Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Measurement
Study Branch: Cybernetics and Robotics

Cubesats Tandem Flights

BACHELOR THESIS

Author:	Šuhajda Matej
Thesis Supervisor:	prof. RNDr. René Hudec, CSc.
Year:	2024

BACHELOR‘S THESIS ASSIGNMENT

I. Personal and study details

Student's name:	**Šuhajda Matej**	Personal ID number:	**507347**
Faculty / Institute:	**Faculty of Electrical Engineering**		
Department / Institute:	**Department of Radioelectronics**		
Study program:	**Cybernetics and Robotics**		

II. Bachelor’s thesis details

Bachelor’s thesis title in English:

Cubesats Tandem Flights

Bachelor’s thesis title in Czech:

Cubesats Tandem Flights

Guidelines:

The current rapid development of the CubeSat type of mini satellite and the rapidly increasing frequency of its implementation and application represent a potential for the implementation of student and scientific space experiments at universities such as CTU. In addition to the rapid development of proprietary CubeSat technologies and technical solutions, there has been a recent rapid development in their application for various scientific fields.

An interesting extension of application possibilities is represented by CubeSats in tandem arrangement or even multiple CubeSats in formation. For example, a tandem arrangement allows the design of a space telescope with a longer focal length, which would not be possible for a single CubeSat.

The student is expected to conduct a review of the status of tandem and formation flying CubeSats with a focus on the study of their mutual control methods with emphasis on the achievable accuracy (distance, orientation) and discuss the design of an X-ray telescope CubeSat mission consisting of two individual CubeSats. The final goal of the mission design should be a mission feasibility study and a subsequent discussion regarding the determination of the limits on accuracy and stability of the relative position of the two bodies. The feasibility study should include a discussion of an experiment recently under study at the CTU FEE namely a tandem flight with an X-ray telescope i.e. arrangement where one satellite carries the optics and the other one the detector.

Bibliography / sources:

[1] Maimi A. K., Agrawal V.: Satellite technology-principles and applications, Wiley 2007, ISBN: 978-0-470-03335-7
[2] Fortescue P.,Stark J., Swinerd G.: Spacecraft systems engineering, 3rd edition, Wiley 2003, ISBN: 978-0-470-85102-9
[3] Tribble, Alan C.: Space Environment Implications for Spacecraft Design. Princeton University Press 2003, ISBN: 978-0-69-110299-3
[4] Bryson, Arthur E. Jr.: Control Systems for Aircraft and Spacecraft. Princeton, 1994. ISBN: 9781400880034
[5] CubeSat101: Basic Concepts and Processes for First-Time CubeSat Developers, NASA CubeSat Launch Initiative.
[6] Mission Success Handbook for Cubesat Missions, NASA Goddard Space Flight Center
[7] Nanosatellites and Applications to Commercial and Scientific Missions, Adriano Camps.
[8] Small satellites for space science: A COSPAR scientific roadmap, Robyn M. Millan, Rudolf von Steiger, Meir Ariel, Sergey Bartalev, Maurice Borgeaud, Stefano Campagnola, Julie C. Castillo-Rogez, René Fléron, Volker Gass, Anna Gregorio, David M. Klumpar, Bhavya Lal, Malcolm Macdonald, Jong Uk Park, V. Sambasiva Rao, Klaus Schilling, Graeme Stephens, Alan M. Title, Ji Wu.
[5]-[8] cubesats related handbooks are for download here; https://moodle.fel.cvut.cz/course/view.php?id=8096

Name and workplace of bachelor’s thesis supervisor:

prof. RNDr. René Hudec, CSc. Department of Radioelectronics FEE

Name and workplace of second bachelor’s thesis supervisor or consultant:

Date of bachelor’s thesis assignment: **12.02.2024** Deadline for bachelor thesis submission: **24.05.2024**

Assignment valid until:
by the end of summer semester 2024/2025

prof. RNDr. René Hudec, CSc. Supervisor’s signature	Head of department’s signature	prof. Mgr. Petr Páta, Ph.D. Dean’s signature

III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

. Date of assignment receipt	Student’s signature

Declaration

Čestne vyhlasujem, že som túto prácu vypracoval samostatne na základe získaných teoretických vedomostí a že všetkú použitú literatúru a ďalšie pramene som v práci vyznačil.

V Prahe dňa ....
Šuhajda Matej

Acknowledgement

Ďakujem prof. RNDr. Renému Hudecovi, CSc. za vedenie mojej práce.

Šuhajda Matej

Názov práce:
Cubesats Tandem Flights

Autor: Šuhajda Matej

Študijný program: Kybernetika a Robotika

Vedúci práce: prof. RNDr. René Hudec, CSc.

Abstrakt: Táto práca študuje problematiku nanosatelitov typu CubeSat a ich použitie v rámci teórie distribuovaných vesmírnych systémov. Konkrétne sa práca zaoberá štúdiou spolupráce viacerých CubeSatov vo forme napr. formácií či konštelácií, spolu s analýzou možností na určenie a riadenie polohy a orientácie CubeSatu za použitia rôznorodých senzorov či aktuátorov. Sú rozobrané schopnosti a limity jednotlivých prístupov v tejto oblasti. Takisto sú rozobrané a diskutované možné prístupy k vzájomnému riadeniu a vzájomnej kontrole viacerých CubeSatov v rámci formácie. Vyústením a prínosom práce je štúdia uskutočniteľnosti vesmírneho teleskopu, pozostávajúceho z dvoch CubeSatov, ktoré by leteli vo svojej tesnej blízkosti, kde jeden by niesol optiku a druhý detektor. Takáto konfigurácia by umožňovala ohniskovú vzdialenosť, ktorá by bola väčšia než akú by bolo možné dosiahnuť s jediným CubeSatom.
Kľúčové slová: CubeSat, Tandem, Lietanie vo Formácii, Vesmírny Ďalekohľad

Title:
Cubesats Tandem Flights

Author: Šuhajda Matej

Study Branch: Cybernetics and Robotics

Abstract: This thesis studies the issue of CubeSat nanosatellites and their application in the framework of distributed space systems theory. Specifically, the thesis deals with the study of cooperation of multiple CubeSats in the form of, e.g. formations or constellations, together with the analysis of the possibilities for determining and controlling the attitude of a CubeSat using a variety of sensors or actuators. The capabilities and limitations of different approaches in this area are discussed. Additionally, relative control methods for multiple CubeSats within a formation are studied and discussed. The contribution of the work is a feasibility study of a space telescope consisting of two CubeSats flying in close proximity to each other, where one would carry the optics and the other the detector. Such a configuration would allow the design of a space telescope with a longer focal length, something which would not be achievable with a single CubeSat.
Key words: CubeSat, Tandem, Formation Flying, Space Telescope

Contents

List of Acronyms

AC	Attitude Control
ADCS	Attitude Determination and Control System
CalPoly	Californian Polytechnic State University
COTS	Commercial-Off-The-Shelf
CPDGPS	Carrier Phase Differential GPS
CPOD	CubeSat Proximity Operations Demonstration
CSS	Cosine Sun Sensor
DL	Downlink
DOF	Degrees-Of-Freedom
DSS	Distributed Space Systems
ELaNa	Educational Launch of Nanosatellites
EO	Electro-Optical
FF	Formation Flying
FOG	Fibre Optic Gyroscope
GNC	Guidance, Navigation & Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
IoT	Internet-Of-Things
ISL	Intersatellite Link
ISS	International Space Station
LEMUR	Low Earth Multi-Use Receiver
LEO	Low Earth Orbit
LICIACube	Light Italian CubeSat for Imaging of Asteroids
LIDAR	Light Detection and Ranging
LINUSS	Lockheed Martin In-Space Upgrade Satellite System
LoS	Line-Of-Sight
LRF	Laser Range Finder
MEMS	Micro-Electro-Mechanical System

MUSAS	Multi-CubeSat Relative State Determination by Array Signal Detection
NASA	National Aeronautics and Space Administration
PAN	Pathfinder for Autonomous Navigation
PPOD	Poly Picosatellite Orbital Deployer
RANGE	The Ranging And Nanosatellite Guidance Experiment
RF	Radio Frequency
R&D	Rendezvous & Docking
SoC	Street-Of-Coverage
TRL	Technology Readiness Level
UL	Uplink
VISORS	Virtual Super Optics Reconfigurable Swarm
VTXO	Virtual Telescope for X-ray Observations

List of Figures

List of Tables

Introduction

A disruptive innovation. This could be another term used to describe the paradigm shift caused by an eminent representative of the nanosatellite category, i.e. a CubeSat. This small, cubical satellite has managed to revolutionise the way we think about and conduct space exploration and research. It has allowed access to this particular area of science to many institutions, organisations, and the like because of lower development costs due to the availability of commercial-off-the-shelf components. Thousands of universities around the world have participated in space-related research thanks to CubeSats, which in turn opened new possibilities for student engagement.

CubeSat and the technology surrounding it have undergone rapid development in recent years, which has only magnified its popularity and resulted in an increase in its deployment. CubeSats arranged in tandem or in a formation open up new intriguing avenues of application. One compelling example is the potential to create a space telescope with an extended focal length, a feat unattainable with just a single CubeSat.

A feasibility study of this particular problem is one of the goals of this work. In the spirit of this, the thesis begins by introducing the term CubeSat and showcasing the impact it has had on the world of space-related research. Chapter 3 introduces the theory of distributed space systems, which paves the way for the next four chapters, i.e. Chapters 4-7, where CubeSats and their applications are studied in particular deployment arrangements. The Guidance, Navigation, and Control theory of CubeSats is contained within Chapter 8, where the nature of various sensors and actuators is closely examined. Chapter 9 contains a discussion of various possible approaches to relative navigation between multiple space vehicles. This leads to the last and final chapter of this thesis, which, among other things, contains the aforementioned feasibility study.

Chapter 1

CubeSat Revolution

In 1957, the Soviet Union launched Sputnik I, the world's first artificial satellite, from the Baikonur Cosmodrome. This small spherical satellite, weighing almost 100 kilogrammes, was equipped with radio transmitters and emitted a unique signal as it orbited the Earth. This event marked the beginning of the space age, sparking the space race and accelerating the development of satellite technology, leading to the rapid growth of space exploration.
Since then, thousands of satellites have been designed, manufactured, and launched. They have come in various shapes and sizes, with weights ranging from a few kilogrammes to megatons. They have provided us with countless opportunities for scientific research, many of which were considered impossible in the past. Despite their immense contribution, the size and mass of satellites have reached their limits. At the same time, a new wave of interest emerged in the scientific community. Jordi Puig-Suari, a professor at CalPoly[1], and Bob Twiggs, a professor at Stanford University, recognised this opportunity in 1999 and laid the groundwork for a new type of small satellite, the Cube Satellite or CubeSat [1].

1.1 Characteristics

When discussing spacecraft, the term *small* is typically used to describe their mass or size. Although there may be a variety of characteristics by which we could distinguish between various types of small satellites, whether that would be their orbits or mission application, we will follow the traditional path and use the most prevalent classification, which is based on mass, see below in Fig. 1.1.

---

[1] Californian Polytechnic State University

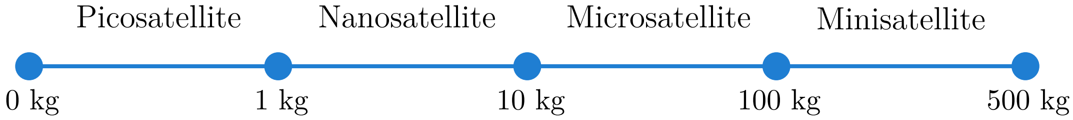

Figure 1.1: Satellite classification based on mass. Image by author.

This thesis aims to study a prominent representative of the nanosatellite group, the CubeSat. The basic CubeSat standard is 1U, where U denotes a unit. 1U CubeSat can be described as a 10 × 10 × 10 cube-shaped satellite, weighing up to 2 kilogrammes. The 1U configuration is not the exclusive or only option. CubeSats also come in 2U, 3U, or even 12U configuration. Various possible options are shown in Fig. 1.2.

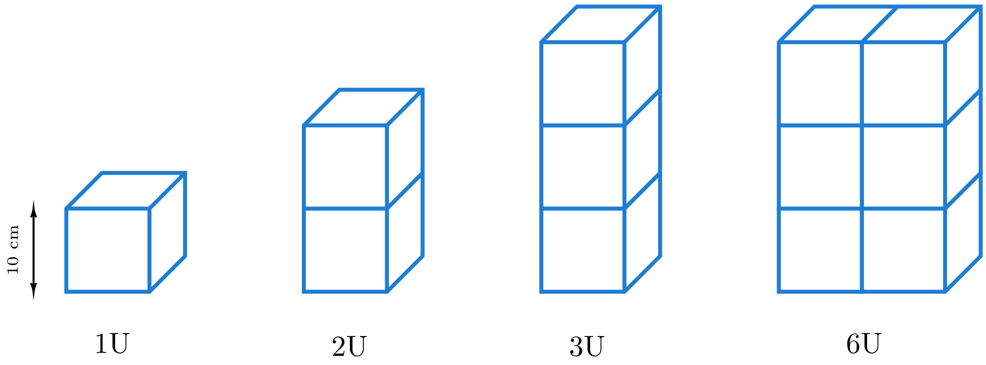

Figure 1.2: Possible CubeSat options. Image by author.

The CubeSat standard adheres to a very strict set of rules regarding its size, mass, internal structure, i.e. components and more [2]. Counterintuitively, the restricted nature of the CubeSat platform bears certain advantages. One such advantage is that it makes the development process more straightforward, thus reducing the overall financial cost and enabling organisations, i.e. universities, to utilise this platform in their various space-related applications. It also allows third-party companies to mass-produce components and offer COTS[2] parts, making the CubeSat platform even more accessible to a wider audience. These key elements result in reduced engineering and development costs, which proves to be a huge advantage of this platform [3]. That said, it is only reasonable to conclude that CubeSats have revolutionised space exploration and are proving to be a force to be reckoned with.

---

[2] Commercial-Off-The-Shelf

1.2 Operation

Initially conceived as educational tools and experimental platforms [4], CubeSats quickly outgrew their humble origins. What began as a handful of experimental missions has blossomed into a vibrant ecosystem, increasingly becoming a viable scientific platform. Although CubeSats are typically only limited to being secondary, auxiliary payloads, they have gained great momentum in recent years across both scientific and commercial spheres, resulting in increased deployment usage. The raw number of CubeSats deployed has steadily grown, as shown in Fig. 1.3.

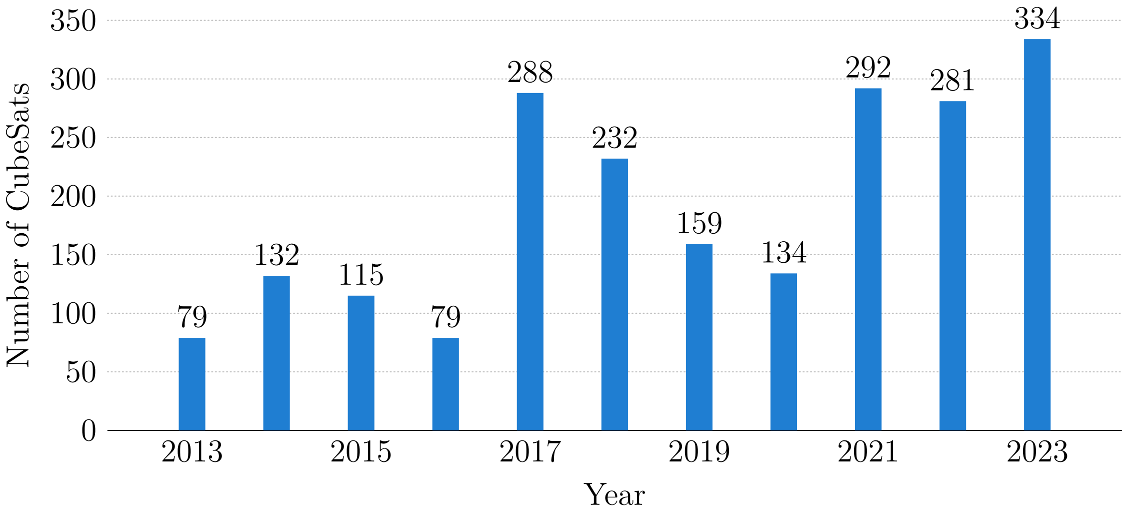

Figure 1.3: Number of CubeSats deployed per year [3].

1.3 Space Access

An additional notable factor, which in no small way contributes to the increasing popularity of CubeSats, is one of the possible ways to launch them into space (not an uncommon approach is to deploy them from the ISS[4] [6]). Deployers (dispensers) act as a bridge between CubeSat and launch vehicles. PPOD[5], developed by CalPoly, was the first dispenser for CubeSats [4]. It can hold up to three 1U CubeSats or a combination totalling three Us. Although various dispensers now exist, providing an undeniable advantage thanks to their modularity and compatibility in general, they all share the basic concept. Securely house CubeSats during launch and release them into space on command. Modern deployment mechanisms may include spring-loader pushers, pneumatic ejection, or electromagnetic systems [3].

---

[3] CubeSat database data kindly provided by Mr. Cesar A. Costa from Centro de Gestão e Estudos Estratégicos. For further reference, see [5].

[4] International Space Station

[5] Poly Picosatellite Orbital Deployer

1.4 Ridesharing

To achieve their desired orbit in the most effective manner, CubeSats often take advantage of rideshare programmes provided by commercial launch providers and space agencies, such as SpaceX-Rideshare [7] or XO-Ride [8]. Rideshare programmes allow multiple payloads to be transported on the same launch vehicle, offering several benefits to those seeking access to space. This phenomenon is called piggybacking. One significant advantage is cost savings; by sharing the launch vehicle, rideshare allows smaller organisations, startups, or universities to enter the world of CubeSat. Another key factor is that rideshare enables frequent launches as multiple payloads can be sent simultaneously. This increases efficiency and provides a wider range of options for spacecraft in terms of the preferred orbit and launch window. However, it is important to note that rideshare does have limitations and trade-offs, such as potential scheduling delays and strict requirements for compatible payloads [9]. An interesting option to consider might also be a microlauncher, such as Electron [10], since such small-scale launch vehicles are optimised and designed to provide a cost-effective launch service for payloads in the micro and nanosatellite range, including CubeSats.

Chapter 2

CubeSat Applications and Possibilities

The indisputable advantages of CubeSats are obvious. Whether it is (1) their cost effectiveness, where they have managed to drastically reduce the manufacturing, launch, and operational costs compared to traditional spacecraft due to their small nature, COTS parts and standardised design, or it is the consequent (2) more rapid development cycle, thanks to which scientists can improve, iterate, and experiment with the technology on a much larger scale. Not less valuable is also their modular and flexible essence, which enables access to both a broader spectrum of applications and, at the same time as briefly touched upon earlier, a wider variety of institutions.

Although initially, one of the primary objectives behind the development of CubeSats was to promote education and demonstrate new technology in the field of aerospace engineering and space science, in recent years its influence sphere and the possibilities of use have expanded considerably, further increasing the scientific value of the CubeSat platform. This reflects positively in the great diversity of applications in various fields of scientific research, Earth observation and remote sensing, telecommunication, or demonstration of novel technologies, such as water-based propulsion systems [11]. This fact has been recognised by many studies that an interested reader can refer to, such as [12], [13] or [14].

2.1 Science

In scientific research, CubeSats have enabled investigations in aeronomy, space geophysics, and astronomy, providing valuable data to expand our understanding of the universe. Of particular significance is the role of CubeSats in monitoring space weather phenomena, such as solar flares or coronal mass ejections from the Sun, which can significantly impact Earth's infrastructure, including satellites, power grids, and communication systems. CubeSats offer a cost-effective solution for continuous monitoring of the space environment, including the thermosphere, ionosphere, and magnetosphere, aiding in atmospheric research and early warning systems for space weather events; see [15] or [16].

2.2 Earth Observation

Moreover, CubeSats are revolutionising Earth observation capabilities, providing rapid and frequent imaging of the planet's surface in different spectral bands. This is due to their quick development and launch options, which are significant advantages compared to the lengthy development process of larger satellites, which can typically span several years. This is especially beneficial for monitoring natural disasters, urban development, agricultural activities, and environmental changes. CubeSats, such as those deployed by companies such as Planet Labs [17], offer high-resolution imaging with the ability to revisit locations frequently, capturing dynamic processes such as severe storms and changes in land use.

2.3 Education and Technology Demonstration

Additionally, continuing with their original goal, CubeSats serve a dual purpose as educational tools and technology demonstrators. They offer students valuable hands-on experience in space project development. Through CubeSat projects, students gain practical knowledge in spacecraft design, integration, and operation, fostering essential skills in teamwork and systems engineering. Furthermore, CubeSats contribute to the advancement of telecommunications technology through experiments such as innovative antenna designs [18]. Likewise, they encourage the initiative to further miniaturise internal components or systems and improve existing algorithms. These experiments push traditional communication methods' boundaries, exploring new data transmission and reception techniques in space environments.

2.4 Discussion

Overall, this gives sufficient reason to assume that the number of CubeSats in use will only grow, opening up new possibilities. While single vehicles certainly carry their own benefits and advantages, the hope is to achieve greater gains using many inexpensive, distributed, simple machines utilising cooperation to achieve the same or enhanced functionality as traditional single monolithic vehicles.

