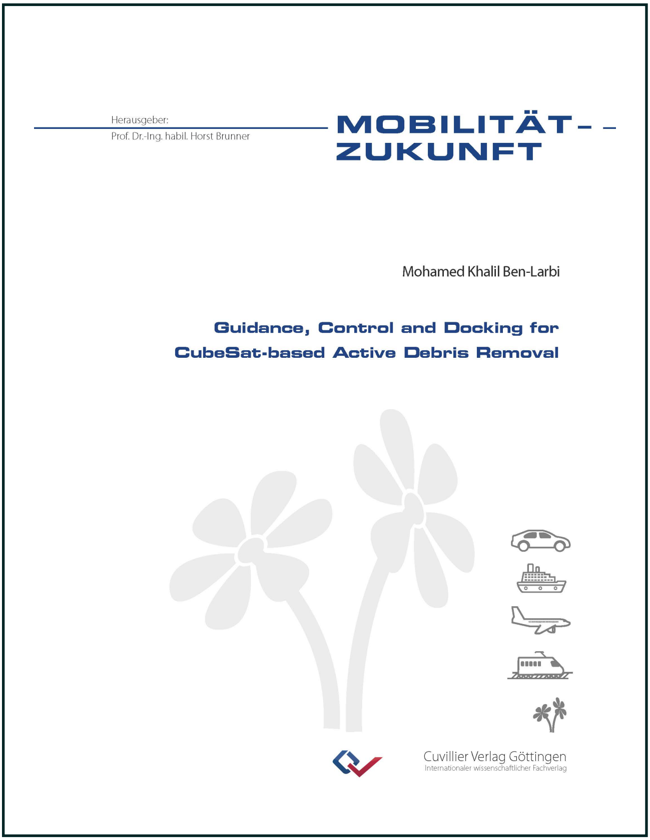
Mohamed Khalil Ben-Larbi (Autor)

Guidance, Control and Docking for CubeSat-based Active Debris Removal


Herausgeber:
Prof. Dr.-Ing. habil. Horst Brunner
MOBILITÄT – – ZUKUNFT
Mohamed Khalil Ben-Larbi
Guidance, Control and Docking for CubeSat-based Active Debris Removal
Cuvillier Verlag Göttingen
Internationaler wissenschaftlicher Fachverlag

https://cuvillier.de/de/shop/publications/8869

Chapter 1

1 Introduction

> *In contrast to a widespread cliché, the satellite problems still require the research on the level more fundamental than just tracing the microscopic influence of yet another tesseral harmonic.*
>
> Slawomir Breiter, Dynamics of Natural and Artificial Celestial Bodies, 2001

Contents

1.1 Motivation

1.1.1 The evolution of space technology and environment

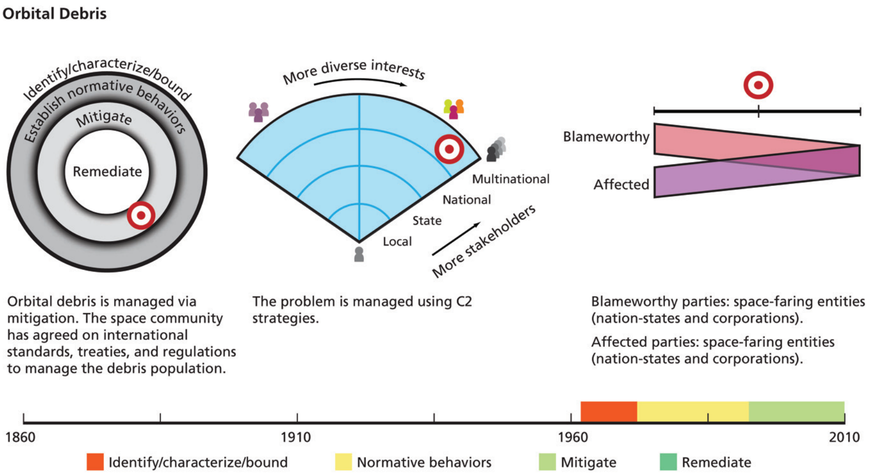
Sixty years of space activities left us with a big heritage reflected in successful missions, which made it possible for mankind to explore the outer space and even set foot on the moon and soon on other planets. However, the trends in space industry are changing at rapid pace and limited information can be reliably predicted about its future evolution in the long term. Therefore, these trends have to be constantly studied to identify the evolving challenges, new capabilities, and potential solutions.

