DOI: 10.13009/EUCASS2023-016

Sustainable Space Hub at EPFL: a review of ongoing research projects

Stephan Hellmich[★,†], Mathieu Udriot[•], Xiao-Shan Yap[•], Emmanuelle David[•], Alexandre A. Looten[◇],
Mathieu Salzmann[∇], Guillaume Anciaux[∨], Mohamed Bouri[⊙]
[★] *EPFL Laboratory of Astrophysics*
[•] *EPFL Space Center (eSpace)*
[◇] *EPFL Laboratory for Processing of Advanced Composites*
[∇] *EPFL Computer Vision Laboratory*
[∨] *EPFL Computational Solid Mechanics Laboratory*
[⊙] *EPFL Biorobotics Laboratory*
Ecole Polytechnique Federale de Lausanne, 1015 Lausanne, Switzerland
stephan.hellmich@epfl.ch, mathieu.udriot@epfl.ch [†]Corresponding author

Abstract

EPFL Space Center (eSpace) is a pioneer in space sustainability. With the Clean Space Initiative, initially proposed to deorbit Swisscube which eventually spun off from EPFL as the ClearSpace-1 mission to recover a Vega Secondary Payload Adapter (Vespa) from orbit, the Center can draw on a decade of experience in space sustainability. More recently, in 2019 eSpace initiated a two-year pilot phase of a research initiative on sustainable space logistics (RISSL) which became the starting point of several consortium projects that attracted many stakeholders and resulted in the development of a space logistics modelling software for mission profile evaluation and optimization. The success of this pilot phase encouraged the Center to continue exploring this new domain. In 2021 EPFL was selected to host the Space Sustainability Rating (SSR), which incentivizes space operators to adopt more responsible mission design and operational behaviour. Because the definition of sustainability in space is constantly evolving, eSpace is continuously improving the formulation of the SSR in order to address emerging environmental, societal, and economic factors in the assessment. Current research and development projects cover the topics life cycle assessment of space transportation vehicles, assessing space debris risks, material research to optimize the reentry phase, optimisation of space logistics and mission design, physical characterization of orbital debris and developing policy options and interrelations with Earth system governance. These projects will help assess and improve the situation in space and mitigate the impact of space activities on Earth.

In order to unite EPFL's forces in the domain of sustainability in space, eSpace has recently introduced the Sustainable Space Hub (SSH). Five institutes within EPFL are currently involved in research and development projects in the field of space sustainability. The goal of the SSH is to coherently manage and foster the growth of these topics. The SSH is connecting these individual projects in a workflow that rests on three intertwined domains: *measure*, *understand*, and *act* for space sustainability. The projects associated with each domain are essential for finding solutions to the problems arising from the rapidly increasing space activities, the risk from space debris, and the generated atmospheric impacts. The SSH will help identify and promote new technologies in space sustainability with new services in orbit and on the ground. This paper presents the organisation of the new Sustainable Space Hub, and highlights ongoing research and development conducted in this domain. It discusses the three domains, shows how the development of the individual project benefits from the hub, and gives an outlook on future projects related to space sustainability at EPFL.

1. Introduction

Space around Earth has become a busy place. Since the launch of Sputnik in 1957, over 6,000 rockets have been successfully launched, carrying more than 15,000 satellites to Earth's orbit[1]. Today, there are about 10,300 satellites

---

[1] https://sdup.esoc.esa.int/discosweb/statistics/

DOI: 10.13009/EUCASS2023-016

in orbit, of which 7,700 are still functioning. Costs for development and launch have significantly decreased in recent years, which resulted in a steep increase of satellites in orbit. The left panel of Figure 1 shows that, compared to an almost constant rate of objects launched to orbit over the first five decades of space exploration, the rate increased by a factor of 20 during the last decade.

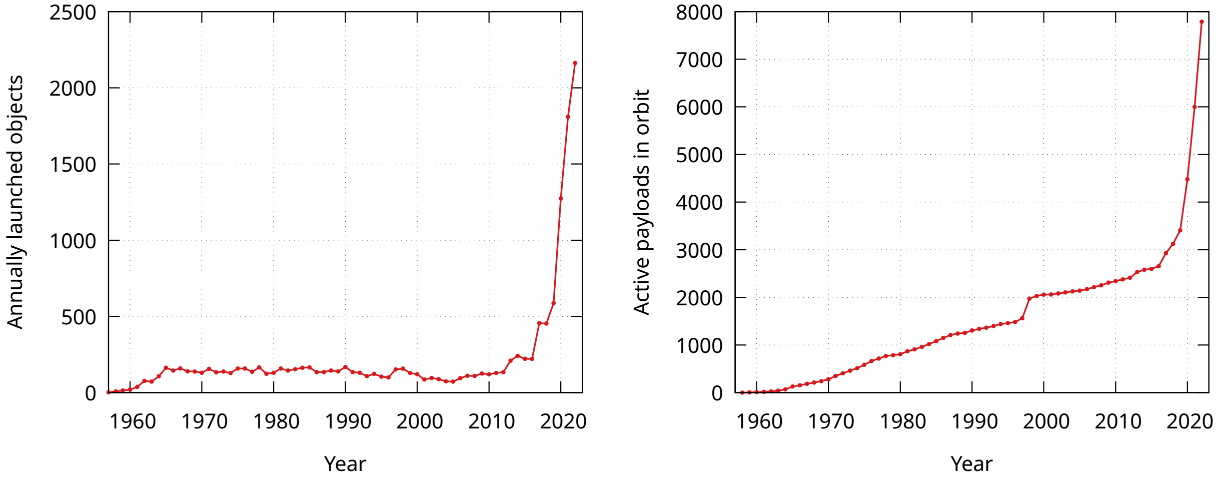

Figure 1: Left: Number of objects annually launched into orbit [2]. Right: Number of active satellites in orbit [3].

With every new satellite, numerous additional objects such as upper stages, payload adapters and smaller mission-related objects are left in orbit. Collisions and fragmentation events further result in a steep increase of space debris, leading to an expected number of one million particles larger than 1 cm currently orbiting Earth [4]. As a result, securing the active satellites is becoming more and more of a challenge. For example, the satellites in SpaceX's Starlink constellation had to perform more than 26,000 collision avoidance maneuvers between late 2020 and late 2022 [33](during that time, the constellation consisted of about 3,300 satellites). Detecting potential collisions requires an enormous amount of observation and computational effort. Space surveillance networks constantly monitor the entire population of space objects to predict close flybys and issue warnings to satellite operators. These activities are necessary not only to secure the active satellites, but also to prevent a collision cascade, known as the Kessler Syndrome [16], which would cause certain regions of the orbit to become completely inaccessible.

The ever-increasing number of objects launched into space and the lack of binding regulations for space sustainability have resulted in the risk of losing access to low Earth orbit (LEO) if we do not take immediate countermeasures. Simulations by ESA show that even if we stop launching any new objects into orbit, the number of particles will increase for centuries due just to the collisional evolution of the existing space objects [21]. This means that in order to secure the access to orbit, we do not only need to minimize the effect of new satellites sent to space, but also to perform Active Debris Removal (ADR) [3] [20].

In addition to these space-related issues, the impact of our rapidly growing space activities is becoming increasingly apparent in other areas as well. For example, the growing number of launches generates significant emissions during production and from the combustion [17], the latter whose effects on the atmosphere we are just beginning to understand [25]. Re-entering objects, like disposed satellites and launcher stages, demise in the atmosphere, releasing atoms and aerosols, the impacts of which are similarly unknown for now [26]. Furthermore, fragments that survive re-entry release toxic substances [22], endangering both humans and the environment [4].

Also scientific measurements are increasingly affected by space objects. Optical observations are more and more contaminated by tracks of satellites crossing the field of view, and intentional [27] and unintentional [6] signals from satellites are increasingly interfering with radio astronomy. Currently, the impact of satellites and space debris on astronomical observations from Earth [11] and Earth orbit [18] is not significant, but as the number of satellites grows and the sensitivity of next-generation telescopes increases, their impact on astronomical observations will cause serious problems [1].