Chapter 3

Distributed Space Systems

The benefits and consequent capabilities of CubeSat seem unrivalled. The demand for and interest in technology is ever-growing. The technologies contained in individual components or sensors are becoming more accessible, more advanced, and perhaps more importantly, *smaller*. This miniaturisation leads to the idea of collectively combining individual singular *small* CubeSats into a larger whole. Such an action, i.e., creating a distributed system of multiple spacecraft, means a significant broadening of the horizons for scientific and commercial purposes.

A generally agreed upon definition of DSS[1] is the following [19]:

> "A space system that allocates functionality among multiple spacecraft that interact to achieve desired goals."

This definition includes a wide range of concepts that allocate program-, mission-, or spacecraft-level functionality to different units, which may be owned and operated by one or more organisations [19]. This definition is in alignment with perhaps a bit more straightforward definition:

> "An end-to-end system including two or more space vehicles and a cooperative infrastructure for science measurement, data acquisition, processing, analysis and distribution."

provided by [20].

---

[1] Distributed Space Systems

3.1 Cooperation in Animal Kingdom

Before proceeding further into the world of CubeSat space collaboration and its numerous opportunities, let us now for a second conduct a so-called *Gedankenexperiment* in the realms of the animal kingdom, very similarly to what author in [21] imagined. By doing so, we shall aim to fathom whether our ordinary day-to-day life does not already provide us with sufficient inspiration, and thus a thought basis for a deeper understanding of the following study of distributed space systems.

Let us first imagine two animals encountering each other in a critical situation, perhaps akin to a pair of European storks engaged in the intricate ritual of mating at their nest. This close encounter prompts thoughts of rendezvous and docking scenarios in spaceflight, where precise geometric conditions are paramount for success. Moving beyond individual encounters, when two or more animals of the same species coordinate their movements in a synchronised manner, we witness the emergence of a formation, such as when large birds gracefully glide through the sky in a V-shaped formation. Although rendezvous and formations represent localised or moderately separated scales of animal distribution, globally distributed and interacting animals, albeit rarer, also exist. Consider the communication and navigation network formed by fin and blue whales, which spans the entire planet. The calls of these creatures can spread across entire ocean basins, serving as a global means of communication and navigation, although limited today by human-generated noise. Drawing parallels to space exploration, we can consider a constellation as a global communication and navigation network established by typically 20-30 globally distributed spacecraft. As such, it mirrors the interconnectedness observed in whale networks. Just as whales synchronise their songs across vast distances, satellites in constellations collaborate to facilitate communication and navigation across the cosmos. Another interesting form of distributed animal behaviour is the swarm, which is made up of a few tens to thousands of individual members, often insects, fish, or birds. Although the objectives of swarm behaviour, such as minimising predation risk or optimising rest periods, may not yet be understood, the parallels to space missions are evident. Swarms, like satellites, exhibit coordinated movements and interactions, demonstrating the power of collective intelligence in distributed systems.

3.2 Potential of DSS

For years, the model of space infrastructure has relied heavily on traditional large satellites. Such spacecraft are often susceptible to single points of failure and are costly to replace or upgrade. They operate from high orbits, utilising their high vantage points to offer maximum coverage and connection. However, the advent of small satellites in recent years and their consequent usage in distributed systems, mainly constellations, offers a paradigm shift and a new way to overcome limitations and issues stemming from classical spacecraft operations.

Regarding Earth monitoring and remote sensing, there is an ever-rising need for increased spatial and time coverage. Constellations of small satellites such as Cube-

Sats can increase the geographical coverage from low orbits through their strength in numbers. Although each satellite essentially sees only a small portion of the planet, such a spatial distribution of multiple spacecraft looking at the same region allows for direct interferometric observations and shorter revisit times (time elapsed between two consecutive observations of the same point on Earth by a satellite).

Another significant application related to satellites is communication. Small, low-orbiting satellites in constellations can offer continuous global coverage in communication across the whole planet [22]. This goes hand in hand with another key usage possibility, that is, IoT[2]. Logistics companies use small and inexpensive transmitters to track their shipping containers, but only when within the range of wireless networks. CubeSat constellations, such as those in development at OQ Technologies Lacuna Space, will detect weak, low-bandwidth signals from IoT devices to track shipment worldwide from orbit [23].

Using small satellites such as CubeSats also changes how distributed space systems work in general. For example, traditional satellites remain in orbit for many years or centuries after they stop working. In contrast, atmospheric drag and gravitation will pull smaller CubeSats from orbit within a shorter period of time, compared to classical satellites. Secondly, a more rapid development cycle allows companies and institutions to iteratively replace each deorbiting satellite with a new one, based on the latest technology. Thus, the new constellation can improve its performance and introduce new capabilities. This factor is even more reinforced if we realise that the distributed space systems are not rigidly connected. This means their relative spatial arrangement can be flexibly adjusted to meet mission requirements, facilitating scalability and expansibility. In addition, the distribution of payloads and subsystems across multiple spacecraft inherently introduces redundancy, thus enhancing mission robustness. Should a critical subsystem fail on one spacecraft, the integrity of the mission remains intact. To conclude, we could say that the main advantages of DSS in relation to CubeSats are, inter alia, the following.

- enhanced scientific capabilities through direct interferometric observations,
- improved temporal and spatial resolutions with shorter revisit times
- increased mission robustness and autonomy.

3.3 Mission Architecture Classification

When talking about satellite mission architectures, we can distinguish two primary categories. The first category consists of monolithic systems which rely on a single satellite to achieve scientific objectives. The second category, of much greater interest to us, is distributed systems. They involve multiple satellites, i.e. two or more, aiming to accomplish a certain mission goal. It is particularly the latter, which has been on the rise in terms of interest, that is the subject of this study and will be examined in greater depth.

---

[2] Internet-Of-Things

Despite the fact that additional definitions regarding further subclassification of distributed space systems differ [24], [25], we shall hereafter consider the following classification introduced by [21], see Fig. 3.1.

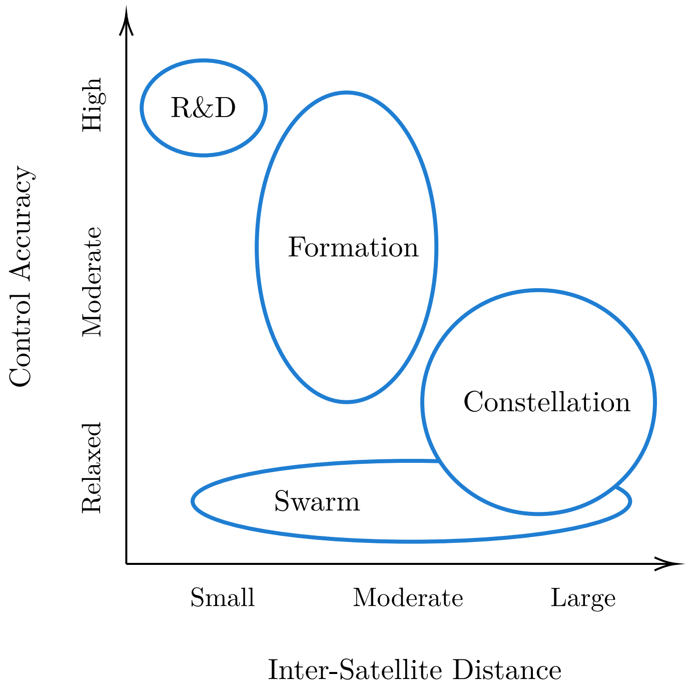

Figure 3.1: Classification of distributed space systems [26].

Spacecraft that perform R&D[3] require high (centimetre-level) control accuracy and operate at a small (metre-level) intersatellite distance. Spacecraft in a constellation require very relaxed (kilometre-level) control accuracy and operate at large (> 1000 km) inter-satellite distances. Formations fill the gap between R&D and constellations and generally require high to moderate (metre-level) control accuracy and commonly operate at moderate (tens of metres to several kilometres) intersatellite distance [26].

---

[3] Rendezvous & Docking

Chapter 4

Rendezvous & Docking

The general premise of the R&D concept could be characterised in various ways. Generally speaking, we could define it in the following manner:

> "Two objects in space moving in close proximity of each other."

Additionally, we could also allow the definition to include a notion of proximity operations, such as various orbital manoeuvres, circumnavigations relative to each other, etc. These proximity operations play a key role in many R&D missions, whether that is pure technology testing or direct demonstration, spacecraft assembly or repair.

4.1 Key Principles and Mating Strategies

Rendezvous and docking missions usually involve a sequence of precise orbital manoeuvres and trajectories to bring two spacecraft in the desired proximity and achieve controlled physical contact. The active vehicle, known as the chaser (leader), is typically guided toward the passive vehicle, known as the target (follower), for the final approach. This approaching phase demands precise control over the chaser's position, velocity, attitude, and angular rates to facilitate the mating process within narrow parameters. We could distinguish between two primary mating strategies [27]:

- Docking: the chaser makes contact, and it is captured by the docking interface of the target vehicle. The docking sequence is controlled by the GNC[1] system of the chaser, which controls the vehicle state parameters.
- Berthing: the chaser GNC system delivers the vehicle to a meeting point with nominally zero relative velocities and angular rates. The main difference lies in how contact is carried out through a manipulator, located either on the chaser or the target, that grasps the other vehicle, transfers it to the final position and

---

[1] Guidance, Navigation & Control

inserts it into the interfaces of the relevant target berthing port. One benefit of berthing is that it does not require exact alignment with the target.

4.2 Concept Development

4.2.1 First Steps

The world's first space rendezvous took place nearly 60 years ago. It was on December 15, 1965, when two US spacecraft, Gemini VI-A and Gemini VII, approached each other within a distance as close as 30 centimetres.

Figure 4.1: Photo of the Gemini VII spacecraft taken through the hatch window of the Gemini VI-A spacecraft during rendezvous. Image: NASA, S65-63194

The original primary objective of Gemini VI-A (Gemini VI at the time) was to rendezvous and dock with the Agena spacecraft, which was supposed to be launched into orbit separately. However, the mission's objective had to be altered because Agena exploded during launch. Instead, Gemini VII was launched first, with astronauts Frank Borman and Jim Lovell onboard. NASA[2] then decided to launch Gemini VI, now called Gemini VI-A, again to achieve rendezvous and docking objectives. On 15 December 1965, Gemini 6A was relaunched and successfully performed the

---

[2] National Aeronautics and Space Administration

first rendezvous in space with Gemini 7, which was still in orbit. Similarly, the first space docking in the history of space exploration took place on 16 March 1966. This achievement is credited to Gemini VIII and was successfully performed under the command of Neil Armstrong, who was still a rookie at that time, who managed to dock with the target vehicle. The first *automated* space docking is credited to the Soviets for their Kosmos 186 and Kosmos 188 missions, on October 30, 1967. Both unmanned Soviet spacecraft were launched as part of the Soviet Union's space programme.

4.2.2 Further Advancement and Contemporary State

The further development of the R&D concept could be traced through the decades, with some important milestones as early as the late mid-twentieth century, when, for instance, in 1969, the lunar module Eagle separated and then, after the lunar surface operations were done, again rejoined with the commander module Columbia. Although in the beginning it was more about technological demonstrations, or rather defining what mankind was capable of, attention today is turning to important applications related to the increasing number of objects in space and to the ever-increasing interest in space research and exploration in general.

An important milestone in the development of R&D concept in CubeSat waters marks the CPOD[3] mission [28]. It was originally conceived in 2012, and the satellites were completed in 2015. It aimed to, for the first time, execute entire sequences of rendezvous, proximity operations, and docking of two 3U CubeSats. This included proximity operations from various distances, approach scenarios, and lighting conditions with nominal operating distances ranging from 50 to 2 kilometres and a full range of distances from 0.5 metres to 25 kilometres. However, due to a combination of certain issues and limitations, which essentially resulted in the vehicle featuring previous generation hardware, and despite the recent launch date missing out on seven years of upgrades and refinements, the two vehicles ultimately launched in May 2022 [29]. According to the official website [28], as of 23 June 2023, the mission officially ended after the spacecraft fuel was depleted. The report states that although multiple attempts brought the CPOD spacecraft closely together, thus ultimately achieving rendezvous and demonstrating the ability of the two spacecraft to remain at determined points relative to each other, the system-level guidance, navigation, and control systems made it difficult to complete the full planned set of manoeuvres, which ultimately led to the depletion of all fuel before the final docking could be completed. Both 3U spacecraft will now safely burn up in the atmosphere, providing important lessons to be learnt from this mission [29].

Described as *by far the smallest spacecraft to have accomplished a rendezvous and proximity operation so close* was the AeroCube-10 mission launched in 2019 [30]. The mission consisted of two 1.5U CubeSats aiming to demonstrate precision satellite-to-satellite pointing, deployment of atmospheric probes for in situ measurement of air density, and small-spacecraft proximity operations (no docking was planned) using propulsion from a steam thruster among other objectives. On 22 July 2020,

---

[3] CubeSat Proximity Operations Demonstration

one of the CubeSats manoeuvred itself within 22 metres of its sibling CubeSat and snapped a series of photos while orbiting at 17,000 miles per hour [30]. One of the photographs can be seen in Fig. 4.2.

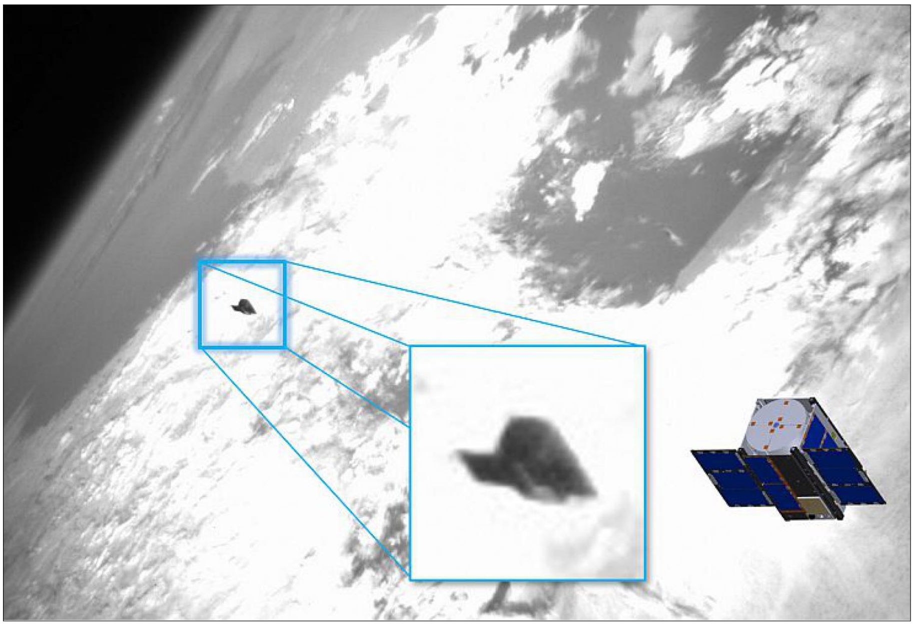

Figure 4.2: Photo of AeroCube-10A in space taken by AeroCube-10B [30].

Hoping to continue in this success was in January 2022 launched the PAN[4] mission via NASA's ELaNa[5] [31], at the time regarded as one of the most advanced autonomous CubeSat systems that has ever flown [32]. The aim of the project was to demonstrate autonomous control algorithms for rendezvous and docking manoeuvres; low-power reconfigurable magnetic docking technology; and compact, lightweight, and inexpensive precision relative navigation using carrier-phase differential GPS[6]. Unfortunately, the two spacecraft survived only for four months because of a software change that disabled some of the spacecraft's functionality. Although the two spacecraft demonstrated some compelling subsystem technologies, raising them to TRL[7] 6, the authors note that the mission was only minimally successful [33].

There have also been other applications. Seeker, the 3U CubeSat free-flying space inspector, and Kenobi, its communications relay launched on April 17, 2019 [34]. The project was greenlit in September 2017 and was marked as the ISS "X" project at the Johnson Space Center. "X" projects are conceived with the intention of having an expedited time frame from concept to deliverable. In contrast, the average payload can take *years* to make it from conception to the ISS, Seeker aimed to be ready in under two years [34].

The goal of the mission was to provide an ultra-low-cost approach to highly automated extravehicular inspection of crewed or uncrewed spacecraft. To be precise, it aimed to perform inspection-like manoeuvres within 50 metres of the target vehicle

---

[4] Pathfinder for Autonomous Navigation

[5] Educational Launch of Nanosatellites

[6] Global Positioning System

[7] Technology Readiness Level

(Cygnus, its launch vehicle) and then dispose of itself to burn up in the atmosphere [35]. It completed its objective on 19 September 2019, during a 60-minute period of time [36].

An equally important possible usage, as mentioned in the opening of this chapter, is the possibility of in-situ spacecraft repair. The intention of showing how small satellites can be used to upgrade constellations or provide life-extension services such as refuelling was the objective of the LINUSS[8] mission [37]. Launched at the end of 2022 and deployed in January 2023, consisting of a pair of 12U CubeSats, it has successfully demonstrated various rendezvous and proximity operations, thus validating essential manoeuvring capabilities for future space upgrade and servicing missions [38], [37].

Various other promising missions are planned as well. One such future mission is TAMARIW [39]. TAMARIW will consist of two 3U satellites that will be launched in a docked state as a single 6U. Once deployed, the two satellites will start the experimentation phase by separating only a few centimetres before docking immediately. This gap will increase with each subsequent experiment up to a distance of 500 metres. By doing so, the TAMARIW mission will provide valuable data for the development of CubeSat R&D technology and will be a crucial step towards future CubeSat proximity operation missions [39].

There are also some novel local mission proposals. Specifically, the Czech VZLUSAT3 mission concept, designed to demonstrate the feasibility of small satellite proximity operations [40]. The mission will involve two 6U CubeSats, the proximity spacecraft (VS3-A) and the target spacecraft (VS3-B). The goal is to execute a series of proximity manoeuvres to achieve various objectives, including in-orbit inspection, inter-satellite communication, and formation flying. The hope is also to demonstrate critical capabilities like spacecraft inspection by mission-specific proximity camera.

4.3 Summary

Unstoppable technological advancement coupled with various successful missions broadens the horizons of the R&D concept, demonstrating its capability. Thus, we can safely assume that an overwhelming number of missions will rely on R&D. On a final note, let us now reiterate the most important characteristics, system conditions and constraints that underscore the complexity of R&D operations [27]:

- Launch and phasing trajectory planning,
- Manoeuvres in close proximity to the target station,
- On-board system requirements and constraints,
- Constraints related to communication links.

---

[8] Lockheed Martin In-Space Upgrade Satellite System

Chapter 5

Formation Flying

The idea of formation flying could be traced back to the millennium change. One of the first pioneers of the concept were Landsat 7 and EO-1 (launched in April 1999 and in November 2000, respectively), where EO-1 followed Landsat 7 in its orbit by exactly one minute [41]. Interest in the FF[1] concept has always resonated greatly in areas such as astronomy and Earth observation due to the opportunity of a higher spatial and temporal resolution by the virtue of interferometric and other distributed observation techniques, where large space interferometers have been proposed since the early 2000s [42].

The attention to FF has notably risen again in recent years, underlining the key benefits it offers in terms of mission cost, performance, and flexibility compared to a monolithic and complex vehicle. The distribution of functions and payload among multiple spacecraft operating in a coordinated way gives the possibility to enhance the mission science return, increasing the flexibility of the mission, and potentially allowing for multiple mission goals within the life-span of the satellites. Moreover, using a network of cooperative satellites increases redundancy in the event of a failure (i.e., decreased loss in the case of an individual failure) [43]. These positive aspects enable extensive applications, such as Earth mapping and atmospheric data collection coupled with scientific studies along with observations and communication systems [44].

---

[1] Formation Flying

5.1 Definition

An exact definition of formation flying in relation to the concept of spacecraft flying is not strictly set. Past definitions have not clearly distinguished the boundaries of the concept from spacecraft constellations. This resulted in the following definition, introduced by [45] where spacecraft FF is defined as

> "A set of more than one spacecraft whose dynamic states are coupled through a common control law. In particular, at least one member of the set must (1) track a desired state relative to another member, and (2) the tracking control law must at the minimum depend upon the state of this other member."

For completeness, let us also mention the following definition, proposed by NASA's Goddard Space Flight Center:

> "Spacecraft formation flying is the tracking or maintenance of a desired relative separation, orientation, or position between or among spacecraft."

Therefore, it can be seen that although individual authors and researchers adjust and alter the concrete definition to their needs [44], [46], the concept has solid foundations and key aspects are agreed on. We can also notice that the desired relative separation between satellites is not required to remain constant in time in order to match the definition and thus qualify as formation flying. This led to the introduction of slightly more relaxed definitions, such as the one given in [47] where the authors note that satellite formation flying can also be defined as

> "Two or more satellites flying in prescribed orbits at an approximately constant separation distance from each other for a given period of time."

Approximately constant and *given period of time* are necessary in the definition due to certain issues discussed in greater detail therein.

5.2 Characterisation

S. Mathavaraj and R. Padhi in [47] also distinguish between various architectures with respect to formation flying, among other things based on configuration or modus operandi. This includes:

- Trailing configuration where the spacecraft share the same orbit and follow each other on the same path maintaining specified relative angular separation from the centre of Earth whenever the chief satellite is at the perigee. The authors remark on the fact that only in the case of circular orbits is this relative angular separation maintained constant at all times. However, in the case of elliptic orbits, this relative angular separation continues to vary depending on the location of the satellites.
- A cluster in which a group of satellites are located in formation close to each other and are placed in orbits such that they remain close to each other. Satellites in a cluster usually fly in close formation, but not necessarily in a trailing configuration.