The space debris issue

The successful and failed attempts to bring objects into orbit have something in common: they both generate space debris on a long term [1]. Broken or disused satellites, depleted rocket upper stages, and fragments generated by explosions or collisions are constantly orbiting the Earth [1]. The population of these objects is called "space debris". Meanwhile, the increasing number of space debris is liable to compromise current and future missions. With about 2500 tons of material in Low Earth Orbit (LEO) [2], mostly space debris, collisions processes can cause a chain reaction and render entire orbit regions unusable [3, 4]. Therefore, mitigation guidelines [5] were defined by the Inter-Agency Space Debris

Coordination Committee (IADC), adopted by the United Nations Committee on the Peaceful Uses of Outer Space (UNOOSA), and endorsed by the United Nations General Assembly [6] in its Resolution 62/217 of 22 December 2007. To translate this consensus into engineering praxis, the International Organization for Standardization (ISO) issued a family of standards describing requirements and implementation measures to ensure that spacecraft (s/c) and launch vehicle orbital stages are designed, operated and disposed of in a manner that prevents them from generating debris throughout their orbit lifetime and reduces the casualty risk on ground associated with their atmospheric re-entry [7]. Despite these efforts, the number of objects in the space debris environment will continue to increase even in case of suspension of all human space activities, driven by collisions in the $700 - 1000$ km altitude range [8].

The practical relevance of the space debris issue has been demonstrated by several events over the past decades, such as the collision of the Cosmos 2251 and Iridium 33 in 2009 [9], the impact of a fragment of debris on the European Sentinel-1A satellite in 2016 [10], or the weekly performed evasive maneuvers of the Irridium constellation [11]. Scientists from all over the world agree that measures must be taken not only to limit the production of new space debris but also to actively remove already existing space debris from orbit [5, 7, 12]. Such an endeavour is called Active Debris Removal (ADR) [13]. Simulations indicate that, in addition to the implementation of mitigation guidelines, *several large space debris objects need to be removed* from their respective orbit each year to enable long-term safe and sustainable use of LEO [13].



Orbital debris is managed via mitigation. The space community has agreed on international standards, treaties, and regulations to manage the debris population.

The problem is managed using C2 strategies.

Blameworthy parties: space-faring entities (nation-states and corporations).

Affected parties: space-faring entities (nation-states and corporations).

Figure 1.1: Baiocchi and Welser framework applied to the orbital debris issue [14], the red target marker on each graph indicates the current state.

Dave Baiocchi and William Welser [14] studied the necessary milestones to be met in order to develop strategies for addressing orbital debris, such as mitigation measures or remedial techniques. To achieve this, they compared the space debris issue with other analogous problems faced by humanity in the last century such as airline security, or oil spills and defined a framework to describe these problems. In this framework, four stages of increasingly aggressive measures to cope with such problems have been identified: identifying, characterizing, and bounding the problem; establishing normative behaviors; mitigation; and remediation. Moreover, the stakeholder community is described with respect to its size and diversity.

According to the left graph in Fig. 1.1, the space debris problem has been in the mitigation stage already since the 1990s and is represented by a series of concentric rings. As the actions move towards the center of the rings, they become more aggressive in nature. The top stage "Remediate" is reached as soon as effective ADR is operational. The middle graph classifies the stakeholder community using the metric of size/diversity whereas the right graph uses the metric of overlap in the communities generating debris ("blameworthy") and those being affected by it ("affected"). It is apparent from the middle graph (cf. red target marker position) that the stakeholder community is multinational and very diverse. This diversity and the conflicting interests reduce the overlap between the communities generating debris and being affected by it (cf. red target marker on the right graph), which significantly complicates the task of addressing the space debris issue. Two main observations from the report are considered of major interest by the author of this thesis and are listed below:

> “The approach used to address a problem must be able to *adapt as the problem (and its stakeholders) change* over time [...]. Each community should be constantly reidentifying the problem, standardizing new behavioral norms, refining mitigation techniques, and, if necessary, developing new remedies [...]. For example, if someone suddenly launches 1,000 microsatellites, the debris problem will require a whole *new approach*, starting at the outer ring with identify, characterize, and bound.” [14, p. 61]
>
> “Remedies must be *designed and tested to work under the actual operating conditions*. This is the biggest lesson from the Deepwater Horizon spill. All of the remedies fielded during the first 40 days of the spill were not effective because they had not been tested or proven to work in deepwater drilling conditions. Fielding a demonstration technology will prove useful only if it will provide operators and engineers with relevant information about the technical performance of the actual working conditions [...] , or the development will risk being considered purely academic and not operationally useful.” [14, p. 64]

A decade after the report was published, the cited example of launching 1000 microsatellites is more realistic than ever and the need for a demonstration technology is still up to date. This evolution of space technology and its stakeholder called “New Space Era” is described in the next paragraph.

The new space era

For several decades space activities were restricted to governmental space agencies [15]. The s/c were usually unique specimen, specifically designed for each mission, which made the development process lengthy and costly. While commercial space activities began in the 1960s (cf. Fig. 1.2), they were limited and required support from national space agencies in terms of funding, technical capabilities, and access to orbit in order to design, produce, and operate satellites [15].