The Sustainable Space Hub (SSH), has the objectives to increase awareness of the debris situation in near-Earth space, study environmental impacts, and develop tools to identify technology gaps and support sustainable mission design,

---

[2] https://www.unoosa.org/oosa/osoindex/search-ng.jspx/

[3] https://www.space-track.org/

[4] https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers

DOI: 10.13009/EUCASS2023-016

Sustainable
Space Hub

Figure 2: Logo of the Hub

addressing also sustainability challenges from the perspective of policies and governance. To better organize the individual projects and initiatives, we define within the hub three domains: *Measure* - to fill knowledge gaps about space objects and about the environmental implications of space exploration and exploitation, *Understand* - to analyze and quantify these environmental implications to identify the aspects with the greatest impact and *Act* - to provide support for Active Space Debris removal, tools that incorporate space sustainability as early as possible during mission design and guidelines for space policy making. These domains correspond to the stages of the individual projects on the way towards a more sustainable behavior in space. We will present in this article all EPFL activities related to sustainability in space, in order to give an overview of the expertise developed within the hub and a preview of how we envision to expand these activities, also taking into account future challenges.

2. EPFL activities to promote sustainability in space

2.1 Projects under the Active Debris Removal In Orbit Services (ADRIOS) framework

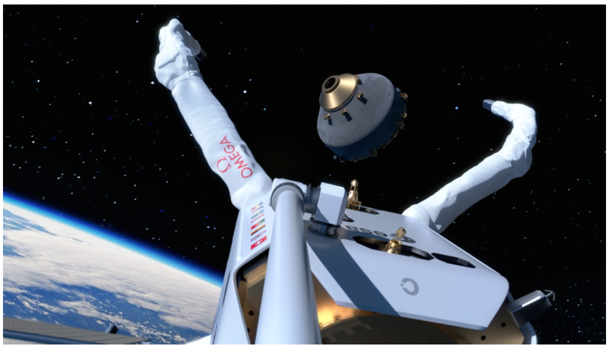

Figure 3: Artistic impression of ClearSpace-1 capturing Vespa. Courtesy and © Clearspace.

The ClearSpace-1 mission [2] represents an unprecedented attempt to capture a large debris and remove it from orbit. The targeted object is a Vega Secondary Payload Adapter (Vespa), an ESA-owned space object that has been orbiting Earth since 2013 in an approximately 800 km by 660 km altitude gradual disposal orbit. ClearSpace SA, the company behind the mission, emerged from an EPFL spin-off whose original plan was to deorbit Swisscube, the first Swiss satellite to be launched. Although ClearSpace is now an independent company spun off from EPFL, there is still close collaboration between the two institutions. To support the ClearSpace-1 mission, in 2021 eSpace started ADRIOS, a framework to coordinate ADR related activities that are performed by a consortium of EPFL Labs. The objective of ADRIOS is not only to help removing Vespa from orbit, but also to develop and demonstrate the entire value chain required for a sustainable and commercial ADR service and to set a precedent in the space industry. This initiative aims to build the capacity for a future commercial market for in-orbit services, and for institutional and private sector needs, placing its focus strongly on the hub's *act* domain.
As the prime contractor for the ClearSpace-1 mission, ClearSpace is responsible for systems engineering, flight and ground software development, management of ground and mission control infrastructure, as well as mission operations. The EPFL Laboratories for Computer Vision, Embedded Systems, Computational Solid Mechanics, Realistic Graphics as well as the Rehabilitation and Assistive Robotics Group of the Biorobotics Laboratory are forming the consortium for the ADRIOS framework to support ClearSpace with these responsibilities. Within the mission and system developments, EPFL is responsible for the capture system, relative navigation and also supports system engineering. eSpace acted as a central point of contact for the involved labs and suprevised the work of several engineers.

2.1.1 Capture System Technologies

In order to accurately model the forces that act on the ClearSpace-1 chaser during the capture process, a research group of the Computational Solid Mechanics Laboratory developed a novel dynamical simulator. Since the calculations need to be performed as quickly as possible, the biggest challenge in developing this simulator was its efficiency. The high computational demands of traditional finite elements make them unsuitable for the required long-term simulations,

DOI: 10.13009/EUCASS2023-016

while rigid body mechanics on the other end allow fast calculations but cannot take into account the deformation of the long arms of the chaser. Therefore, the developed numerical simulator was chosen to employ simplified models, where each arm is an assembly of three non-linear deformable segments that followed the Nonlinear Geometrically Exact Rod Model [35]. Furthermore, novel contact laws were designed to accurately model damped impacts on the materials elected. A highly optimized simulation prototype was provided, which is capable of handling multi-body dynamics between rigid and reduced-model-deformable objects, including contact and friction. The core engine of the simulator was published as open-source software, as agreed by the IP agreement.

Within a collaborative project with ClearSpace the research group REHAssist of the Laboratory of Biorobotics and the Laboratory of Translational Neural Engineering supported the development of the key technologies that are required to capture an uncooperative target in space. Therefore, the ClearSpace-1 chaser with its 4-fingers grasp to capture the target was entirely simulated in Gazebo [5], an open-source simulator provided by the Open-Source Robotic Foundation. For the simulation, the chaser is approximated by basic shapes, such as boxes and cylinders. Boxes were used to represent the overall shape of the chaser and the cylinders to visualize the joints. In order to be as realistic as possible, the simulated target was based on a CAD model of Vespa. The simulator accounts for the relative movement and dynamics of target/chaser, stresses within the capture system and the motion of the arms. The simulations were used to evaluate different control algorithms, considering various navigation and rendez-vous scenarios. As a result, the TRL for the proximity and contact sensing system as well as the tentacle control was increased from 2 to 4, reaching a robust adaptronic capture system design.

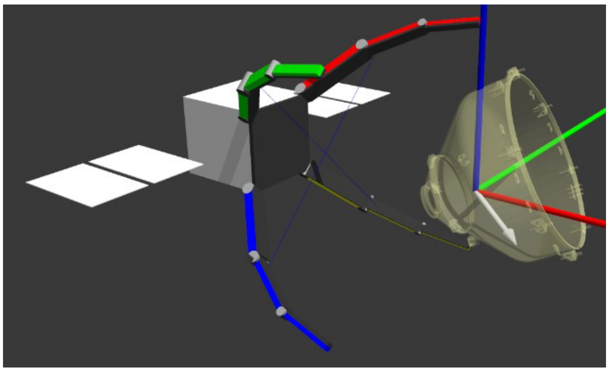

Figure 4: ClearSpace-1 with its 4-fingers grasp to capture space debris, simulated with Gazebo.

2.1.2 Relative Navigation Technologies

In the context of the ADRIOS project, the Computer Vision Lab (CVLab) developed image-based solutions to estimate the relative 3D position and 3D orientation, a.k.a. 6D pose, of the target w.r.t. the camera. This was achieved via a deep learning strategy aiming to predict the image locations of 3D keypoints representing the corners of the bounding box enclosing the target CAD model. In essence, such outputs can be thought of as 3D-to-2D correspondences, from which the 6D pose can be obtained using a traditional Perspective-n-Point algorithm. One of the main challenges that CVLab had to face in the context of space debris capture was the wide depth variations that occur across different views of the target. To address this, CVLab designed a deep neural network making predictions at different levels in the network structure, combining these predictions to improve robustness [15]. To train this model, the Realistic Graphics Lab (RGL) developed a simulation engine based on Mitsuba to create a render realistic scenes depicting the target debris, accounting for its material properties, as well as space-related phenomena such as the Earth albedo. This allowed CVLab to train their deep network on a large amount of synthetic images for which the ground-truth 6D pose can be obtained automatically. To further ensure that the resulting deep network would perform well on real images, CVLab developed a refinement procedure based on optical flow, which was observed to generalize well across different image domains [14].

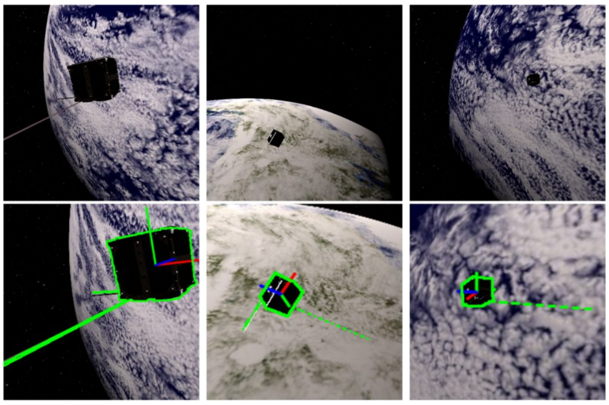

Figure 5: 6D pose estimation on simulated images of SwissCube.

