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Spaceborne and ground-based sensor collaboration: Advancing resident space objects' orbit determination for space sustainability

Niki Sajjad[1,2](✉), **Mehran Mirshams**[1], and **Andreas Makoto Hein**[2]

1. *Space Research Laboratory, Department of Aerospace Engineering, K. N. Toosi University of Technology, Tehran 16569-83911, Iran*
2. *Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg 1855, Luxembourg*

ABSTRACT

The limited space around the Earth is getting cluttered with leftover fragments from old missions, creating a real challenge. As more satellites are launched, even debris pieces as small as 5 mm must be tracked to avoid collisions. However, it is an arduous and challenging task in space. This paper presents a technical exploration of ground-based and in-orbit space debris tracking and orbit determination methods. It highlights the challenges faced during on-ground and in-orbit demonstrations, identifies current gaps, and proposes solutions following technological advancements, such as low-power pose estimation methods. Owing to the numerous atmospheric barriers to ground-based sensors, this study emphasizes the significance of spaceborne sensors for precise orbit determination, complemented by advanced data processing algorithms and collaborative efforts. The ultimate goal is to create a comprehensive catalog of resident space objects (RSO) around the Earth and promote space environment sustainability. By exploring different methods and finding innovative solutions, this study contributes to the protection of space for future exploration and the creation of a more transparent and precise map of orbital objects.

KEYWORDS

resident space objects (RSO)
space debris
orbit determination
tracking
ground-based sensors
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Review Article

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1 Introduction

Technological advancements have increased the demand for satellites, leading to rapid growth in the number of pieces of debris in orbit. Therefore, it is fundamental to develop methods and strategies to identify and mitigate the hazards associated with debris to preserve the usability of the space environment over long timescales.

The number of objects, their combined mass, and surface area in the space environment have steadily increased since the space age, leading to unintended collisions between operational payloads and space debris. Although advanced space surveillance sensors have improved the tracking of smaller pieces of debris, their origins remain partially unknown.

Notably, space traffic has undergone significant changes since 2015, driven by miniaturized space systems, extensive satellite constellations, and increased commercial activity. In 2022, launch rates reached unprecedented levels across diverse mass and type categories [1].

As of May 2023, Orbiting Now [2] recorded 8268 active satellites from low Earth orbit (LEO) to geosynchronous orbit (GEO), 7469 of which were in LEO. These are accompanied by debris, many of which are unknown and have not yet been tracked. If all planned constellations are deployed without special disposal and replacement strategies, LEO will soon accommodate hundreds of thousands of operational satellites, resulting in approximately 20,000 satellites reentering the atmosphere annually [3]. However, LEO is not the only concern. The European Space Agency (ESA) estimates that there are approximately 34,000 objects greater than 10 cm, 900,000

✉ niki.sajjad@ext.uni.lu, niki.sadjad@email.kntu.ac.ir

objects from 1 to 10 cm, and more than 128 million objects from greater than 1 mm to 1 cm orbiting the Earth [1, 4]. Among them are discarded rocket stages, defunct satellites, and unidentified debris objects and fragments. Satellites below 150 km require approximately 25 years to descend and burn into the atmosphere, while approximately 2000 years are required for satellites at 1200 km altitude without deorbiting systems [4]. Figure 1 shows an illustration of the estimated space debris objects around the Earth, whereas Fig. 2 demonstrates the already tracked objects in LEO.

Fig. 1 Space debris conceptual demonstration in different orbits [5].

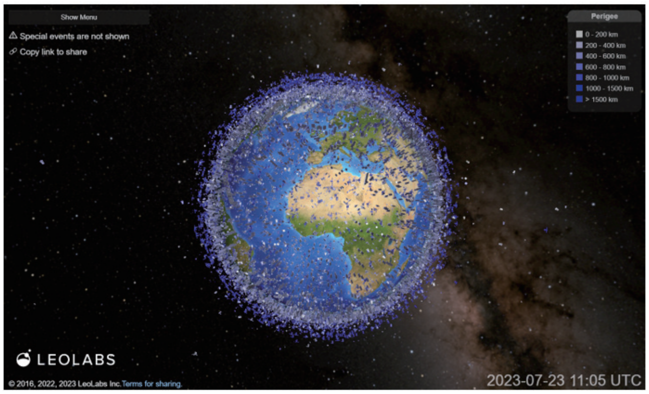

Fig. 2 Distribution of space objects in LEO. Credits: LEOLABS [4].

Identifying pieces of debris in space and their precise orbit, shape, size, and attitude makes the space environment transparent to everyone. This helps spacecraft developers understand the risks they face, plan urgent maneuvers, and make on-orbit service missions possible. To date, different companies, organizations, and researchers have attempted to create a transparent and public map of LEO to GEO, but there is still a gap in achieving this goal. Achieving universal access to crucial information about resident space objects (RSO) orbiting the Earth is currently hindered by technological gaps and organizational policies. However, it is imperative to have a comprehensive understanding of the actual state of in-orbit conditions. This study focuses on the technological aspects of the problem, whereas the policies and regulations surrounding it are not covered.

Orbit determination and pose estimation methods for uncooperative objects are growing rapidly, paving the way for RSO identification and trajectory estimation.

2 Space debris programs and current gaps

During the late 1970s and the 1980s, debris-related space activities increased. Programs to observe and support these activities were established and grew simultaneously. As an example, in 1979, NASA initiated what is now known as the Orbital Debris Program Office (ODPO). This happened after the visible reentries of spacecraft such as Cosmos 954 and Skylab in 1977 and 1979, respectively. Collaborations with the ESA about debris occurred in 1987 and eventually brought other agencies into conversation in the following years [6].

In 1993, the Inter-Agency Space Debris Coordination Committee (IADC) was founded, involving multiple space agencies worldwide. This international community seeks to develop guidelines and implement coordinated efforts to address space debris and its associated risks [6].

Other organizations and groups, such as the Center for Orbital and Reentry Debris Studies (CORDS), have been established since the late 1990s to focus on corporations' research and technological applications in the areas of space debris, collision avoidance, and reentry breakup [7].

These centers have monitored space debris and space traffic management to assess risks in orbit. Some of these databases are publicly accessible, whereas others are available exclusively to organizations or governments.

Despite all the technological developments, humans have observed only a fraction of orbital debris owing to the limited capabilities of on-ground facilities. Atmospheric limitations and disturbances, such as light pollution and weather conditions, such as humidity and sand storms, as well as space weather phenomena, affect ground stations and interrupt the observation. Currently, the threshold for ground-based space surveillance systems is, at best, around 1 cm or greater in LEO and 1 m in GEO [8, 10, 11, 23]. This problem has led to the development of in-orbit spacecraft for monitoring orbital objects and estimating their relative distance from the observer, their orbit, and with special conditions, their attitude. The task of a spacecraft involves tracking an object and determining its orbit, which is of significant importance for upcoming on-orbit servicing and debris removal missions [27]. The results are combined with ground-based observations to create a precise map.

However, sending satellite constellations to demonstrate this technology without improving its sustainability will add more debris to the orbit. In addition, other challenges appear, such as the rapid change in illumination in orbit, satellite power constraints, satellites' high orbital velocity, spaceborne sensors' accuracy limit, and the increasing risk of collision in orbit. Considering the aforementioned challenges, it is essential to reduce the number of required sensors, which results in a reduction in the number of satellites required.

Tracking facilities, space-object detection and identification methods, and orbit-determination algorithms are vital for space situational awareness and traffic management. These components enable the monitoring and characterization of space objects. Advanced sensors in tracking facilities detect and track objects, whereas sophisticated algorithms identify and classify objects. Orbit determination algorithms process tracking data to accurately calculate orbits and predict future positions, which are essential for collision avoidance and resource planning.

The current gaps can be summarized as follows:

- Observation limitations: Ground-based facilities face constraints owing to atmospheric and environmental factors, which limit their ability to detect and track small space debris.
- Threshold constraints: Current publicly available surveillance systems have minimum detection thresholds of approximately 1 cm in LEO and 1 m in GEO, posing challenges in tracking smaller debris.
- Technological hurdles: Overcoming challenges, such as rapid illumination changes, power constraints, high orbital velocities, and sensor accuracy limits, is crucial. Additionally, enhancing tracking facilities, object identification, and orbit determination methods are required.
- Collision risk: With the growing number of objects in space, effective collision avoidance strategies are essential to mitigate the increased collision risk.
- Sensor optimization: Reducing the reliance on a large number of sensors and satellites while maintaining effectiveness is a key challenge in space debris tracking.
- Global collaboration: International cooperation is pivotal in establishing guidelines and developing collaborative methods to address space debris challenges.

Ongoing research aims to enhance algorithms and foster international collaboration to improve situational awareness for a safer and more sustainable space environment. The following sections review each task and the unique challenges regarding the entire RSO tracking and orbit determination mission.

3 Space debris tracking facilities

Tracking is the surveillance that locates each piece of debris in orbit. Many different on-ground and in-orbit methods exist to detect space objects, catalog them, enter them into a database, and estimate their locations.

Several countries have played a role in space surveillance programs coordinated by their respective space agencies, such as NASA, Roscosmos, the Japan Aerospace Exploration Agency (JAXA), and ESA. International projects are key in space data collection and space debris measurements. However, as space debris has recently emerged as a topic of growing importance and interest in the field of research, very few studies in the scientific literature address the results of space debris programs.

Space debris tracking facilities can be categorized into two general groups: ground-based and space-based facilities.

3.1 Ground-based tracking facilities

Ground-based observations encompass two categories: ground-based radar and ground-based optical observations. Currently, more than 50 radars are dedicated globally to space targets and space debris monitoring. Ongoing efforts are aimed at expanding the networks of the available radar systems tailored for space control. Ground-based radar detection methods offer advantages in terms of size and weight flexibility. Optimal radar configurations typically employ a large-aperture antenna and significant transmitting power to achieve high detection accuracy and extend the detection range. However, limitations arise because of the fourth power relationship between the target signal loss and distance, which constrains radar detection to lower orbits. Moreover, operational challenges linked to atmospheric transmission jitter, ionospheric scintillation, astronomical refraction error, and atmospheric attenuation impose constraints on radar operations within lower frequency bands, which in turn restrict the detection accuracy of ground-based radar. Currently, ground-based radars still face difficulties in accurately identifying small-sized space debris [73].

Space debris detection and tracking encounter significant hurdles, primarily owing to the limited availability of in-orbit tracking instruments, which rely mainly on ground-based facilities that are susceptible to atmospheric and weather-related disruptions [13]. The current state of detection systems faces increasing difficulty in effectively identifying smaller debris, primarily owing to technological constraints, substantial power demands, and the significant financial investments required for system installation and maintenance. Consequently, priority is often given to monitoring larger, more hazardous objects given their elevated risk of collision.

In radar-tracking methods, the wavelength of the detector is ideally close to the diameter of the target object. As most radar systems operate using wavelengths larger than 10 cm or more minor operating frequencies than 3 GHz, it is increasingly challenging to detect smaller debris particles as their apparent diameter decreases according to Rayleigh's Scattering Law, which explains why the general limitation on size is approximately 10 cm. Additionally, if shorter wavelengths were used, the atmospheric attenuation of the signals would become much greater and yield inaccurate readings [46].