An example mission of the first type is RANGE[2] [48]. RANGE launched on December 3, 2018, on board the SpaceX Falcon-9 rocket. It involved two 4-kilogramme 1.5U CubeSats flying in a leader-follower formation. The main goal of the mission was to improve the positioning (relative and absolute) capabilities of nanosatellites while also potentially measuring the relative distance between the satellites down to millimetres inter-satellite laser ranging measurements. The onboard instrumentation included state-of-the-art global positioning system (GPS) receivers linked to miniaturised atomic clocks for precise orbit determination. Additionally, the relative positions of the satellites were to be measured using a compact inter-satellite laser ranging system that would also double as a laser communications system. Although the satellites did not have an active propulsion system, the objective was to control the separation distance of the satellites using differential drag techniques [48]. At the time of writing this, the last known report of the satellites [49] seems to be in the last year, i.e. 2023, and so the current state of the mission is unknown since no further information has been released.

Striking balance between the two types and the use of both architectures was among the goals of the NetSat mission [50] that included four 3U CubeSats, cf. Fig. 5.1. Launched in 2020 and still operational [51], it aimed to demonstrate and advance the technology required for formation flying. Among other things, it performed automated multisatellite operations and demonstrated inter-satellite communication and automatic message forwarding.

The Tianwang-1 mission [52], launched in 2015, had a similar goal in mind. It aimed to demonstrate autonomous formation flying, coupled with intersatellite communication using software-defined radio, with one 3U CubeSat and two 2U CubeSats.

To paint the full picture, a representative case of the second type of architecture was the SAMSON mission [53]. SAMSON consisted of three 6U CubeSat spacecraft.

---

[2] The Ranging And Nanosatellite Guidance Experiment

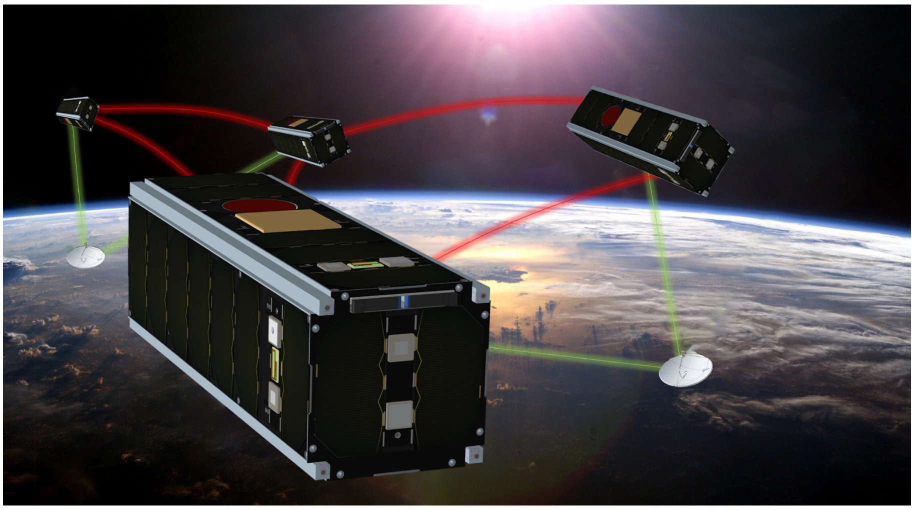

Figure 5.1: NetSat mission illustration [50].

Launched in 2021, its objectives were to (1) demonstrate long-term autonomous cluster flight of multiple satellites and (2) geolocate a cooperative radiating electromagnetic source on Earth [54]. The three satellites were launched together with approximately the same semi-major axis, eccentricity, and inclination and separated in orbit to form a cluster with relative distances ranging from 1000 metres for the closest two to 250 kilometres for the farthest two [53].

Chapter 6

Constellations

Multisatellite missions that do not satisfy the definition of formation flying missions are called constellation missions. For example, even though specific relative positions are actively maintained, GPS satellites constitute a constellation because their orbit corrections require only the position and velocity (states) of the individual satellite, as noted in [45], [55]. The idea of space constellations can be traced back to the 1960s of the previous century [19]. During that time period, weather forecasting was an area of particular interest and underwent rapid development. Starting with TIROS-1, the first U.S Earth civil observing satellite, followed by other TIROS satellites, and after a certain period of time, even second and third-generation instruments, a series of incrementally improved satellites emerged. The authors in [19] note that since the lifetimes of some of those vehicles overlapped intentionally to improve coverage and decrease the re-visit time, they could be considered as predecessors of current space constellations. In other words, CubeSat constellations are based on all of the positive characteristics of CubeSats that we have already exhaustively discussed. Within the DSS theory, they are on an imaginary pedestal, where the hope is to fully exploit available resources and possibilities driven by individual singular CubeSats within one large entity, and that is the constellation itself.

6.1 Constellation Design and Architectures

The usual goal of constellation design is to optimise the coverage over a specific region or improve (reduce) needed revisit times. For example, when talking about the coverage of any CubeSat mission, it is mainly dependent on different parameters such as the number of satellites, the number of orbital planes, the elevation angle, the inclination, the altitude, the orbital plane spacing, and the eccentricity of the orbit [56]. However, at this point, it is important to mention a very important fact. In general, constellation architectures have spacecraft with the same altitude and inclination that are distributed over multiple orbital planes [57]. At the same time, accomplishing this with CubeSats would be of greater difficulty. This comes down to two main reasons. CubeSat constellation mission would require either (1) a dedicated launch vehicle per plane to achieve this for a primary multiple-CubeSat mission or

(2) a partnership with complementary primary missions that launch the CubeSats into their desired orbits. The first option naturally introduces significant financial constraints on the mission planning, while the second option would require multiple identical launch opportunities or a transfer vehicle and longer CubeSat lifetimes. A viable option is to launch each CubeSat as a secondary auxiliary payload on different mission, i.e. launch vehicle. To make this work, one can use programmes such as NASA's ELaNa, which aims to make secondary payload opportunities available at low cost as often as possible. However, launch as a secondary payload would result in a non-traditional constellation architecture [57]. This phenomenon is usually described as *ad-hoc constellations*. Instead of the CubeSat constellation being subject to a given theoretical structure, once deployed, they form a constellation based on particular characteristics and options hinged on the nature of deployment, which may vary to a certain extent from the traditional architecture. Such constellations have a longer setup time than an intentional constellation, however, their revisit times and achievable performance are on par [57]. For further reading, an interested reader is referred to articles such as [58] and references therein.

Constellation architectures and their applications have been extensively studied [59], [60], [61]. Common types of constellation architectures, among others, include the Walker constellation, Street-Of-Coverage, or the Flower constellation.

6.1.1 Walker Constellation

The Walker constellation, named after John G. Walker, who first introduced the concept in the 1970s [62], [63] and helped it develop further tremendously, is a constellation of symmetric design. In other words, all satellites and orbital planes are uniformly distributed.

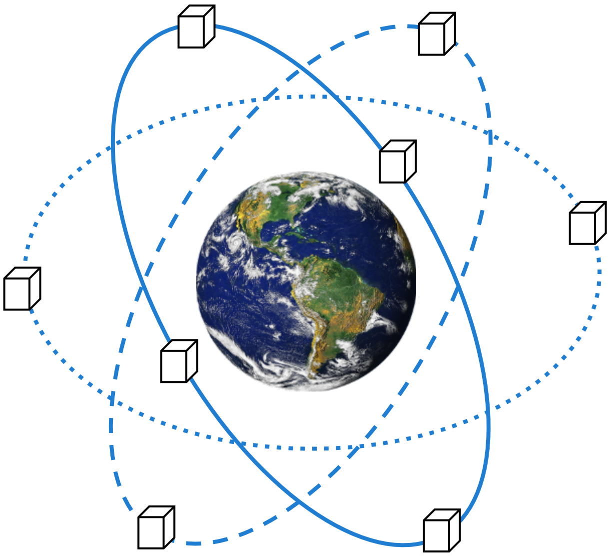

Figure 6.1: Illustrative example of Walker constellation [56].

The Walker constellation is generally described by the notation **n/p/f**, where **n** stands for the total number of satellites in the constellation (also marked as **t**), **p** is the number of orbital planes and **f** is the phasing parameter, i.e. the relative spacing between satellites in adjacent planes. This parameter **f** takes value between 0 and **p-1** and is equal to **f** × **360 / t** [64]. Usually, another important detail is also included, which is the slope **i**. Together, the notation reads **i:n/p/f**.

One significant advantage of this design approach is that the effect of perturbations is approximately the same on each satellite. Moreover, satellites at constant altitudes have the same resolution and signal strength, as noted in [65].

For example, when designing a CubeSat Walker constellation to maximise longitudinal global coverage, the approach discussed in [56] might be considered. The authors note that the minimum number of CubeSat per orbital plane n and the minimum number of orbital planes N_p required for a circular orbit can be determined as:

$$n = \left\lceil \frac{360}{2\theta} \right\rceil, \quad N_p = \left\lceil \frac{360}{4\theta} \right\rceil, \tag{6.1}$$

respectively, where $\lceil \cdot \rceil$ is the ceiling function and θ is the Earth central angle of coverage. Based on Figure 6.2, the angle θ can be determined as:

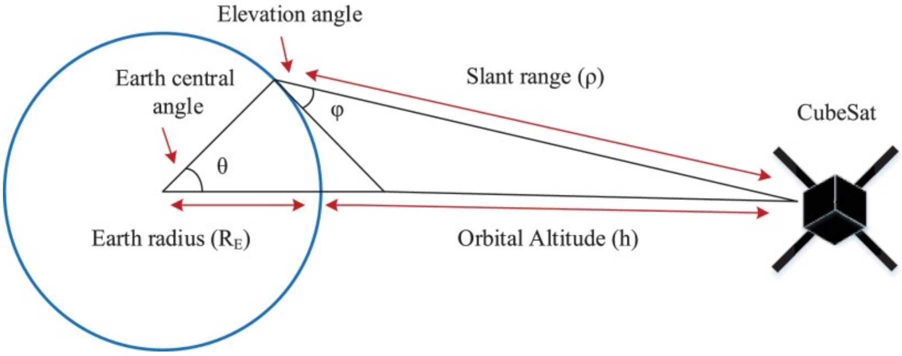

Figure 6.2: Coverage geometry for CubeSats [56].

$$\theta = \arcsin\left(\frac{\varrho \sin(90 + \phi)}{h + R_E}\right). \tag{6.2}$$

The range ϱ can be calculated such as:

$$\varrho^2 - 2R_E \varrho \cos(90 + \phi) = (R_E + h)^2 - R_E^2. \tag{6.3}$$

6.1.2 Street-of-Coverage Constellation

The main goal of the Street-of-Coverage type of constellation is to provide continuous coverage of a particular Earth region or even to provide global coverage of Earth as well. SoC[1] is based on the concept of having several trailing satellites located at the same altitude and orbital plane. In order to form a continuous satellite coverage, i.e. a street, at least three trailing satellites are placed per plane. The situation can be seen in Fig. 1, where the beam of coverage of individual satellites overlaps, thus forming a single street and, consequently, covering the desired region.

This then naturally begs the question of how many orbital planes, i.e. streets, are needed and what their inclination should be. There are two possible cases. (1) For regional coverage at high latitudes or any region, including the pole, researchers found that the best results were achieved by polar orbits spread over 180 degrees, cf. Fig. 6.3. (2) In case the focus was on a region in low to mid-latitudes, the optimal SoC architecture will consist of inclined orbital planes, with ascending nodes symmetrically distributed around the Earth's equator, cf. Fig. 6.4.

Figure 6.3: Optimal SoC constellation for continuous global coverage [66].

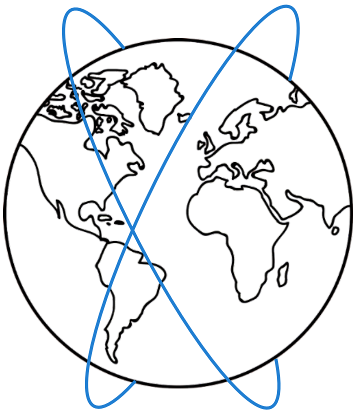

Figure 6.4: Optimal SoC constellation for continuous zonal coverage of low to mid-latitudes [66].

---

[1] Street-Of-Coverage

6.1.3 Flower Constellation

An additional constellation architecture is the Flower constellation. First introduced by [67] it consists of satellites moving on the same closed-loop trajectory with respect to a rotating frame [68], [56]. These architectures open up new possibilities in fields such as telecommunications, Earth and space observation, or new kinds of formation flying schemes [67]. An example of such a constellation is depicted in the following; cf. Fig. 6.5.

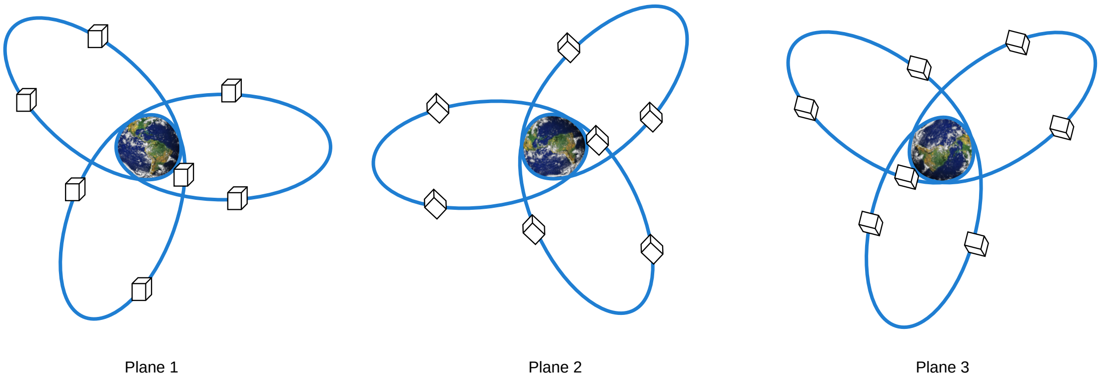

Figure 6.5: Illustration of a Flower constellation in three different orbital planes [56].

6.2 CubeSat Constellations

Interest in the CubeSat constellation market has been growing steadily in recent years. This has resulted in a growing number of commercial applications and, at the same time, is also proving to attract new, emerging businesses as well. This notion has also been recognised in various studies, such as [69].

At the moment, the biggest CubeSat constellation is undoubtedly the Flock constellation, run by the company PlanetLabs [70]. The constellation currently consists of more than 100 3U CubeSats, which provide 3 to 5-metre resolution images of the Earth for a variety of mapping applications including several humanitarian and environmental applications, from monitoring deforestation and urbanisation to improving natural disaster relief and agricultural yields around the world. The company also consistently improves their individual spacecraft and tries to regularly update the constellation, which has resulted in more than 500 hundred spacecraft being launched [71], [72].

We could also mention another market player, that is the company Swarm [73], which operates its 0.25U CubeSat constellation. Using at least 7 different orbital planes, the objective is to provide global connectivity for IoT devices at the lowest cost [74], [73]. Their 2021 annual report states that at that time they had already reached the milestone of 120 operational satellites in orbit [75]. However, the final number target should be 150 individual CubeSats.

Last but not least, achieving similar success, that is, having more than 100 spacecraft in orbit, is the company Spire and its LEMUR[2] constellation [76]. Each LEMUR is a 3U CubeSat equipped with different instruments such as AIRSAFE, STRATOS or SENSE, see [77]. The constellation vehicles are used to track maritime, aviation and weather activity from space.

6.3 Discussion

If we take into consideration the popularity of CubeSats, and the proposed number of future constellations involving CubeSats [78], it is inevitable that the amount of spacecraft present in space, especially LEO[3], where most CubeSats operate, will rise exponentially. This begs the question of space congestion, for the space around the Earth is becoming increasingly cluttered with debris, both natural and man-made. Natural debris includes meteoroids and micrometeorites, whereas man-made debris includes fragments of defunct satellites, spent rocket stages, etc. This debris poses a significant threat to active satellites as collisions, such as a millimetre-size hit to Sentitel-1A [79], can cause damage or even destroy them. CubeSats, being small and often deployed in larger numbers, such is the case with constellations, contribute to the overall population of objects in Earth's orbit. In addition, unlike larger satellites, CubeSats often lack propulsion systems for precise orbital manoeuvers or deorbiting, making them more susceptible to contributing to the long-term space debris problem. As a result, the increasing use of satellites in general has sparked discussions about the said growing issue [80], [81], sometimes referred to as Kessler syndrome. On the other hand, there have been proposals and studies, such as [82] on the deployment of CubeSats, to combat this issue. Certain mission proposals even envision CubeSats flying in a formation of two, see [83].

---

[2] Low Earth Multi-Use Receiver

[3] Low Earth Orbit

Chapter 7

Swarms

Swarms mark the next potential technological advancement step. Let us first recall how the author of the classification used throughout this work imagined the idea of satellite swarms [21]:

> "Biologically inspired DSS consisting of several tens to several thousand individual spacecraft, each with limited functional capability."

As such, we could thus declare a swarm to be a globally controlled cluster, that is, a cloud of *primitive*, single elements working together towards a certain (mission) goal [84].

Nevertheless, it is pertinent to note that such nomenclature certainly overlaps to a certain extent with the definition of constellations and formation flying introduced in this work. However, it should be noted and it is vital to remember that as a subclass of DSS, it is unlikely that swarms will replace other space systems. In contrast, their power lies in particular, *niche* applications. This is underlined by the fact that in the case of swarms, it is of no importance which singular element performs a specific action, provided that within a certain period of time, at least one element is available to do so, i.e. in a desired position. This goes hand in hand with the fact that none of the elements in the swarm are essential for the overall functionality. Although, naturally, each element of the swarm must be designed with as much care as possible, it is not necessary to have a single-point failure design [85].

However, the bigger the number of spacecraft involved, the higher the cost limitations are, which in turn, among other things, puts extended emphasis on further miniaturisation. For example, this could be observed within the KickSat-2 mission, launched in 2018 [86]. The KickSat was a 3U CubeSat, where one U was reserved for running the spacecraft, providing power, communications, and data handling, while the other two Us served as a house for deploying over 100 centimetre-scale miniaturised spacecraft called ChipSats. These ChipSats included power, sensor, and communication systems on a printed circuit board that weighed just 5 grammes. They were meant as a general purpose platform with the aim of opening up space access to an extended number of people [87].

Swarms also seem to be highlighting their potential in much more technologically demanding areas. The planned COMMUTE mission [88], which aims to explore and study Uranus, is hoping to use 16 CubeSats, dividing them into clusters of 4 with each having 4 identical spacecraft. Each group will be equipped with specialised instrumentation, exploring Uranus more extensively and performing planned plunges into its atmosphere while using the mothership as a communications relay with the Earth.

Chapter 8

Guidance, Navigation & Control

A common denominator across the whole field of distributed space systems and especially paramount in formation flying in general is the theory of guidance, navigation, and control, along with its consequent applications. Before moving forward, it is essential to assign a clear meaning to each of these terms. Hence, hereinafter, when describing the motion process of a spacecraft, we will be using the following disambiguation, based on [89]:

- Guidance: calculate desired target position and velocity (orbital motion), and target attitude and rotational rate (attitude motion), in order to achieve the desired objectives,
- Navigation: determine current satellite position and velocity (orbital motion), and satellite attitude and rotational rate (attitude motion).
- Control: make changes in satellite position and velocity (orbital motion), and satellite attitude and rotational rate (attitude motion), or keep them to certain fixed values, by means of actuators.

Motion of an object in the realms of space, i.e. a satellite such as the CubeSat, is exceptionally complex. All the more challenging is the study of its behaviour, or rather the effort to be able to predict this behaviour, model it, describe it, and consequently control it. This difficulty arises from multiple factors, such as the influence of chaotic and often uncertain influences, for instance atmospheric drag, radiation pressure, or various other perturbations etc. For satellites in LEO, that is, where the vast majority of CubeSats are positioned, the magnitude of position vector errors can grow by about 2.5 kilometres per week, even with significant post-processing and state filtering [90], [91]. Deeper understanding of the CubeSat dynamic in space and mainly the knowledge on how to counteract on these undesired elements and errors is crucial to ensure hassle-free progress throughout the mission, which in turn helps towards the success of the mission itself, but also for the survival of the CubeSat too, through power-generation etc.

8.1 Attitude Determination and Control System

In case a mission utilises the concept of formation flying, i.e. contains a set of two or more spacecraft coupled through a common control law, it is apparent that the quality and capabilities of each individual member of the formation determine the overall mission success and magnitude of the scientific return. Laying at the core of this dilemma in CubeSats is the ADCS[1], sometimes also denoted as ACS, i.e., Attitude Control System. Located in the centre of the GNC, ADCS is one of the many satellite subsystems. A system-level scheme of this system can be seen below, cf. Fig. 8.1.