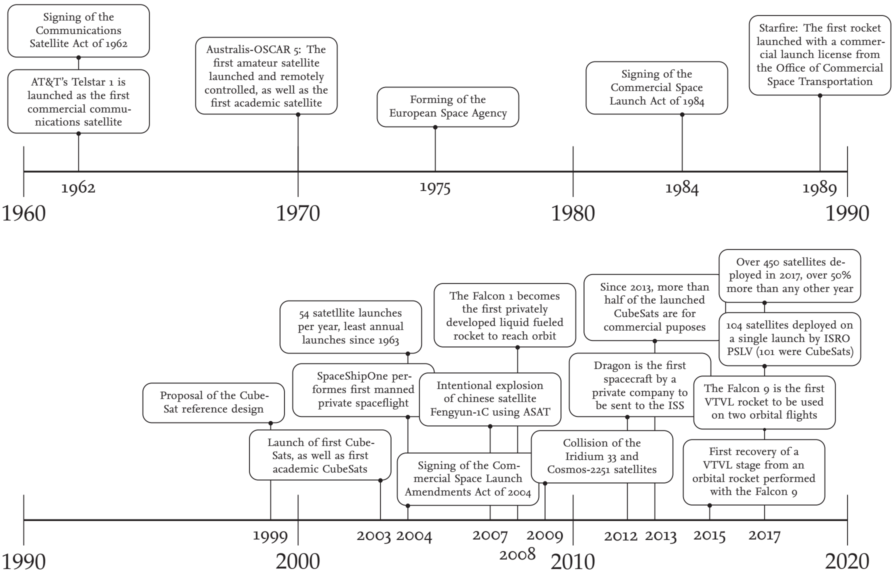


Figure 1.2: A timeline for the evolution of space stakeholders, technology, and environment including selected significant events [15].

In the late 1970s, industrial deregulation policies were implemented in the US and later all over the world as a result of new thinking about the effectiveness of governmental regulation. While the airline deregulation act was amended in 1978, it took several years for effective space-related deregulation acts to be passed in the 1980s. It wasn’t until the 2010s that the commercial space industry began to emerge,

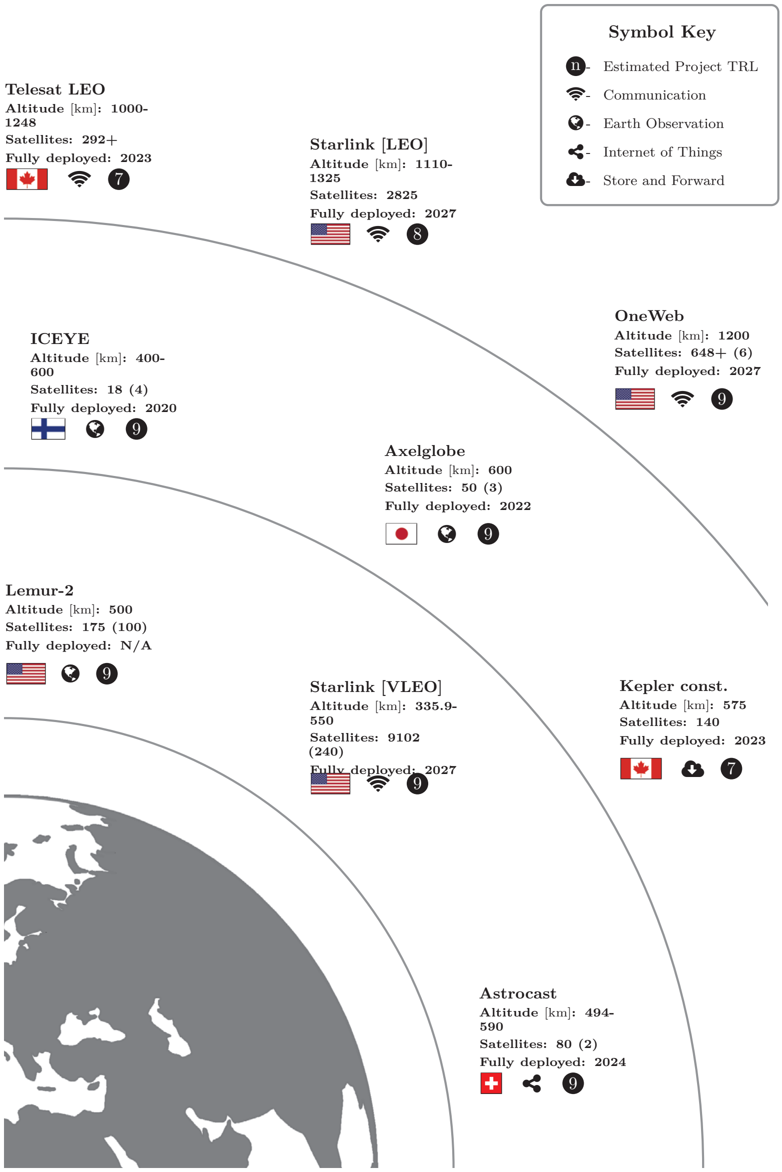


Figure 1.3: Selection of announced constellations in the LEO and MEO regime with advanced Technology Readiness Level (TRL) [15]. The number of deployed satellite is enclosed in parentheses based on data from the year 2019.

