters from the initial orbit in which they are left by the launcher. The publication also suggested that differential orbits based on natural precession are relatively cheap \( \Delta V \) alternatives to launcher selection and large propulsion systems, but require significantly more time to form the constellation.
5.3 Publication III: Towards space-grade 3D-printed, ALD-coated small satellite propulsion components for fluidics

This publication aimed at studying how manufacturing of complex systems and components could be performed more effectively and with novel results by employing additive manufacturing (AM) and atomic layer deposition (ALD) in a method that combines both. In-space propulsion was used as the test case, and simple mass flow restrictor components were designed which employ the venturi-effect to restrict the flow of mass through them. These and simpler, smaller test pieces were made from several plastic materials suitable for use in additive manufacturing, and were coated with aluminum oxide in order to see the potential of the coating as a gas diffusion barrier, as well as whether it affects the properties of the flow going through the restrictors. Out of four commonly used plastics in additive manufacturing, two turned out to be suitable for ALD, acrylonitrile butadiene styrene (ABS) and polyamide PA 2200. The test were made with a simple bang-bang flow controller and a mass spectrometer, and a scanning electron microscope and energy-dispersive x-ray spectroscopy confirmed that the coating had formed.

As a result, for ABS there were indications of increased structural integrity as well as some slight indications of decreased outgassing at higher temperatures. The flow properties of ABS and PA 2200 were also improved, likely due to the ABS print smaller cracks being patched up and the PA 2200 print surface smoothing out during the coating process.

5.4 Publication IV: Aalto-1 Earth Observation CubeSat Mission - Educational outcomes

This publication summarized the methods and results of the various educational and managerial processes and novelties tried and implemented during the Aalto-1 project. The size progression towards smaller satellites and the savings in launch prices coming from that has enabled smaller countries, and even institutions to join and start their own space technology projects more actively. Moreover, the adoption of standards for these small satellites made the development process feasible for even smaller student teams.

The popular CubeSat standard, especially in university circles, was further encouraged by university trends of more integrative teaching ap-
proaches. Throughout the duration of the project, students were involved in tasks requiring multidisciplinary teamwork, understanding of theory, practical and managerial skills, as well as primarily self-enforced use of schedules.

The result of the work was documentation practices which are more suitable for a small satellite student project compared to more traditional space projects, with emphasis on online documentation and peer/self-assessment besides more traditional forms of written documentation and student assignments.

5.5 Publication V: The Aalto-1 nanosatellite navigation subsystem: development results and planned operations

The goal of this publication was to describe in detail the technology and development behind one of the subsystems of Aalto-1, the navigation subsystem. The CubeSat relies on two-line elements provided by US Air Force, which give accuracy normally of around several kilometers. To improve on this, work on a GPS receiver system onboard the satellite was started.

The resulting subsystem consisted of a GPS receiver from the company Fastrax and an antenna from Adactus. The subsystem was designed upwards from the RF and electronic components themselves in Aalto University, and was tested with a GPS signal simulator with the help of Space Systems Finland, as well as during environmental and operational tests onboard the engineering and flight models of the satellite. The system together with the analysis tools developed for the purpose can determine the satellite state vector within 5 m and with a 0.05 m/s accuracy.

5.6 Publication VI: Online documentation approach for assisted system engineering and assessment in student projects.

This publication aimed at describing the online documentation system created and adopted during the Aalto-1 CubeSat project. A novel system was needed as earlier, more traditional aerospace project documentation and management practices were not an ideal match for use in (primarily) a student project where the membership was in a constant flux, the input of the workforce was unsure and communication could at times be patchy. The analysis and development work described in the publication resulted
in online tools (using such online content sharing platforms as Google Drive) where up-to-date system engineering information and project documentation can be effectively shared between the different working teams.

5.7 Publication VII: Particle Swarm Optimization with Rotation Axis Fitting for Magnetometer Calibration

This publication analysed the use of a novel algorithm used in calibrating the magnetometer results of the Aalto-1 magnetic tests. It combined scalar checking with a novel rotation axis fitting objective and avoids the requirement for perfectly aligned measurement axis. This algorithm is able to improve on the standard particle swarm optimization (PSO) algorithm implementation in the magnetic domain without the need for compromising the number of estimated parameters. The simulations show that the improved algorithm is capable of accurately estimating calibration parameters under varying ambient magnetic field magnitudes of, as well as where the algorithm’s accuracy is affected by data quality (such as small number of data points), unbalanced loci in one side of the sphere, and noise level.

The experimental test was performed for the engineering model of Aalto-1 nanosatellite at a magnetic test facility operated by the Finnish Meteorological Institute.
6. Concluding remarks

This thesis work aimed at a more efficient and speedier development of space missions using small satellites and their related technology as a tool for research. It was a cross-sectional study through a complete nanosatellite mission, Aalto-1, and during the project tackled all of its technical and managerial problems, from the chalkboard design of the satellite to finishing the ground segment and to the project team management. The project helped in determining better the potential and limitations of small satellite technology. A result of the development of Aalto-1 was the realization that constellations are a natural application for small satellite technology, and that this technology in turn opens up a range of new, previously impossible applications.