The space surveillance network (SSN) is a large-scale network of optical and radar sensors and helps the United States Strategic Command (USSTRATCOM) hold and maintain large databases of cataloged objects in LEO [9, 12]. Ground-based radars, optical telescopes, and laser systems are used to detect, track, and catalog objects larger than 5–10 cm in the populated low Earth orbit, and those larger than 0.3–1.0 m at greater altitudes (medium and geostationary Earth orbits, MEO and GEO). The US Combined Space Operations Center (CSpOC, formerly known as Joint Space Operations Center, JSpOC) is another center that coordinates the large amount of data coming from the SSN, elaborates on the orbital parameters, and makes them available in the correct format, which is the two-line element set (TLE).

The ODPO utilizes ground-based radars to characterize the distribution of small debris. The ODPO continuously monitors the LEO debris environment through radar measurements. In 2019, the Haystack Ultrawideband Satellite Imaging Radar (HUSIR) provided one of the recent data on LEO debris, with a focus on debris as small as 5.5 mm below 1000 km altitude, a size critical that drives mission-ending risk to robotic spacecraft in LEO. It can measure objects down to approximately 3 mm depending on the altitude and sensors used, which is much smaller than the publicly available SSN catalog [108]. This dataset is not accessible to everyone; therefore, the accessible detection size range has not changed in many reports.

USA maintains a comprehensive tracking system that monitors over 22,000 objects, whereas the Grand Réseau Adapté à la Veille Spatiale (GRAVES) [14, 26], a bistatic radar system, catalogs around 2500–3000 objects. Other significant resources for space surveillance include LeoLabs [22], a commercial radar-tracking service provider established in 2016. LeoLabs is actively expanding its global radar network and data service platform to facilitate the safe deployment of satellite services and to offer detailed visibility into the LEO ecosystem for government space agencies. Another collaborative initiative, the International Scientific Optical Network (ISON) [21], was founded in 2004 as an independent source of data on natural and artificial space objects for scientific and applied purposes. Figure 3 illustrates the presence of these space surveillance networks.

Owing to the limitations of ground-based optical telescopes for imaging satellites, there is a need for new high-resolution imaging methods for high-orbit satellites. For example, intensity correlation imaging (ICI) is an emerging optical synthetic aperture imaging technique that utilizes intensity interferometry arrays to achieve high-resolution imaging. ICI overcomes the constraints imposed by atmospheric turbulence and lens aberration, resulting in reduced complexity and cost compared with traditional approaches. However, challenges such as a low signal-to-noise ratio and deviations in measuring


GRAVES
EUSST Network

LeoLabs-Midland Space Radar

ISON Worldwide Scientific Optical
Network/ASPOS OKP system

Fig. 3 Space surveillance networks [15, 25, 28].

the spatial frequency modulus arise when observing faint targets [19]. Simulation of noise and analysis of ICI imaging quality has provided valuable insights for enhancing the performance of ICI in future research. Recent advancements in noise-reducing phase-retrieval algorithms have overcome the long integration time traditionally associated with ICI. This method utilizes a spatially distributed array of small flux-collecting apertures and can operate in both ground- and space-based configurations. Electronic coupling of the apertures enables unlimited baseline measurements and high-resolution imaging. Although a complete ICI array has yet to be built, the development of ground-based facilities holds promise for improvements in this imaging technique [16, 17].

Space-based surveillance satellites are rare owing to the high cost and complexity involved in launching a system into space. The only instruments currently in operation for tracking debris in orbit are called SBVs, American surveillance satellites. There are other examples of orbital debris sensors, such as the GORID and DEBIE satellites [18]. However, these sensors are intended to detect collisions and do not detect or track debris. Therefore, they do not contribute to the cataloging of debris populations or orbit determination. Each country has its own surveillance system; however, the lack of data sharing among space monitors poses a challenge, resulting in fragmented surveillance efforts. Additionally, the absence of a standardized coding system makes it difficult to effectively integrate the available information. Currently, object descriptions are limited to simple representations, such as spheres, and fail to capture crucial properties such as size, shape, and material composition. Currently, a publicly accessible database containing comprehensive information on these objects is unavailable.

3.2 Space-based debris tracking instruments

Onboard sensors were initially introduced to enhance the accuracy of space debris observation [29–31] and have since become the cornerstone of modern SSA programs [32, 33]. These sensors offer superior performance in terms of accuracy, wide field of view, and weather insensitivity with the added benefit of uninterrupted measurements owing to the absence of atmospheric turbulence [34]. While radar technology has been proposed as an alternative to optical sensors, its implementation is complex, requiring significant power consumption and a large spacecraft size and mass [35–37]. Therefore, optical sensors, including CCD [38], CMOS [39], and photon-counting sensors [40], have become cost-effective and practical solutions for small satellite missions, such as CubeSats [41]. Advances in state-of-the-art optical sensors, miniaturization of space components, and increased onboard processing power have led to the emergence of new space mission concepts, such as Autonomous Assembly of Reconfigurable Space Telescopes (AAReST) [42], the Space-Based Telescope for Feasible Refinement of Ephemeris (STARE) [43], and Sapphire [31]. Following this trend, a mission for space debris surveillance has been proposed [44], in which a network of distributed optical sensors is utilized to form multiple spacecraft.

Recently, several small satellite missions have been developed and launched into orbit to accelerate surveillance programs in space. Among these missions, STRATHcube [18] is an active project proposing to launch CubeSat at LEO as a demonstrator of passive bistatic radar (PBR) technology. Thus, signal-processing algorithms for space-debris detection developed at Strathclyde University will be tested. This concept involves a radar receiver and antenna mounted on a low-altitude orbiting CubeSat that maneuvers higher-altitude orbiting satellites to capture radio signal broadcasts. These signals may have been altered by objects orbiting between the active satellite and the CubeSat, suggesting the presence of debris [47].

The DebriSat project (Fig. 4) is a collaboration between the ODPO, the Air Force Space and Missile Systems Center (SMC), the Aerospace Corporation (Aerospace), the University of Florida (UF), and the Air Force Arnold Engineering Development Complex (AEDC). The project has four primary goals: (i) design and fabricate a 56-kg class spacecraft ("DebriSat") representative of modern spacecraft in the LEO environment; (ii) conduct a hypervelocity laboratory impact test to simulate a catastrophic fragmentation event of DebriSat; (iii) collect, measure, and characterize all fragments down to 2 mm in size; and (iv) use the data to improve space situational awareness applications and satellite breakup models for better orbital debris environment definition.

VISDOMS (Verification of In-Situ Debris Optical Monitoring from Space) is an ongoing project from ESA that aims to statistically monitor small sub-catalog objects (< 1 mm) in low-Earth orbit and beyond. Its secondary goal is the geostationary surveillance from satellites in a low-Earth orbit. A passive optical telescope with a wide FOV (3° × 3°) will be deployed on a dedicated microsatellite (~150 kg) or as a hosted payload. The mission's nominal lifetime is approximately 5 years, targeting launch in 2030 after a hosted payload launch in 2026 [75].

In addition, many researchers are currently investigating the use of star trackers to determine RSO orbits. For example, ESA's research [74] aims to utilize unused downlink capacities in the Earth Observation missions for star tracker imagery and space debris observations. It collected and processed approximately 2000 star-tracker observations, revealing unidentified moving bodies. Collaboration between the Earth Observation Ground Data Systems section, Space Debris office, and SWARM Flight Control team resulted in a preliminary ground segment prototype, including observation intentions, triage, uplink, downlink, and data processing elements. It also explored the flight operation concept for multiple Earth Observation missions having star trackers to assess their applicability.

Moreover, the use of multiple star trackers has been explored to enhance orbit determination. Innovative strategies have been proposed using star trackers with a dedicated algorithm onboard satellites to monitor space debris without interfering with the primary mission. A multistar tracker space debris detection and positioning method with constant geocentric observation was introduced, demonstrating its efficacy in detecting and positioning space debris. These results highlight the potential benefits of cooperative network observation using multiple star trackers [73]. It is mentioned that every satellite with a star tracker can be used as a space-surveillance observer.

Onboard cameras were also tested for orbit determination [77]. This study highlights the effectiveness of angles-only navigation for non-cooperative target approaches. Autonomous Vision Approach Navigation and Target Identification (AVANTI) [76] demonstrated the successful visibility of a tiny picosatellite at distances of up to 50 km.

Currently, the private sector i construct and manage s entering the space-debris monitoring area by proposing space-based missions. Vyoma [104], a pioneering space startup, is one of them and aims to an advanced satellite-based observation system dedicated to space debris monitoring (Fig. 5). The spaceborne nature of the system allows for continuous sensor operation, effectively

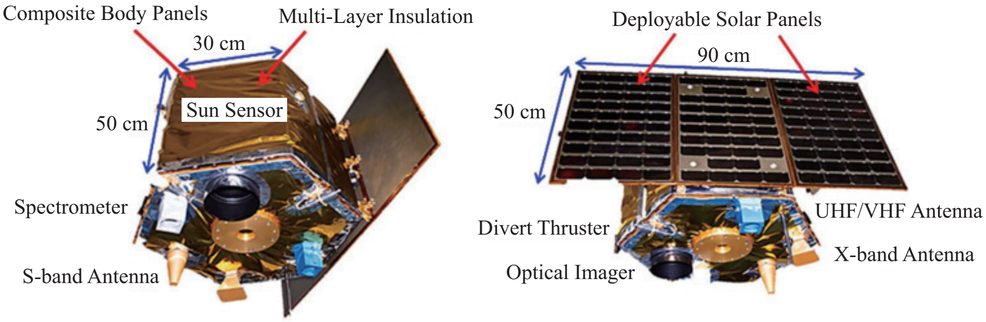

Fig. 4 Illustration of the DebriSat satellite from two different perspectives [45].

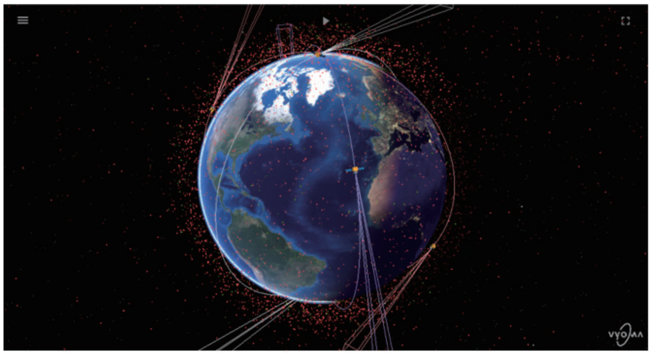

Fig. 5 Vyoma's visualization tool for constellation design. Credits: Vyoma [105].

covering a vast expanse of space and reobserving objects with an unmatched frequency of up to 30 times per day. By leveraging cutting-edge data processing algorithms, Vyoma will offer an array of essential services, including orbit determination, debris cataloging, collision warnings, and full automation of planning and execution maneuvers, to ensure that satellite operations are conducted safely and efficiently. Localization of space objects is accomplished using two sensor systems: onboard optical cameras for observing Sun-illuminated objects relative to satellites and onboard global navigation satellite system (GNSS) receivers for precise orbit determination of their own satellites, and hence the observed space debris.