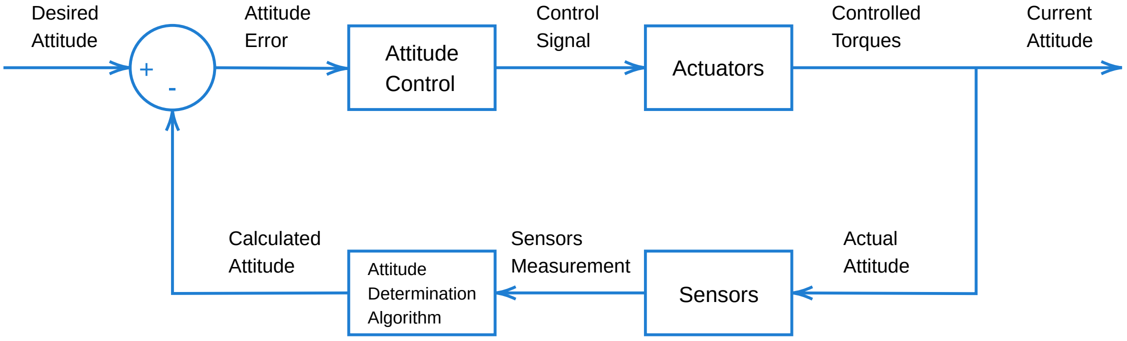

Figure 8.1: System level block diagram of the ADCS [92].

8.2 Control State

In general, we could try to describe the nature of ADCS and its subsequent relationship to CubeSat using the following image, cf. Fig. 8.2.

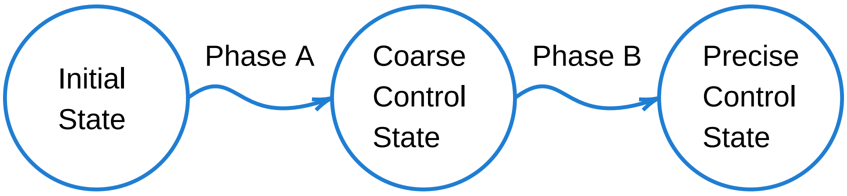

Figure 8.2: CubeSat control state illustration. Image by author.

The basis consists of three control states that a CubeSat can happen to be in. The first state is the initial state that CubeSat finds itself in upon being deployed from a launch vehicle or the ISS. This state could also be described as state of no control, since upon deployment, the satellite has full absence of any information regarding its position, altitude, etc. and may experience high rotation. It is thus apparent that this is the state *every* satellite faces instantaneously when deployed and after

---

[1] Attitude Determination and Control System

the first system start. The second state could be imagined as a state of coarse control only. During the presence within this state, generally the knowledge about a CubeSat is limited or only approximate. In other words, the inaccuracy, i.e. an error vector, may still be too big for particular mission requirements. The final state is the precise or fine control state. With CubeSat being in this state, the accuracy, precision, and control capabilities are all at their possible maximum.

8.3 State Transition

In order for CubeSat to pass from one state to another, it has to undergo a certain transition, i.e., a phase, as depicted in the original image, i.e., Fig. 8.2. This phase consists of three elements that work in synergy. The first element, or a step, is to acquire the necessary information and data. The sensors on-board play a key role in this, since they are the ones responsible for this procedure. Next, the data are fed into a particular algorithm. A very popular choice is the TRIAD algorithm, where attitude determination is carried out by two vector measurements in two coordinate systems [93]. Another option is the extended Kalman filter [94], [95]. Other possible options are discussed and described extensively in a variety of sources, such as [96]. The algorithm, along with the AC[2] subsystem, then decides on what action is required, e.g., how much torque is needed, to achieve the desired attitude, and calculates the necessary commands that are then sent to actuators, which represent the final step. The whole principle can be seen in the image below, cf. Fig. 8.3.

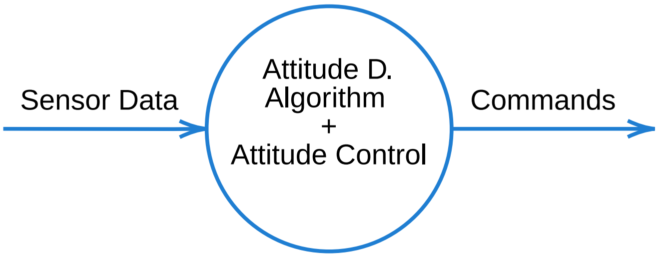

Figure 8.3: Symbolic state transition illustration. Image by author.

Naturally, the processes included in these transition phases are not one-time actions. They occur continuously to guarantee active correction of potential errors and fluctuations. However, certain hardware components, i.e. sensors and actuators, are better suited for and have more efficient use in a particular phase, that is, A or B. In the spirit of this, let us now take a look at the most common components.

---

[2] Attitude Control

8.4 Sensors

8.4.1 Magnetometer

The inexpensive, small, and lightweight magnetometers with low power consumption are a fairly popular option for determining the attitude on CubeSats [97]. They measure the strength and direction of the local magnetic field, which, when compared with the high-fidelity model of the magnetic field of Earth, can yield useful information about the attitude of spacecraft [98]. However, there are certain constraints. For one, measurements from a three-axis magnetometer can provide information on only two axes of the spacecraft attitude [99]. Additionally, the sensor itself can be affected by a nearby magnetic field, such as the one produced by magnetic coils or by on-board circuits or even the chassis of the spacecraft itself [97]. A solution to this proves to be to place the sensor outside the CubeSat [97], cf. Fig. 8.4.

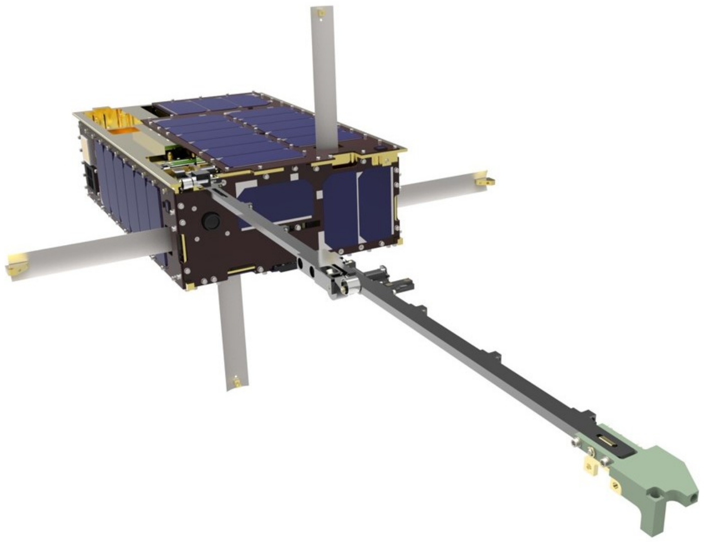

Figure 8.4: Dellingr 6U CubeSat with extended boom containing the said sensor thus mitigating possible issues [100].

Furthermore, the quality of output depends heavily on the field modelling, which, coupled with possibly noisy measurements and variability of the Earth's magnetic field, gives enough reason for why some have declared them the least accurate attitude reference sensors [101]. Nevertheless, they are still a viable option for coarse attitude determination, i.e. might often be used in what we denoted as Phase A.

8.4.2 Earth/Horizon Sensor

Because the Earth is large and bright in the infrared during both sunlight and eclipse for satellites in LEO, sensors that can detect the Earth's limb in the infrared can be used by the ADCS system to provide nearly uninterrupted fine attitude knowledge [102]. The emitted radiation forms a *horizon*, i.e. a split between the illuminated part of the body and the darkness of space. This discontinuity is then typically exploited by the Earth sensor, also often called an Earth horizon sensor, in general terms a horizon sensor (since it can be used for any planet) [103].

Figure 8.5: Image of a horizon sensor [104].

8.4.3 Sun Sensor

Sun sensors are, by nature, similar to the aforementioned Earth sensors. They are used to determine the direction of the Sun with respect to the body frame of the spacecraft [98]. This direction can then be used to help estimate the attitude, although to obtain a complete three-axis attitude estimate, at least one additional independent source of attitude information is required [103]. Generally, we could distinguish between two major categories of Sun sensors [89], that is, (1) coarse Sun sensors and (2) fine Sun sensors (each might prove more suitable for a particular phase, that is, Phase A and Phase B respectively).

Into the first category, we could, for example, include a CSS[3], which is based on photocells. The sensor output is based on the current generated by the cell, which is approximately proportional to the cosine of the angle α between the Sun and the normal to the photocell $\vec{n}$ [103], cf. Fig. 8.6.

---

[3] Cosine Sun Sensor

The equation thus writes [105]:

$$I(\alpha) = I_0 \cdot \cos(\alpha). \tag{8.1}$$

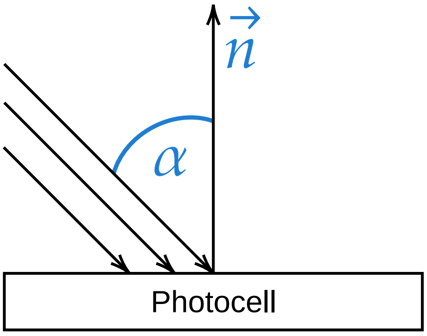

Figure 8.6: Cosine Sun sensor principle with sun rays hitting the photocell [105].

Generally, a larger number of these sensors might be installed on a single spacecraft, each pointing in a different direction to ensure complete sky coverage and increased accuracy [103].

A quadrant Sun sensor might be put into the second category. Quadrant Sun sensors typically operate by shining sunlight through a square window onto an array of photodiodes. The current generated by each photodiode is a function of the direction of the Sun relative to the sensor boresight. The measured currents from all four cells are then mathematically combined to produce the angles to the Sun [103].

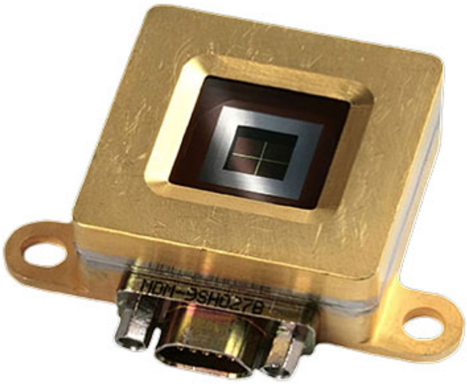

Figure 8.7: Image of a quadrant Sun sensor [106].

8.4.4 Star Tracker

Star trackers can provide an accurate attitude estimate in all three axes. They can do so independently, by taking a picture of the sky, i.e. star constellations, and comparing this picture with a catalogue stored in their memory. Once the stars have been identified, the inertial attitude of the spacecraft is calculated [105]. Albeit these sensors can do this accurately, they are also subject to certain limiting factors, such as the stellar distribution around the star sensor and the stellar brightness, the dimensions of the sensors themselves or the exposure time [107].

Figure 8.8: Image of a star tracker sensor [108].

8.4.5 Gyroscope

Gyroscopes are used to measure the angular velocity. In the case of CubeSats, the typical use-case consists of two types of such sensors, that is, a (1) FOG[4] and a (2) MEMS[5] gyroscope [89]. The former offers superior precision compared to the latter; however, the latter usually has greater durability, which, coupled with its smaller size, makes it a good practice to include for increased redundancy or in case of emergency [89]. As such, the former might find use in Phase B, and the latter might find use in Phase A.

---

[4] Fibre Optic Gyroscope

[5] Micro-Electro-Mechanical System

8.5 Actuators

8.5.1 Magnetorquer

A magnetorquer is a device that can provide torques perpendicular to the local magnetic field [103]. This happens by generating a magnetic moment by electrical current, which then interacts with the ambient magnetic field, that is, the one of Earth, producing the external torque acting on the vehicle [89]. CubeSats in LEO can take advantage of this with the aim of controlling their attitude such as when detumbling (Phase A) or when trying to stabilise themselves further (Phase B). It is apparent that the device works only in the presence of a magnetic field. Thus, it is important to take into account factors such as field strength, orbit height, or the presence of the field itself when planning to use magnetic torquers [101]. These actuators are small in mass, low in power consumption and high in reliability [109]. They can also be used to unload the momentum of complementary control actuators such as reaction wheels [98].

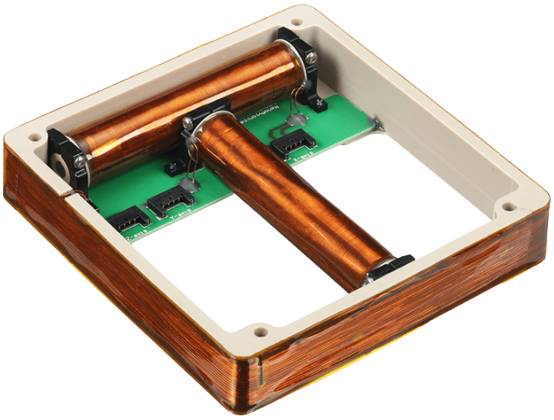

Figure 8.9: Image of a CubeSat magnetorquer [110].

8.5.2 Reaction Wheels

These momentum exchange actuators are based on the acceleration and deceleration of spinning rotors (inside the wheels), with a nominal condition of zero angular velocity [101]. They make it possible to control the attitude of the spacecraft by the reaction effects of the rotation, i.e. by counteracting on it. Put differently, they exchange momentum with the spacecraft by changing wheel speed, i.e. if the satellite body spins in one direction, the reaction wheel spins in the other direction [111]. This fact is apparent when we consider the following equation [112], since both the wheels and the satellite can be thought of as a spinning mass:

$$\vec{H}_t = \vec{I}_s\vec{\omega}_s + \vec{I}_w\vec{\omega}_w, \tag{8.2}$$

where $\vec{H}_t$ denotes the total angular momentum, $\vec{I}_s$ is the moment of inertia of the satellite body and $\vec{\omega}_s$ represents its angular velocity. Similarly, the same applies to the subscript w, which is for wheels.

One of their advantages is the fact that they need no propellant. This comes in handy, especially for spacecraft such as CubeSats, where space is limited. However, they also have their disadvantages. Since disturbance torques acting on the satellite gradually accumulate as angular momentum stored in them, they need to be periodically de-saturated using, for instance, a magnetorquer [89]. For full three-axis control, a spacecraft requires three wheels mounted orthogonally. However, a four-wheel configuration is often used to provide fault tolerance [105].

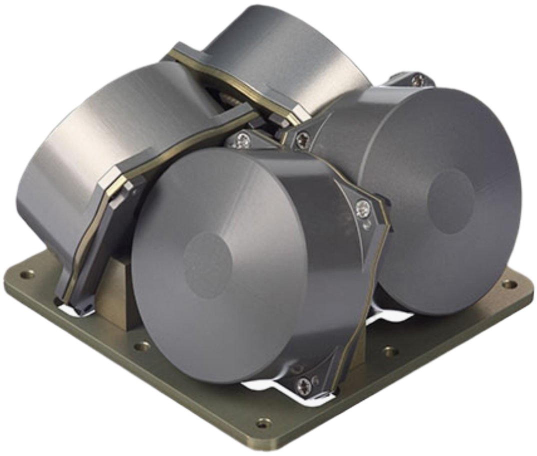

Figure 8.10: Image of CubeSat reaction wheels [113].

8.6 Propulsion

A component that can fundamentally improve the functionality of a CubeSat and thus increase the possible scientific return of a mission is the propulsion system. Although the desire for such a system has been on the rise, the actual deployment rate is rather rare [114]. One factor to account for this is the limited mass, volume and budget when it comes to CubeSats, which makes it challenging to port existing technology to a smaller form-factor [114]. Typical propulsion systems are cold gas thrusters, electric or chemical propulsion, and solar sails. [115] Each of these would merit a dedicated discussion, so an interested reader might refer to [116] or [117].

8.7 Discussion

Naturally, the list of hardware components discussed in the previous passages of the text is not complete. There is a great variety of components that a CubeSat might carry that ought to be specifically tailored to mission requirements. For example, there is also the possibility of having an integrated ADCS system that would house the individual components under one body.

An example of such a component is Gen 1: CubeADCS [118]. Nevertheless, an exhaustive summary of the majority of components and their current state-of-the-art with regard to small satellites such as CubeSats can be found in [103]. We will include a table containing the hardware we discussed; see Table 8.1.

Component	Performance	TRL
Magnetometer	± 75000 [nT] resolution	9
Earth/Horizon Sensor	0.25 [°] accuracy	7-9
Sun Sensor	0.1 [°] accuracy	7-9
Star Tracker	8 [arcsec] pointing knowledge	7-9
Gyroscope	0.15 [$^\circ \cdot \mathrm{h}^{-1}$] bias stability, 0.02 [$^\circ \cdot \mathrm{h}^{-1/2}$] ARW	7-9
Magnetorquer	0.15 [Am^2]–15 [Am^2]	7-9
Reaction Wheels	0.00023 [Nm] PT, 0.0005 [Nms] SG	7-9

Table 8.1: State-of-the-art GNC components [103].

Of great importance might also be a survey that contains the frequency of deployment of individual hardware pieces, such as [97]. Equally important are studies such as [119] in which the complete picture of attitude control has been studied.

Chapter 9

Communication and Relative Navigation

A key factor and an integral part of every mission are its means of communication. During the operation of a satellite, the communication links are used for commanding, retrieving telemetry, tracking, and ranging, and tasks such as applying software updates. Additionally, communication links relay and broadcast signals and downlink payload data [120]. The two common types of nanosatellite communication links, i.e. space-to-ground links (UL[1], DL[2]) and ISL[3] are are displayed in Fig. 9.1.

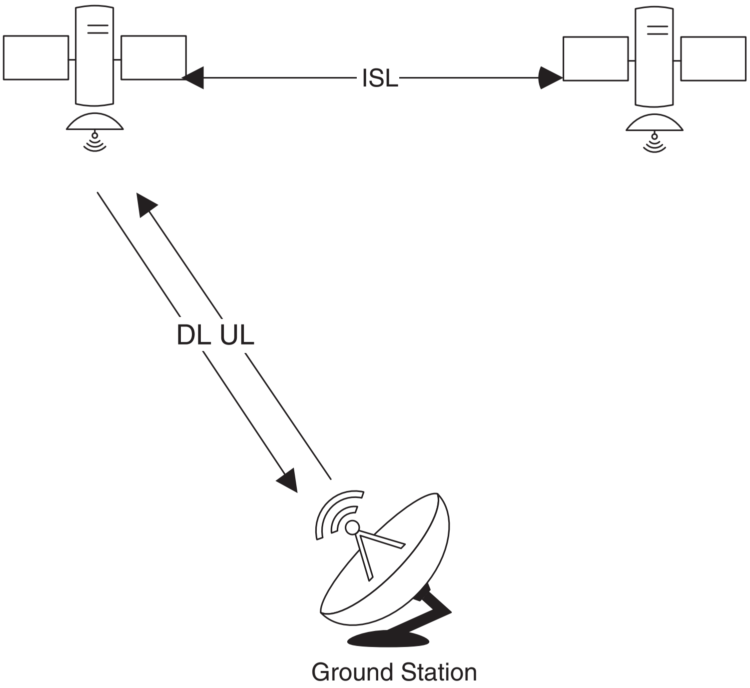

Figure 9.1: Illustration of nanosatellite links [120].

---

[1] Uplink

[2] Downlink

[3] Intersatellite Link

Space-to-ground communication is the default for virtually all communication services provided by satellites. ISL is an emerging technology among nanosatellites, as a means of coordinating and transmitting data within satellite formations and constellations [120].

When talking about FF, evidently, the capability of ISL is directly proportional to the magnitude of possible scientific return. In other words, the more accurately and reliably ISL is implemented, the more certain and better the result a given mission can achieve.

This leads to the problem of state estimation. Estimating the state of a satellite, e.g. its relative position and velocity within the formation is complex. It is in effect a large-scale optimal data-fusion problem, where one has to not only fuse many different data types, e.g. optical, radio, inertial, but also incorporate redundant data measurements to obtain the state estimate. This fusion must be done on-board, autonomously, and in real time while accounting for delayed and dropped communicated data and time-varying sensing and communication topologies. An estimation problem of such proportions is not encountered in single-spacecraft applications [44].

That being said, a satellite flying in a formation with other vehicles typically carries, among other sensors, particular devices that provide measurements of the relative position between itself and other spacecraft in formation [44]. D'Amico in his work [121] regarding autonomous formation flying in LEO summarised possible approaches to the issue of relative navigation in the following manner, see Table. 9.1.

Technology	**Accuracy**
GNSS	m-cm
Radio Frequency	m-cm
Optical metrology	mm-μm
Laser interferometry	nm

Table 9.1: Formation flying metrology technologies [121].

Similarly, a study of formation flying with CubeSats [122] identified the following possible implementations and their limits, that is, the maximum range and sensing accuracy, cf. Fig. 9.2.

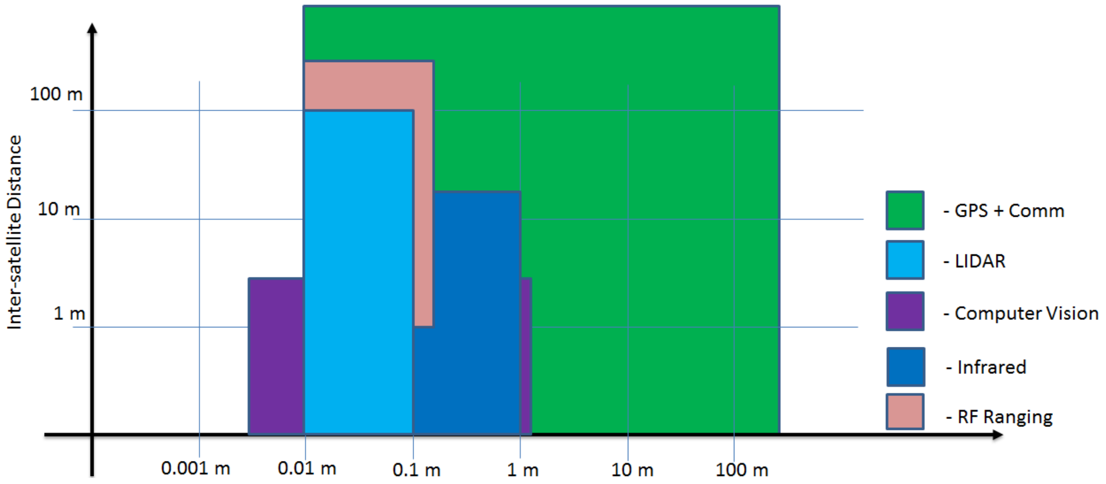

Figure 9.2: Comparison of relative position determination technologies [122].