---

[5] https://gazebosim.org/home

DOI: 10.13009/EUCASS2023-016

2.1.3 Embedded AI for Aerospatial Navigation

Led by EPFL's Embedded Systems Laboratory, a collaboration between the School of Business and Engineering Vaud (HEIG-VD), ClearSpace and the EPFL Embedded Systems, Computer Vision and Realistic Graphics laboratories supported ClearSpace in AI-based aerospatial navigation. In order to provide an efficient computing architecture for deep learning algorithms on field-programmable gate array (FPGA) platforms, an ultra-low power embedded System-on-a-Chip computing architecture was designed. Further, the deep learning algorithms needed to be optimized to maximise the use of this heterogeneous architecture, comprising a number of processors and custom-made accelerators on an FPGA. These efforts advanced the required AI-based technologies for relative navigation and rendezvous using radar technologies from TRL 3 to TRL 4. This first part of the project was financed by Innosuisse (Application no. 38398, IP-ICT).

Electronic devices operating in space are exposed to harsh conditions, which can spontaneously alter data stored in memories or registers, increasing the error rate in calculations. The Embedded Systems Laboratory has investigated the use of an ensemble approach to improve robustness against such errors in AI applications, particularly deep neural networks (DNNs). Although DNNs naturally present some degree of robustness against errors — which often can be seen as an additional source of input noise — the extreme environment in space requires additional protections at the algorithmic level. Therefore, a technique that breaks down a DNN into an ensemble of smaller DNNs was investigated [23]. By averaging the predictions of this ensemble of smaller DNNs, redundancy is increased and the robustness of the whole network is increased without increasing the total size of the model nor its number of arithmetic operations. The experiments in the context of the ADRIOS framework show that this approach increases the accuracy of the DNN for error rates of $\sim 10^{-5}$ and limiting the accuracy drop at higher error rates.

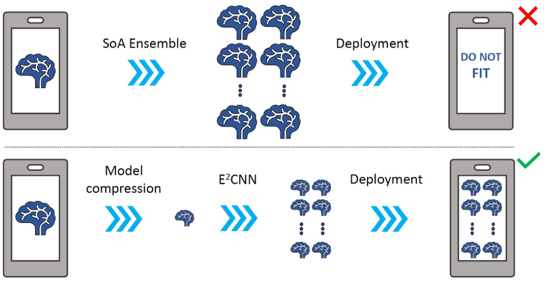

Figure 6: Traditional ensemble (top) compared to the E2CNNs architecture (bottom). In E2CNNs, the initial model is first compressed and then replicated several times to build up an ensemble that meets the same memory requirements of the original model.

2.2 Space debris physical characterization

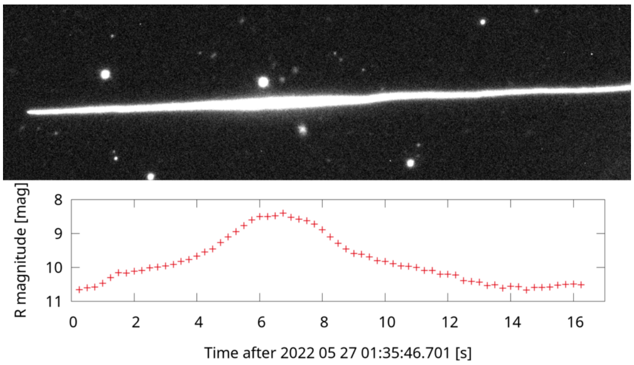

Figure 7: Satellite trail, detected on a ESO VST image and the lightcurve measured from the streak.

A better understanding of the current status of the space object population is essential for both sustainable mission planning and active space debris removal. Space Surveillance and Tracking (SST) networks provide information on the orbital distribution of the observable satellite and debris population but only very little is known about the physical characteristics such as spin rate and axis, and size and material properties of space debris. Compared to orbit determination, where only a few measurements per object and orbit are needed, physical characterization usually requires continuous observations of individual targets [36]. There are only a few stations that are currently preforming these kind of observations on a regular basis, such as the Zimmerwald Observatory in Switzerland [38] or the Geophysical Observatory in Slovakia [37]. However, there exist a lot of publicly available historical data from large telescopes that has never been looked at for space debris. Although these observations were not intended for physical characterization of space objects, they contain valuable information and offer a unique possibility to study the evolution of the debris population. Within a 4-year SNSF BRIDGE project [6], the EPFL Laboratory of Astrophysics (LASTRO) is developing new algorithms to effectively detect satellites and space debris in such large astronomical data archives. Highly advanced machine learning methods are required to scan the enormous amount of data (e.g. several 100 TB for the ESO VST archive) for the streak-like features that space objects leave on these images [24]. Retrieving the rotational and physical properties from the streaks requires sophisticated photometric data analysis methods [13]. Lightcurves (time series of

---

[6] https://data.snf.ch/grants/grant/194729

DOI: 10.13009/EUCASS2023-016

brightness measurements) are extracted from the intensity profiles of the streaks. These lightcurves can further be used to obtain information on the tumbling state, size and composition of the observed target. The analysis methods are designed to be easily adapted to process new data, so that the database can be regularly updated as new data is available. The goal of the project is to create a publicly available data base of space object physical properties, placing it in the *measure* and *understand* domains of the hub.

In order to perform follow-up observations and to complement the data found in the astronomical archives, eSpace and LASTRO are currently upgrading TELESTO, a 60cm telescope at the Geneva Observatory to make it usable for astrometric and photometric observations of space objects. The improvements include software updates that allow to track on satellites as well as hardware upgrades that will enable remote access to the telescope. After these improvements, TELESTO will acquire photometric measurements on a regular basis that contributes to the data base of space object physical properties.

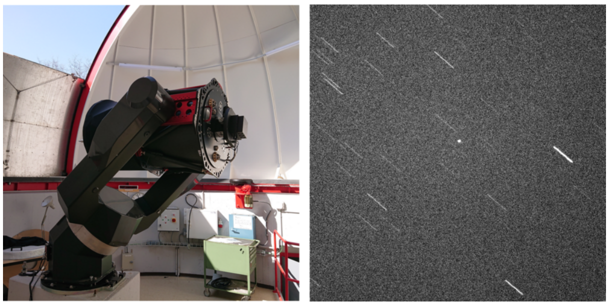

Figure 8: Telesto telescope at the Observatory of Geneva (left) and an image taken with Telesto of D-Orbit's space craft that hosts Bunny, an onboard computer developed by students of the EPFL Spacecraft Team.

Also the EPFL student association Space Situational Awarness (SSA) Team is working on novel techniques for satellite detection and physical characterization. They already have two optical telescopes and are currently designing their first ground station that will be permanently set up at the AstroVal observatory. The data acquired with these telescopes will be used to develop and test novel algorithms for object detection, orbit determination, collision probability calculations and physical characterization.

2.3 6D pose estimation of unseen objects

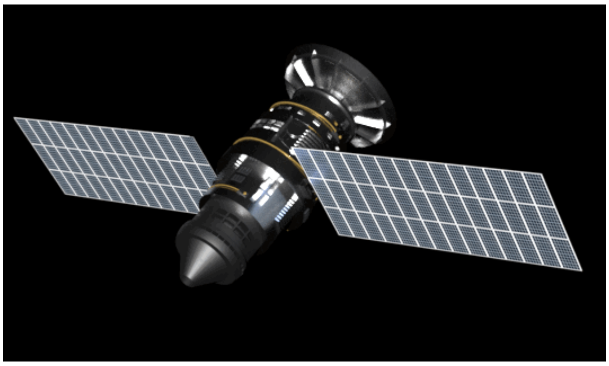

Figure 9: Synthetic image to train and validate neural networks for 6D pose estimation in space.