Performing orbit and attitude determination using a visual sensor like a camera is more efficient in terms of mass and distance than using sensors such as light detection and ranging (LIDAR). This approach is particularly attractive because it requires minimal power. In addition, monocular cameras are preferred over stereo systems. This is because of their relative simplicity as spacecraft—especially emerging small spacecraft such as CubeSats—do not have a sufficiently large baseline for effective stereo vision. To enable autonomous estimation, service providers must use fast and robust computer vision algorithms to compute the relative position and attitude of a target from one monocular image or a series of monocular images.

Vision-based sensors can be broadly categorized into two types based on their operational mechanism: active and passive devices. Active devices, such as LIDAR sensors and time-of-flight (TOF) cameras, require an external source of energy to function, whereas passive devices, such as monocular and stereo cameras, collect radiation from their surroundings without any additional power [48]. For spacecraft navigation purposes, electro-optical sensors that combine stereo cameras and LIDAR sensors with one or more monocular cameras are commonly used to overcome the partial observability arising from the lack of range data [49–53]. Monocular cameras are currently being investigated as viable alternatives because they can provide fast and accurate orbit and attitude estimations under low power and mass requirements [53]. Stereo cameras and LIDAR sensors, on the other hand, are less flexible and less convenient in terms of operational range, power consumption, and processing power [54].

In-orbit debris-tracking instruments can ultimately offer relative orbit determination with respect to the observer's position in orbit, and in a closer range, they provide a relative 6D pose estimation of the target. A comprehensive review of the pose estimation methods developed is presented in Section 4, which provides solutions for addressing the lack of precise orbit determination using ground-based facilities.

4 Resident space objects' orbit determination challenges

After reviewing various research papers, the RSO orbit determination methods and challenges can be classified into three distinct groups. The first group comprises known and trackable spacecraft in orbit equipped with GNSS and/or orbit propagators. The second group consists of space debris fragments that lack sensors or active processors but are still large enough to be tracked by current sensors. The third group encompasses debris objects that neither provide orbital data nor can be tracked, and remain unknown in the space environment. Each group has its own challenges and gaps exist in achieving high-precision, low-power, and low-cost methods. Table 1 provides an overview of the challenges associated with each group. Detailed investigations of each challenge are presented in the following sections.

4.1 Cataloged RSO with TLE data

The Joint Space Operations Center (JSpOC) maintains an up-to-date catalog of the Earth-orbiting objects and collects the orbits of all unclassified spacecraft, along with tracked space debris in the Two-Line Element (TLE) catalog. These orbits are continually updated

Table 1 Overview of current orbit determination challenges for different RSO groups

Challenge	Cataloged RSO with TLE data	Trackable uncataloged RSO	Hard-to-track uncataloged RSO
Lack of TLE update	●	●	●
Limited accuracy of TLE	●	●	●
Requiring additional observation data	●	●	●
Requiring object identification and classification		●	●
Too short arc or uncorrelated track		●	●
Long intervals of observation		●	●
Lack of sufficient information to extract orbital parameters		●	●
Lack of sufficient detecting sensors and hardware			●
Requiring complicated on-board processing			●
Requiring novel IOD methods[1]			●

[1] IOD: Initial orbit determination.

using observations from a network of 25 sensors, including radars and optical instruments, collectively referred to as the SSN. However, TLEs have fundamental limitations such as limited accuracy and lack of update or analysis capability in the SGP4 computer code [106]. TLEs provide positional accuracy estimates ranging from several hundred meters to several kilometers (1-sigma) for LEO, a few kilometers for medium-Earth orbit (MEO), up to tens of kilometers for geostationary orbit (GEO), and dozens of kilometers for highly eccentric orbits [110]. Various studies have focused on improving TLE accuracy, generating covariance matrices, and exploring operational applications. Ref. [78] provides a comprehensive summary of the literature on TLEs, their use, and accuracy.

Initial efforts were made to assess the viability of orbit determination processing for TLE information, with much more research extending the analysis and conducting practical operations, such as conjunction analyses. In general, two solutions are available: extracting additional information from TLEs or fusing TLEs with independent data. Both solutions utilize orbit determination; however, the former offers more options. The latter approach is the best means to determine the accuracy and covariance information, but it is more challenging because it requires additional observational data [79].

There are methods that do not include TLE for orbit determination but instead operate directly in osculating orbital elements or Cartesian position and velocity coordinates. These methods usually involve calculating the state-transition matrix to connect the measurement space variables to the initial condition of the space object, which is essentially the Jacobian of the mapping from the measurement to the state. A new method [113] was proposed to combine advancements in semi-analytic satellite theory with statistical methods to accurately compute a direct mapping between the TLE elements and state space in a derivative-free manner.

4.2 Trackable uncataloged RSO

If the object is not cataloged, aside from the challenges of improving the TLE and orbit determination data accuracy, the RSO identification challenge arises. On-ground or in-orbit observation methods should participate in the identification of an object, categorizing it, and preparing it for the process. The primary challenge in computing the orbits of observed space debris is the identification (correlation) of two or more sets of observational data. When a piece of space debris passes above an observation station and remains visible for a short time, it is termed a pass (for geosynchronous satellites, a pass is defined by the duration of observing time for one night). Observations of a specific object during a pass are referred to as a too short arc (TSA), also known as a tracklet or uncorrelated track. Data from a TSA are considered to belong to the same object because they can be connected by a smooth curve (usually a straight line or a great circle). For instance, if an image moves with fixed stars, the debris produces a trail, and the two extremes of the trail are measured [71].

The data of one TSA are insufficient for orbit determination; for example, if there are only two angular observations (as in the case of a trail), there are four equations and six unknown orbital elements. Consequently, solving the identification problem becomes necessary before addressing the orbit-determination problem. This involves finding two or more TSAs belonging to the same physical object and establishing an orbit that fits all the observations (linkage between

TSAs). Although this discussion pertains to optical observations, a similar formulation is applicable to radar data [71].

This challenge occurs in both ground-based and space-based object identification but is worse during space-based observations owing to the high orbital velocity of the target and the observer.

4.3 Hard-to-track uncataloged RSO

For the third group, apart from the aforementioned challenges, there is a challenge with insufficient sensors or algorithms. Advanced sensors, such as ground- and space-based radars and optical sensors (as previously mentioned), along with sophisticated data processing algorithms, are vital for enhancing space debris tracking. These technologies enable the detection of smaller and untracked debris objects, improve orbit determination accuracy, and provide reliable trajectory predictions. Machine learning algorithms aid in the automated identification and classification of space debris in large datasets. For instance, Dumitrescu *et al.* [107] proposed a novel deep learning-based architecture for the automatic detection and classification of space objects in a supervised manner. It was tested on a dataset consisting of real-world images from telescopes that were preprocessed, and an in-depth analysis of the proposed novel relabeling architecture was performed.

If the identification problem is solved, the current initial orbit determination (IOD) and orbit determination (OD) methods can come in and play a vital role in small debris orbit determination and cataloging.

4.4 Initial orbit determination challenges

IOD is a fundamental process in space object tracking, involving the estimation of a resident space object's preliminary orbit from measurements acquired through diverse sensor systems, such as Doppler, laser-ranging, and radar [80]. Each sensor captures specific subsets of six position and velocity parameters that characterize the orbital motion of the object [92]. In the case of optical observations, angles-only IOD relies on three measurements: an epoch and two angular values.

To compute the initial orbit, these measurements were subjected to various available algorithms tailored to IOD tasks. The field of IOD algorithms is an extensive area of research that encompasses a wide array of methodologies. Classical methods such as Laplace and Gauss have historically been employed for orbit determination. More recently, contemporary techniques such as Escobal's double-R and Gooding's method have emerged as viable alternatives to address specific challenges in the process [82–84].

Advancements in IOD algorithms are crucial for enhancing orbit estimation accuracy and providing reliable initial orbital solutions, thereby contributing to the overall efficiency and precision of space object tracking and orbit determination.

Classical methods, such as the Laplace and Gauss methods [85], face challenges in short-arc tracklet IOD [86]. The double-R iteration method [85] and the Gooding method are more suitable but require accurate initial ranges for proper convergence. Milani *et al.* [87] introduced the concept of an admissible region (AR) by assuming an elliptical orbit and constraining the semi-major axis (SMA) and eccentricity within specific bounds. This approach allows the determination of a solution region called the admissible region, where the true orbit parameters are highly likely to reside. Originally proposed for the short-tracklet IOD of celestial bodies, the AR concept was adapted for single-tracklet IOD and tracklet-to-tracklet association (T2T-A) methods for Earth-orbiting objects [71, 94].

DeMars and Jah [88] proposed the constrained admissible region (CAR) method for solving the IOD problem of objects in the geosynchronous Earth orbit (GEO) belt using the Gaussian Mixture Model (GMM) to represent the probability distribution of orbital elements. Hussein *et al.* [89] further considered measurement and orbit uncertainty, leading to a probabilistic admissible region (PAR), allowing the multi-hypothesis filter to converge faster by promptly eliminating unlikely hypotheses.

Ansalone and Curti [90] introduced a genetic algorithm for an angles-only IOD on a very short tracklet, providing at least one solution, although global optimality may not be guaranteed. Sang *et al.* [91] proposed the range-search (RS) method that converts the angles-only IOD to a Lambert problem by assuming range measurement values at two selected observation epochs. Huang *et al.* [92] presented an SMA-search method for GEO objects, assuming near-zero orbit eccentricity.

Tracklet association methods have also been explored. Hill *et al.* [93] proposed the covariance-based tracklet association (CBTA) method, propagating the initial states and covariances of two tracklets to a common epoch and computing the Mahalanobis distance between them for the T2T-A decision. However, covariance propagation can be time-consuming and inaccurate, affecting the performance of the method.

The AR concept was applied to tracklet association. Tommei *et al.* [71] used AR to associate a pair of too-short-arcs (TSA) of space debris and computed a preliminary orbit. Li *et al.* [94] introduced an AR-based triangulation subdivision and iterative searching method for T2T-A of space-based optical tracklets. Fujimoto *et al.* [95, 96] generated ARs for each tracklet, mapped them into a six-dimensional Poincare space, and determined the T2T-A based on the intersection of ARs. Siminski *et al.* [97] studied the AR+IVP (initial value problem) and BVP (boundary value problem) association methods, with the latter offering faster performance. Cai *et al.* [98] improved the IVP method using a new loss function defined in a nonsingular canonical space. Lei *et al.* [99] applied a geometrical approach to nearly circular orbits to solve for T2T-A.

According to Sabol *et al.* [100], the uncertainty propagation of a low Earth orbit (LEO) object is significantly affected by the quality and quantity of observations as well as the choice of the coordinate system used to represent the state of the object. A high-performance T2T-A method is essential for efficiently utilizing observed uncatalogued space-based optical tracklets (UCTs) to expand the object catalog [101, 102]. This motivated the development of a T2T-A method based on the angles-only Gooding IOD method, considering orbit perturbations [103].