with the first commercial supply of the International Space Station (ISS), plans to land on mars, and over 10000 constellations satellites announced [15]. The evolution in the space sector, driven by new players, is often referred to as "*Space 4.0*" or "*New Space*". Recent Developments linked to this evolution are the several announcement and filings at the Federal Communications Commission (FCC) regarding the deployment of large satellite constellations, often with the purpose of providing global internet coverage. A selection of these constellations, expected to be deployed in the near future, is shown in Fig. 1.3. However, traditional satellite internet faced several challenges including low capacity, high cost, and long latency due to the distance signals must travel. To address these issues, some of these new constellations are using LEO rather than geostationary satellites [15]. A comprehensive list of proposed constellations from the the last decades is given by Ben-Larbi et al. [15].

Meanwhile, a new stakeholder, educational institutions, has shown increasing interest in space activities by developing small satellites known as CubeSats [15]. These satellites, which are typically less than 50 kg and adhere to the CubeSat design standard, were developed by the California Polytechnic State University (CalPoly) in 1999 and have undergone numerous revisions since, most recently in 2014 [16]. The standard specifies a "unit", which is a cube with edges measuring 100 mm, and allows for the creation of satellites with sizes ranging from one unit (1U) to 27 units (27U). There are official specifications for 1.5U, 2U, 3U, 6U, 12U and 27U CubeSats [16–18]. This so-called "*Microspace*" movement, which began in the in the 1990's and early 2000's (cf. Fig. 1.2), is considered as precursor to "*New Space*". The state of the art for commercial off-the-shelf (COTS) technologies suitable for CubeSats is evolving rapidly, signaling the start of a transition from an educational to a commercial, low-cost platform. The Planet Lab Dove constellation [19], which consists of over 200 CubeSats, is a good example of this transition. Nano-launch providers such as Rocket Labs are now offering fast and frequent access to orbit, and larger CubeSat units, including 12U and 27U, are being explored for increased capabilities [20].

The space industry shift towards the "mass-production" of small, standardized, modular, distributed systems appears to be inevitable. This trend is also driven by the many advantages of distributed systems compared to monolithic systems such redundancy, cost efficiency, and enhanced realisability [15]. Fig. 1.2 summarizes the evolution of space stakeholders, technology, and environment highlighting key events that demonstrate the need for rethinking and adaptation in order to put the space debris issue and ADR on terms appropriate for the 21st-century [15].

1.1.2 Problem statement

The space debris issue will be one of the prevailing problems in the Space 4.0 era. In 2022, there are approximately 5000 active satellites orbiting Earth [21, 22]. Current plans of private companies envisage the deployment of large constellations (cf. Fig. 1.3), some consisting of tens of thousands of satellites. This dramatic development is raising concern about the safety of space operations [23, 24], even in case of diligent compliance with the IADC mitigation guidelines [5]. The growth in space traffic simply increases the probability of accidents and system failures and renders the development of a reliable technology for ADR missions indispensable. The most urgent goal is to ensure the survival of the space environment for future generations by slowing down the increase or completely reversing the generation of new fragments. Two important characteristics of the space debris issue have to be taken into account while designing any future solution:

1. It has a dynamical character and the approach used to address it should be adapted to changes. In this context, the trends of the New Space Era should be taken into account.
2. Its remediation technology should be proven to work under actual operating conditions. The required ADR solution must be affordable and achieve a high TRL.

> The central concept proposed in this thesis is the engineering of CubeSat based ADR while ensuring a reliable and effective testing procedure of the proposed design. To put this road map into practice, a series of *scientific, technological, and algorithmic challenges* have to be be addressed. This thesis offers some ideas to meet these challenges.

1.2 State of the art

1.2.1 Historical overview of rendezvous in space

Rendezvous in space is a process which brings a vehicle (*chaser*) in the vicinity of another vehicle (*target*) in orbit. To achieve this, both s/c must –at the same time, within close tolerances– have the same position, the same velocity vector, and a predefined relative attitude to each other [25, p. 4]. The mating process is usually concluded with docking, i.e. the chaser navigates itself into the target's docking interface, or with berthing where a manipulator, located on one s/c, is used to grapple the second once rendezvous is achieved at a predefined meeting point.

As early as 1966, Neil Armstrong and Dave Scott successfully docked Gemini 8 to the unmanned Gemini Agena Target Vehicle [26]. While the United States space program focused on performing rendezvous manually, the Soviet Union pursued from the very beginning a different approach based on standardized operations and already conducted the first successful automated rendezvous in 1967 [27,

p. 138]. The number of missions involving Rendezvous and Docking (RVDO), depicted in Fig. 1.4, has evolved relatively fast since then, relying heavily on the knowledge acquired during these milestones, and neither the Apollo program nor the ISS would have been imaginable without the RVDO capability. A detailed historical review of the rendezvous experience can be found in the works of Polites [28], Nolet [29, pp. 31-48], and Woffinden [30, pp. 41-58].