Within the same BRIDGE project and as a continuation of the work done to develop relative navigation technologies for ClearSpace-1 (section 2.1.2), CVLab is advancing the 6D pose estimation methods for a more general application in ADR. One limitation of the currently used methods is that they can only recognize objects of known shapes. However, because the shape and appearance of space debris may have been altered due to fragmentation or the long term influence of the space environment, the pose estimation technique must be capable of dealing with such previously unseen objects. This is achieved by preventing the neural network from learning object-specific features by computing multi-scale local similarities between the query image and synthetically-generated reference images [34]. Furthermore, despite being trained on synthetic data because of the lack of available real space images, the methods must be generalized to images acquired in space, that is, to a different image domain than the one they were trained for [31]. Finally, as the capture will proceed in an autonomous fashion, all computation must be performed on the spacecraft, which yields the additional challenge of working with limited resources. This opens the door to developing deep network compression and quantization strategies dedicated to the image-based 6D pose estimation task. Usually, neural networks for image processing techniques are trained and validated on annotated real data. However, in the case of 6D pose estimation in space, the amount of such data is very limited. Therefore, CVLab is currently creating a test and validation data set based on synthetic images of space objects. This data set will not only be used to train and evaluate the pose estimation networks developed at CVLab but also provide test set that can be used within the community of machine learning based image processing as a reference to compare future algorithms.

DOI: 10.13009/EUCASS2023-016

2.4 Space Sustainability Rating R&D

The Space Sustainability Rating (SSR) is a rating system with the mission to incentivize space actors to design and implement sustainable and responsible space missions for the long-term sustainability of the space environment. eSpace has been hosting the rating since 2021 and made it operational in 2022, issuing ratings to companies all around the world. It became an independent association in June 2023.
The current rating is made of 6 technical *modules*, each of them focusing on one aspect of the definition of space sustainability that is promoted (see figure 10. The "mission index" module computes a value for space debris risks based on the probability and severity (consequences) of a collision in orbit [19]. DIT stands for "detectability, identification, and trackability", COLA for "collision avoidance capabilities", and ADOS for "application of design and operation standards". The "data sharing" modules include incentives to increase transparency and share valuable data that can be beneficial to safety in orbit, and the "external services" module encourages operators to prepare for in-orbit services, such as active debris removal, which will be ready to operate in the coming years. All modules are detailed on the SSR website[7].

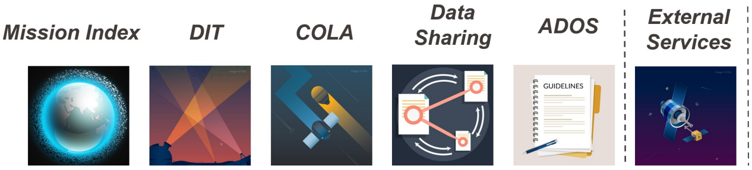

Figure 10: Current SSR modules.

As an independent but recognised association, SSR will continue to receive the support from eSpace for research and development projects to increase the scope of the rating, including with new modules and rating formulas. In particular, it can be seen that the current formula is focusing on the in-space impacts of a space mission (satellites or constellations, but mostly excluding the launch segment). Projects are ongoing to also account for the impacts of space missions on astronomical observations, and on the Earth ecosystem (including the atmosphere and the oceans). SSR spans all three domains of the SSH (figure 16), with a strong focus on *understanding* the aspects that are related to the sustainability of a space mission, but also including *measurements* that are needed to define the modules, and recommendations given to operators as an *action* for potential improvement.
Regarding **impacts on astronomical observations**, eSpace is collaborating with the Policy Hub of the International Astronomical Union Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS) for the creation of a "Dark and Quiet Skies" module (DQS), tackling impacts in both the visible and radio spectra. This development aims to answer the growing concern amongst scientists and astronomers that the exponential increase in satellites in LEO will significantly degrade the quality of images and data taken with telescopes, for example in South Africa, where the Square Kilometre Array (SKA) mid frequency observatory could be greatly affected by constellations emitting in the 5b band (around 10 GHz), directly adjacent to an observed and protected frequency band for radio astronomy[8].
Satellites and constellations can mitigate their impact on astronomy both during mission and spacecraft design and during operations. For the former, a special coating or visors to lower sunlight reflection have been tested [5, 29]. For the latter, attitude control is an option to avoid reflecting visible light towards the ground, especially during orbit raising. Transmissions towards observatories can be avoided by steering or stopping the telecommunication beam emitted by satellites while passing over protected (mostly empty) regions.
The Dark and Quiet Skies (DQS) module will consist of two components, addressing the impacts on both optical and radio astronomy. As with the other SSR modules, the DQS module will (i) assess the impact of a given mission that can be composed of one or several spacecrafts, and (ii) account for efforts from operators to mitigate their impact through design or operation of their satellites.
Assessing a mission's **impacts on the Earth environment**, such as effects on ozone depletion, or land and water contamination was an idea since the beginning of the SSR [9]. However, in order to focus on space debris risks, which had more visibility and traction, these and many more effects been left aside so far. In the past years, Life Cycle Assessment (LCA) has become a recognized method to capture the environmental impacts of a product over its whole life cycle. LCA can be performed as a first step towards ecodesign, an approach to reduce the environmental footprint

---

[7] https://spacesustainabilityrating.org/

[8] https://www.skao.int/en/news/198/skao-needs-corrective-measures-satellite-mega-constellation-operators-minimise-impact-its

[9] https://www3.weforum.org/docs/WEF_Space_Sustainability_Rating_2021.pdf

DOI: 10.13009/EUCASS2023-016

of a product over its entire lifecycle already in the design phase. The GreenSat studies, funded by ESA, published in 2019 [7,28], confirmed LCA is applicable to space systems and that the ecodesign approach can indeed be implemented in the space sector.

An ongoing project at eSpace is looking at how to include these impacts within the SSR formulation [8] so operators applying for a rating will also be incentivized to act on these aspects and trade-offs can be performed between mitigations of in-orbit impacts with environmental impacts on Earth.

Because LCA is multi-step and multi-criteria, accounting for the manifold environmental impact categories along the whole life cycle of a product or service, the challenges are to define how to normalize the score (from an impact unit to a value between 0 and 1) and to define a single score formula to group all normalized impact scores into a single value output that can be used with the scores of the other module (see figure 11.) Two unsuccessful attempts to define such formulas were made during the ESA CleanSpace Industry Days in 2017 and 2022.

To reach a consensus for a single score formula, Marnix et al. [8] have conducted a survey following the DELPHI method, with the participation of experts in environmental impacts of space systems from academia, industries (incl. spacecraft operators, manufacturers, launch complex operators, launch vehicle providers, etc.), and agencies.

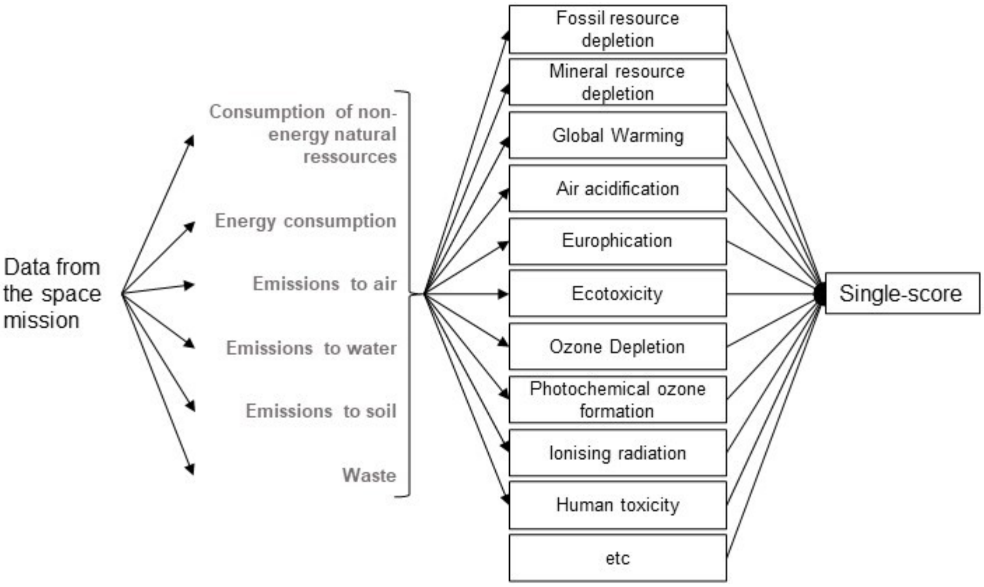

Figure 11: Process from inputs to a single score formula for the LCA module

In parallel, another project is investigating the creation of a new rating, specifically made to assess launch vehicles: A **Launch Vehicle Sustainability Rating** (LVSR). In the same mindset as the SSR, the goal will be to incentivize launch vehicle providers to implement sustainable design and operational decisions, to reduce environmental impacts and space debris risks.