Zhao *et al.* [70] presented a brief introduction to the single-tracklet IOD methods, followed by the development of the T2T-A method. The authors conduct extensive tests using various orbit types, including LEO, high elliptical Earth orbit (HEO), medium Earth orbit (MEO), GEO, and Molniya objects, to validate the proposed T2T-A method. However, research is ongoing to improve the accuracy and computational cost of IOD. Recent methods exhibit highly promising computational efficiency for the rapid and reliable cataloging of new objects using optical tracklets. Future plans include conducting extensive tests using real-world observations for all orbit types.

In summary, the main challenges in initial orbit determination (IOD) for space-object tracking include estimating preliminary orbits from diverse sensor measurements, where traditional methods such as Laplace and Gauss struggle in short-arc tracklet IOD. Accurate initial range measurements are required in contemporary methods such as double-R and Gooding. Admissible region (AR) concepts are used to bind the orbit parameters, and various techniques, such as genetic algorithms, range-search, and SMA-search methods, have been explored. Managing the uncertainty propagation in low Earth orbit (LEO) objects is crucial. Ongoing research should enhance the IOD accuracy and computational efficiency, particularly for the efficient cataloging of new objects.

4.5 Additional challenges and considerations

The most urgent action that can be taken to tackle the space debris issue is to create a precise map of orbits. Without knowing the exact location of each piece of debris and estimating the trajectories of millions of objects in space, we cannot be notified of the potential collisions. Moreover, knowing the size, shape, and attitude of every piece of space debris helps predict collisions more precisely. Otherwise, only center-to-center collision predictions will be available. For example, if tracking data show the possibility of conjunction between two objects at a distance of 7 m, this number refers to the distance of the centers of the satellites but does not consider the shape and size of each object. Spaceborne sensors can be a great help for this purpose.

Since 2010, many studies have been conducted on this topic to use spaceborne sensors and develop strategies for optical observations in orbit. However, as designing, developing, and constructing new space systems is time-consuming, the dream has not yet been realized, and there is a massive gap in the detection, tracking, and orbit determination of space debris, specifically hundreds of millions of untracked objects smaller than 1 cm in LEO and 10 cm in GEO. Moreover, the existing methods tend to be costly and require extensive expertise, rendering them inaccessible to many people, including university students and various nations. According to the ESA, collisions with debris greater than 10 cm in size can catastrophically destroy a spacecraft, generating fragments that contribute to Kessler syndrome. Debris larger than 1 cm can disable operational spacecraft or cause explosions in decommissioned spacecraft, whereas millimeter-sized debris can damage or disable subsystems in operational spacecraft [112].

The main tracker of space debris is the USA's 18th Squadron, which has been operating since 1957. However, others, including the ESA, Russia, and China, also retain their own data. There were two main problems with this setup. Although phased-array surveillance radar systems continuously scan the sky to detect objects in lower orbits, they can only obtain observations every few days. Moreover, there are limitations to what they capture. Most radars currently tracking debris travel as far as 4000 km (SpaceX's Moon-bound Falcon 9, for example, is well beyond that). The farther you go, the more difficult it is to track them. Another problem is the lack of collaboration in sharing space surveillance data, which hinders the sustainability of space operations. Insufficient sharing of timely and accurate data on space debris impedes effective space traffic management and collision avoidance. Improved international collaboration and data-sharing frameworks are crucial for enhancing situational awareness, reducing collision risks, and ensuring the sustainable use of space.

Space safety and sustainability are being taken seriously as awareness of the dangers and risks posed by debris and satellite constellations continues to increase.

5 Advances in pose estimation for space-based relative orbit determination

As mentioned in Section 2.2, space-based instruments provide the relative orbit and attitude data for the target. Since 2019, in-orbit spacecraft pose estimation has become an ESA-defined challenge for students and researchers to showcase the latest achievements in the development of AI algorithm. This challenge is gaining momentum with algorithms that improve the accuracy and convergence under varying lighting conditions [20].

Although the pose estimation method was not originally planned for RSO orbit determination, this competitive trend can contribute to advancing object tracking and relative orbit determination methods. The Ph.D. thesis from Alexander Cropp in 2001 [111] presented a method for estimating the relative position and orientation of a known target microsatellite using passive imagery, with applications in future autonomous satellite docking missions. The method estimates six relative rotation and translation parameters with respect to the camera by analyzing a single monocular image and leveraging the knowledge of the target spacecraft. The pose estimation process consists of modular sections involving line detection in the image, correspondence matching with a priori target information, and generating multiple possible pose estimates for further processing through least-squares minimization. The final estimate vector and covariance matrix were obtained for each frame. The estimated target location over time allowed the estimation of relative orbit parameters. Location estimates are filtered to fit an orbit model based on Hill's Equations [114], and the statistical information gathered from each estimate is included in the filter process when estimating the orbit parameters, which are used for mission planning and safety analysis of potential orbit maneuvers near the target. Detailed simulation testing was performed to validate the accuracy of the method, accounting for various factors such as lighting conditions, reflections, and transformations between the inertial, target, and camera frames of reference.

If the observer satellite has an accurate orbit and attitude determination system, the relative orbit determination information from the target can be transformed to determine the orbit of the object in the Earth inertial reference frame (Fig. 6).

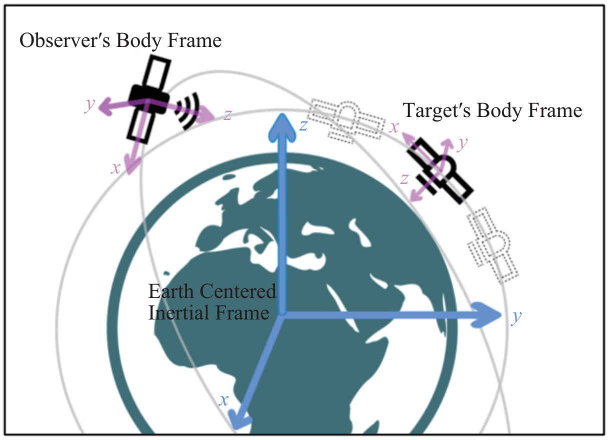

Fig. 6 Demonstration of reference frames and spaceborne relative orbit determination over time.

Satellite-to-satellite pose estimation has been successfully demonstrated at various distances in space. However, the specific distance at which this can be performed depends on many factors, including the capabilities and technologies of the satellites involved, sensors and instruments used for pose estimation, and mission objectives. For example, PRISMA [115] is a demonstration mission for formation-flying and on-orbit-servicing critical technologies involving two spacecraft launched in low Earth orbit in June 2010. This effort was rewarded with four successful rendezvous rehearsals ranging up to 10 km and distances down to 50 m using the vision-based navigation system. The "far range" is considered as the distance of kilometers and the "close range" has been demonstrated from 100 to 50 m. The close-range vision-based system operates to determine the relative pose of the target satellite, but the far-range vision-based system can detect and track moving targets from tens of kilometers to a few decameters away, making it suitable for performing vision-based rendezvous with non-cooperative objects.

In the realm of real-time 6DOF (degrees of freedom) pose estimation for high-end, reliable applications at far-range distances, two main options stand out: target-based systems and shape-based systems. Target-based systems use fiducial targets attached to the tracked object, which are tracked using cameras, stereo vision, or laser-tracking systems. In contrast, shape-based systems generate 3D images of the tracked object and align them with a preexisting model of the object without necessitating the addition of targets to the object [116].

Satellites in close proximity commonly use relative navigation and pose estimation techniques for proximity operations, such as rendezvous and docking missions. These techniques often involve GPS-based navigation, laser rangefinders, optical cameras, and other sensors to determine the relative positions and orientations between satellites.

For more distant satellite-to-satellite pose estimation, such as in the context of scientific missions or satellite formations, this becomes more challenging owing to increased communication and sensor limitations. Beyond a few decameters, the accuracy of pose estimation may decrease because of factors such as signal strength, sensor resolution, and potential perturbations from other celestial bodies [116].

In recent years, there have been initiatives for the formation flying missions and satellite constellations involving satellites separated by hundreds or even thousands of kilometers. These missions typically employ advanced sensor technologies and sophisticated algorithms for pose estimation, to overcome the challenges associated with operating at such distances.

5.1 Algorithm development

Several pose-estimation methods for space-based applications have been proposed. This section reviews these methods, regardless of the relative distance between the observer and the target. The development of adequate sensors and hardware is essential to enable each method and advancement to contribute to the progress of mid-to-far-range pose estimation and relative orbit determination.

Malan [55] used monocular vision for relative pose estimation between satellites in formation flight. Song and Cao [56] employed monocular vision and a sliding window Hough transform to estimate the pose of non-cooperative targets, focusing on identifying triangular structures (Fig. 7). Oumer *et al.* [57] have modeled the appearance of a satellite at close range for pose estimation with the application of on-orbit servicing by targeting the TerraSAR-X satellite and replicating the outer surface of the rear side of it in the lab (Fig. 8).

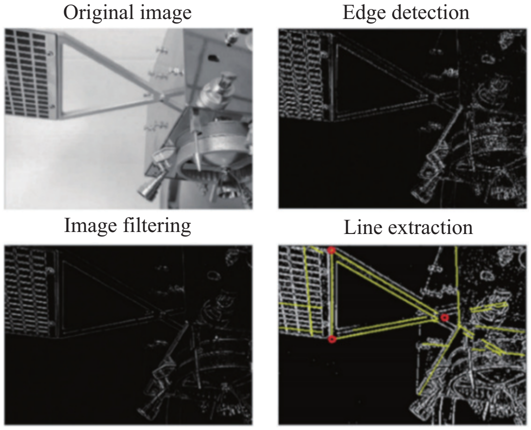

Fig. 7 Extracting triangle lines from images of a non-cooperative satellite [56].

Dong and Zhu [58] conducted the dynamic capturing of a non-cooperative object using a robotic arm. The pose of the target was determined using a vision-based tracking system that employed an EKF to perform a recursive estimation of the target's states. Furthermore, a monocular camera was attached to the end of the robot to capture images of the moving target. Lichter and Dubowsky [59] proposed an architecture for computing the states and shapes of objects using 3D vision sensors (Fig. 9). The solution overcomes the drawbacks of Malan and Song's method by using four 3D sensors arranged in a tetrahedron formation around the target to capture

Fig. 8 Artistic rendition of TerraSAR-X (left) and the rear side replica of the satellite (right), used for appearance learning. Reproduced with permission from Ref. [57], © International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS) 2017.

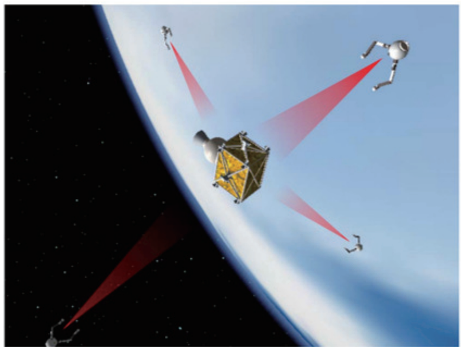

Fig. 9 Cooperative sensor configuration. Reproduced with permission from Ref. [59], © IEEE 2004.

a dense point cloud of the target. This is an accurate method but is not feasible for all missions. Four satellites were required to continuously update their relative positions.