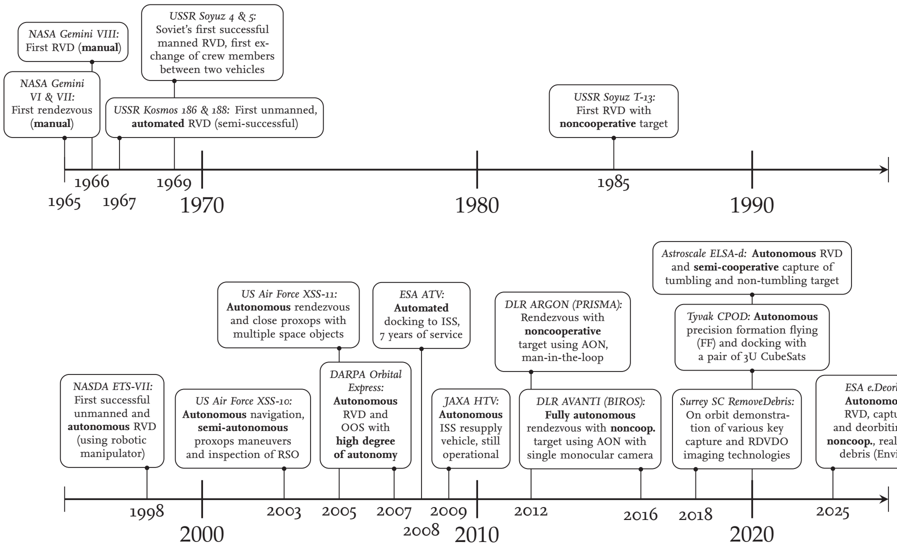


Figure 1.4: A time line for the evolution of space rendezvous and docking capabilities including significant missions and milestones.

The successful Engineering Test Satellite No. 7 (ETS-VII) mission by Japan in 1998, conducted by the National Space Development Agency of Japan (NASDA), laid the foundation for H-II Transfer Vehicle (HTV) developed by Japanese Aerospace Exploration Agency (JAXA) for automated resupply of the ISS [31]. The HTV, first mission to the ISS conducted in 2009 [31], involve automated rendezvous while berthing is performed manually by the crew on board the ISS. A further s/c developed for supplying the ISS is the European Automated Transfer Vehicle (ATV), which was first launched in 2008 and has been retired in 2015 [32]. Unlike HTV, the European ATV uses docking ports automatically [33]. The United States first attempt at automated rendezvous, as late as 2005, was the Demonstration of Autonomous Rendezvous Technology (DART) mission conducted by the National Aeronautics and Space Administration (NASA) [34]. After a collision with the Target satellite and fuel depletion the mission was aborted, resulting in failure [34]. The Orbital Express mission conducted by Defense Advanced Research Projects Agency (DARPA) successfully performed automated rendezvous and on-orbit servicing [35].

1.2.2 Mission architecture and operations for rendezvous and docking

A RVDO mission consists of a sequence of phases put into operation through orbital maneuvers and controlled trajectories. The nomenclatures differ slightly in literature but one can distinguish between the following main phases as defined by Fehse [36, pp. 8-28] and depicted in Fig. 1.5: launch, phasing, far-range rendezvous, close-range rendezvous, mating, and -in the case of ADR- the de-orbit phase.

Similar to the deployed rendezvous technologies, mission design has been historically highly customized so that every RVDO strategy has to be tailored for a specific mission. The International Deep Space Interoperability Standards are in this context an effort to facilitate cooperative space endeavors. The first draft of these standards prepared by the ISS membership has been published in 2019 and includes eight disciplines areas, inter alia, rendezvous [37]. One common feature all unmanned RVDO missions share is that, due to limited communication possibilities and risk of link failures, maneuvers and operations have to be performed to a large extent automatically. However, automatic does not mean completely autonomous. In Earth orbit, there is no need for complete autonomous RVDO. On the contrary, interaction with human operators is often desired as it can increase safety, improve the chances