The concept of small satellites within a constellation also presented several limitations as well as requirements, which were delved into and evaluated during the thesis. This led to deeper research into one of these requirements - efficient and fast manufacturing. Additive manufacturing was seen early on as an attractive method of developing and producing space technology components suitable for all sized space missions. Additive manufacturing however faced issues of material selection and durability in space, leading to consideration of combining this method with another powerful method, namely atomic layer deposition, which can produce nanometer-level structures and gas diffusion barriers.

The thesis made solid contributions to the research and development of space technology in several ways. The work was essential to starting and developing the CubeSat mission Aalto-1, a mission which itself as a mission achieved novel technological development. The direct technology developed in Aalto-1 and its continuation project Aalto-2 was spun off later into a start-up company. The work performed on a constellation design was a continuation of Aalto-1, which eventually spawned another com-
Commercial spin-off utilizing the technology.

The combination of additive manufacturing and atomic layer deposition methods was an innovative research topic, as not much previous research on this specific topic exists. Various polymers and plastic have been coating with ALD in an effort to create a gas diffusion barrier. None, however, have concentrated combining micro-scale AM and nano-scale ALD to study the effect of their combination.

The thesis questions posed at the beginning of this work can be answered as such:

• Is it possible to decrease a space mission development timeline using lower mass, standardized space technology (small satellites), and is the mission able to then produce novel results? Yes it is. Aalto-1 as a project was a thorough cross-section of a space mission which, while physically smaller and thus cheaper, had many of the challenges and complexity of a traditional large space mission. The project began with almost no resources and little practical experience, and in order to achieve progress had to redevelop many technical and managerial processes to work effectively in a CubeSat mission. Publications presented in this thesis give concrete examples of how to decrease the development timeline and improve process efficiency, such as by using the CubeSat standard, COTS components as well as more flexible and faster communication and documentation tools.

• What are the main bottlenecks and benefits associated with small satellite technology? The study has shown light on the limitations of small satellite technology, which are important and have to be considered carefully during the whole design process starting with already with the mission statement. The size of the satellite directly relates to the performance of the payload instrument. The size also affects power production and communication apertures. All of these limitations limit also the range of applications where smaller satellites can be used. Benefits in turn include faster development time, as well as the possibility for a more cost effective mission.

• How influential is orbit design for small satellite space missions? Orbit design is important especially for constellations, as all satellites work in synchrony and with certain parameters dependent on complete constel-
Concluding remarks

lation goals, as well as environmental factors (air drag, for instance) that orbit maintenance. Launch opportunities and strategies with which the constellation can be built have to also be carefully considered. Constellations are likely to be one of the main applications for small satellite missions, as while their payload performance decreases with decreasing size, their temporal resolution in turn increases with larger numbers of satellites working together.

- *Is the combination of additive manufacturing and atomic layer deposition effective technology for a space mission?* Yes, the research into the combination of additive manufacturing (AM) and atomic layer deposition (ALD) revealed indications that ALD could potentially protect AM components from the space environment and launch loads.

The analysis points to several directions which would enable more rapid space missions. Two of the areas which require further work and which are closely linked to this thesis are - firstly, further research and development of the combination of additive manufacturing and atomic layer deposition, and secondly how to accelerate and make new technological development with this new combination. Both additive manufacturing and atomic layer deposition by themselves have a very broad range of current and possible future applications, and the range of applications for their combination can potentially be even broader. The work should develop new applications that use the possibility of the small-scale complexity that both technologies are inherently capable of creating, and how that can be effectively combined and used to create applications, particularly in the context of space technology.

This work should be continued again using small satellites as tools thanks to their relatively affordable costs and quicker development times. As especially CubeSats can be developed and built relatively quickly, new technology such as AM components enforced with an ALD coating can be developed parallel with the rest of the development of the satellite, taking advantage of the testing and verification procedures a satellite and its components have to endure in order to be comfortably sent to space. The technology is already being tested in the Suomi100 CubeSat project, where one of the components of the satellite is designed for and built with AM.

Secondly, more work is required in future to study constellations and their
Concluding remarks

applications as well as limitations. As small satellites are ideal for use as constellations, the recent trend in mega-constellations involves hundreds or even thousands of them working together in orbits. This direction opens even more applications as well as makes some of their current limitations even more difficult. Thus a working solutions how such constellation systems could efficiently overcome, or at least lessen, these limitations becomes even more important.

Future research work should also include working with this problem starting from the other side - looking into and developing more refined applications for small satellites, which better take into consideration the capabilities of that technology.
References


[22] Sanghoon Ji, Gu Young Cho, Wonjong Yu, Pei-Chen Su, Min Hwan Lee, and Suk Won Cha. Plasma-enhanced atomic layer deposition of nanoscale


[34] Paul Muri and Janise Mcnair. A survey of communication sub-systems for intersatellite linked systems and cubesat missions. *Journal of Communications*, 7(4), Jan 2012.