Shahid and Okouneva [61] investigated the pose determination of high-value satellites in geosynchronous orbits using LIDAR scans and iterative closest point (ICP) matching. Scans of the satellite surfaces were matched with the known computer-aided design (CAD) models of the targets. Woods and Christian [62] used an ICP algorithm with flash LIDAR measurements. Although this algorithm could be sufficient, it requires good initial estimation. A poor initial guess can lead to significant errors in the pose estimation. They overcame this problem by implementing a novel clustered viewpoint feature histogram (CVFH) method. This solution was coupled with an EKF to perform a pose estimation of the target.

Pesce *et al.* [63] proposed a new pose-estimation method that uses stereo vision sensors and an EKF algorithm. No prior information about the target was assumed; however, the relative attitude dynamics were exploited by parameterizing the inertia matrix of the target. Additionally, the inertial component was successfully estimated. This helps the dynamic model converge to consistent and accurate values of the inertia parameters. They concluded that space-based applications require a robust and reliable stereo feature tracker. Occlusions and poor lighting can significantly affect vision system functionality, and this method relies heavily on accurate point cloud information of the target.

Using a monocular camera as the chaser's sensor, the pose-determination framework has been created using a convolutional neural network (CNN) and tested extensively on different datasets [65]. Therefore, as long as the sensor noise can be pre-modeled or removed using pre-processing techniques, CNNs are more likely to be able to determine poses using real spatial images. This method only required training the last layer of the network. Several research projects have been conducted for non-cooperative pose estimation using monocular imagery. D'Amico *et al.* [64, 65], in particular, proposed a pose initialization algorithm based on the perceptual grouping of edges detected in an image and least-squares optimization techniques. Tests were conducted on actual space images acquired during the PRISMA mission. Most of the proposed algorithms employed the point cloud obtained with LIDAR-based sensors owing to their robustness to Sun illumination. The effectiveness of this type of sensor for the attitude and position estimation of a spacecraft was demonstrated in both laboratory experiments and tests during space missions using the ISS as a target vehicle.

Recently, a study has shown a simple and fast algorithm using a deep neural network (DNN) for angles-only relative orbit determination. The nonlinear mapping model of the DNN proved effective in estimating relative positions, outperforming the relative velocities. In co-elliptical orbits, the distance estimation errors are below 9.7% with only three angle measurements at a 600 s interval. For non-coplanar orbits, reducing the angle interval to 50 s resulted in distance estimation errors of less than 9.9%. This algorithm is promising for GEO-type orbits [120].

5.2 Hardware development and test facilities

Unlike LIDAR, RADAR, and stereo camera sensors, monocular cameras reduce complexity and save cost, mass, and power. However, reducing the number of sensors to a single camera complicates the processing system [24].

Several other challenges will arise when we want to test our algorithms on the Earth. Most orbit determination tests are performed using software-based simulations by accessing real and synthetic images from satellites in orbit. However, pose-estimation methods often combine with hardware-in-the-loop (HIL) test facilities. This section reviews different testbeds and hardware development and discusses opportunities for these methods to solve the orbit determination problem.

To implement such a 6DOF mission, two main parts are needed on our testbed to make it closer to the orbit situation: a suspension system and an attitude/position control system. The suspension system is responsible for reducing the friction between the satellite platform and the flat surface under it to simulate the space situation, whereas the attitude/position control system is required for the 3D or 2D movement of satellites to perform the rendezvous mission. Rails (Fig. 10), air bearings (Fig. 11), robotic arms (Fig. 12), and air floating tables (Fig. 13) are commonly used to implement and test algorithms in the laboratory.

Raising awareness about space debris can drive advancements in the testbeds used to demonstrate new algorithms and techniques to identify, monitor, track, and even remove debris. As our understanding of the risks posed by space debris increases, there has been a greater focus on developing innovative solutions. Enhanced testbeds allow students, researchers, and engineers to simulate real-world scenarios and assess the effectiveness of their proposed methods for detecting, tracking, and mitigating space debris. By promoting knowledge sharing within the space community, these testbeds contribute to the development of more robust and efficient technologies aimed at ensuring the safety and sustainability of outer space.

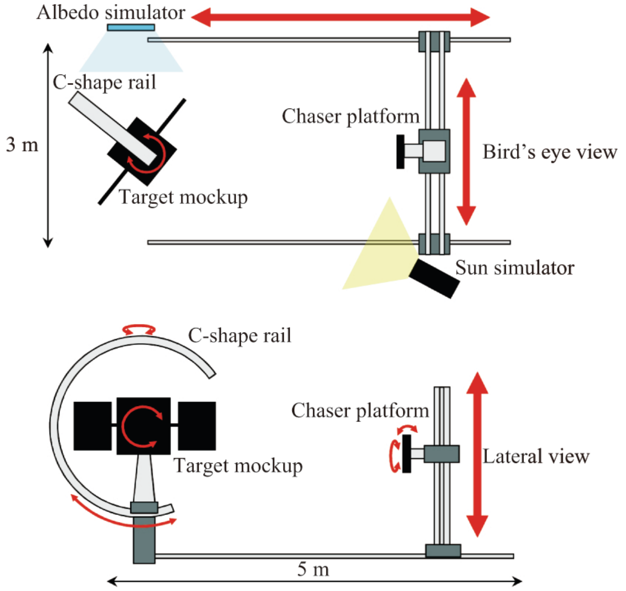

Fig. 10 Schematic representation of the proximity operation testbed [27].

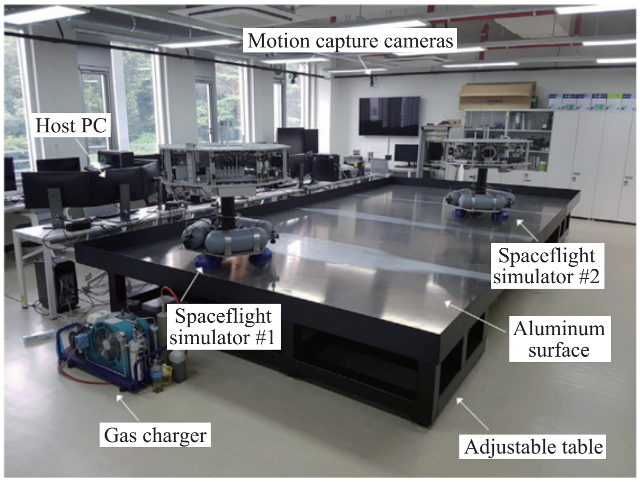

Fig. 11 Overview of the ASTERIX facility. Reproduced with permission from Ref. [66], © IAA 2018.

In addition, with the continuous development of commercial off-the-shelf (COTS) components, more affordable facilities are likely to be introduced. This, in turn, enhances the accessibility of RSO pose estimation and orbit determination implementation for students.

Despite these advancements, several challenges remain in the development of algorithms that achieve high accuracy while maintaining low power consumption and computational cost. In addition, ensuring the availability of accurate sensors, sufficient processors, and replication

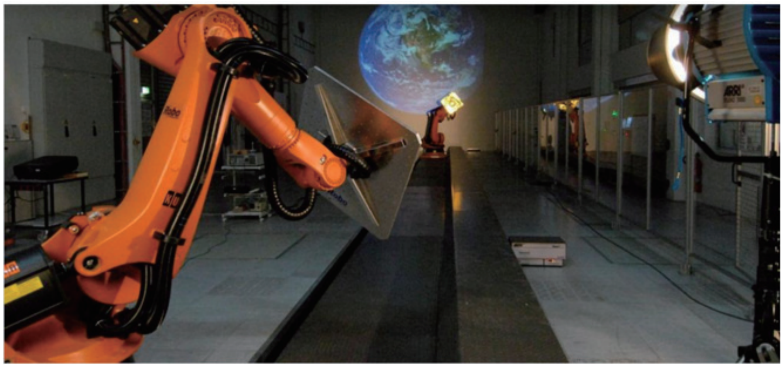

Fig. 12 European proximity operations simulator [68].

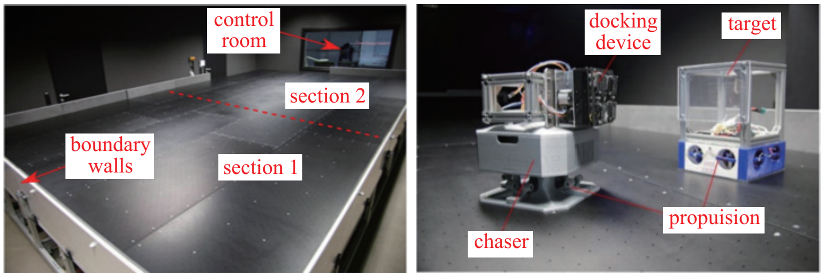

Fig. 13 Overview of the ELISSA laboratory [67].

of space-like lighting conditions in the laboratory poses significant obstacles. Furthermore, coordinate-frame transformations are necessary when scaling down the distances between objects in space to the limited distances achievable in the laboratory.

5.3 Current pose estimation challenges

Dealing with uncooperative objects in space, which often have unknown properties, poses significant technical challenges. There is no one-size-fits-all solution and obtaining accurate pose information remains difficult. Many studies have suggested using cost-effective monocular cameras because of their efficiency and low power consumption; however, they can struggle with varying observation conditions.

6D pose estimation from a single image of an unknown object is a complex task because it often relies on a known object geometry using methods such as model-based and template-based approaches. Some studies proposed using LIDAR or range finders for enhanced accuracy, whereas others explored stereo camera sensors.

LIDAR sensors can deliver reliable measurements over larger distances but require more processing and have higher implementation costs. LIDAR sensors are typically used with an ICP algorithm to perform model matching of the target. Kalman filters were used extensively in this study. The EKF has been the most popular filter used in the past 30 years for pose estimation in the field of autonomous robotics. However, the performance of Kalman filters depends on the input of the initial conditions and measurements, with strong assumptions about the noise properties. This does not affect the convergence quality but may influence the filter's performance in terms of convergence speed and accuracy. Pose estimation is a genuine problem for real-world applications in various fields. Artificial intelligence plays a vital role in reducing the number of sensors and improving image processing algorithms. Hence, the use of a monocular camera instead of a set of vision-based sensors is expected for space monitoring in the near future.

Based on the studies, pose estimation and navigation challenges are as follows:

- Prior knowledge of the target is required in various studies. At least the size of the object should be known beforehand to measure the relative distance between the observer and target from the images.
- There is a huge lighting issue in space that makes some methods need illuminators.
- Most algorithms need a good initial guess of the target

pose. A poor initial guess can lead to significant errors in the pose estimation.

- A tumbling target makes the determination slow.
- Orbital velocity is too high to let the observer detect and thoroughly analyze the target.
- Satellite on-board processing for pose estimation remains limited and requires improvement in algorithm optimization or the development of new algorithms.

Table 2 shows commonly used sensors for monitoring and rendezvous missions.