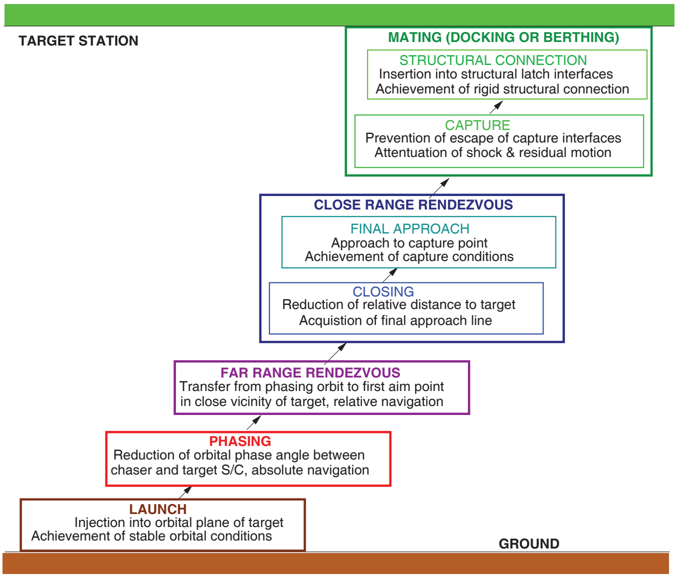


Figure 1.5: Main phases of a rendezvous mission [25, p. 11].

of mission success, and reduce complexity [36, pp. 336-337]. When dealing with a non-cooperative target, e.g. ADR, the mission architecture is identical to that of conventional RVDO for far ranges. However, the short-range phases pose several challenges that do not occur during conventional RVDO [38]:

- The handover from absolute navigation to relative navigation is dictated by the accuracy of the target's orbit determination and happens much earlier (some kilometers relative range) than in classical RVDO. This is challenging for optical sensors which are typically designed to operate in the range of hundreds of meters.
- It is necessary to estimate the target's shape and motion based on in-situ measurements, which is a challenging task in every aspect: absence of sensors or reflectors, lack of a-priori information, image processing, illumination conditions, guidance scheme, etc.
- Depending on the used mating technology, it might be necessary to synchronize the chaser and target motion for mating. This signifies that the challenges addressed in the previous point have to be met in real time and may involve the use of additional monitoring systems.
- In case of contact-based mating, a capture strategy has to be elaborated, based on the identified target characteristics, and despite the absence of dedicated interfaces for such a task. Furthermore, a robust control strategy shall de-tumble the chaser/target assembly in presence of significant uncertainties regarding inertial properties.

1.2.3 Rendezvous and docking with a non-cooperative target

Rendezvous with a non-cooperative satellite has mostly been subject to theoretical studies with only a few on-orbit experiments and a *single manned mission* (Soyuz-T 13) flown in 1985 by the soviet cosmonauts Vladimir Dzhanibekov and Viktor Savinykh [39, pp. 47-52], as shown in Tab. 1.1.

Soyuz T-13 was an effort to rescue the Salyut 7 space station which abruptly ceased communicating with mission control in February 1985 [39, pp. 99-100]. The Soyuz s/c, equipped with the Igla system for automatic rendezvous, was slightly modified to this purpose to include control levers in the descent module for manual proximity operations [39, pp. 47-52]. Moreover, the cosmonauts used a hand held laser range finder to estimate their relative distance. During the successful final approach and docking conducted in June 8 1985, Salyut was rolling slowly about its long axis and its electrical system was entirely down. The station air was breathable despite low temperature as both cosmonauts began on board investigations. Dzhanibekov determined that the solar array pointing system had a malfunction caused by a sensor failure which prevented the batteries from recharging. In an impressive On-Orbit

Servicing (OOS) endeavor, the cosmonauts used Soyuz-T 13 to perform attitude control and point the solar panels towards sunlight. Air heaters were activated on June 10, attitude control recovered on June 13 enabling automatic docking with a Progress freighter on June 23, and normal atmospheric humidity achieved at the end of July. Two of the eight batteries and the water heater were destroyed and had to be replaced. Until Salyut 7 system was restored, the cosmonauts used a powerful television light to heat fluids and Soyuz-T13 air generation system [39, pp. 99-100]. It was during this historic mission that Dzhanibekov noticed the so called "Dzhanibekov effect" [40]: the periodic flipping motion of a wingnut rotating around its second principal axis due to the instability of this rotational motion [41].

However spectacular the Soyuz-T 13 mission might be, one has to keep in mind that it was manually executed by cosmonauts on board the Soyuz s/c. The target s/c geometry was well known and Salyut 7 was equipped with a dedicated docking interface which is not always the case for defunct s/c. Furthermore, the manned mission was flown few months after loss of contact so that the space station was almost intact and its motion was still stable, slow, and uniform. Altogether, the specificity of this mission and the lack of public scientific data make it difficult to derive systematic conclusions about the ADR issue. Therefore, more recent missions listed in Tab. 1.1 focus on technology demonstration in representative scenarios and provide important information on the subsystem level. We will elaborate on this in the next sections.

Table 1.1: Brief overview of missions involving rendezvous with non-cooperative targets.