Indeed it has been identified that the largest contributors to debris risks on-orbit are mission-related objects and rocket bodies generated by launch vehicles [21]. Passivating and deorbiting upper stages are thus critical actions to safeguard valuable orbits, since a number of these objects end up crossing crowded low Earth (LEO) and geostationary orbits (GEO), threatening numerous operating satellites. Scoring the footprint of space missions by issuing a rating to spacecraft operators which includes the launch segment is not effective because the operators have little to no influence on the design and operations of the launch vehicle(s). Of course they can have an effect when selecting the launchers, however, this step is mostly driven by availability, cost, and performance of the launch vehicle. Therefore, a different rating formula needs to be developed to issue ratings directly to the companies that provide the launch systems.

In its current form, the LVSR consistis of five modules [9]. The same "mission index" score, as used in SSR, outputs a value of space debris risks during the orbital phase of the mission. In the case of launchers, it was important to be able to model highly elliptical orbits which is now possible. Other modules include questions about the ascent trajectory (ground to space), the end-of-life, and data sharing and transparency. Depending on the outcome of the LCA module project, life cycle assessment could also be added to the rating's score, maybe with an adapted formula specific for launch vehicles.

A first LVSR formula is being tested with the help of voluntary launch vehicle providers to improve it with further development. The feedback has mentioned frequent questions about the rating process, similar to those faced by SSR at the beginning, which can be solved with better explanations and by writing of a user manual. But a recurring,

DOI: 10.13009/EUCASS2023-016

more technical question is about including a notion of efficiency for the score. Weighting the score by the launcher performance (kg of payload to a given orbit) has pros and cons: this information is useful when performing an LCA to describe the functional unit. Computing the impacts per kg of payload delivered is interesting to compare two systems with the same objectives, for example to perform design trade-offs. While the orbit type often affects the available mitigation strategies, for instance at end-of-life between a (controlled) reentry, and a graveyard orbit, in the case in which only the in-space mission phases are assessed, the payload mass should not become an excuse to allow a system to generate more impacts in space. It is proposed for now to issue a rating for each *type* of mission, for launchers that have different configurations to access different orbits, and mention the launcher class (between small, medium, heavy, and super-heavy-lift) as indication of the performance but without affecting the score. Once LCA is included, the normalisation used for computing a score of the module will change depending on the launch vehicle class.

The remaining open questions will be researched in the coming months, to make the LVSR ready for use.

2.5 Sustainable Space Logistics and Optimisation

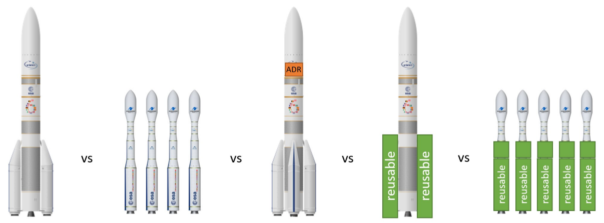

Figure 12: Example of different configurations that could be compared within ACT (if fulfilling the same functional unit).

For a few years, eSpace has been working on space logistics optimization, in particular with its **Technology Combination Analysis Tool** (TCAT), which was developed for ESA during the Sunrise and DAWN projects. The tool is able to simulate two types of scenarios, active debris removal missions and constellation deployments, using only high level inputs so it can be used early in the design phase to conduct feasibility studies and trade-offs [30]. The required inputs are parameters that roughly describe the launch vehicle, the constellation configuration, the in-space vehicles (kick-stage, ADR servicer), and the target orbits. Based on these specifications, TCAT determines the total fleet of vehicle(s) that is required, provides a plan with phases and manoeuvres for each of them, and provides a set of Key Performance Indicators (KPIs). The user can further define if the algorithm should optimise the mission for minimum propellant consumption (thus minimum cost by reducing the number of launches needed), or for minimum mission duration.

TCAT has been developed using object-oriented programming (OOP) so that it can easily be adapted to new scenarios such a missions towards the Moon or Lagrange points, include new vehicles with wider services (refilling, repairing, etc.) and the corresponding mission phases for these new scenarios.

Within the SSL thematic, eSpace is also leading a consortium working on the development of the **Assessment and Comparison Tool** (ACT), to automatize rapid quantitative analysis of the environmental impacts of different space transportation vehicles (STVs) and compare them. All models need to fulfill a functional unit (FU) on the format: "To place X tons of payload into orbit Y", with X and Y defined before the analysis. Only configurations fulfilling the same FU can be compared, even if their systems and architecture are different (figure 12).

The complete description of the tool, its capabilities, and prospective test cases assessed using it, are given in [10]. The tool is based on LCA principles as explained above, which spans over the three domains: in *measure* by making life cycle inventories to prepare the environmental study, in *understand* by the life cycle impact assessment (LCIA), and in *act*, because LCA results can be used as inputs to implement an ecodesign process to reduce the footprint and mitigate environmental hotspots. The LCA scope and system boundaries are limited by the current scientific knowledge, for instance regarding atmospheric impacts during the launch event or the reentry, or impacts in the oceans when objects are falling back down after their missions. The tool ACT can further be extended to include a LCA module in the LVSR (section 2.4), as indicated in figure 13.

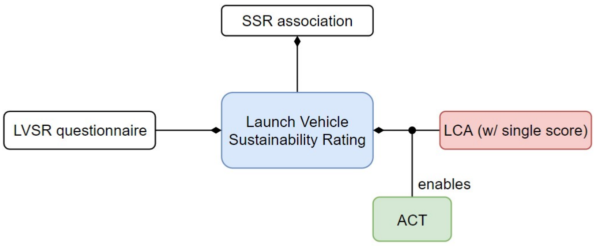

Figure 13: Diagram of three inter-related SSH projects (LCA, ACT, and LVSR) in support of the SSR association.

DOI: 10.13009/EUCASS2023-016

2.6 Composite Systems for Enhanced Spacecraft Demisability

Several mitigation aim to minimize the consequences of space operations and foster a safe and sustainable space environment. The current barriers to immediate actions are hindered by various knowledge uncertainties and technology gaps, especially for the design-for-demise (D4D) approach, which seeks to modify spacecraft design processes to enable the safest possible destructive reentry through material substitution, specific geometries, or dedicated subsystems. This approach takes place in the end-of-life management section of a space mission, placing it in the *act* domain of the hub.

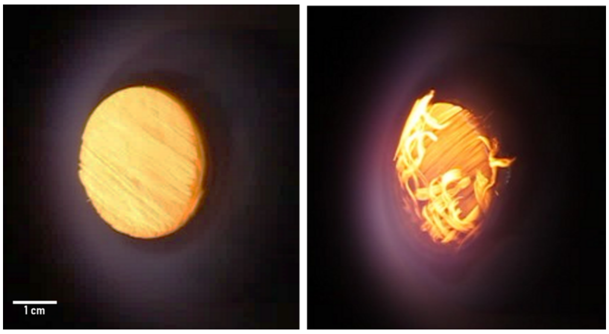

Figure 14: Plasma wind tunnel demise evaluation under relevant uncontrolled reentry conditions in the test facility at IRS. Demise state comparison after 30s exposure between critically resistant carbon (left) vs demisable carbon-flax hybrid (right) fiber reinforced polymer.

Within the framework of a collaborative European research group (NPI) launched by EPFL and the European Space Agency (ESA) with the support of institutional and industrial partners, the EPFL Laboratory for Processing of Advanced Composites (LPAC) focuses on the design and experimental assessment of innovative composite components with the objective of enhancing the overall spacecraft demisability upon typically critical uncontrolled reentry. The goal of the improvements is to achieve higher altitude break-ups in order to expose internal components as early as possible to the destructive environment. The demisability assessment is performed at material and lab scale component levels by static and dynamic reentry simulation tests, carried out using a laboratory-scale high-temperature creep test developed at EPFL and the plasma wind tunnel testing facility at the Institute of Space Systems (IRS) in Stuttgart, Germany.