Table 2 Possible sensors for monitoring and pose estimation missions

Pose estimation sensors	Observer's pose information	Gyro
		Sun sensor
		Magnetometer
		Star tracker
		Earth horizon sensor
		GPS/GNSS
	Target's relative pose information	LIRIS (laser infrared imaging sensor)
		Microwave radar
		LiDAR (light detection and ranging)
		IR camera
		Visible camera (stereo, monocular)
		TriDAR (triangulation LiDAR)
		Thermal imager
		Relative GPS

Sensor selection criteria for the observer satellite are based on:

- Mass
- Power consumption
- Adaptation to different targets/operational flexibility
- Accuracy
- Field of view/optical properties
- Update rate

A tradeoff exists between reducing the number of sensors, which leads to decreased satellite mass and power consumption, and the complexity of processing and object tracking. Microwave radars offer high precision but suffer from drawbacks such as large volume requirements, high power consumption, and high cost [117]. In contrast, LIDAR has fewer volume and power consumption disadvantages but has a limited coverage of only 1 km [118]. GNSS combines the advantages of microwave radars and LIDAR [119]. However, GNSS is only suitable for cooperative targets equipped with navigation receivers and communication capabilities.

In contrast, optical cameras have small volume, low mass, and low power consumption, making them versatile for various applications. However, they can only accurately measure the relative line-of-sight (LOS) angle. Consequently, for the on-orbit service of non-cooperative targets, optical cameras are the ideal choice, because they fulfill the requirements of a simple and reliable relative measurement system [120].

Using a single camera sensor can significantly reduce the size and mass of the observer satellite. However, this approach poses challenges and limitations in debris-monitoring missions, necessitating constraints on the observation time to periods of adequate illumination. Alternative methods, such as incorporating an illuminating system on the observer satellite, are available but contribute to increased mass. Therefore, the mission design plays a crucial role in addressing the unique challenges associated with in-orbit debris monitoring. To enable onboard monitoring, the current attitude and position of the debris must be regularly estimated during the mission. This estimation process consists of two main steps: data acquisition using sensors, and data processing to determine the current pose of the target in real time.

Furthermore, the determination of the observer's pose is a pivotal element in both pose estimation and orbit determination of the target object. Substantial errors in the observer's position and attitude render space-based pose estimation methods ineffective for accurately calculating the orbit of an object. The optimized number of times required to observe the target and obtain the orbital parameters is another challenge that should be addressed in future research.

6 Sustainability issue

In-orbit debris tracking and pose estimation would be a game-changer for RSO orbit determination. However, satellite constellations can create hazards and risks in orbit. Thus, reusing the in-orbit infrastructure to tackle this problem may be the best possible solution. Using this method, existing satellites with specific hardware can be employed as in-orbit debris trackers to combine space- and ground-based data and create a precise dataset. Future projects will present a feasibility study regarding the statistical analysis performed on operational satellites to identify challenges and solutions concerning hardware and software. Furthermore, some critical aspects of the mission, such as power consumption, the ability to reprogram satellites in orbit, using tracking sensors, and the computational cost of the processor, should be analyzed. The core of future research will be the development of an algorithm for the selected set of sensors and hardware to address these constraints.

The key question is whether we can leverage the existing spaceborne infrastructure to establish effective space monitoring. How many satellites are required to achieve the objective? Additionally, how many existing satellites can be reprogrammed and repurposed for this mission? Hundreds of sensors in orbit have excessive spare time during their missions. Can a collaborative platform be made to monitor and characterize space debris using these components? However, these questions remain to be answered.

7 Conclusions

This study reviewed different methods for RSO orbit determination through a comprehensive examination of current on-ground and space-based tracking facilities, sensors, and hardware selection. Various algorithms have been explored for the detection, orbit determination, and pose estimation of small to large RSO pieces that move around the Earth. Using all these methods, this study investigated the existing gaps in accessing a clear map of space debris from LEO to GEO.

Advancements in astronomical imaging have the potential to revolutionize on-ground monitoring and enable substantial improvements in orbit determination methods. With the development of new arrays, ground-based facilities hold great promise for significant advancements in the future. Simultaneously, spaceborne sensors, space-based debris tracking, and orbit determination methods are rapidly improving and gaining attention. Different universities and the public and private sectors have attempted to initiate in-orbit missions for space debris monitoring. However, many missions have proposed constellations of observer satellites or space telescopes that could potentially add more satellites and risks to the orbit. Unless operators demonstrate the genuine necessity of a mission and adhere to stricter sustainability regulations for a safer orbital environment, we should consider limiting the expansion of satellite constellations. A potential solution for sustainable and precise orbit determination is to reduce the number of sensors required, reuse the space infrastructure, and use powerful sensors such as current EO cameras or star trackers on existing operational satellites. As mentioned in this paper, various sensors on satellites can be used along with their main missions to take part in the space debris monitoring and orbit determination problem. The main challenges include reprogramming capabilities, onboard processing constraints, power availability, need for long observation intervals, and tracking methods to precisely determine the orbit of fast-moving objects in space.

This study introduces a monocular camera as a low-power solution for spaceborne sensors, which involves complex algorithms and image processing to determine the poses of RSOs. Additionally, on-orbit satellites hold the potential for relative orbit determination through advancements in pose-estimation methods. However, achieving precision in these methods requires high-precision attitude and orbit determination of the observer satellite with respect to the Earth's inertial reference frame. However, ground-based facilities can enhance the precision of these methods.

In summary, for space-based observations, equipping the observer spacecraft with a monocular camera or star tracker as a payload, along with GPS and attitude sensors such as a Sun sensor, magnetometer, and gyro, is essential. This combination of instruments enables the precise determination of both the relative orbit and attitude of the target as well as the accurate calculation of the observer's own orbit and attitude. Ultimately, this comprehensive setup allows the extraction of the vital orbit and attitude information of the target. If they are in very close proximity (10–20 m), the use of an alternate metrology system, such as LiDAR, is the best solution to maintain a safe distance from the target without any delays in processing the algorithm. Satellites with these sensors, along with a sufficient processor for on-board image processing (or at least pre-processing) and high data rates (exceeding 100 Mbit/s) for real-time payload data downlink, are candidates to fill the current gaps in creating a network of space- and ground-based facilities to map space debris.

A comprehensive and transparent map of space can be achieved by fostering international collaboration between ground-based and in-orbit infrastructures. This collaborative effort will enhance our understanding and monitoring of objects in space, ultimately contributing to improved RSO orbit determination and increased space situational awareness.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

[1] ESA ESOC. ESA's annual space environment report. **2023**. Available at https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

[2] Information on https://orbit.ing-now.com (cited 23 July 2023)

[3] William, A. Protecting the LEO environment. *The Journal of Space Safety Engineering*, **2022**, 9(3): 449–454.

[4] ESA. ESA & UNOOSA space debris infographics and podcast. **2021**. Available at https://www.esa.int/Space_Safety/Space_Debris/ESA_UNOOSA_space_debris_infographics_and_podcast

[5] ESA. Distribution of space debris in orbit around Earth, **2019**. Available at https://www.esa.int/ESA_Multimedia/Videos/2019/02/Distribution_of_space_debris_in_orbit_around_Earth

[6] IADC Steering Group and Working Group 4. IADC space debris mitigation guidelines. **2020**. Available at https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf

[7] Information on https://aerospace.org/cords (cited 25 July 2023)

[8] Blake, J., Chote, P., Pollacco, D., Feline, W., Privett, G., Ash, A., Eves, S., Greenwood, A., Harwood, N., Marsh, T., *et al.* DebrisWatch I: A survey of faint geosynchronous debris. *Advances in Space Research*, **2021**, 67(1): 360–370.

[9] Klinkrad, H. *Space Debris: Models and Risk Analysis* (*Springer Praxis Books*). Springer, **2006**.

[10] Muntoni, G., Montisci, G., Pisanu, T., Andronico, P., Valente, G. Crowded space: A review on radar measurements for space debris monitoring and tracking. *Applied Sciences*, **2021**, 11(4): 1364.

[11] Muntoni, G., Schirru, L., Pisanu, T., Montisci, G., Valente, G., Gaudiomonte, F., Serra, G., Urru, E., Ortu, P., Fanti, A. Space debris detection in low Earth orbit with the Sardinia radio telescope. *Electronics*, **2017**, 6(3): 59.

[12] Sato, T., Wakayama, T., Tanaka, T., Ikeda, K. I., Kimura, I. Shape of space debris as estimated from radar cross section variations. *Journal of Spacecraft and Rockets*, **1994**, 31: 665–670.

[13] Afanasev, A., Biktimirov, S. CubeSat formation architecture for small space debris surveillance and orbit determination. *Information and Control Systems*, **2021**, 4: 37–46.

[14] Bonnal, C., Francillout, L., Moury, M., Aniakou, U., Perez, J. D., Mariez, J., Michel, S. CNES technical considerations on space traffic management. *Acta Astronautica*, **2020**, 167: 296–301.

[15] Accès ONERA. GRAVES, the 1st European space surveillance system. **2019**. Available at https://www.onera.fr/en/news/graves-the-1st-european-space-surveillance-system

[16] Hyland, D. C. Algorithm for determination of image domain constraints for intensity correlation imaging. *Applied Optics*, **2022**, 61(35): 10425–10432.

[17] Hyland, D. C. Improved integration time estimates for intensity correlation imaging. *Applied Optics*, **2022**, 61(33): 10002–10011.

[18] Creed, L., Graham, J., Jenkins, C., Riofrio, S. D., Wilson, A. R., Vasile, M. STRATHcube: The design of a CubeSat for space debris detection using in-orbit passive bistatic radar. In: Proceedings of the 72nd International Astronautical Congress, **2021**: IAC-21,A6,1,2,x66530.

[19] Li, X., Gao, X., Lu, C., Tang, J. Analysis and simulation of intensity correlation imaging noise towards high-orbit satellite. In: Proceedings of the 27th Conference of Spacecraft TT&C Technology in China, **2015**: 429–437.

[20] Kisantal, M., Sharma, S., Park, T. H., Izzo, D., Märtens, M., D'Amico, S. Satellite pose estimation challenge: Dataset, competition design and results. *IEEE Transactions on Aerospace and Electronic Systems*, **2020**, 56(5): 4083–4098.

[21] Molotov, I., Zakhvatkin, M., Elenin, L., Canals Ros, L., Graziani, F., Teofilatto, P., Schildknecht, T., Ehgamberdiev, S., Aliev, A., Ivashchenko, Y., *et al.* ISON network tracking of space debris: Current status and achievements. *RMxAA* (*Serie de Conferencias*), **2019**, 51: 144–149.

[22] Griffith, N., Lu, E., Nicolls, M., Park, I., Rosner, C. Commercial space tracking services for small satellites. In: Proceedings of the 33rd Annual AIAA/USU Conference on Small Satellites, **2019**: SSC19-WKVI-03.

[23] Pradhan, B., Hickson, P., Surdej, J. Serendipitous detection and size estimation of space debris using a survey zenith-pointing telescope. *Acta Astronautica*, **2019**, 164: 77–83.

[24] Sharma, S., Damico, S. Neural network-based pose estimation for noncooperative spacecraft rendezvous. *IEEE Transactions on Aerospace and Electronic Systems*, **2020**, 56(6): 4638–4658.