Mission	Year	Operator	Description	Status	Ref.
RemoveDEBRIS	2018	Surrey SC	ADR technology demonstration	success	[42–44]
AVANTI (FireBird)	2016	DLR	rendezvous using angles only navigation with an actual non-cooperative target	success	[45]
ARV/ARGON (PRISMA)	2012	DLR	rendezvous technology demonstration using angles only navigation	success	[46, 47]
Soyuz T-13	1985	USSR	manned docking and repair	success	[39]

1.2.4 Proposed ADR concepts

A wide range of possible ADR mission architectures exists. The most obvious example is the use of a single chaser dedicated to removing a large debris object [38]. Such an architecture is particularly interesting for 1st generation missions, to demonstrate the performance of the implemented technology [12], as supposed in the European Space Agency (ESA) e.Deorbit mission.

Another approach widely discussed in literature [12, 48, 49], is the use of a single complex s/c equipped with multiple de-orbit kits to remove a series of debris objects. In this scenario, the prime s/c is responsible for performing close-range operations and is equipped with the necessary tools to mount the de-orbit kits on the surface of the target. The kits are then used to maneuver the target into Earth's atmosphere for re-entry. However, the specific mission design depends on the technological concept being used for the removal. There are two main properties used to categorize ADR concepts and determine the mission architecture [38]:

- The *capture* and mating (docking), which can be grouped in contactless- and contact-capturing methods. These can be further sub-divided based on the nature of the connection and the technology used, as illustrated in the gray box in Fig. 1.6.
- The *removal* and de-orbiting. The approach used for removal is often related to the method of capture, although this is not always the case (see Fig. 1.6). For example, the use of laser beams for capture is a contactless-capturing method that inherently defines the deorbiting technique, while the use of robotic grippers for capture could involve either propulsion or drag sails for removal.

Numerous concepts have been proposed for space debris removal, including the use of net [42–44], harpoon [42–44], and robotic devices [50, 51]. These capturing techniques have been the focus of recent research because they are based on technologies that are already proven on Earth such as robotic manipulation and sling load operations. However, documented on-orbit demonstrations listed in Tab. 1.1 are limited to a few on-orbit subsystem validation experiments such as optical navigation (cf. Fig. 1.7) and capture (cf. Fig. 1.8) [38].

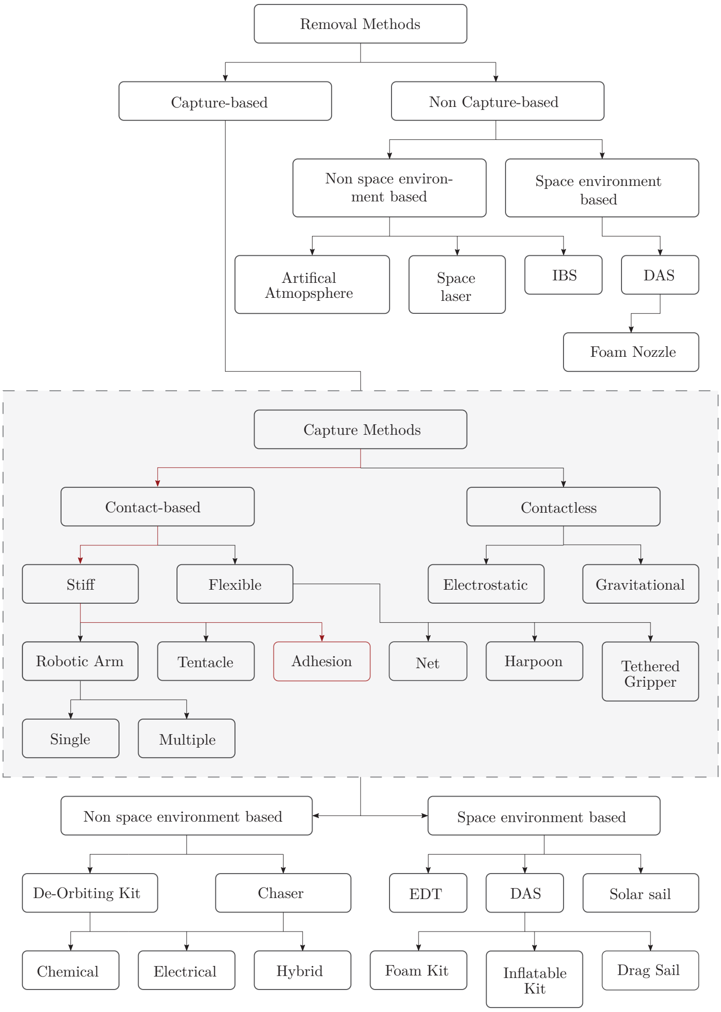
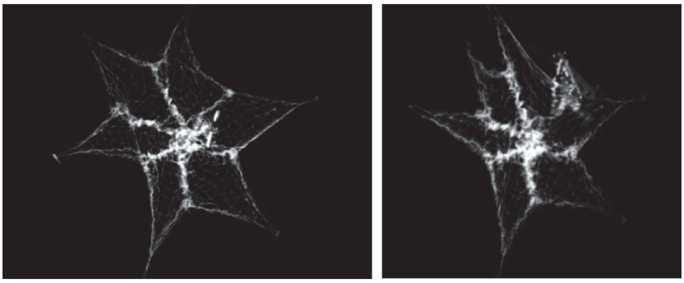
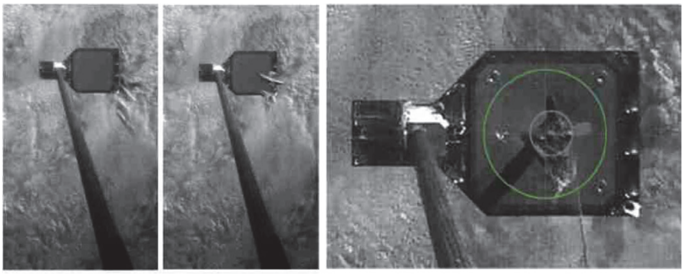