9.1 GPS-Based Relative Navigation

The use of the GPS is not restricted to the immediate vicinity of the Earth alone. Similar signal coverage can be achieved up to altitudes of at least 1 500 kilometres, which covers most of the LEO, where the vast majority of CubeSats are positioned, and thus opens the way for GPS navigation in space [123]. This fact is associated with the ability to track and use numerous individual GPS satellites. It is one of the reasons why relative navigation based on GPS is the most common method for formation flying and R&D of CubeSats [124].

Although the functionality of spaceborne GPS devices and regular GPS devices meant for terrestrial use remains the same, the nature and design of the former are much more challenging compared to the latter. For one, the spaceborne GPS has to account for the high signal dynamics and the more hostile environment [123]. There are also additional limitations, such as frequent changes in GPS visible satellites, transmission time delays between individual satellites, or just the amount of computation required [124]. One of the possible solutions that aims to mitigate negative influences as much as possible is the usage of CPDGPS[4]. CPDGPS is a promising technology for relative navigation, since processing single-difference (or even double-difference) carrier-phase measurements allows determining the relative positions of the satellite with high precision [125]. This comes from the fact that the determination of the relative position of adjacent spacecraft in a formation typically yields improved results by subtracting carrier phases from the two user spacecraft to a common GPS satellite. The resulting single-difference measurements allow for a reduction of systematic errors through the cancelation of common error terms [126]. This has resulted in centimetre-level accuracy being demonstrated in orbit by, for instance, the PRISMA mission [127] or even some other formations, see [125] and references therein.

However, it is important to note that the deployment of such technology aboard a CubeSat has not been reported yet, and the separation of the aforementioned

---

[4] Carrier Phase Differential GPS

missions spanned from several hundred metres to kilometres. On the other hand, this technology has great potential, as generally the signal does not necessarily have to be based on GPS only. In case the spacecraft uses other systems, such as Galileo, GLONASS or BeiDou, we are talking about GNSS[5]-based navigation.

9.2 Radio Frequency-Based Relative Navigation

Knowledge of the state of a satellite in formation can also be acquired via RF[6] signals. Specifically, this metrology method is based on ranging signals being exchanged by spacecraft, which are then used to measure the range (or range rate) between them [128]. In order to achieve this, some common techniques when it comes to estimating the range, i.e. the distance between two points, are time-of-flight, carrier phase shift, or Doppler shit.

In the context of intersatellite ranging methods, RF-based is the most mature [129]. One of the reasons for this is that despite the fact that GPS-based technology (or GNSS when talking in general) is capable of delivering precision at centimetre level, it bears certain limiting factors. Firstly, at altitudes above the GNSS constellations (e.g. GPS satellite are orbiting at an altitude of approximately 20.200 km), only the very weak GNSS signals from the sidelobes on the opposite side of the Earth may be discontinuously available [130]. Additionally, author in [130] notes that poor geometric dilution of precision and slow LoS[7] vector dynamics between the receivers and GNSS satellites may make the precise GNSS carrier phase-based solution difficult.

To mitigate some of the issues discussed above, a common approach is to design and implement standalone devices mounted on individual spacecraft that provide a relative range of information. Some of the possible implementations and their characteristics are listed below; see Table 9.2.

RF System	Frequency Band	Mission	Ranging Accuracy
Star Ranger	Ku	TechSat21	sub-cm
AFF	Ka	St-3	1 cm
CCNT	S	St-5	1 cm
FAS	S	TPF	0.5 m, 1° LOS
SPTC	L	-	2-5 m
FFRF	S	PRISMA	1 cm, 1° LOS in fine mode

Table 9.2: RF metrology overview. For full reference, see [130].

---

[5] Global Navigation Satellite System

[6] Radio Frequency

[7] Line-Of-Sight

9.3 Vision-Based Relative Navigation

Last but not least, vision-based equipment can be used. This type of relative navigation is often deployed in the case of deep space exploration or when the form factor is limited, as in the case of CubeSats [131]. Sometimes, this particular area of navigation is also referred to as EO[8]. Generally speaking, the term *EO sensors* is used to indicate a wide variety of devices capable of collecting radiations reflected and/or directly emitted by the surrounding environment in the optical spectrum [132]. In addition, they can be active or passive depending on whether they include an energy source to emit radiation or not [132]. A disambiguation that describes the nature of this method can be seen in Fig. 9.3.

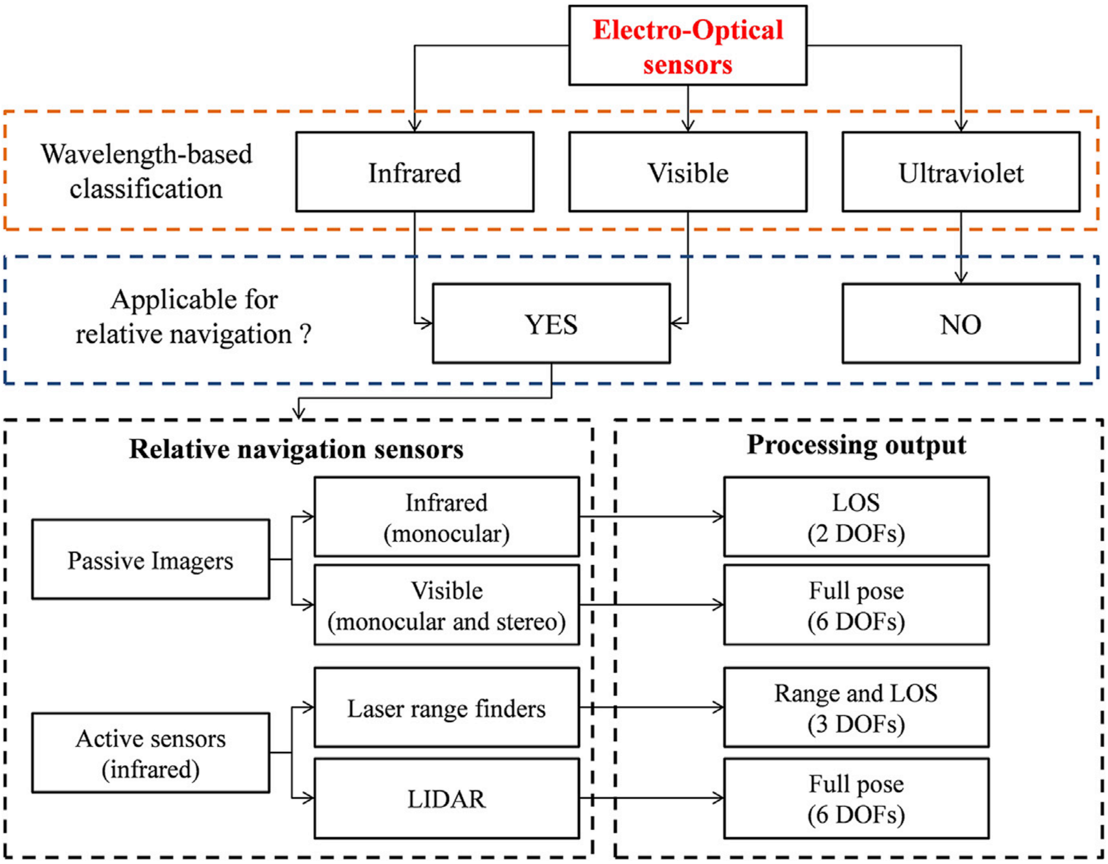

Figure 9.3: Classification of EO sensors [132].

Typically, passive visible-light cameras and active LIDAR[9] systems are used. [132].

LIDAR is a remote sensing method that uses laser light to measure distances to objects. By emitting laser pulses and analyzing the reflected light, LIDAR can measure the distance between the sensor and the illuminated object. Some LIDARs, such as 3D LIDARs, even allow the estimation of the 6-DOF[10] pose of the target.

---

[8] Electro-Optical

[9] Light Detection and Ranging

[10] Degrees-Of-Freedom

Another popular device used is LRF[11]. These devices are based on a single detector that measures the distance travelled by a single laser beam and therefore they can only estimate the range and LoS of the target [131].

Validation of such technologies in space is, for instance, planned within missions such as SpEye, see [133]. In general, metrology based on optical principles can offer higher accuracy than, for example, the last two methods discussed. However, one constraint is that optical sensors tend to have a rather small field of view. They also tend to have a smaller range, which may require high-performance hardware. This might prove problematic in the case of CubeSats, where power and space are limited. Another important fact to take into consideration is that, for instance, sunlight (or essentially any light) might blind or saturate the device.

9.4 Technology Fusion and Future Promises

In the previous passages of the text, we covered the most common technologies and principles used for relative navigation in FF, i.e., when the desire is to acquire the knowledge of e.g. position and velocity of another spacecraft within the formation. Usually, it is a good practice to exploit and include a broad spectrum of these technologies, whether for increased accuracy, additional robustness, or redundancy. However, when talking about CubeSats, with such an approach, one might encounter certain complications due to the limited nature of the CubeSat itself. That is why it is essential to work out and acknowledge the particular requirements of a mission and which implementation might be the most suitable.

With this in mind, in the context of the theory of relative navigation, we can recognise multiple attempts at technology fusion or novel approaches to the issue.

Studies such as [131] propose a fusion between GNSS-based navigation and vision-based navigation. On the other hand, there is a study on the fusion of a RF-based navigation and vision-based navigation, see [134]. Another novel approach MUSAS[12], was studied in [135].

Nevertheless, we shall not omit the new arising solution to the issue in question, which is especially paramount in the case of a virtual space telescope consisting of two CubeSats, to be discussed below, and that is technology based on vision navigation that utilises light sources or artificial markers placed on the target spacecraft. This idea has been studied extensively [136], [137]. Despite the fact that this particular area is still in active development, several solutions and implementations have already been proposed.

For example, studies such as [138] have reported experimental results that demonstrate the capability to attain pose and relative state estimates in line with accuracy requirements to ensure autonomous and safe close-proximity operations, e.g., up to sub-cm and sub-degree error levels in relative position and attitude, respectively.

---

[11] Laser Range Finder

[12] Multi-CubeSat Relative State Determination by Array Signal Detection

In addition, the algorithm's computational runtime in question has shown to be compatible with real-time implementation at an acquisition frequency of 2 Hz.

Moreover, the authors of [139] have studied relative navigation of spacecraft with respect to a passively cooperative object, tailored for CubeSats, involving a LRF working in near-infrared bandwidth and a monocular camera as navigation sensors. The former is used as both a sensor and an illumination source for the observed scene. They achieved pixel-level reprojection errors corresponding to sub-millimetre accuracy.

Furthermore, for minimal relative distances and subsequent docking, a novel approach was studied in [140]. A system that can be housed in half-U has been investigated, which would allow for obtaining the complete relative state from the 10 m range and be robust to illumination conditions and stray light. This study also uses carrier phase GPS, which would be used to achieve such a small separation distance in the first place.

Lastly, solutions for relative navigation of CubeSats in the deep space have also been proposed, see [141].

With that being said, it can be assumed that this particular method of relative navigation will see some major breakthroughs and the most eminent development, namely, thanks to artificial intelligence, computer vision, or neural network solutions.

Chapter 10

Mission Study

10.1 Motivation

In recent years a great variety of novel application studies and mission envisions, utilising one or more CubeSats, has been on the horizon. Their goal is to extend the field of possible CubeSat utilisation through technology demonstration, which should subsequently result in a possible paradigm shift. One prime example is asteroid surveillance. This particular CubeSat usage case has been addressed in multiple studies, such as [142], [143] or the one carried out under CTU as well [144]. A handful of missions have also been carried out for this purpose, while others are still in their development stage. An example of the former is LICIACube[1] [145], which played a crucial role in the homonymous mission that took place in September 2022. LICIACube successfully completed the first asteroid flyby performed by a CubeSat. With a maximum Earth distance of approximately 14 million km during its operational phase, LICIACube is currently one of the nanosatellites that operated the farthest from our planet in a robotic exploration mission [145]. Another example is the Near-Earth Asteroid Scout mission [146], which hoped to travel to and image an asteroid during a close flyby using a solar sail as its primary propulsion. Unfortunately, according to [146], the project team was not able to communicate with the spacecraft after the launch. Regarding the latter, some proposed missions include the ASPECT CubeSat [147] which aims to characterise resources on asteroid surfaces or the MILANI CubeSat [148] which will be carried by the HERA mothercraft and will take 3 years to travel from the LEO to the Didymos binary system of asteroids. Expected to reach the asteroids in 2027, MILANI will be deployed to survey the surface with a hyperspectral imager combining visible and near-infrared wavelengths to survey the surface of the asteroids. It will also carry an Italian-built dust detector capable of detecting tiny dust particles, volatiles, and light organic matter, characterising the molecular composition of the larger asteroid bodies [148]. Some interesting possible future extensions, already being studied, include landing on an asteroid, see [149]. We can hence safely conclude that this particular application area will likely gain even more attention in the near future. However, what is equally important, and what we should now focus on is the concept of a space

---

[1] Light Italian CubeSat for Imaging of Asteroids

telescope, which should consist of two individual CubeSats in the trailing (tandem), i.e. leader and follower configuration.

10.2 Tandem Space Telescope Concept

If we take into consideration the disambiguation we have followed throughout the whole work, then such an idea, i.e. two CubeSats flying in close proximity of each other, functioning as a space telescope, strikes a delicate balance between rendezvous mission architecture and formation flying. The key lies in adopting the close-range approach capability of the former and communication coupled with interconnection from FF. Studies such as [150] envision the concept to consist of two CubeSats flying at a constant distance of a few metres up to hundreds of metres, where the front satellite, i.e. the leader, would carry the telescope optics and the second satellite, i.e. the follower would carry the detector system.

10.2.1 Concept Background

Such a concept has been studied in general since the beginning of this century [151], which has laid the groundwork for mission visions such as SIMBOL-X [152] where the hope was to have three satellites, two carrying focusing mirrors, and one a focal plane detector. The two satellites would be maintained at a distance of 20 m from each other, with a precision of the order of centimetres. Unfortunately, to our best knowledge, the mission has never flown.

A revolutionary pioneer in a broader sense has been the GRACE[2] mission [153]. GRACE consisted of two twin spacecraft that launched on 17 March 2002 and ceased their scientific mission on October 2017. The mission used a microwave ranging system to accurately measure changes in the speed and distance between two identical spacecraft flying in a polar orbit about 220 kilometres apart, 500 kilometres above Earth. The range system was so sensitive that it could detect separation changes as small as 10 microns, which is about one-tenth the width of a human hair over a distance of 220 kilometres [153].

The TanDEM-X mission [154], which stands for *TerraSAR-X add-on for Digital Elevation Measurement*[3] has been in operation since 2010. The main mission concept is based on the coordinated operation of two spacecraft flying in close formation. Using two independent spacecraft provides the flexible and reconfigurable imaging geometry required to meet the mission objectives, such as its primary goal of generating a precise digital elevation model [154]. TanDEM-X was the first formation-flying radar interferometer in space, and it has managed to accomplish unprecedented results. The formation combines a horizontal orbital displacement with vertical separation, resulting in a helix-like relative movement of the satellites along the orbit [156]. The

---

[2] Gravity Recovery and Climate Experiment

[3] The first satellite in the original mission was TerraSar-X. This satellite was then joined by the satellite in question, hence the name.

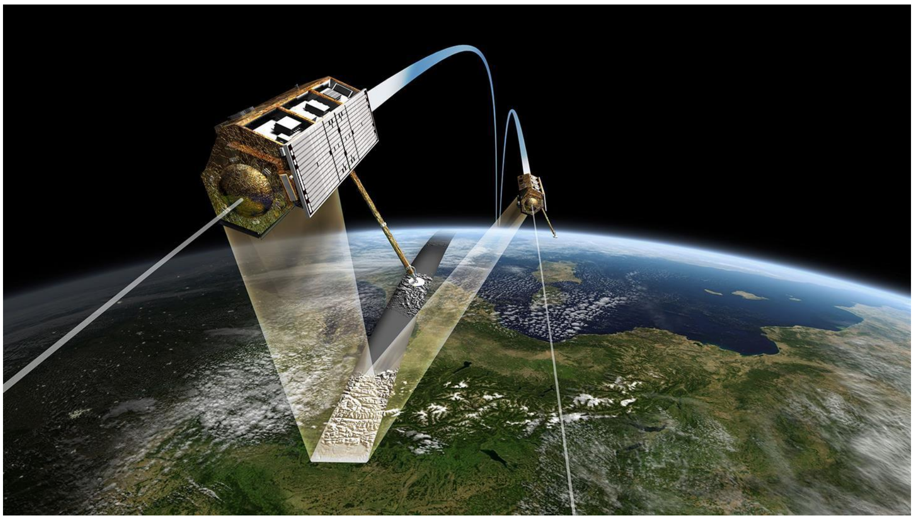

Figure 10.1: Satellite twins TerraSAR-X and TanDEM-X [155].

formation managed to achieve radial and cross-track distances of 360 and 400 m, respectively [156].

Finally, in 2010, the PRISMA mission was launched [157]. PRISMA was a technology mission that aimed primarily at the demonstration of different sensor technologies and guidance navigation strategies for rendezvous and formation flying in space. The mission consisted of two spacecraft, one advanced and highly manoeuvrable called Mango, and one called Tango [157]. Throughout the mission, various relative orbit distances have been achieved, ranging from 1 m to 45 km in along-track separation, up to 1 km cross-track, and to 2-kilometre radial distance [158]. The closest GPS-based approaches were as close as 2 metres. Later in the mission, an even closer approach of 1 metre was performed. This time, navigation was vision-based.

All in all, albeit the spacecraft within these missions were not CubeSats according to the official standard, these missions have helped pave the way towards the general idea of close operation of two spacecraft and at their time were the pinnacle of what was achievable.

10.2.2 Moving Forward

The achievements of these missions did not go unnoticed and were picked up on in the world of nanosatellites as well. A study on CubeSat formation flying published in 2015 [122] based on [159] identified the hitherto state-of-the-art capabilities in the following way, see Table 10.1.

One might notice that the technological apex identified by the authors was composed of two particular missions. The first one, the CPOD mission, has already been covered in 4.2.2. At that time, the second mission, that is, Can-X [160], had not flown yet. Since some time has passed since then and the mission has luckily been realised, we shall now elucidate the results this mission attained. The mission consisted of two identical nanosatellites, CanX-4 and CanX-5. Although slightly larger than a CubeSat ($20 \times 20 \times 20$) [161], it used a technology qualified onboard

Metric		**Proposed Missions**		**Achievable Then**
Position Determination	Absolute	2-5 m	Can-X	1.2 m (RMS)
	Relative	2.5 cm (RMS	Can-X	<2.4 m
Position Control	Absolute	-	-	-
	Relative	1 m	Can-X	5 m (delta V /orbit - 0.93 m/s)
Attitude Determination	Absolute	0.007 deg	CPOD	<0.007 deg
	Relative	0.5 deg	Can-X	<0.014 deg
Attitude Control	Absolute	<0.15 deg	CPOD	0.021 deg (3 σ)
	Relative	1 deg	Can-X	0.042 deg (3 σ)

Table 10.1: State-of-the-art for position and attitude determination and control [122].

CanX-2 (a 3U CubeSat) to perform formation flying [162]. Launched in 2014, the two satellites were deployed separately after their launch, after which a series of drift recovery manoeuvres were executed to bring them within the range of communication of each other. Subsequently, the spacecraft used onboard propulsion, an S-band intersatellite communications link, and relative navigation using CPDGPS techniques to perform a series of precise, controlled, autonomous formations from 1-kilometre range down to 50 metres separation [160].

Based on the results reported [163], the CanX-4/5 became the first formation flying nanosatellites to successfully demonstrate autonomous formation flight with submeter control error and relative position knowledge at the centimetre level. In this sense, the mission has rightfully set the benchmark for small satellite formation flight [160].

Other missions of similar nature followed. CANYVAL-X [164] was a technology demonstration mission with the primary objective of validating technologies that would allow two spacecraft to fly in formation along an inertial line of sight (i.e., align two spacecraft to an inertial source). It aimed to demonstrate a precision dual spacecraft alignment achieving fine angular precision [164]. The mission consisted of two CubeSats, a 1U passive target CubeSat nicknamed Jerry, and a 2U actively controlled CubeSat nicknamed Tom. The hope was to create a virtual telescope, by keeping the relative distance between the spacecraft to at least 10 metres, where one would carry the lens and the other would carry the detector. The mission utilised a vision alignment system that could determine the relative position and relative attitude between the two CubeSats simultaneously [165]. The CANYVAL-X mission was designed and developed from late 2012 to early 2016. The two CubeSats that made up the CANYVAL-X mission were launched in early 2018, and the first beacon was received after 43 days from launch. Unfortunately, due to several problems in the communication system, it was not possible to receive any data transmitted by the CubeSats. [166]. The hope was to receive another beacon signal later, but we were unable to find any further mention.