[25] McGlynn, D. Space mapping. *Berkeley Engineer*, **2018**.

Available at https://engineering.berkeley.edu/news/2018/06/space-mapping/

[26] Michal, T., Eglizeaud, J. P., Bouchard, J. GRAVES: The new French system for space surveillance. In: Proceedings of the 4th European Conference on Space Debris, **2005**.

[27] Ventura, J. Autonomous proximity operations for noncooperative space target. Ph.D. Thesis. Technischen Universität München, **2016**.

[28] Agapov, V., Lapshin, A. Survey and follow-up strategies used in operation of ASPOS OKP to gather observation data on GEO, HEO and MEO objects. In: Proceedings of the 1st NEO and Debris Detection Conference, **2019**.

[29] Gaposchkin, E. M., von Braun, C., Sharma, J. Space-based space surveillance with the space-based visible. *Journal of Guidance, Control, and Dynamics*, **2000**, 23(1): 148–152.

[30] Sharma, J. Space-based visible space surveillance performance. *Journal of Guidance, Control, and Dynamics*, **2000**, 23(1): 153–158.

[31] Maskell, P., Oram, P. Sapphire: Canada's answer to space-based surveillance of orbital objects. In: Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, **2008**.

[32] Flohrer, T., Krag, H., Klinkrad, H., Schildknecht, T. Feasibility of performing space surveillance tasks with a proposed space-based optical architecture. *Advances in Space Research*, **2011**, 47(6): 1029–1042.

[33] Flohrer, T., Schildknecht, T., Musci, R. Proposed strategies for optical observations in a future European Space Surveillance network. *Advances in Space Research*, **2008**, 41(7): 1010–1021.

[34] Vanwijck, X., Flohrer, T. Possible contribution of space-based assets for space situational awareness. In: Proceedings of the 59th International Astronautical Congress, **2008**: 2466–2472.

[35] Carl, J. R., Arndt, G. D., Bourgoise, B. A., Paz, I. Space-borne radar detection of orbital debris. In: Proceedings of the IEEE Global Telecommunications Conference, **1993**: 939–943.

[36] Cao, X. H., Su, F. L., Sun, H. D., Xu, G. D. Space debris observation via space-based ISAR imaging. In: Proceedings of the International Conference on Microwave and Millimeter Wave Technology, **2007**.

[37] Cerutti-Maori, D., Rosebrock, J., Maouloud, I. O., Leushacke, L., Krag, H. Preliminary concept of a space-based radar for detecting MM-size space debris. In: Proceedings of the 7th European Conference on Space Debris, **2017**.

[38] Utzmann, J., Wagner, A., Silha, J., Schildknecht, T., Willemsen, P., Teston, F., Flohrer, T. Space-based space surveillance and tracking demonstrator: Mission and system design. In: Proceedings of the 65th International Astronautical Congress, **2014**.

[39] Middleton, K., Dowell, A., Edeson, R., Escorial-Olmos, D., Fok, S., Morris, N., Naudet, J., Waltham, N. A telescope payload for optical detection of space debris from low-Earth-orbit. In: Proceedings of the 65th International Astronautical Congress, **2014**.

[40] Gruntman, M. Passive optical detection of submillimeter and millimeter size space debris in low Earth orbit. *Acta Astronautica*, **2014**, 105(1): 156–170.

[41] Underwood, C., Pellegrino, S., Lappas, V. J., Bridges, C. P., Baker, J. Using CubeSat/micro-satellite technology to demonstrate the Autonomous Assembly of a Reconfigurable Space Telescope (AAReST). *Acta Astronautica*, **2015**, 114: 112–122.

[42] Simms, L. M. Space-based telescopes for actionable refinement of ephemeris pathfinder mission. *Optical Engineering*, **2012**, 51(1): 011004.

[43] Donath, T., Schildknecht, T., Martinot, V., Del Monte, L. Possible European systems for space situational awareness. *Acta Astronautica*, **2010**, 66(9–10): 1378–1387.

[44] Felicetti, L., Emami, M. R. A multi-spacecraft formation approach to space debris surveillance. *Acta Astronautica*, **2016**, 127: 491–504.

[45] Cowardin, H. M., Hostetler, J. M., Murray, J. I., Reyes, J. A., Cruz, C. L. Optical characterization of DebriSat fragments in support of orbital debris environmental models. *The Journal of the Astronautical Sciences*, **2021**, 68(4): 1186–1205.

[46] Ender, J., Leushacke, L., Brenner, A., Wilden, H. Radar techniques for space situational awareness. In: Proceedings of the 12th International Radar Symposium, **2011**: 21–26.

[47] Persico, A. R., Kirkland, P., Clemente, C., Soraghan, J. J., Vasile, M. CubeSat-based passive bistatic radar for space situational awareness: A feasibility study. *IEEE Transactions on Aerospace and Electronic Systems*, **2019**, 55(1): 476–485.

[48] Pasqualetto Cassinis, L., Fonod, R., Gill, E. Review of the robustness and applicability of monocular pose estimation systems for relative navigation with an uncooperative spacecraft. *Progress in Aerospace Sciences*, **2019**, 110: 100548.

[49] Davis, J., Pernicka, H. Proximity operations about and identification of non-cooperative resident space objects using stereo imaging. *Acta Astronautica*, **2019**, 155: 418–425.

[50] Pesce, V., Lavagna, M., Bevilacqua, R. Stereovision-based pose and inertia estimation of unknown and

uncooperative space objects. *Advances in Space Research*, **2017**, 59(1): 236–251.

[51] Opromolla, R., Fasano, G., Rufino, G., Grassi, M. Uncooperative pose estimation with a LIDAR-based system. *Acta Astronautica*, **2015**, 110: 287–297.

[52] Segal, S., Gurfil, P., Shahid, K. In-orbit tracking of resident space objects: A comparison of monocular and stereoscopic vision. *IEEE Transactions on Aerospace and Electronic Systems*, **2014**, 50(1): 676–688.

[53] Sharma, S., Ventura, J., D'Amico, S. Robust model-based monocular pose initialization for noncooperative spacecraft rendezvous. *Journal of Spacecraft and Rockets*, **2018**, 55(6): 1414–1429.

[54] Opromolla, R., Fasano, G., Rufino, G., Grassi, M. A review of cooperative and uncooperative spacecraft pose determination techniques for close-proximity operations. *Progress in Aerospace Sciences*, **2017**, 93: 53–72.

[55] Malan, D. F. 3D tracking between satellites using monocular computer vision. Master Thesis. University of Stellenbosch, **2005**.

[56] Song, J. Z., Cao, C. X. Pose self-measurement of noncooperative spacecraft based on solar panel triangle structure. *Journal of Robotics*, **2015**, 2015: 472461.

[57] Oumer, N. W., Kriegel, S., Ali, H., Reinartz, P. Appearance learning for 3D pose detection of a satellite at close-range. *ISPRS Journal of Photogrammetry and Remote Sensing*, **2017**, 125: 1–15.

[58] Dong, G. Q., Zhu, Z. H. Autonomous robotic capture of non-cooperative target by adaptive extended Kalman filter based visual servo. *Acta Astronautica*, **2016**, 122: 209–218.

[59] Lichter, M. D., Dubowsky, S. State, shape, and parameter estimation of space objects from range images. In: Proceedings of the IEEE International Conference on Robotics and Automation, **2004**: 2974–2979.

[60] He, Y., Liang, B., He, J., Li, S. Z. Non-cooperative spacecraft pose tracking based on point cloud feature. *Acta Astronautica*, **2017**, 139: 213–221.

[61] Shahid, K., Okouneva, G. Intelligent LIDAR scanning region selection for satellite pose estimation. *Computer Vision and Image Understanding*, **2007**, 107(3): 203–209.

[62] Woods, J. O., Christian, J. A. Lidar-based relative navigation with respect to non-cooperative objects. *Acta Astronautica*, **2016**, 126: 298–311.

[63] Pesce, V., Lavagna, M., Bevilacqua, R. Stereovision-based pose and inertia estimation of unknown and uncooperative space objects. *Advances in Space Research*, **2017**, 59(1): 236–251.

[64] D'Amico, S., Benn, M., Jørgensen, J. L. Pose estimation of an uncooperative spacecraft from actual space imagery. *International Journal of Space Science and Engineering*, **2014**, 2(2): 171.

[65] Sharma, S., Beierle, C., D'Amico, S. Pose estimation for non-cooperative spacecraft rendezvous using convolutional neural networks. In: Proceedings of the IEEE Aerospace Conference, **2018**.

[66] Eun, Y., Park, S. Y., Kim, G. N. Development of a hardware-in-the-loop testbed to demonstrate multiple spacecraft operations in proximity. *Acta Astronautica*, **2018**, 147: 48–58.

[67] Trentlage, C., Yang, J., Ben Larbi, M. K., de Alba Padilla, C. A., Stoll, E. The ELISSA laboratory: Free-floating satellites for space-related research. In: Proceedings of the Deutscher Luft- und Raumfahrtkongress, **2018**.

[68] DLR. European proximity operations simulator (EPOS 2.0). Available at https://www.dlr.de/en/research-and-transfer/research-infrastructure/european-proximity-operations-simulator-epos

[69] Somma, G. L., Bowman, P., Dayas, M., Walker, S., Reid, S., Brunskill, C. Reusing existing space infrastructure to identify and monitor resident space objects. In: Proceedings of the 8th European Conference on Space Debris, **2021**.

[70] Zhao, G. Y., Liu, L., Li, B., Li, Z. W., Sang, J. Z. An orbit determination approach to associating optical tracklets of space objects. *Acta Astronautica*, **2022**, 200: 506–523.

[71] Tommei, G., Milani, A., Rossi, A. Orbit determination of space debris: Admissible regions. *Celestial Mechanics and Dynamical Astronomy*, **2007**, 97(4): 289–304.

[72] Vallado, D. A., Griesbach, J. D. Simulating space surveillance networks. In: Proceedings of the AAS/AIAA Astrodynamics Specialist Conference, **2011**: AAS 11-580

[73] Liu, M. Y., Wang, H., Yi, H. W., Xue, Y. K., Wen, D. S., Wang, F., Shen, Y., Pan, Y. Space debris detection and positioning technology based on multiple star trackers. *Applied Sciences*, **2022**, 12(7): 3593.

[74] Feiteirinha, J. L. F., Kairiss, V., Reggestad, V., Flohrer, T., Maleville, L., Siminski, J., Maestroni, E. STR4SD - Exploring the concept of opportunistically using star-trackers for space debris observations. In: Proceedings of the 1st NEO and Debris Detection Conference, **2019**.

[75] ESA. Space debris projects and core activities. Available at https://www.esa.int/Space_Safety/Space_Debris_Projects_and_Core_Activities

[76] Gaias, G., Ardaens, J.-S., Schultz, C. The AVANTI experiment: Flight results. In: Proceedings of the 10th International ESA Conference on Guidance, Navigation

& Control Systems, **2017**.

[77] Ardaens, J. S., Gaias, G. Angles-only relative orbit determination in low earth orbit. *Advances in Space Research*, **2018**, 61(11): 2740–2760.