Figure 1.6: Classification of proposed active space removal and capture methods. The following acronyms are used: DAS for Drag Augmentation System, EDT for ElectroDynamic Tether, IBS for Ion Beam Shepherd. The red path highlights adhesion-based capture [38].

The navigation demonstrations are the Autonomous Rendezvous (ARV) experiment conducted in April 2011 [46] during the Prototype Research Instruments and Space Mission Technology Advancement (PRISMA) mission, the Advanced Rendezvous Demonstration using Global Positioning System and Optical Navigation (ARGON) conducted in April 2012 [52] during the extended phase of the PRISMA mission, and the Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment carried out in November 2016 during the FireBird mission [45]. All experiments relied exclusively on monocular cameras to extract line of sight information. In addition, the RemoveDebris mission included a demonstration of vision-based navigation using a flash imaging Light Detection and Ranging (LIDAR) in addition to the standard camera [42–44]. This mission also included two capture experiments using a net and a harpoon. During the net capture experiment, a CubeSat was first ejected at low velocity and then captured at $\approx 11.5\,\text{m}$ distance. The second demonstration fired a harpoon system at a deployable target that extends outwards from the Chaser platform with a distance of 1.5 m. These capture technologies required additional features such as the release mechanism for the net, motor-driven winches to ensure the net closure, a cold gas generator to propel the harpoon, and respective power sources.



(a) Net capture experiment during the RemoveDEBRIS mission: net unfolds pulled by 6 throw masses at its vertexes (left) and travels towards the target DSAT-1 (right) [43].



(b) Harpoon capture experiment during the RemoveDEBRIS mission: Harpoon ejecting towards a target fixed at the end of a deployable boom on the chaser s/c (left and middle) and successfully impacting it (right) [43].

Figure 1.7: Overview of on-orbit capture experiments for non-cooperative rendezvous [38].

1.2.5 Small satellite ADR

In the present work, the focus lies on adhesives-based capture methods as an alternative capturing technique (see the highlighted path in Fig. 1.6). In particular, an emerging terrestrial technology for handling applications –the use of synthetic Micropatterned Dry Adhesives (MDA)– is highlighted and its applicability in the context of an ADR mission is discussed [38]. Previous studies have examined the general feasibility of using MDA in space [55, 56], and current research is focusing on developing anisotropic microstructures with directionally-dependent adhesive properties [38]. The benefits of MDA technology include strong adhesion performances in vacuum and their simple integration into potential chaser designs without additional power supply and specific interfaces on the target (i.e. a sizable rigid interface such as a payload adapter or a docking port), as illustrated in Fig. 1.9. This allows a virtually unlimited number of docking attempts to capture space debris and the usage of small s/c buses such as CubeSats due to the low mass, volume, and energy penalties [38].

There have been several proposed concepts for using small spacecraft, such as micro-satellites and CubeSats, for ADR missions. In 2009, Nishida et al. [57] proposed using micro-satellites equipped with flexible robotic arms for ADR, as such s/c are suitable for a piggyback launch of up to ~ 140 kg. In 2015, Udrea and Nayak [58] suggested using a CubeSat-carrying mothership (~ 1100 kg) for ADR, which would inspect the debris, determine its status, and then release six 12U CubeSats to dock to the target debris using electrostatic adhesion. The mothership would then dock with the stabilized debris and perform the deorbiting. In 2016, Hakima and Emami proposed a similar concept using 3U de-tumbling CubeSats equipped with MDA. Ben-Larbi et al. [59] introduced the idea of using CubeSats as independent removal devices in 2017, presenting a preliminary design for a 27U CubeSat to remove defunct s/c of planned mega-constellation using an MDA-based docking mechanism. Propellant-less differential drag control was assumed for far-range formation flight [60]. In 2018, Hakima and Emami [61] upgraded their concept to include deorbiting using 8U CubeSats deployed by the mothership [62]. They have also studied the de-tumbling and deorbiting phases in further publications, including the deorbiter's own attitude estimation [63], rendezvous and synchronization maneuver using three reaction wheels and a single unilateral low thrust propulsion (assuming perfect knowledge of the targets state) [64], and the mission and systems engineering design [65].