Coming with an effort to correct the shortcomings was the CANYVAL-C mission [167]. The CANYVAL-C mission was the follow-up mission of the CANYVAL-X mission. The final goal of the mission was to obtain several images of the solar corona by constructing an artificial solar eclipse with two CubeSats. The two CubeSats in

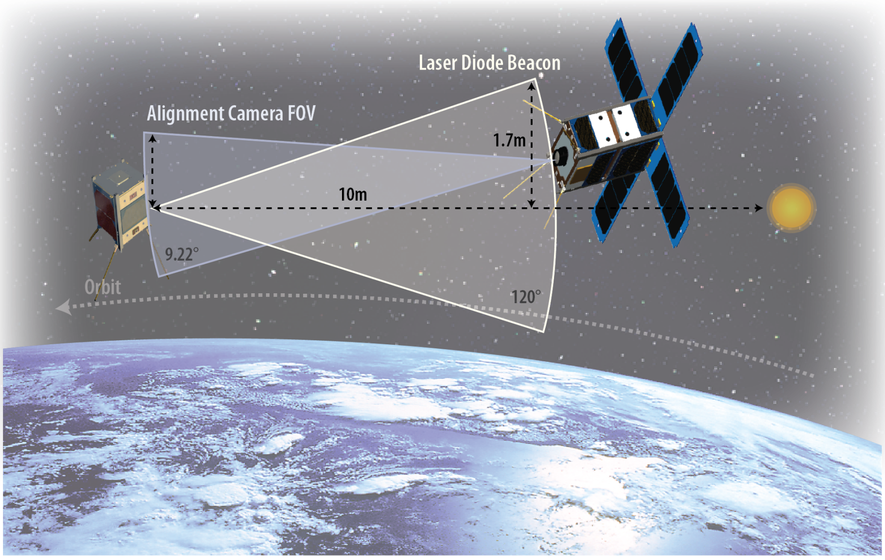

Figure 10.2: Canyval-X mission concept showcase [164].

question were 1U Timon and 2U Pumbaa. The mission requirements and constraints could be summarised using the following table, cf. Table 10.2. The CubeSats were deployed in 2021, but unfortunately, despite the fact that the team behind the mission attempted to identify the CubeSats by operating the ground segment, they have been unable to communicate with either of them via the ground station [167].

Content	**Description**
Constraint	(1) 20 $\sim$ 53 metres for the relative distance (2) Two CubeSats contained in a single deployer
Relative positioning	(1) <5 meter (3σ) for the sphere radius (2) <7.5° (3σ) for the alignment angle

Table 10.2: CANYVAL-C mission requirements and constraints [167].

10.2.3 What Does The Future Hold?

Based on the previous discussion and to our best knowledge, we can conclude that in spite of numerous attempts and actually realised missions, an exact and concrete implementation of the idea of a space telescope consisting of two CubeSats separated by a distance of up to a hundred metres is still lacking. Fortunately, that does not mean that the idea has been abandoned. Quite the opposite, there are numerous mission proposals already. Planned to launch in 2024, that is, this year, is mission VISORS[4] [168], which would consist of two 6U CubeSats. The idea is to have one spacecraft contain the optical payload and the second carry the detector. The former would host a photon sieve payload that acts as a high-resolution lens in the extreme ultraviolet spectrum. The deployable solar panels double as a sunshade, blocking most of the light from regions outside the area of interest from reaching the detector

---

[4] Virtual Super Optics Reconfigurable Swarm

vehicle. The latter spacecraft, i.e. the one with the detector, would collect focused images produced by the photon sieve [168]. The situation is depicted in the image below, cf. Fig. 10.3. Fig. 10.3 also tells us the distance envisioned between the spacecraft vehicles. Secondly, there is the VTXO[5] mission [170]. VTXO will consist of two small satellites. One carrying a phased-fresnel lens and the second an X-ray sensitive camera. The goal of the VTXO project is to develop a space-based X-ray imaging telescope with high angular resolution precision [171], [170]. The original mission proposal [172] and [171] speak of using two 6U CubeSats. Other related works, such as [173] or [174] speak of one 6U CubeSat and one ESPA-class satellite. According to the former (both), the distance between the spacecraft is envisioned to be 100 metres. According to the latter, the distance is 1000 metres (20 in a certain case, see chapter 4 in [173]).

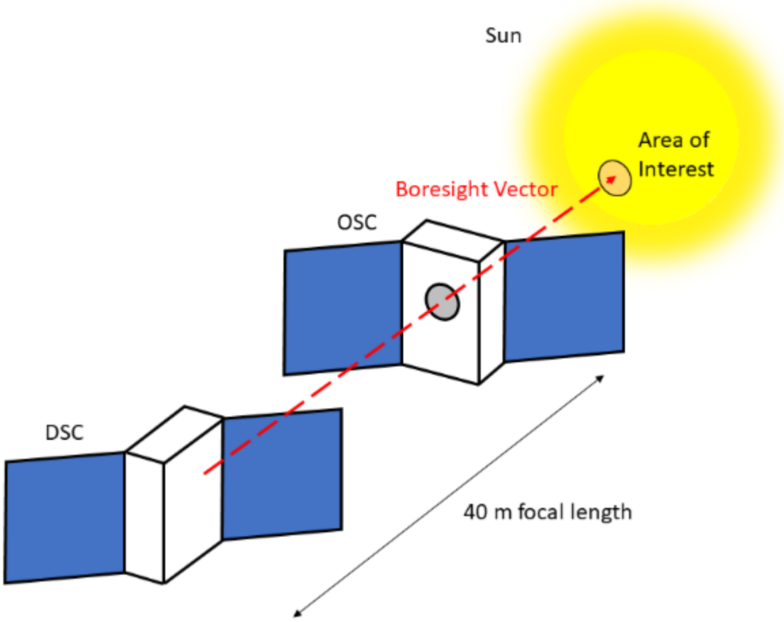

Figure 10.3: VISORS formation configuration [169].

---

[5] Virtual Telescope for X-ray Observations

10.3 Final Thoughts on X-Ray Tandem Telescope Mission Design

We have discussed the important features and technologies present within each CubeSat, consequently within each mission, in Chapters 8 and 9. In Chapter 10, we followed up on this by discussing the past, recent and upcoming missions, thus accessing the current state of the technology with regard to the concept of a CubeSat tandem space telescope. On the basis of the acquired knowledge, we can now try to formulate, i.e. envisage a possible implementation, and discuss the mission design of a tandem flight X-ray space telescope.

As already mentioned multiple times, the CubeSat tandem space telescope concept involves the flight of two CubeSats in close proximity, each carrying a particular payload. The distance between the two would range from a few metres to theoretically a hundred meters or even more. Such an approach, i.e. an implementation, would represent an intersection between R&D and FF since the close proximity of two spacecraft is characteristic for R&D, and at the same time, and perhaps more importantly, the orientation and relative distance between the two CubeSats must be precisely controlled and managed. This stems from the very nature of the space telescope concept itself and captures the nature of the character of FF, where the individual spacecraft are interconnected and the state of one affects the state of the other. In order to ensure such properties, thorough research is crucial, not only in the areas discussed in Chapter 8 and Chapter 9.

Firstly, let us recall the current state-of-the-art, i.e. the contemporary technology state, and what missions achieved it. In the context of proximity operations, one such mission was the CPOD mission, which, although not completely successful, managed to bring the two CubeSats to a distance as close as a few hundred metres. A similar distance, i.e. two hundred metres and with the goal of getting even closer, was achieved by the LINUSS mission [175]. Even a smaller distance, i.e., a mere 20 metres, was achieved by the AeroCube-10 mission. Albeit not strictly a CubeSat, the PRISMA mission has achieved a distance of 1 metre between two spacecraft. However, arguably the most important mission related to the issue discussed in this thesis has been the CanX-4/5 mission. To our knowledge, the unprecedented results achieved by this mission still serve as the absolute technology apex and have not yet been conquered. For completeness, the distance between the two spacecraft was 50 metres, and it was the first autonomous formation flying mission to demonstrate submeter control error and relative position knowledge at the centimetre level. Using its CPDGPS, the relative accuracy of only a few centimetres was achieved.

In terms of the actual payload of the CubeSats, much research has been devoted to this question and numerous studies have already been realised, some of those at CTU as well, see [176], [177], [178] or [179]. On the basis of this, the most feasible option seems to be the deployment of Kirkpatrick-Baez optics. Kirkpatrick-Baez optics are an X-ray focusing system that uses two orthogonal mirrors to focus X-rays. Developed by Paul Kirkpatrick and Albert Baez in the 1940s [180], this design employs two reflective mirrors placed at right angles to each other, with each mirror focusing the X-rays in one dimension (one focuses in the horizontal plane and the other in the vertical plane), cf. Fig. 10.4.

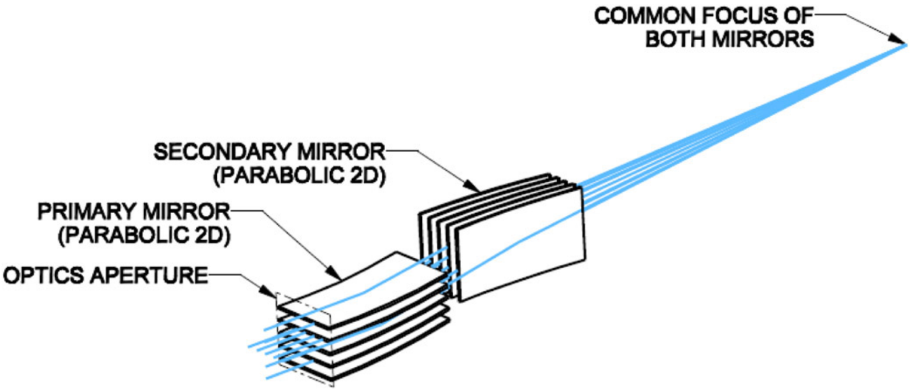

Figure 10.4: The principle of the Kirkpatrick-Baez telescope [181].

By using grazing incidence, where the X-rays strike the mirrors at a very shallow angle, the mirrors can effectively focus the X-rays without significant absorption, which is critical because X-rays can easily penetrate and pass through most materials. Their main advantage in the context of tandem space telescopes lies in their extended focal length, which, among other things, introduces a higher magnification. For example, a focal length of 3 metres is required for focal accuracy of 1 centimetre (R. Hudec, private communication, May 2024).

Therefore, since the implementation of the X-ray space telescope tandem concept would include similar, or even smaller, relative distances, e.g. a couple of metres, we shall also mention technologies that would facilitate such demanding necessity. In this regard, one of the most important technologies appears to be vision-based navigation based on LIDARs, LRFs and mainly the usage of artificial markers or light sources on the leader spacecraft. Solutions already discussed in Chapter 9 seem to be eminent in this regard, where, for example, the system introduced by [140], capable of 6 DOF relative navigation from 10 metre range (with 1 deg and 5 mm at docking distance), which would be robust to particular external factors, was implemented. At the same time, this goes hand in hand with the necessity of having a precise propulsion system, which, based on the commands of an onboard computer coupled with the GNC system and the relative navigation system, would mitigate possible deviations and provide the means of necessary attitude-correcting manoeuvres, in order, for example, to maintain the required distance and allow precise alignment of the axes.

Conclusion

The space revolution sparked by CubeSats is in full swing. The manifold opportunities CubeSats offer are on the rise. The first two chapters of this thesis were in the spirit of those facts, where we introduced the CubeSat concept and showcased its possibilities and diverse applications. Among the advantages of CubeSats were (1) shorter and simpler development process, (2) reduced financial cost, and (3) availability of COTS parts, which in turn creates easier access to space research. Numerous fields of CubeSat application were discussed, such as various science applications (space environmental study, atmospheric research, etc.), Earth observation or technology demonstration missions. We followed up on that with the concept of distributed space systems, where, in the following chapters, i.e. Chapter 4 to Chapter 7, the collaboration of multiple CubeSats was studied and discussed, in particular R&D, FF, CubeSat constellations and an emerging new concept, swarms. We have rigorously defined those concepts, talked through their nature, and remarked on past, present, and future missions. In addition, we discussed a key element in the heart of every CubeSat and that is the GNC system. Coupled with the discussion on the most popular components of the systems, i.e. sensors and actuators, we identified the current state-of-the-art. In addition, Chapter 9 contains a study of various relative navigation solutions. Section 9.4 in the said chapter is especially paramount, where upcoming technology concepts, that might help pave the way towards realising a space telescope consisting of two CubeSats, are discussed.

Finally, serving as the main contribution of this work, we conducted a feasibility study regarding a space telescope consisting of two CubeSats flying in a tandem arrangement, one carrying the optics and the other one the detector, see Chapter 10. The background of the concept was discussed alongside past missions. The upcoming missions, that is, VISORS and VTXO, mark the final step, and it is indeed them that will show what mankind, together with CubeSats, is capable of.

Our own concluding remarks regarding the envisaged tandem CubeSat space telescope concept, together with a discussion on possible implementation, are contained within the last section of Chapter 10, i.e. 10.3.

Overall, this thesis, and namely, the chapter 10, might prove especially helpful to researchers, such as those at CTU, where this idea is extensively studied. It might also serve as a gentle introduction to the subject or as a stepping stone for further studies.

Bibliography

1. *The CubeSat Standard* [`https://www.cubesat.org/about`]. Accessed: 29.10.2023.
2. *CubeSat Design Specification* [`https://www.cubesat.org/cubesatinfo`]. Accessed: 29.10.2023.
3. *CubeSat 101: Basic Concepts and Procesess for First-Time CubeSat Developers* [`https://www.nasa.gov/wp-content/uploads/2017/03/nasa_csli_cubesat_101_508.pdf`]. Accessed: 20.11.2023.
4. PUIG-SUARI, J.; TURNER, C.; AHLGREN, W. Development of the standard CubeSat deployer and a CubeSat class PicoSatellite. In: *2001 IEEE Aerospace Conference Proceedings (Cat. No.01TH8542)*. 2001, vol. 1, 1/347–1/353 vol.1. Available from DOI: `10.1109/AERO.2001.931726`.
5. VILLELA, Thyrso; COSTA, César; BRANDÃO, Alessandra; BUENO, Fernando; LEONARDI, Rodrigo. Towards the Thousandth CubeSat: A Statistical Overview. *International Journal of Aerospace Engineering*. 2019, vol. 2019, pp. 1–13. Available from DOI: `10.1155/2019/5063145`.
6. WUERL, Adam; WUERL, Melissa. Lessons learned for deploying a microsatellite from the International Space Station. In: *2015 IEEE Aerospace Conference*. 2015, pp. 1–12. Available from DOI: `10.1109/AERO.2015.7119213`.
7. *SpaceX - Rideshare* [`https://www.spacex.com/rideshare/`]. Accessed: 5.1.2024.
8. *XO-Ride* [`https://exobotics.space/xo-ride`]. Accessed: 5.1.2024.
9. *CubeSat launch costs, rideshare programs* [`https://www.satcatalog.com/insights/cubesat-launch-costs/`]. Accessed: 5.1.2024.
10. *Electron Rocket* [`https://www.rocketlabusa.com/launch/electron/`]. Accessed: 5.1.2024.
11. *Momentus-X1* [`https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2019-038Y`]. Accessed: 6.1.2024.
12. POGHOSYAN, Armen; GOLKAR, Alessandro. CubeSat evolution: Analyzing CubeSat capabilities for conducting science missions. *Progress in Aerospace Sciences*. 2017, vol. 88, pp. 59–83. ISSN 0376-0421. Available from DOI: `https://doi.org/10.1016/j.paerosci.2016.11.002`.
13. SCARIA, Nikhil. CUBESATS: An Overview of Capabilities And Future Potential. *International Research Journal of Engineering and Technology*. 2020, vol. 07, pp. 1435–1441. ISSN 2395-0056. Available also from: `https://www.irjet.net/archives/V7/i11/IRJET-V7I11238.pdf`.

14. CENTRO DE GESTÃO E ESTUDOS ESTRATÉGICOS-CGEE. CubeSats. 2018.

15. CASPI, Amir; BARTHELEMY, M.; BUSSY-VIRAT, C. D.; COHEN, I. J.; DEFOREST, C. E.; JACKSON, D. R.; VOURLIDAS, A.; NIEVES-CHINCHILLA, T. Small Satellite Mission Concepts for Space Weather Research and as Pathfinders for Operations. *Space Weather*. 2022, vol. 20, no. 2, e2020SW002554. Available from DOI: `https://doi.org/10.1029/2020SW002554`. e2020SW002554 2020SW002554.

16. JEREMIE, Meurisse. The potential of CubeSats for space weather applications. 2014.

17. *Planet Labs* [`https://www.planet.com/products/monitoring/`]. Accessed: 9.1.2024.

18. LIU, Sining; THEOHARIS, Panagiotis Ioannis; RAAD, Raad; TUBBAL, Faisel; THEOHARIS, Angelos; IRANMANESH, Saeid; ABULGASEM, Suhila; KHAN, Muhammad Usman Ali; MATEKOVITS, Ladislau. A Survey on CubeSat Missions and Their Antenna Designs. *Electronics*. 2022, vol. 11, no. 13. ISSN 2079-9292. Available from DOI: `10.3390/electronics11132021`.

19. SELVA, Daniel; GOLKAR, Alessandro; KOROBOVA, Olga; CRUZ, Ignasi; COLLOPY, Paul; WECK, Olivier de. Distributed Earth Satellite Systems: What Is Needed to Move Forward? *Journal of Aerospace Information Systems*. 2017, vol. 14, pp. 1–26. Available from DOI: `10.2514/1.I010497`.

20. LEITNER, Jesse. *Distributed Space Systems: Mission Concepts, Systems Engineering, and Technology Development* [`https://ses.gsfc.nasa.gov/ses_data_2002/020402_Leitner_DSS.pdf`]. Accessed: 10.1.2024.

21. GILL, Eberhard. *Together in space: Potentials and challenges of distributed space systems* [`http://resolver.tudelft.nl/uuid:13b5b1cf-1d3e-44b0-a724-44896cf157db`]. Accessed: 10.1.2024.

22. SU, Weilian; LIN, Jianwen; HA, Tri. Global communication coverage using Cubesats. In: *2017 IEEE 7th Annual Computing and Communication Workshop and Conference (CCWC)*. 2017, pp. 1–7. Available from DOI: `10.1109/CCWC.2017.7868404`.

23. *NanoAvionics to add TIGER-2 satellite to OQ Technology's growing 5G IoT constellation* [`https://nanoavionics.com/news/nanoavionics-to-add-tiger-2-satellite-to-oq-technologys-growing-5g-iot-constellation/`]. Accessed: 14.1.2024.

24. RUIZ-DE-AZUA, Joan A.; CALVERAS, Anna; CAMPS, Adriano. From Monolithic Satellites to the Internet of Satellites Paradigm: When Space, Air, and Ground Networks Become Interconnected. In: DEY, Indrakshi (ed.). *Computer-Mediated Communication*. Rijeka: IntechOpen, 2021, chap. 2. Available from DOI: `10.5772/intechopen.97200`.

25. SHAW, Graeme B. *The Generalized Information Network Analysis Methodology For Distributed Satellite Systems*. 1999. PhD thesis. Massachusetts Institute of Technology, Dept. of Aeronautics and Astronautics.

26. MAESSEN, Daan Corneel. *Autonomous Relative Navigation for Small Spacecraft*. 2014. PhD thesis. Delft University of Technology.

27. PARRINELLO, Domenico. *Mission Analysis for CubeSat Rendezvous and Docking Operations*. 2022. Politecnico Di Torino.

28. *CubeSat Proximity Operations Demonstration (CPOD)* [`https://www.nasa.gov/smallspacecraft/cpod-project/`]. Accessed: 20.1.2024.

29. SPIEGEL, Isaac A.; ZHOU, Bonan; FOX, Brian; DIMATTEO, Jeremiah; GOODLOE, Robert. CubeSat Proximity Operations Demonstration (CPOD) Mission Results [`https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5645&context=smallsat`]. 2023. Accessed: 20.1.2024.

30. *AeroCube-10* [`https://www.eoportal.org/satellite-missions/aerocube-10#status-of-the-aerocube-10-mission`]. Accessed: 20.1.2024.

31. *Pathfinder For Autonomous Navigation* [`https://www.spacecraftresearch.com/pan`]. Accessed: 20.1.2024.

32. *NASA Satellites Launch Aboard Virgin Orbit's LauncherOne* [`https://blogs.nasa.gov/kennedy/2022/01/13/nasa-satellites-launch-aboard-virgin-orbits-launcherone/`]. Accessed: 20.1.2024.

33. *The Pathfinder for Autonomous Navigation: Technologies and Lessons Learned* [`https://www.nasa.gov/smallsat-institute/community-of-practice/the-pathfinder-for-autonomous-navigation-technologies-and-lessons-learned/`]. Accessed: 20.1.2024.

34. *Project X - Seeker* [`https://roundupreads.jsc.nasa.gov/roundup/1130/Project%20X%20Seeker`]. Accessed: 21.1.2024.