The benchmark design for our research is composed of an external sandwich structure panel and its fasteners (through-thickness bolt system). The new systems are compared to baseline critical ones while maintaining equivalent mission-relevant properties. Hybrid reinforcement designs made of carbon and demisable flax fibers reinforcement have been evaluated (figure 14) to substitute aluminium or critical full-carbon composite panel skin. An optimal ply-by-ply version demonstrated promising earlier degradation, especially with the addition of aluminium-magnesium μpowder as matrix filler in addition to improving out-of-plane thermal conductivity. For the fastening system, a novel optimized short carbon fiber reinforced polyetheretherketone bolt has been studied to replace critical stainless steel or titanium alloys currently used. Such replacement allows complete and earlier joint separation by a lower melting temperature than baselines.

2.7 Pushing the frontier of space policy debate

The new project ‘Space sustainability: Policy options and interrelations with Earth system governance’ - funded by the Swiss State Secretariat for Education, Research & Innovation – also contributes significantly to the second SSH domain. The aim of the project is to broaden the framing of space sustainability by explicitly considering its interconnectedness with Earth-bound challenges and provide evidence-based insights for relevant policymaking, by engaging with the Space Sustainability Rating (SSR), OECD Space Forum and the International Telecommunication Union, among others. In collaboration with the International Risk Governance Center (IRGC) at EPFL, the project will focus on understanding consequences resulting from space activities in the following dimensions: (i) environmental implications on the Earth system and policy implications based on life-cycle assessment (LCA); (ii) orbital sustainability and incentive-based policy options offered by the SSR for long-term sustainability of critical satellite infrastructures; and (iii) socio-economic development in particular inequality.

It draws on qualitative and semi-quantitative analysis of primary and secondary data, as well as co-construction of problems and policy options with stakeholders. For example, the project team designed and conducted a scenarios exercise at the "Space capacity allocation for the sustainability of space activities” workshop at Politecnico di Milano (Italy) on 6-8 June 2023. Engaging with a diversity of experts including companies, engineers, policy practitioners, and scientific researchers, the project team jointly discussed with the participants three plausible futures of how the orbital environment would be governed by 2030. They furthermore co-identified potential implications of these scenarios on future earth-space sustainability and discussed policy options by the SSR. The analysis of this project leverages on scientific concepts in the field of earth system governance to derive policy recommendations aimed at environmental sustainability on a planetary scale and global equity.

DOI: 10.13009/EUCASS2023-016

2.8 Concurrent Engineering for sustainable space missions

Completely focused on the *act* domain, illustrated on figure 16, the concurrent engineering (CE) approach for early design studies of space missions or components takes advantage of tools and knowledge introduced above. In this context, *concurrent* refers to the design being conducted in parallel by a number of experts in a facilitated framework to answer customers' needs. Doing so, cooperation between the individual teams is improved and conflicting requirements of the various subsystems are identified and directly addressed by finding trade-offs and compromises. eSpace is continuously improving its concurrent design facility (CDF) both in terms of infrastructure and know-how. It is further used as an educational tool in the frame of a course to teach EPFL students the fundamentals of concurrent engineering for space missions and systems. Building on top of this groundwork, eSpace is offering the use of its CDF, with the facilitation by its trained systems engineers, as a service for partners to perform feasibility studies or early design trade-offs for their concepts. Studies can be mandated as a service by external partners or within EPFL, by labs, for projects or for education purposes.

Before starting the design cycle, a team of systems engineers and study facilitators make a preliminary analysis to define a starting point for the study, including listing the main top-level requirements and constraints for the mission and/or system to be designed. This team also brings together a group of technical experts relevant to the study, that will participate in the work sessions. Experts can be internal or external to the customer's entity. The customers that requested the CE study have a decisive role along the whole study, they also participate to the work sessions, and validate the outcomes. The work sessions start with a kick-off meeting during which systems engineers and the customers describe the rationale, context and scope of the study to the experts. The design then usually starts by looking at the concepts of operations, and high-level mission analysis. Once an architecture is chosen, and based on heritage and current knowledge, experts will iteratively design their subsystems in concurrence with the others. At each iteration, values for the driver parameters such as mass (dry and wet), power, link, etc. budgets will be updated. Due to the concurrent process, the new values are rapidly shared such that the teams designing the individual subsystems are always working with the most recent values. This leads to the margins for each parameter becoming smaller after each iteration as the individual components are better defined and finally results in a convergence of all parameters. Figure 15 illustrates this iterative process. The full CE process, including a preparation phase, CE work sessions, and a final report is explained on the eSpace CDF wiki[10].

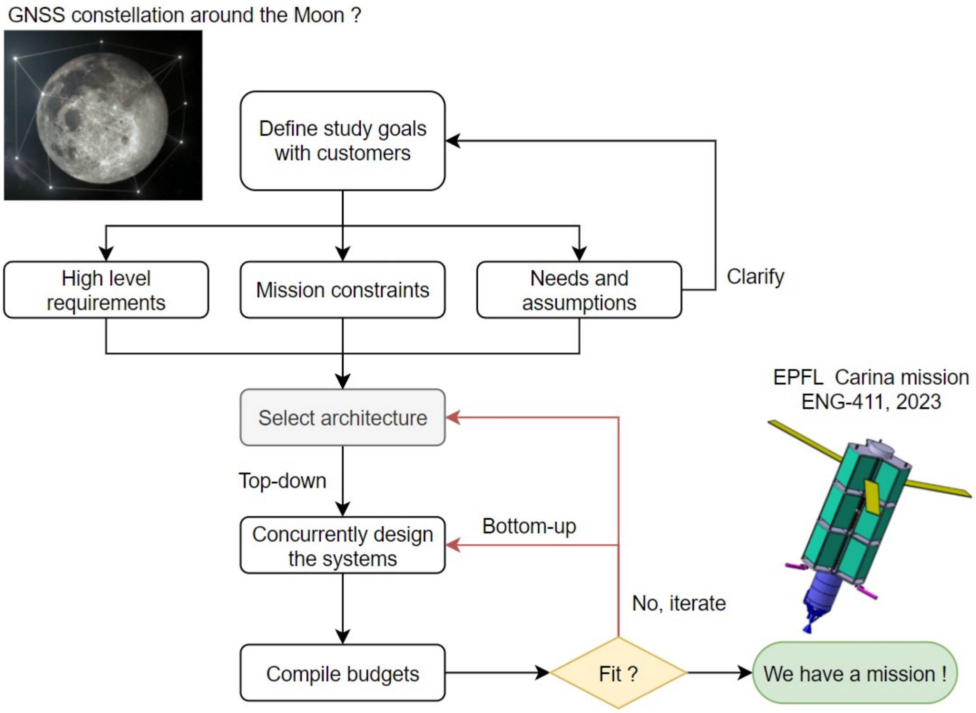

Figure 15: A typical concurrent engineering process, starting with top-down mass allocation, then bottom-up design, and verification before looping back to iterate. Exemplified with context and final results of a mission designed by students at EPFL.

---

[10] https://cdf.epfl.ch/en/concurrent_engineering

DOI: 10.13009/EUCASS2023-016

By including sustainability directly in the concurrent design facility, with tools such as ACT or TCAT (see above), or by inviting experts dedicated to the questions of the sustainability of the mission, eSpace aims at implementing a novel sustainable space concurrent design facility.