[78] Vallado, D. A., Cefola. P. Two-line element sets – Practice and use. In: Proceedings of the 63rd International Astronautical Congress, **2012**: IAC-12.C1.6.12.

[79] Vallado, D., Virgili, B. B., Flohrer, T. Improved SSA through orbit determination of two-line element sets. In: Proceedings of the 6th European Conference on Space Debris, **2013**.

[80] Curtis, H. D. *Orbital Mechanics for Engineering Students*, 3rd edn. Butterworth-Heinemann, **2013**.

[81] Bate, R. R., Mueller, D. D., White, J. E., Saylor, W. W. *Fundamentals of Astrodynamics*, 2nd edn. Dover Publications, **2020**.

[82] Gooding, R. A new procedure for orbit determination based on three lines of sight (angles only). Technical Report. Defence Research Agency Farnborough (United Kingdom), **1993**.

[83] Gooding, R. H. A new procedure for the solution of the classical problem of minimal orbit determination from three lines of sight. *Celestial Mechanics and Dynamical Astronomy*, **1996**, 66(4): 387–423.

[84] Miller, C. A., Frueh, C. A comprehensive comparison among classical and Gooding methods of initial orbit determination in optimized electro-optical sensor networks. In: Proceedings of the 8th European Conference on Space Debris, **2021**.

[85] Escobal, R. P. *Methods of Orbit Determination*. New York: Wiley, **1965**.

[86] Lei, X. X., Li, Z. W., Du, J. L., Chen, J. Y., Sang, J. Z., Liu, C. Z. Identification of uncatalogued LEO space objects by a ground-based EO array. *Advances in Space Research*, **2021**, 67(1): 350–359.

[87] Milani, A., Gronchi, G. F., Vitturi, M. D. M., Knežević, Z. Orbit determination with very short arcs. I admissible regions. *Celestial Mechanics and Dynamical Astronomy*, **2004**, 90(1): 57–85.

[88] DeMars, K. J., Jah, M. K. Probabilistic initial orbit determination using Gaussian mixture models. *Journal of Guidance, Control, and Dynamics*, **2013**, 36(5): 1324–1335.

[89] Hussein, I. I., Roscoe, C. W. T., Mercurio, M., Wilkins, M. P., Schumacher, P. W. Jr. Probabilistic admissible region for multihypothesis filter initialization. *Journal of Guidance, Control, and Dynamics*, **2018**, 41(3): 710–724.

[90] Ansalone, L., Curti, F. A genetic algorithm for Initial Orbit Determination from a too short arc optical observation. *Advances in Space Research*, **2013**, 52(3): 477–489.

[91] Sang, J., Lei, X., Zhang, P., Pan, T., Li, H. Orbital solutions to LEO-to-LEO angles-only very-short-arc tracks. In: Proceedings of the 7th European Conference on Space Debris, **2017**.

[92] Huang, J., Lei, X. X., Zhao, G. Y., Liu, L., Li, Z. W., Luo, H., Sang, J. Z. Short-arc association and orbit determination for new GEO objects with space-based optical surveillance. *Aerospace*, **2021**, 8(10): 298.

[93] Hill, K., Alfriend, K., Sabol, C. Covariance-based uncorrelated track association. In: Proceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit, **2008**: AIAA 2008-7211.

[94] Li, J., An, W., Zhou, Y. Y. Initial orbit determination and correlation of the uncatalogued targets with too short arcs in space-based optical surveillance. *Aerospace Science and Technology*, **2012**, 21(1): 41–46.

[95] Fujimoto, K., Scheeres, D. J. Applications of the admissible region to space-based observations. *Advances in Space Research*, **2013**, 52(4): 696–704.

[96] Fujimoto, K., Scheeres, D. J., Herzog, J., Schildknecht, T. Association of optical tracklets from a geosynchronous belt survey via the direct Bayesian admissible region approach. *Advances in Space Research*, **2014**, 53(2): 295–308.

[97] Siminski, J. A., Montenbruck, O., Fiedler, H., Schildknecht, T. Short-arc tracklet association for geostationary objects. *Advances in Space Research*, **2014**, 53(8): 1184–1194.

[98] Cai, H., Yang, Y., Gehly, S., Wu, S. Q., Zhang, K. F. Improved tracklet association for space objects using short-arc optical measurements. *Acta Astronautica*, **2018**, 151: 836–847.

[99] Lei, X. X., Wang, K. P., Zhang, P., Pan, T., Li, H. F., Sang, J. Z., He, D. L. A geometrical approach to association of space-based very short-arc LEO tracks. *Advances in Space Research*, **2018**, 62(3): 542–553.

[100] Sabol, C., Hill, K., Alfriend, K., Sukut, T. Nonlinear effects in the correlation of tracks and covariance propagation. *Acta Astronautica*, **2013**, 84: 69–80.

[101] Du, J. L., Chen, J. Y., Li, B., Sang, J. Z. Tentative design of SBSS constellations for LEO debris catalog maintenance. *Acta Astronautica*, **2019**, 155: 379–388.

[102] Du, J. L., Lei, X. X., Sang, J. Z. A space surveillance satellite for cataloging high-altitude small debris. *Acta Astronautica*, **2019**, 157: 268–275.

[103] Liu, L., Li, B., Chen, J. Y., Lei, X. X., Zhao, G. Y., Sang, J. Z. Applying Lambert problem to association of radar-measured orbit tracks of space objects. *Research in Astronomy and Astrophysics*, **2021**, 21(12): 301.

[104] Information on https://www.vyoma.space/ (cited 24 July 2023)

[105] Information on https://www.vyoma.space/constellation/ (cited 24 July 2023)

[106] Vallado, D., Crawford, P. SGP4 orbit determination. In: Proceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit, **2008**: AIAA 2008-6770.

[107] Dumitrescu, F., Ceachi, B., Truică, C. O., Trăscău, M., Florea, A. M. A novel deep learning-based relabeling architecture for space objects detection from partially annotated astronomical images. *Aerospace*, **2022**, 9(9): 520.

[108] Murray, J., Kennedy, T., Matney, M., Miller, R. Radar observations from the haystack ultrawideband satellite imaging radar in 2019. In: Proceedings of the 8th European Conference on Space Debris, **2021**.

[109] Information on https://leolabs-space.medium.com/the-iras-ggse-4-close-approach-a99de19c1ed9 (cited 22 July 2023)

[110] Wu, D., Rosengren, A. J. An investigation on space debris of unknown origin using proper elements and neural networks. *Celestial Mechanics and Dynamical Astronomy*, **2023**, 135(4): 44.

[111] Cropp, A. Pose estimation and relative orbit determination of a nearby target microsatellite using passive imagery. Doctoral Dissertation. University of Surrey, **2001**.

[112] Information on https://www.esa.int/Space_Safety/Space_Debris/FAQ_Frequently_asked_questions (cited 20 August 2023)

[113] Cope, E. Semi-analytic approach to rapid orbit determination for the perturbed two-body problem. Master Thesis. The Pennsylvania State University, **2023**. Available at https://etda.libraries.psu.edu/files/final_submissions/28962

[114] Clohessy, W. H., Wiltshire, R. S. Terminal guidance system for satellite rendezvous. *Journal of the Aerospace Sciences*, **1960**, 27(9): 653–658.

[115] Delpech, M., Berges, J. C., Djalal, S., Christy, J. Vision based rendezvous experiment performed during the prisma extended mission. **2012**. Available at https://issfd.org/ISSFD_2012/ISSFD23_FF2_3.pdf

[116] English, C., Okouneva, G., Saint-Cyr, P., Choudhuri, A., Luu, T. Real-time dynamic pose estimation systems in space: Lessons learned for system design and performance evaluation. *International Journal of Intelligent Control and Systems*, **2011**, 16(2): 79–96.

[117] Ma, Y., Ma, C., Xie, Y. H., Wang, F. Space target luminosity measurement based on video remote sensing satellites. *Acta Photonica Sinica*, **2019**, 48(12): 1228002.

[118] Guo, C. B., Xia, X. W., Si, C. M., Liu, P. L., Du, Y. A survey of relative position and attitude measurement for formation flying satellite. *Aerospace Control*, **2018**, 36(6): 83–89. (in Chinese)

[119] MIT Lincoln Lab. The annual report summarizes Lincoln laboratory. **2020**. Available at https://archive.ll.mit.edu/public-ations/index.html

[120] Gong, B. C., Ma, Y. Q., Zhang, W. F., Li, S., Li, X. Q. Deep-neural-network-based angles-only relative orbit determination for space non-cooperative target. *Acta Astronautica*, **2023**, 204: 552–567.

Niki Sajjad is a space engineer with her bachelor degree in electrical engineering/control systems from Isfahan University of Technology and her master degree in space engineering from K. N. Toosi University of Technology. She is currently pursuing a Ph.D. degree in space engineering, focusing on space debris monitoring, and is a visiting researcher at the University of Luxembourg. Since 2017, Niki has been a member of four different student satellite projects as an ADCS (Attitude Determination and Control System) and HIL (Hardware-in-the-Loop) engineer. She has won several awards with the recent ones being as IAF (International Astronautical Federation) Emerging Space Leaders Grant in 2022 and the Swiss Government Excellence Scholarship as a research fellow at EPFL for 2023/2024. Niki is highly motivated to work toward space and the Earth sustainability to serve humanity and pave the way for the next generations to become key players in the space sector.

Mehran Mirshams is an associate professor in the Space Engineering Department of the Faculty of Aerospace Engineering at K. N. Toosi University of Technology. He holds his Ph.D. degree in aerospace engineering with a specialization in space system engineering from Moscow Aviation Institute (MAI), his M.Sc. degree in aerospace engineering from the same university, and his B.Sc. degree in mechanical engineering from the Isfahan University of Technology. He has received notable recognition for his contributions to the field, earning the K. N. Toosi University of Technology Best Researcher Award in 2012, 2016, and 2019. Throughout his career, he has held key roles, including overseeing the space system engineering education plan at Iranian Universities and establishing the Space Research Laboratory, where he has served as its head at the Faculty of Aerospace Engineering since October 2005. He is deeply passionate about advancing space generation education and training. One of his notable achievements is the design, development, and establishment of the School's Space Laboratory in primary, middle, and high schools. Additionally, Mehran Mirshams has played a pivotal role as the Vice-President of Academic Affairs and the Director of International Educational Joint Programs. His dedication to advancing aerospace engineering education and research underscores his commitment to academic excellence and knowledge advancement on an international scale.

Andreas Makoto Hein is an associate professor of space systems engineering (SpaSys) at SnT, University of Luxembourg. Before SnT, he worked as a system architect at IRT-SystemX, designing autonomous transportation systems with Transdev. He was formerly a researcher at the Industrial Engineering Lab at CentraleSupélec—Université Paris-Saclay in the area of mobility, industrial ecology, and systems engineering. He obtained his bachelor and master degrees in aerospace engineering from the Technical University of Munich and conducted his Ph.D. research at the same university and the Massachusetts Institute of Technology. He has published over 70 articles in peer-reviewed international journals and conferences. He is the recipient of the Exemplary Systems Engineering Doctoral Dissertation Award and the Willy Messerschmitt Award.