35. PEDROTTY, Sam; SULLIVAN, Jacob; GAMBONE, Elisabeth; KIRVEN, Thomas. Seeker Free-Flying Inspector GNC System Overview. In: 2019.

36. *Seeker Vision* [`https://www.gavincmartin.com/project/seeker-vision/`]. Accessed: 21.1.2024.

37. BARNHART, David J.; SHOEMAKER, David M.; KING, Ellis T.; LOGUE, Thomas "TJ"; LAVIS, Michael J. *LM LINUSS™ - Lockheed Martin In-Space Upgrade Servicing System* [`https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5648&context=smallsat`]. Accessed: 21.1.2024.

38. *Lockheed Martin takes aim at satellite servicing market* [`https://spacenews.com/lockheed-martin-takes-aim-at-satellite-servicing-market/`]. Accessed: 21.1.2024.

39. *The TAMARIW Mission: A Pioneering CubeSat Rendezvous and Docking Experiment* [`https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5690&context=smallsat`]. Accessed: 26.5.2024.

40. *VZLUSAT-3 Pioneering Proximity Operations with CubeSat Satellites* [`https://ibws.cz/wp-content/uploads/conference_uploads/2024/contributions/small_satellites_a_instrumental_session/vladimir__daniel_vzlusat3_-_pioneering_proximit_2024.pdf`]. Accessed: 23.5.2024.

41. UNGAR, S.G. Overview of EO-1, the first 120 days. In: *IGARSS 2001. Scanning the Present and Resolving the Future. Proceedings. IEEE 2001 International Geoscience and Remote Sensing Symposium (Cat. No.01CH37217)*. 2001, vol. 1, 43–45 vol.1. Available from DOI: `10.1109/IGARSS.2001.976052`.

42. BRISTOW, John; FOLTA, David; HARTMAN, Kate. A formation flying technology vision. In: 2000. Available from DOI: `10.2514/6.2000-5194`.

43. DI MAURO, Giuseppe; LAWN, M.; BEVILACQUA, Riccardo. Survey on Guidance Navigation and Control Requirements for Spacecraft Formation-Flying Missions. *Journal of Guidance, Control, and Dynamics*. 2017, vol. 41, pp. 1–22. Available from DOI: `10.2514/1.G002868`.

44. HADAEGH, Fred Y.; GURKIRPAL, Singh; AÇIKMEŞE, Behcet; SCHARF, Daniel P.; MANDIĆ, Milan. Guidance and Control of Formation Flying Spacecraft. In: SUKHATME, Gaurav (ed.). *The Path to Autonomous Robots*. Boston, MA: Springer US, 2009, pp. 1–19. ISBN 978-0-387-85774-9.

45. SCHARF, D.P.; HADAEGH, F.Y.; PLOEN, S.R. A survey of spacecraft formation flying guidance and control (part 1): guidance. In: *Proceedings of the 2003 American Control Conference, 2003*. 2003, vol. 2, pp. 1733–1739. Available from DOI: `10.1109/ACC.2003.1239845`.

46. SCHILLING, Klaus. I-3d: Formations of Small Satellites. In: 2020, pp. 327–339. ISBN 9781119042044. Available from DOI: `10.1002/9781119042044.ch15`.

47. MATHAVARAJ, S.; PADHI, Radhakant. Introduction and Motivation. In: *Satellite Formation Flying: High Precision Guidance using Optimal and Adaptive Control Techniques*. Singapore: Springer Singapore, 2021, pp. 1–12. ISBN 978-981-15-9631-5. Available from DOI: `10.1007/978-981-15-9631-5_1`.

48. *The Ranging And Nanosatellite Guidance Experiment* [`https://cshaft.gtri.gatech.edu/missions-2/range/`]. Accessed: 24.1.2024.

49. *SatNOGS Network* [`https://network.satnogs.org/observations/?norad=43773&observer=&station=&results=d1&start=&end=&transmitter_mode=`]. Accessed: 24.1.2024.

50. SCHARNAGL, Julian; HABER, Roland; DOMBROVSKI, Veaceslav; SCHILLING, Klaus. NetSat—Challenges and lessons learned of a formation of 4 nano-satellites. *Acta Astronautica*. 2022, vol. 201, pp. 580–591. ISSN 0094-5765. Available from DOI: `https://doi.org/10.1016/j.actaastro.2022.09.036`.

51. *SatNOGS DB* [`https://db.satnogs.org/satellite/OZSW-9908-0796-8166-3293`]. Accessed: 24.1.2024.

52. *Tianwang 1A* [`https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2015-051D`]. Accessed: 25.1.2024.

53. *Adelis - SAMSON* [`https://asri.institute/space-missions/adelis-samson/`]. Accessed: 25.1.2024.

54. GURFIL, Pini; HERSCOVITZ, Jacob; PARIENTE, Meidad. SSC12-VII-2 The SAMSON Project – Cluster Flight and Geolocation with Three Autonomous Nano-satellites. In: 2012.

55. SCHARF, D.P.; HADAEGH, F.Y.; PLOEN, S.R. A survey of spacecraft formation flying guidance and control. Part II: control. In: *Proceedings of the 2004 American Control Conference*. 2004, vol. 4, 2976–2985 vol.4. Available from DOI: `10.23919/ACC.2004.1384365`.

56. SAEED, Nasir; ELZANATY, Ahmed; ALMORAD, Heba; DAHROUJ, Hayssam; AL-NAFFOURI, Tareq Y.; ALOUINI, Mohamed-Slim. CubeSat Communications: Recent Advances and Future Challenges. *IEEE Communications Surveys & Tutorials*. 2020, vol. 22, no. 3, pp. 1839–1862. Available from DOI: `10.1109/COMST.2020.2990499`.
57. MARINAN, Anne; NICHOLAS, Austin; CAHOY, Kerri. Ad hoc CubeSat constellations: Secondary launch coverage and distribution. In: *2013 IEEE Aerospace Conference*. 2013, pp. 1–15. Available from DOI: `10.1109/AERO.2013.6497174`.
58. HULTERMANS, M.A.A. A Theoretical Ad Hoc Lunar Communication Network With CubeSats as Secondary Payload of Lunar Missions. 2019. Available also from: `http://essay.utwente.nl/78708/`.
59. KENNEDY, Andrew; CAHOY, Kerri. Performance Analysis of Algorithms for Coordination of Earth Observation by CubeSat Constellations. *Journal of Aerospace Information Systems*. 2017, vol. 14, pp. 451–471. Available from DOI: `10.2514/1.I010426`.
60. GONCHARENKO, Yuriy V.; BERG, Wesley; REISING, Steven C.; ITURBIDE-SANCHEZ, Flavio; CHANDRASEKAR, V. Design and Analysis of CubeSat Microwave Radiometer Constellations to Observe Temporal Variability of the Atmosphere. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. 2021, vol. 14, pp. 11728–11736. Available from DOI: `10.1109/JSTARS.2021.3128069`.
61. PERAL, Eva; TANELLI, Simone; HADDAD, Ziad; SY, Ousmane; STEPHENS, Graeme; IM, Eastwood. Raincube: A proposed constellation of precipitation profiling radars in CubeSat. In: *2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. 2015, pp. 1261–1264. Available from DOI: `10.1109/IGARSS.2015.7326003`.
62. WALKER, J. G. *Circular Orbit Patterns Providing Continuous Whole Earth Coverage*. 1970. Tech. rep. Royal Aircraft Establishment Farnborough (United Kingdom).
63. WALKER, J. G. Some Circular Orbit Patterns Providing Continuous Whole Earth Coverage. *Journal of British Interplanetary Society*. 1971.
64. GUAN, Meiqian; XU, Tianhe; GAO, Fan; NIE, Wenfeng; YANG, Honglei. Optimal Walker Constellation Design of LEO-Based Global Navigation and Augmentation System. *Remote Sensing*. 2020, vol. 12, p. 1845. Available from DOI: `10.3390/rs12111845`.
65. MELAKU, Shimeles Demissie; KIM, Hae-Dong. Optimization of Multi-Mission CubeSat Constellations with a Multi-Objective Genetic Algorithm. *Remote Sensing*. 2023, vol. 15, no. 6. ISSN 2072-4292. Available from DOI: `10.3390/rs15061572`.
66. CHOBOTOV, Vladimir A. Orbital Coverage. In: *Orbital Mechanics, Third Edition*. 2002, chap. 15, pp. 411–452. Available from DOI: `10.2514/5.9781600862250.0411.0452`.
67. MORTARI, D.; WILKINS, Matthew; BRUCCOLERI, Christian. The Flower Constellations. *Journal of the Astronautical Sciences*. 2004, vol. 52. Available from DOI: `10.1007/BF03546424`.

68. HUANG, S.; COLOMBO, C.; BERNELLI-ZAZZERA, F. Multi-criteria design of continuous global coverage Walker and Street-of-Coverage constellations through property assessment. *Acta Astronautica*. 2021, vol. 188, pp. 151–170. ISSN 0094-5765. Available from DOI: `https://doi.org/10.1016/j.actaastro.2021.07.002`.

69. KULU, Erik. *Satellite Constellations - 2021 Industry Survey and Trends* [`https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5092&context=smallsat`]. Accessed: 4.2.2024.

70. *Planet - Flock Imaging Constellation* [`https://www.eoportal.org/satellite-missions/planet#mission-status`]. Accessed: 4.2.2024.

71. *Planet Labs* [`https://www.nanosats.eu/org/planet-labs`]. Accessed: 4.2.2024.

72. *Dove Satellite Sensor Constellation* [`https://www.satimagingcorp.com/satellite-sensors/other-satellite-sensors/dove-3m/`]. Accessed: 4.2.2024.

73. *Swarm* [`https://swarm.space/`]. Accessed: 5.2.2024.

74. *Swarm Network Architecture Overview* [`https://swarm.space/wp-content/uploads/2022/06/Swarm-Network-Architecture-Overview.pdf`]. Accessed: 5.2.2024.

75. *SWARM'S 2021 YEAR IN REVIEW* [`https://swarm.space/swarms-2021-year-in-review/`]. Accessed: 5.2.2024.

76. *Spire Global UK Nanosatellite Technology Developments for Earth Intelligence Applications* [`https://ceoi.ac.uk/wp-content/uploads/2021/09/UK-EO-Week-Spire-Nanosat-Tech-Dev-for-Earth-Intelligence-Apps_reduced_part-1.pdf`]. Accessed: 5.2.2024.

77. *Spire Instruments* [`https://earth.esa.int/eogateway/missions/spire`]. Accessed: 5.2.2024.

78. *CubeSat Commercial Constellations* [`https://www.nanosats.eu/tables#constellations`]. Accessed: 17.5.2024.

79. *Copernicus Sentinel-1A satellite hit by space particle* [`https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Copernicus_Sentinel-1A_satellite_hit_by_space_particle`]. Accessed: 17.5.2024.

80. MATNEY, Mark; VAVRIN, Andrew; MANIS, Alyssa. *Effects of CubeSat Deployments in Low-Earth Orbit* [`https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/509/SDC7-paper509.pdf`]. Accessed: 17.5.2024.

81. OSTROM, Chris L.; OPIELA, John N. *Orbital Debris Mitigation And CubeSats* [`https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/143/SDC8-paper143.pdf`]. Accessed: 17.5.2024.

82. CLARK, Christopher P. *A Feasibility Study of CubeSat Architectures for Space Debris Removal from Low Earth Orbit*. 2021. Massachusetts Institute of Technology.

83. *A CubeSat Formation For Space Debris Characterisation* [`https://uit.no/project/qbdebris`]. Accessed: 17.5.2024.

84. ENGELEN, Steven; GILL, Eberhard K.A.; VERHOEVEN, Chris J.M. Systems engineering challenges for satellite swarms. In: *2011 Aerospace Conference*. 2011, pp. 1–8. Available from DOI: `10.1109/AERO.2011.5747259`.

85. VERHOEVEN, C.J.M.; BENTUM, M.J.; MONNA, G.L.E.; ROTTEVEEL, J.; GUO, Jian. On the origin of satellite swarms. *Acta Astronautica*. 2011, vol. 68, no. 7, pp. 1392–1395. ISSN 0094-5765. Available from DOI: `https://doi.org/10.1016/j.actaastro.2010.10.002`.

86. *KickSat* [`https://kicksat.github.io/`]. Accessed: 25.1.2024.

87. *KickSat 2* [`https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2018-092G`]. Accessed: 25.1.2024.

88. BARNES, Dylan; CUMMINGS, Andrew. *COMMUTE: Cubesat swarm Orbital Maneuvers for a Mission to study Uranus' aTmospheric Environment* [`https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5777&context=smallsat`]. Accessed: 29.1.2024.

89. KUWAHARA, Toshinori. *Introduction to CubeSat Attitude Control System* [`https://www.unoosa.org/documents/pdf/psa/access2space4all/KiboCUBE/AcademySeason2/On-demand_Pre-recorded_Lectures/KiboCUBE_Academy_2021_OPL14.pdf`]. Accessed: 10.2.2024.

90. VALLADO, David. An Analysis of State Vector Prediction Accuracy. 2007.

91. LEE, Zachary Thomas. *CubeSat Constellation Implementation And Management Using Differential Drag*. 2017. Massachusetts Institute of Technology.

92. GABER, Khaled; EL MASHADE, Mohamed; ABDEL AZIZ, Ghada. High-precision attitude determination and control system design and real-time verification for CubeSats. *International Journal of Communication Systems*. 2020, vol. 33. Available from DOI: `10.1002/dac.4311`.

93. CHESSAB MAHDI, Mohammed. Attitude Determination and Control System design of KufaSat. *International Journal of Current Engineering and Technology*. 2014, vol. 4, pp. 2910–2920.

94. BARONI, Leandro. Kalman filter for attitude determination of a CubeSat using low-cost sensors. *Computational and Applied Mathematics*. 2017, vol. 37. Available from DOI: `10.1007/s40314-017-0502-5`.

95. *CubeSat Attitude Determination via Kalman Filtering of Magnetometer and Solar Cell Data* [`https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1152&context=smallsat`]. Accessed: 16.2.2024.

96. MARKLEY, F. Landis; CRASSIDIS, John L. Static Attitude Determination Methods. In: *Fundamentals of Spacecraft Attitude Determination and Control*. New York, NY: Springer New York, 2014, pp. 183–233. ISBN 978-1-4939-0802-8. Available from DOI: `10.1007/978-1-4939-0802-8_5`.

97. XIA, Xiwang; SUN, Guowen; ZHANG, Keke; WU, Shufan; WANG, Tian; XIA, Lei; LIU, Shanwu. NanoSats/CubeSats ADCS survey. In: *2017 29th Chinese Control And Decision Conference (CCDC)*. 2017, pp. 5151–5158. Available from DOI: `10.1109/CCDC.2017.7979410`.

98. ZHU, Frances. A Guide to CubeSat Mission and Bus Design. In: Pressbooks, [n.d.], chap. 8.

99. CARLETTA, Stefano; TEOFILATTO, Paolo; FARISSI, M. Salim. A Magnetometer-Only Attitude Determination Strategy for Small Satellites: Design of the Algorithm and Hardware-in-the-Loop Testing. *Aerospace*. 2020, vol. 7, no. 1. ISSN 2226-4310. Available from DOI: `10.3390/aerospace7010003`.

100. *Dellingr 6U CubeSat* [`https://technology.nasa.gov/patent/GSC-TOPS-37`]. Accessed: 24.2.2024.

101. BASSISSI, Enrico. *Spacecraft Attitude Dynamics and Control - Attitude Control of a 6U Cubesat*. 2021. Tech. rep. Politecnico di Milano.

102. NGUYEN, Tam; CAHOY, Kerri; MARINAN, Anne. Attitude Determination for Small Satellites with Infrared Earth Horizon Sensors. *Journal of Spacecraft and Rockets*. 2018, vol. 55, no. 6, pp. 1466–1475. Available from DOI: `10.2514/1.A34010`.

103. *State-of-the-Art of Small Spacecraft Technology - Guidance, Navigation, and Control* [`https://www.nasa.gov/smallsat-institute/sst-soa/guidance-navigation-and-control/#5.3`]. Accessed: 11.2.2024.

104. *Horizon Sensor for Nano-Satellites* [`https://www.satcatalog.com/component/horizon-sensor-for-nano-satellites-hsns/`]. Accessed: 25.2.2024.

105. WERTZ, James R. Attitude Hardware. In: *Spacecraft Attitude Determination and Control*. Ed. by WERTZ, James R. Dordrecht: Springer Netherlands, 1978, pp. 155–216. ISBN 978-94-009-9907-7. Available from DOI: `10.1007/978-94-009-9907-7_6`.

106. *Mini Fine Sun Sensor* [`https://www.satcatalog.com/component/mini-fine-sun-sensor/`]. Accessed: 25.2.2024.

107. FIALHO, Marcio A. A.; MORTARI, Daniele. Theoretical Limits of Star Sensor Accuracy. *Sensors*. 2019, vol. 19, no. 24. ISSN 1424-8220. Available from DOI: `10.3390/s19245355`.

108. *CubeSat Star Tracker* [`https://www.aac-clyde.space/what-we-do/space-products-components/adcs/st200`]. Accessed: 25.2.2024.

109. KIMURA, Koki; SHOJI, Yasuhiro; SATOH, Satoshi; YAMADA, Katsuhiko. Attitude control experiment of a spinning spacecraft using only magnetic torquers. *Advances in Space Research*. 2023, vol. 71, no. 12, pp. 5386–5399. ISSN 0273-1177. Available from DOI: `https://doi.org/10.1016/j.asr.2023.02.018`.

110. *CubeSat Magnetorquer SatBus MTQ* [`https://nanoavionics.com/cubesat-components/cubesat-magnetorquer-satbus-mtq/`]. Accessed: 25.2.2024.

111. DELABIE, Tjorven. *Attitude Determination And Control* [`http://www.s3l.be/usr/files/di/fi/2/Lecture13_ADCS_TjorvenDelabie_20181111202.pdf`]. Accessed: 10.2.2024.

112. *What is a Reaction Wheel?* [`https://www.reactionwheel.ca/resources/reactionwheel.html`]. Accessed: 10.2.2024.

113. *CubeSat Reaction Wheels Control System SatBus 4RW0* [`https://nanoavionics.com/cubesat-components/cubesat-reaction-wheels-control-system-satbus-4rw/`]. Accessed: 25.2.2024.

114. PÁSCOA, José; TEIXEIRA, Odelma; RIBEIRO, Gustavo. A Review of Propulsion Systems for CubeSats. In: 2018. Available from DOI: `10.1115/IMECE2018-88174`.

115. LEMMER, Kristina. Propulsion for CubeSats. *Acta Astronautica*. 2017, vol. 134, pp. 231–243. ISSN 0094-5765. Available from DOI: `https://doi.org/10.1016/j.actaastro.2017.01.048`.

116. *State-of-the-Art of Small Spacecraft Technology - In-Space Propulsion* [`https://www.nasa.gov/smallsat-institute/sst-soa/in-space_propulsion/`]. Accessed: 11.2.2024.

117. TUMMALA, Akshay Reddy; DUTTA, Atri. An Overview of Cube-Satellite Propulsion Technologies and Trends. *Aerospace*. 2017, vol. 4, no. 4. ISSN 2226-4310. Available from DOI: `10.3390/aerospace4040058`.

118. *Gen 1: CubeADCS* [`https://www.cubesatshop.com/product/gen-1-cubeadcs-3-axis/`]. Accessed: 11.2.2024.

119. POLAT, Halis; VIRGILI-LLOP, Josep; ROMANO, Marcello. Survey, Statistical Analysis and Classification of Launched CubeSat Missions with Emphasis on the Attitude Control Method. *Journal of Small Satellites*. 2016, vol. 5, pp. 513–530.

120. APPEL, Nicolas; RÜCKERL, Sebastian; LANGER, Martin; KLEIN, Rolf-Dieter. I-2e. In: *Nanosatellites*. John Wiley & Sons, Ltd, 2020, chap. 6, pp. 115–141. ISBN 9781119042044. Available from DOI: `https://doi.org/10.1002/9781119042044.ch6`.

121. D'AMICO, Simone. *Autonomous Formation Flying in Low Earth Orbit*. 2010. PhD thesis. Politecnico di Milano, Italy.

122. SUBRAMANIAN, Giri; FOUST, Rebecca; CHEN, Derek; CHAN, Stanley; TALEB, Younes; ROGERS, Dayne; KOKKAT, Jobin; BANDYOPADHYAY, Saptarshi; MORGAN, Daniel; CHUNG, Soon-Jo; HADAEGH, Fred. Information-Driven Systems Engineering Study of a Formation Flying Demonstration Mission using Six CubeSats. In: 2015. Available from DOI: `10.2514/6.2015-2043`.

123. MONTENBRUCK, Oliver; D'AMICO, Simone. GPS Based Relative Navigation. In: *Distributed Space Missions for Earth System Monitoring*. Ed. by D'ERRICO, Marco. New York, NY: Springer New York, 2013, pp. 185–223. ISBN 978-1-4614-4541-8. Available from DOI: `10.1007/978-1-4614-4541-8_5`.

124. SHIM, Hanjoon; KIM, O-Jong; YU, Sunkyoung; KEE, Changdon; CHO, Dong-Hyun; KIM, Hae-Dong. Precise in-orbit relative navigation technique for rendezvous mission of CubeSats using only GPS receivers. *CEAS Space Journal*. 2024, vol. 16, no. 1, pp. 117–137. ISSN 1868-2510. Available from DOI: `10.1007/s12567-023-00488-x`.