3. Conclusions and outlook

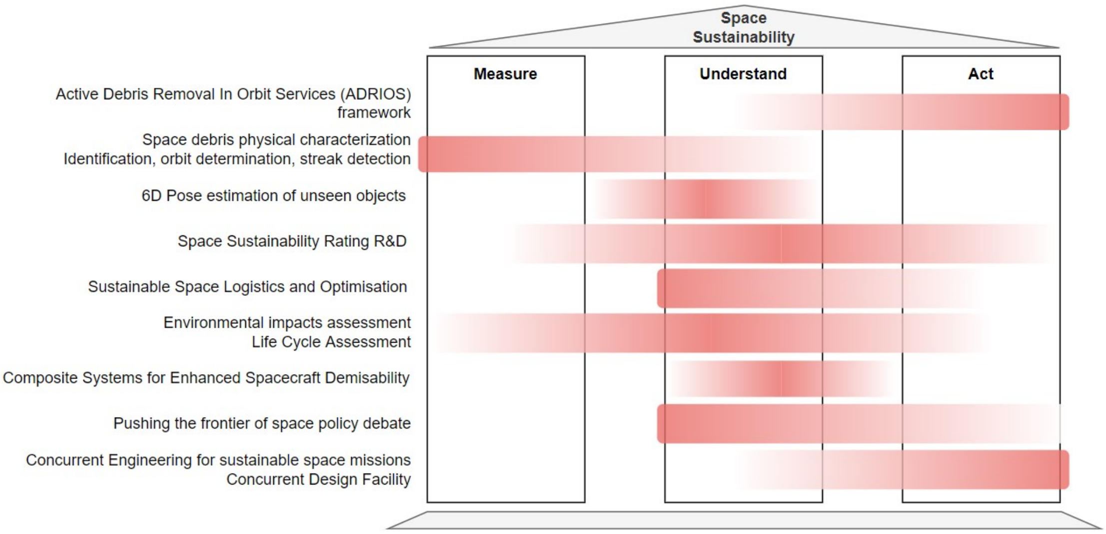

Figure 16: EPFL projects overlapped on the three SSH domains.

Figure 16 summarizes all presented EPFL activities related to sustainability in space. It can be seen that the projects are well distributed over the three domains of the hub. However, it is clear that the understanding of some critical aspects of how space systems impact the environment is still very limited. Another problem is the often limited access to basic research data, which is critical for assessing the situation and defining mitigation measures. Therefore, we intend to expand the scope of activities in the future to address remaining knowledge gaps and promote open data research practices within the orbital debris and space sustainability research community.

In order to achieve these objectives, LASTRO and eSpace, in cooperation also with the University of Bern and Hewlett Packard Enterprise submitted a proposal to a Multidisciplinary Applied Research Ventures in Space (MARVIS) call with the goal to create a database containing space objects observations and their physical properties. This database will be very valuable for the community of orbital debris research and provide important information for ADR. We will also extend our observation capabilities and explore the possibility of space based surveillance and tracking existing satellites and sensors in orbit. This will allow us to observe the population of small orbital debris that can not be observed with the currently available ground based SST infrastructure.

Further, as part of a consortium of European universities and space agencies, eSpace is applying for a Marie Skłodowska-Curie Actions (MSCA) doctoral network that will tackle the environmental impact of launchers, especially the impacts of high altitude atmospheric emissions during launch and reentry. The projects will focus on basic research and provide measurements that are required for modelling, and impact characterisation. In particular, EPFL's Laboratory for Processing of Advanced Composites will host a PhD to investigate the use of composite structures for Launchers and perform End-of-Life impact analysis of the fiber and matrix materials demise during the destructive re-entry in the atmosphere. In this way, we can identify potentially problematic components, especially for the upper atmosphere, and propose material combinations that meet the mechanical and structural requirements throughout the mission and, at the same time, minimize environmental impact. The results from these studies will provide important input for advancing SSL. This will be done in parallel to the next phase of the LPAC project on demisability (section 2.6) that will prioritize the identified innovative technologies' readiness level improvement through specific space qualification testing. Moreover, by developing a direct experiment-to-model approach, the uncertainties in modelling composite material demise can be effectively reduced. This multi-collaborative research aims to reduce current knowledge and technical gaps regarding composite materials' demise and implement these technologies on a typical spacecraft platform to move a step forward toward casualty risk mitigation.

The Assessment and Comparison Tool (ACT) (section 2.5), that will be extended to also consider new LCA aspects, will be adapted considering the outcomes of the above-mentioned studies. The foreseen extension of the tool will

DOI: 10.13009/EUCASS2023-016

improve the current modelling and prepare it to be used for future projects and for commercialization. As a first application of ACT, it is planned that it will become part of an ESA-funded concept study on the future family of European launch vehicles. The Technology Combination Analysis Tool (TCAT) currently optimises the mission based on design constraints for the vehicles. A development idea would be to add a new layer to the code that reversely optimises the design(s) of the vehicle(s) based on mission constraints. More efforts also need to be done to improve visual outputs and to add KPIs. A link should be made between the space debris models and the planning of mission, to include the former as a KPI in trade-offs.

In terms of space sustainability policies and interrelations with earth system governance, the SERI project above is just the beginning of an important research agenda. Building on early findings of the current project, future studies should start specifying conceptual and technical indicators for earth-space sustainability both in terms of environmental and social aspects. Having clear and more systematically derived indicators will allow better measurement of earth-space sustainability outcomes when assessing specific space activities. In addition, future studies should also better specify the trade-offs between Earth-bound and space-based sustainability challenges when assessing the effectiveness of different policies and governance.

The current activities within the hub mostly focus on the implications of space exploration and exploitation on Earth and in Earth's orbit. However, with regard to the current development, we will need to widen the scope to also account for the recently growing lunar [32] and eventually also martian [12] exploration plans.

In parallel to the research projects, labs and centers at EPFL also have the mission to contribute to education. In this respect, stakeholders of the hub are setting up space sustainability *task forces* for interdisciplinary student teams at EPFL. This will materialize with groups of semester and master projects in which students will use and adapt tools like the ACT (section 2.5) or the SSR, for their own projects (i.e. suborbital rockets, cubesats, rovers, etc.). They will be encouraged to use the three domains approach at their own level.

Other student projects will contribute to other ongoing research, for instance with the EPFL Space Situational Awareness (SSA) team, and help R&D efforts for the space Sustainability Rating (section 2.4).

Acknowledgements

The authors would like to thank all partners who helped in writing and reviewing the article, and the consortia members who took or take part in one of more of the projects mentioned in this review. In particular Véronique Michaud (LPAC), Muriel Richard (ClearSpace), Antonio Caiazzo (ESA) for the section on Alexandre Looten's thesis (section 2.6, which is supported by an ESA NPI #4000129740/20/NL/MH/hm in collaboration with Beyond Gravity, Icotec, Bcomp, Belstead Research LTD, IRS-Stuttgart and ClearSpace). We would also like to thank Stephanie Parker for proofreading the article.

References

[1] John C. Barentine, Aparna Venkatesan, and Jessica et al. Heim. Aggregate effects of proliferating low-Earth-orbit objects and implications for astronomical data lost in the noise. *Nature Astronomy*, 7(3), 2023. `doi:10.1038/s41550-023-01904-2`.

[2] Robin Biesbroek, Sarmad Aziz, and Andrew et al. Wolahan. The clearspace-1 mission: ESA and clearspace team up to remove debris. In *8th European Conference on Space Debris*, Darmstadt, 2021. ESA Space Debris Office. URL: `https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/320`.

[3] Christophe Bonnal, Jean-Marc Ruault, and Marie-Christine Desjean. Active debris removal: Recent progress and current trends. *Acta Astronautica*, 85, 2013. `doi:10.1016/j.actaastro.2012.11.009`.

[4] Michael Byers, Ewan Wright, Aaron Boley, and Cameron Byers. Unnecessary risks created by uncontrolled rocket reentries. *Nature Astronomy*, 6(9):1093–1097, 2022. `doi:10.1038/s41550-022-01718-8`.

[5] Richard E Cole. A sky brightness model for the starlink "visorsat" spacecraft. *Research Notes of the American Astronomical Society*, 4(10), 2020. `doi:10.3847/2515-5172/abc0e9`.

[6] F. Di Vruno, B. Winkel, and C. G. et al. Bassa. Unintended electromagnetic radiation from Starlink satellites detected with LOFAR between 110 and 188 MHz. *Astronomy & Astrophysics*, 2023. `doi:10.1051/0004-6361/202346374`.

[7] An Vercalsteren et al. Greensat – executive summary report (proba). Technical report, VITO - Vision on Technology, ESA, 2019. URL: `https://nebula.esa.int/sites/default/files/neb_study/2513/C4000121203ExS_0.pdf`.

[8] Marnix Verkammen et al. A consensus-based single-score for life cycle assessment of space missions: Preliminary results. In *10TH European Conference for Aeronautics and Space Sciences (EUCASS)*, Lausanne, Switzerland, 2023.