125. RENGA, Alfredo; GRASSI, Michele; TANCREDI, Urbano. Relative Navigation in LEO by Carrier-Phase Differential GPS with Intersatellite Ranging Augmentation. *International Journal of Aerospace Engineering*. 2013, vol. 2013. ISSN 1687-5966. Available from DOI: `10.1155/2013/627509`.

126. GILL, Eberhard; RUNGE, Hartmut. Tight formation flying for an along-track SAR interferometer. *Acta Astronautica*. 2004, vol. 55, no. 3, pp. 473–485. ISSN 0094-5765. Available from DOI: `https://doi.org/10.1016/j.actaastro.2004.05.044`. New Opportunities for Space. Selected Proceedings of the 54th International Astronautical Federation Congress.

127. D'AMICO, Simone; ARDAENS, Jean-Sebastien; DE FLORIO, Sergio. Autonomous formation flying based on GPS — PRISMA flight results. *Acta Astronautica*. 2013, vol. 82, no. 1, pp. 69–79. ISSN 0094-5765. Available from DOI: `https://doi.org/10.1016/j.actaastro.2012.04.033`. 6th International Workshop on Satellite Constellation and Formation Flying.

128. MAESSEN, D.; GILL, E.; GRELIER, T.; DELPECH, M. Radio Frequency-Based Relative Navigation. In: *Distributed Space Missions for Earth System Monitoring*. Ed. by D'ERRICO, Marco. New York, NY: Springer New York, 2013, pp. 225–266. ISBN 978-1-4614-4541-8. Available from DOI: `10.1007/978-1-4614-4541-8_6`.

129. YANG, Yang; LI, Yong; RIZOS, Chris; DEMPSTER, Andrew G.; YUE, Xiaokui. Inter-satellite Ranging Augmented GPS Relative Navigation for Satellite Formation Flying. *Journal of Navigation*. 2014, vol. 67, no. 3, pp. 437–449. Available from DOI: `10.1017/S0373463313000763`.

130. SUN, R. *Relative Nagivation for Satellite Formation Flying based on Radio Frequency Metrology*. Wohrmann, 2014. ISBN 978-94-6186-358-4. Dissertation (TU Delft). Delft University of Technology.

131. CAPUANO, Vincenzo; HARVARD, Alexei; CHUNG, Soon-Jo. On-board cooperative spacecraft relative navigation fusing GNSS with vision. *Progress in Aerospace Sciences*. 2022, vol. 128, p. 100761. ISSN 0376-0421. Available from DOI: `https://doi.org/10.1016/j.paerosci.2021.100761`.

132. OPROMOLLA, Roberto; FASANO, Giancarmine; RUFINO, Giancarlo; GRASSI, Michele. A review of cooperative and uncooperative spacecraft pose determination techniques for close-proximity operations. *Progress in Aerospace Sciences*. 2017, vol. 93, pp. 53–72. ISSN 0376-0421. Available from DOI: `https://doi.org/10.1016/j.paerosci.2017.07.001`.

133. OPROMOLLA, Roberto; NOCERINO, Alessia; NAPOLANO, Giuseppe; FASANO, Giancarmine; GRASSI, Michele; CAPUANO, Vincenzo; ILLIANO, Simone; VOTTA, Raffaele; RINALDI, Marianna; LECCESE, Giuseppe; NATALUCCI, Silvia. Electro-Optical Based Relative Navigation for Close-Range Inspection and Rendezvous in the SpEye CubeSat-Based Mission. In: 2024. Available from DOI: `10.2514/6.2024-2453`.

134. PALMERINI, Giovanni B. Relative navigation in autonomous spacecraft formations. In: *2016 IEEE Aerospace Conference*. 2016, pp. 1–10. Available from DOI: `10.1109/AERO.2016.7500944`.

135. WANG, Jiao; ZHANG, Ruonan; YUAN, Jianping; LUO, Jianjun. Multi-CubeSat Relative Position and Attitude Determination Based on Array Signal Detection in Formation Flying. *IEEE Transactions on Aerospace and Electronic Systems*. 2019, vol. 55, no. 6, pp. 3378–3393. Available from DOI: `10.1109/TAES.2019.2910362`.

136. JUNKINS, John; HUGHES, Declan; WAZNI, Karim; PARIYAPONG, Vatee. Vision-Based Navigation For Rendezvous, Docking And Proximity Operations. 2002, vol. 101.

137. ALONSO, Roberto; CRASSIDIS, John; JUNKINS, John. Vision-based relative navigation for formation flying of spacecraft. In: *AIAA Guidance, Navigation, and Control Conference and Exhibit.* [N.d.]. Available from DOI: `10.2514/6.2000-4439`.

138. NAPOLANO, Giuseppe; VELA, Claudio; NOCERINO, Alessia; OPROMOLLA, Roberto; GRASSI, Michele. A multi-sensor optical relative navigation system for small satellite servicing. *Acta Astronautica.* 2023, vol. 207, pp. 167–192. ISSN 0094-5765. Available from DOI: `https://doi.org/10.1016/j.actaastro.2023.03.008`.

139. VELA, Claudio; NAPOLANO, Giuseppe; NOCERINO, Alessia; OPROMOLLA, Roberto; GRASSI, Michele; MANZO, Matteo; AMORUSO, Salvatore; DONFRANCESCO, Guido Di. A Relative Navigation Module Based on Visual and Ranging Measurements for CubeSat Applications. In: *2022 IEEE 9th International Workshop on Metrology for AeroSpace (MetroAeroSpace).* 2022, pp. 305–310. Available from DOI: `10.1109/MetroAeroSpace54187.2022.9856244`.

140. PIRAT, Camille; ANKERSEN, Finn; WALKER, Roger; GASS, Volker; MÄUSLI, P.-A. Guidance, Navigation and Control for Autonomous Cooperative Docking of CubeSats. In: 2018.

141. ANDREIS, Eleonora; FRANZESE, Vittorio; TOPPUTO, Francesco. An Overview of Autonomous Optical Navigation for Deep-Space CubeSats. In: 2021.

142. BOTTIGLIERI, Claudio; PICCOLO, Felice; GIORDANO, Carmine; FERRARI, Fabio; TOPPUTO, Francesco. Applied Trajectory Design for CubeSat Close-Proximity Operations around Asteroids: The Milani Case. *Aerospace.* 2023, vol. 10, p. 464. Available from DOI: `10.3390/aerospace10050464`.

143. LANDIS, Geoffrey; OLESON, Steven; MCGUIRE, Melissa; BURKE, Laura; MARTINI, Michael; FITTJE, James; PACKARD, Thomas. A Cubesat Asteroid Mission: Propulsion Trade-offs. In: 2014. ISBN 978-1-62410-303-2. Available from DOI: `10.2514/6.2014-3755`.

144. POMAHAĆ, Vít; HUDEC, René; DÖHRING, Thorsten. CubeSat tandem flight for asteroid surveillance. In: HUDEC, René; PINA, Ladislav (eds.). *EUV and X-ray Optics: Synergy between Laboratory and Space VIII.* SPIE, International Society for Optics and Photonics, 2023, vol. 12576, 125760H. Available from DOI: `10.1117/12.2672396`.

145. SCARPA, Eugenio; BATTEZZATI, Niccolò; CIAGLIA, Sarah; TRICARICO, Pasquale; COTUGNO, Biagio; FAZZOLETTO, Emilio. *The First-Ever Asteroid Fly-By Performed by a CubeSat: Outcomes of the LICIACube Mission* [`https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5592&context=smallsat`]. Accessed: 25.2.2024.

146. *NEA Scout* [`https://science.nasa.gov/mission/nea-scout/`]. Accessed: 25.2.2024.

147. KOHOUT, T.; NÄSILÄ, A.; TIKKA, T.; GRANVIK, M.; KESTILÄ, A.; PENTTILÄ, A.; KUHNO, J.; MUINONEN, K.; VIHERKANTO, K. *Asteroid Spectral Imaging Mission (ASPECT) CubeSat to characterize resources on asteroid surfaces* [`https://meetingorganizer.copernicus.org/EPSC2017/EPSC2017-496.pdf`]. Accessed: 25.2.2024.

148. *MILANI* [`https://terranorbital.com/missions/milani/`]. Accessed: 25.2.2024.

149. RUSCONI, Martina; FERRARI, Fabio; TOPPUTO, Francesco. The effect of a rocky terrain for CubeSat landing on asteroid surfaces. *Advances in Space Research*. 2023, vol. 71, no. 1, pp. 829–844. ISSN 0273-1177. Available from DOI: `https://doi.org/10.1016/j.asr.2022.10.056`.

150. HUDEC, René; POMAHAC, Vit; DÖHRING, Thorsten; STANIK, Eva; KLAUS, Schilling. *DGaO Jahrstagung*. Vol. 2023, Space Telescopes based on Satellite Tandem Flights. 2023. Available also from: `https://www.dgao-proceedings.de/abstract/abstract_only.php?id=2951`.

151. METTLER, Edward; BRECKENRIDGE, William G.; QUADRELLI, Marco B. Large Aperture Space Telescopes in Formation: Modeling, Metrology, and Control. *The Journal of the Astronautical Sciences*. 2005, vol. 53, no. 4, pp. 391–412. ISSN 2195-0571. Available from DOI: `10.1007/BF03546360`.

152. TAGLIAFERRI, Gianpiero; DUIGOU, Jean-Michel; PARESCHI, Giovanni; FIORE, Fabrizio; FERRANDO, Philippe; LAURENT, Philippe; MALAGUTI, Giuseppe; CLEDASSOU, Rodolphe; PIERMARIA, Mauro; MARLE, Olivier; GIOMMI, Paolo. Simbol-X: a formation flight mission with an unprecedented imaging capability in the 0.5-80 keV energy band. In: 2017, p. 17. Available from DOI: `10.1117/12.2308202`.

153. *GRACE Launch* [`https://grace.jpl.nasa.gov/system/internal_resources/details/original/98_gracelaunch_press_kit.pdf`]. Accessed: 27.2.2024.

154. *TanDEM-X - Satellite* [`https://tandemx-science.dlr.de/cgi-bin/wcm.pl?page=TDM-Satellite`]. Accessed: 27.2.2024.

155. *Global 3D elevation model from the TanDEM-X mission now freely available* [`https://www.dlr.de/en/latest/news/2018/4/20181008_3d-elevation-model-tandem-x-mission`]. Accessed: 28.2.2024.

156. KRIEGER, Gerhard; ZINK, Manfred; BACHMANN, Markus; BRÄUTIGAM, Benjamin; SCHULZE, Daniel; MARTONE, Michele; RIZZOLI, Paola; STEINBRECHER, Ulrich; WALTER ANTONY, John; DE ZAN, Francesco; HAJNSEK, Irena; PAPATHANASSIOU, Kostas; KUGLER, Florian; RODRIGUEZ CASSOLA, Marc; YOUNIS, Marwan; BAUMGARTNER, Stefan; LÓPEZ-DEKKER, Paco; PRATS, Pau; MOREIRA, Alberto. TanDEM-X: A radar interferometer with two formation-flying satellites. *Acta Astronautica*. 2013, vol. 89, pp. 83–98. ISSN 0094-5765. Available from DOI: `https://doi.org/10.1016/j.actaastro.2013.03.008`.

157. *PRISMA* [`https://www.ohb-sweden.se/space-missions/prisma`]. Accessed: 27.2.2024.

158. BODIN, Per; NOTEBORN, R.; LARSSON NORDSTRÖM, Robin; KARLSSON, Thomas; D'AMICO, Simone; ARDAENS, Jean-Sébastien; DELPECH, Michel; BERGES, Jean-Claude. Prisma Formation Flying Demonstrator: Overview and Conclusions from the Nominal Mission. In: 2012, vol. 144.

159. BANDYOPADHYAY, Saptarshi; SUBRAMANIAN, Giri; FOUST, Rebecca; MORGAN, Daniel; CHUNG, Soon-Jo; HADAEGH, Fred. A Review of Impending Small Satellite Formation Flying Missions. In: 2015. Available from DOI: `10.2514/6.2015-1623`.

160. BONIN, Grant; ROTH, Niels; ARMITAGE, Scott; NEWMAN, Josh; RISI, Ben; ZEE, Robert E. *CanX–4 and CanX–5 Precision Formation Flight: Mission Accomplished!* [`https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3167&context=smallsat`]. Accessed: 25.2.2024.

161. SHKOLNIK, Evgenya L. On the verge of an astronomy CubeSat revolution. *Nature Astronomy*. 2018, vol. 2, no. 5, pp. 374–378. ISSN 2397-3366. Available from DOI: `10.1038/s41550-018-0438-8`.

162. *CanX-4 and CanX-5* [`https://www.utias-sfl.net/canx-4-and-canx-5/`]. Accessed: 27.2.2024.

163. ROTH, Niels H.; RISI, Ben; GRANT, C. Cordell; ZEE, Robert E. *Flight Results From The CANX-4 And CANX-5 Formation Flying Mission* [`https://www.utias-sfl.net/wp-content/uploads/4S%202016%20-S10_2_303_Roth.pdf`]. Accessed: 25.2.2024.

164. *CANYVAL-X* [`https://svs.gsfc.nasa.gov/vis/a010000/a012000/a012025/FactSheet_v12.pdf`]. Accessed: 27.2.2024.

165. PARK, Jae-Pil; PARK, Sang-Young; SONG, Young Bum; KIM, Guk Nam; LEE, Kwangwon; OH, Hyungjik Jay; YIM, Jin-Chul; LEE, EunJi; HWANG, Soon-Hong; KIM, SungWoo; CHOI, Kyung Yun; LEE, Dong Shin; KWON, Sang Hoon; KIM, Min-Sik; YEO, Seung-Won; KIM, Tae-Hyun; LEE, Seunghee; LEE, Kang Been; SEO, Joong-Won; CHO, Won-Hyuk; LEE, Jungpyo; PARK, Jung-Hyun; KIM, Yong Woo; KANG, Seok Ju; HWANG, Jiyoon; LEE, Soo Hwi; YANG, Jin-Ho; JIN, Sungmin; LEE, Young Ro. CANYVAL-X Mission Development Using CubeSats. In: *Space Operations: Contributions from the Global Community*. Ed. by CRUZEN, Craig; SCHMIDHUBER, Michael; LEE, Young H.; KIM, Bangyeop. Cham: Springer International Publishing, 2017, pp. 681–691. ISBN 978-3-319-51941-8. Available from DOI: `10.1007/978-3-319-51941-8_30`.

166. SONG, Youngbum; LEE, Young Ro; PARK, Jae-Pil; PARK, Sang-Young. CANYVAL-X: Operational Scenario and Strategy. In: *2018 SpaceOps Conference*. [N.d.]. Available from DOI: `10.2514/6.2018-2636`.

167. KIM, Geuk-Nam; PARK, Sang-Young; LEE, Taeyang; KANG, Dae-Eun; KIM, Namgyu; JEON, Soobin; LEE, Eunji; SONG, Youngbum. *Development of Formation Flying CubeSats and Operation Systems for the CANYVAL-C Mission: Launch and Lessons Learned* [`https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5111&context=smallsat`]. Accessed: 25.2.2024.

168. *Project: VIrtual Super Optics Reconfigurable Swarm (VISORS)* [`https://slab.stanford.edu/projects/visors`]. Accessed: 1.3.2024.

169. *Concept of Operations For The VISORS Mission: A Two Satellite Cubesat Formation Flying Telescope* [`https://par.nsf.gov/servlets/purl/10348394`]. Accessed: 1.3.2024.

170. *VIRTUAL TELESCOPE FOR X-RAY OBSERVATIONS* [`https://nmnasaepscor.com/cooperative-agreement-notice-current/`]. Accessed: 1.3.2024.

171. PIRAYESHSHIRAZINEZHAD, Reza; NASERI, Asal; MOREU, Fernando; STOCHAJ, Steven; SHAH, Neerav; KRIZMANIC, John. Attitude Control Optimization of a Two-CubeSat Virtual Telescope in a Highly Elliptical Orbit. In: 2019, pp. 233–258. ISBN 978-3-030-11535-7. Available from DOI: `10.1007/978-3-030-11536-4_11`.

172. *VTXO Proposal* [`https://nmnasaepscor.com/wp-content/uploads/2017/09/Proposal-VTXO-for-website.pdf`]. Accessed: 1.3.2024.

173. KRIZMANIC, John; SHAH, Neerav; CALHOUN, Philip C.; HARDING, Alice K.; PURVES, Lloyd R.; WEBSTER, Cassandra M.; CORCORAN, Michael F.; SCHRADER, Chris R.; STOCHAJ, Steven J.; RANKIN, Kyle A.; SMITH, Daniel T.; KOTA, Krishna; PARK, Hyeongjun; BOUCHERON, Laura E.; NASARI, Asal. VTXO: the virtual telescope for x-ray observations. In: HERDER, Jan-Willem A. den; NAKAZAWA, Kazuhiro; NIKZAD, Shouleh (eds.). *Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray*. SPIE, 2020. Available from DOI: `10.1117/12.2562714`.

174. RANKIN, Kyle; STOCHAJ, Steven; KRIZMANIC, John; SHAH, Neerav; NASERI, Asal. *Virtual Telescope for X-Ray Observations* [`https://core.ac.uk/reader/224735024`]. Accessed: 25.2.2024.

175. *Lockheed Martin Successfully Maneuvers Two Cubesats for On-Orbit Service Demo* [`https://www.satellitetoday.com/space-economy/2023/04/18/lockheed-martin-successfully-maneuvers-two-cubesats-for-on-orbit-service-demo/`]. Accessed: 22.5.2024.

176. DÁNIEL, Vladimír; MARŠÍKOVÁ, Veronika; HUDEC, Rene; PÍNA, Ladislav; INNEMAN, Adolf; PELC, Karel. Small Spacecraft Payload Study for X-ray Astrophysics including GRB Science. *Universe*. 2022, vol. 8, no. 3. ISSN 2218-1997. Available from DOI: `10.3390/universe8030144`.

177. HUDEC, Rene; FELDMAN, Charly. Lobster Eye X-ray Optics. In: *Handbook of X-ray and Gamma-ray Astrophysics*. Springer Nature Singapore, 2022, pp. 1–39. ISBN 9789811645440. Available from DOI: `10.1007/978-981-16-4544-0_3-1`.

178. HUDEC, Rene. Kirkpatrick-Baez (KB) and Lobster Eye (LE) Optics for Astronomical and Laboratory Applications. *X-Ray Optics and Instrumentation, 2010. Special Issue on X-Ray Focusing: Techniques and Applications, id.139148*. 2010, vol. 2010. Available from DOI: `10.1155/2010/139148`.

179. HUDEC, Rene; PINA, Ladislav; MARŠÍKOVÁ (SEMENCOVÁ), Veronika; NENTVICH, Ondrej; URBAN, Martin; INNEMAN, A. Kirkpatrick Baez X-ray optics for astrophysics: Recent status. *Contributions of the Astronomical Observatory Skalnaté Pleso*. 2018, vol. 48.

180. KIRKPATRICK, Paul; BAEZ, A. V. Formation of Optical Images by X-Rays. *J. Opt. Soc. Am.* 1948, vol. 38, no. 9, pp. 766–774. Available from DOI: `10.1364/JOSA.38.000766`.

181. *Grazing incidence imaging x-ray optics: the return of Kirkpatrick-Baezg* [`https://spie.org/news/3859-grazing-incidence-imaging-x-ray-optics-the-return-of-kirkpatrick-baez#_=_`]. Accessed: 22.5.2024.

Appendix

A Street-Of-Coverage Illustration

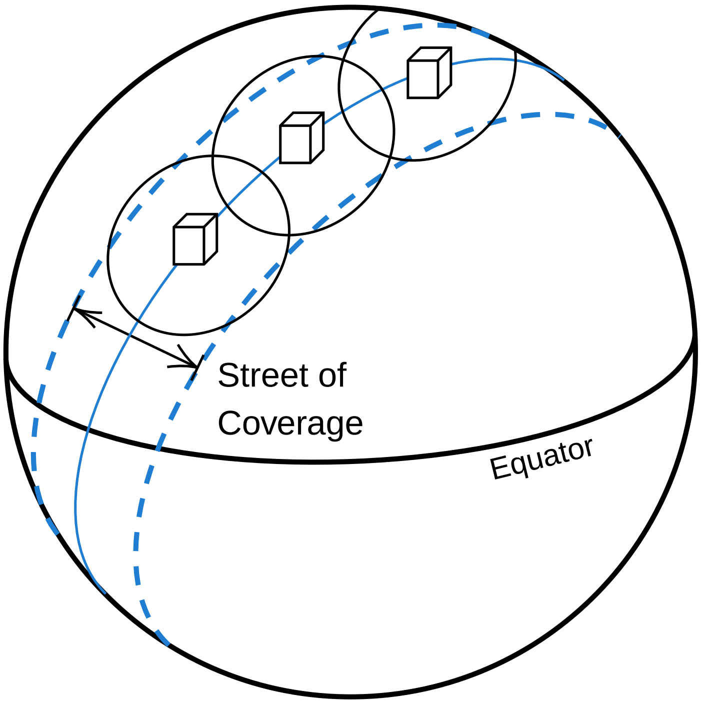

Figure 1: Continuous street of coverage from a single orbit plane [66].