[9] Mathieu Udriot et al. Development of a launch vehicle sustainability rating. In *73rd International Astronautical Congress*, Paris, France, 2022. URL: https://iafastro.directory/iac/paper/id/71425/summary/.

[10] Mathieu Udriot et al. Rapid life cycle assessment software for future space transportation vehicles' design. In *10TH European Conference for Aeronautics and Space Sciences (EUCASS)*, Lausanne, Switzerland, 2023.

[11] Olivier R. Hainaut and Andrew P. Williams. Impact of satellite constellations on astronomical observations with ESO telescopes in the visible and infrared domains. *Astronomy & Astrophysics*, 636, 2020. doi:10.1051/0004-6361/202037501.

[12] Jennifer L Heldmann, Jennifer Heldmann, and Ali M et al. Bramson. Accelerating Martian and Lunar Science through SpaceX Starship Missions. Technical report, Planetary Science and Astrobiology Decadal Survey, 2021. URL: https://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/5489366/111-381503be1c5764e533d2e1e923e21477_HeldmannJenniferL.pdf.

[13] Stephan Hellmich, Elisabeth Rachith, Belén Yu Irureta-Goyena Chang, and Jean-Paul Kneib. Harvesting large astronomical data archives for space debris observations. *proceedings of the 2nd NEO and Debris Detection Conference*, 2023. URL: https://conference.sdo.esoc.esa.int/proceedings/neosst2/paper/98.

[14] Yinlin Hu, Pascal Fua, and Mathieu Salzmann. Perspective Flow Aggregation for Data-Limited 6D Object Pose Estimation. In *Computer Vision – ECCV 2022*, volume 13662. Springer Nature Switzerland, Cham, 2022. Series Title: Lecture Notes in Computer Science. doi:10.1007/978-3-031-20086-1_6.

[15] Yinlin Hu, Sebastien Speierer, Wenzel Jakob, Pascal Fua, and Mathieu Salzmann. Wide-Depth-Range 6D Object Pose Estimation in Space. In *2021 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, Nashville, TN, USA, 2021. IEEE. doi:10.1109/CVPR46437.2021.01561.

[16] Donald J. Kessler and Burton G. Cour-Palais. Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research: Space Physics*, 83(A6), 1978. doi:10.1038/d41586-023-00048-7.

[17] Ioannis W. Kokkinakis and Dimitris Drikakis. Atmospheric pollution from rockets. *Physics of Fluids*, 34(5), 2022. doi:10.1063/5.0090017.

[18] Sandor Kruk, Pablo García-Martín, and Marcel et al. Popescu. The impact of satellite trails on Hubble Space Telescope observations. *Nature Astronomy*, 2023. doi:10.1038/s41550-023-01903-3.

[19] Francesca Letizia, Stijn Lemmens, Benjamin Bastida Virgili, and Holger Krag. Application of a debris index for global evaluation of mitigation strategies. *Acta Astronautica*, 161, 2019. doi:10.1016/j.actaastro.2019.05.003.

[20] Darren McKnight, Rachel Witner, and Francesca et al. Letizia. Identifying the 50 statistically-most-concerning derelict objects in LEO. *Acta Astronautica*, 181, 2021. doi:10.1016/j.actaastro.2021.01.021.

[21] ESA Space Debris Office. Esa's annual space environment report, 2023. URL: https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf.

[22] Carmen Pardini and Luciano Anselmo. Uncontrolled re-entries of spacecraft and rocket bodies: A statistical overview over the last decade. *Journal of Space Safety Engineering*, 6(1), 2019. doi:10.1016/j.jsse.2019.02.001.

[23] F. Ponzina, M. Peón-Quirós, A. Burg, and D. Atienza. E2CNNs: ensembles of convolutional neural networks to improve robustness against memory errors in edge-computing devices. *IEEE Transactions on Computers*, 70(08), 2021. doi:10.1109/TC.2021.3061086.

[24] Elisabeth Rachith, Belen Yu Irureta-Goyena Chang, and Jean-Paul Kneib. Detection methods for a statistical analysis of the population of satellites and space debris from astronomical images. *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2022. URL: https://amostech.com/TechnicalPapers/2022/Poster/Rachith.pdf.

DOI: 10.13009/EUCASS2023-016

[25] Robert G. Ryan, Eloise A. Marais, Chloe J. Balhatchet, and Sebastian D. Eastham. Impact of Rocket Launch and Space Debris Air Pollutant Emissions on Stratospheric Ozone and Global Climate. *Earth's Future*, 10(6), 2022. doi:10.1029/2021EF002612.

[26] Leonard Schulz and Karl-Heinz Glassmeier. On the anthropogenic and natural injection of matter into Earth's atmosphere. *Advances in Space Research*, 67(3), 2021. doi:10.1016/j.asr.2020.10.036.

[27] Evan T Smith. *Impact of Radio Frequency Interference and Real-Time Spectral Kurtosis Mitigation*. PhD, West Virginia University Libraries, 2022. doi:10.33915/etd.11467.

[28] Nicolas Thiry, Pierre-Alexis Duvernois, and Bernard Charlot. Greensat – executive summary report (sentinel 3). Technical report, GreenSat Consortium, ESA, 2019. URL: https://nebula.esa.int/sites/default/files/neb_study/2506/C4000121203ExS.pdf.

[29] J. Tregloan-Reed, A. Otarola, and E. et al. Unda-Sanzana. Optical-to-NIR magnitude measurements of the Starlink LEO Darksat satellite and effectiveness of the darkening treatment. *Astronomy & Astrophysics*, 647, 2021. doi:10.1051/0004-6361/202039364.

[30] Mathieu Udriot, Anne-Marlène Rüede, Emmanuelle David, and Jean-Paul Kneib. Research initiative sustainable space logistics: an overview on the work performed at epfl from 2019 to 2021 in space logistics modelling and optimisation. *9th European Conference for Aeronautics and Space Sciences (EUCASS)*, 2022. doi:10.13009/EUCASS2022-6058.

[31] Vidit Vidit, Martin Engilberge, and Mathieu Salzmann. CLIP the Gap: A Single Domain Generalization Approach for Object Detection. In *IEEE/CVF conference on Computer Vision and Pattern Recognition*, 2023. URL: https://openaccess.thecvf.com/content/CVPR2023/papers/Vidit_CLIP_the_Gap_A_Single_Domain_Generalization_Approach_for_Object_CVPR_2023_paper.pdf.

[32] Alexandra Witze. LIFT OFF! ARTEMIS ROCKET LAUNCH KICKS OFF NEW ERA OF HUMAN MOON EXPLORATION. *Nature*, 2022. doi:10.1038/d41586-022-02310-w.

[33] Alexandra Witze. 2022 was a record year for space launches. *Nature*, 2023. doi:10.1038/d41586-022-02310-w.

[34] Chen Zhao, Yinlin Hu, and Mathieu Salzmann. Fusing Local Similarities for Retrieval-Based 3D Orientation Estimation of Unseen Objects. In *Computer Vision – ECCV 2022*, volume 13661. Springer Nature Switzerland, Cham, 2022. doi:10.1007/978-3-031-19769-7_7.

[35] O. C. Zienkiewicz, R. L. Taylor, and David Fox. Chapter 13 - A Nonlinear Geometrically Exact Rod Model. In *The Finite Element Method for Solid and Structural Mechanics (Seventh Edition)*. Butterworth-Heinemann, Oxford, seventh edition edition, 2014. doi:10.1016/B978-1-85617-634-7.00013-2.

[36] Jiří Šilha. Space Debris: Optical Measurements. In *Reviews in Frontiers of Modern Astrophysics: From Space Debris to Cosmology*. Springer International Publishing, Cham, 2020. doi:10.1007/978-3-030-38509-5_1.

[37] Jiří Šilha, Stanislav Krajčovič, and Matej et al. Zigo. Space debris observations with the Slovak AGO70 telescope: Astrometry and light curves. *Advances in Space Research*, 65(8), 2020. doi:10.1016/j.asr.2020.01.038.

[38] Jiří Šilha, Jean-Noël Pittet, Michal Hamara, and Thomas Schildknecht. Apparent rotation properties of space debris extracted from photometric measurements. *Advances in Space Research*, 61(3), 2018. doi:10.1016/j.asr.2017.10.048.