

Optimization and Automated Reasoning for Designing Future Space Missions

Max Bannach^{*1}, Johannes Klaus Fichte^{*2}, Dario Izzo^{*3},
Inês Lynce^{*4}, and Giacomo Acciarini^{†5}

1 ESA / ESTEC – Noordwijk, NL. max.bannach@esa.int

2 Linköping University, SE. johannes.fichte@liu.se

3 ESA / ESTEC – Noordwijk, NL. dario.izzo@esa.int

4 INESC-ID – Lisbon, PT. ines.lynce@tecnico.ulisboa.pt

5 University of Surrey – Guildford, GB. g.acciarini@surrey.ac.uk

Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 25362 *Optimization and Automated Reasoning for Designing Future Space Missions*, which explored fundamental optimization and reasoning tasks that arise in early stages of designing complex space missions. Such tasks include *selecting* and *scheduling* the bodies that should be encountered, *routing* a spacecraft across multiple bodies optimally, or strategically *placing facilities* to support future missions. Many of these problems are still solved by hand, as current missions only contain a few celestial objects. However, with larger and increasingly complex missions, these problems become more relevant and, thus, there is an increasing need to solve space-related optimization, scheduling, and planning problems automatically.

Despite the promising opportunities for collaboration, the entry barrier to many of these problems remains high for those without a background in celestial mechanics. Conversely, modern tools and techniques from constraint reasoning and optimization are still largely unfamiliar to many aerospace researchers. The Dagstuhl Seminar 25362 successfully established a bridge between computer scientists working in automated reasoning and experts from the space domain focused on mission analysis and operations. This Dagstuhl Seminar brought together researchers from academia, industry, and space agencies, fostering interdisciplinary dialogue. Problems and tools from both communities were presented in a language accessible to the other, laying the groundwork for future joint research and development.

Seminar August 31 – September 3, 2025 – <https://www.dagstuhl.de/25362>

2012 ACM Subject Classification Applied computing → Aerospace; Applied computing → Operations research; Astrodynamics; Computing methodologies → Artificial intelligence; Theory of computation → Automated reasoning; Theory of computation → Constraint and logic programming

Keywords and phrases Automated Reasoning, Satellite Constellation Design, Space Logistics, Trajectory Optimization, Astrodynamics, Global Trajectory Optimization

Digital Object Identifier 10.4230/DagRep.15.8.80

* Editor / Organizer

† Editorial Assistant / Collector



Except where otherwise noted, content of this report is licensed under a Creative Commons BY 4.0 International license

Optimization and Automated Reasoning for Designing Future Space Missions, *Dagstuhl Reports*, Vol. 15, Issue 8, pp. 80–94

Editors: Max Bannach, Johannes Klaus Fichte, Dario Izzo, Inês Lynce, and Giacomo Acciarini



Dagstuhl Reports

Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

1 Executive Summary

Max Bannach (ESA / ESTEC – Noordwijk, NL)

Johannes Klaus Fichte (Linköping University, SE)

Dario Izzo (ESA / ESTEC – Noordwijk, NL)

Inês Lynce (INESC-ID – Lisbon, PT)

License © Creative Commons BY 4.0 International license
© Max Bannach, Johannes Klaus Fichte, Dario Izzo, and Inês Lynce

Many tasks in early-stage mission design are still solved *manually*, as mission profiles tend to be small and subject to numerous constraints. However, the rise of the *new space* movement has significantly reduced mission costs and increased their frequency, creating a growing demand for *automation* in early design phases. This shift brings traditional computer science problems into focus, including *route planning* (e.g., traveling salesperson problems), *reliability analysis* (e.g., model counting), *scheduling* (e.g., graph coloring), and *facility location* (e.g., dominating set problems). As a result, automating mission design requires close collaboration between mission analysts and experts in automated reasoning. Yet, many of the modern tools developed in cost-optimal reasoning (e.g., maximum satisfiability), probabilistic reasoning (e.g., model counting), and constraint reasoning remain largely unfamiliar to the aerospace research community. Historically, this community has focused more on *local optimization*, e.g., computing optimal trajectories between celestial bodies, rather than on global optimization, like identifying optimal sequences across multiple targets. The goal of this Dagstuhl Seminar 25362 *Optimization and Automated Reasoning for Designing Future Space Missions* was to establish a bridge between these two communities to enable and activate future collaborations.

Computational Competitions

Early in the seminar, a shared passion quickly emerged as common ground between both communities: *computational competitions*. These are deeply rooted in the automated reasoning field, with flagship events such as the annual SAT competition [10] and the MAX-SAT evaluation [6]. Computer scientists showed strong interest in the efforts of mission analysts to establish similar competitions within the space domain, e.g., the bi-annual Global Trajectory Optimisation Competition (GTOC) [1] and ESA’s Space Optimization Competition (SPOC) [8]. Conversely, aerospace researchers were keen to learn from the SAT community’s long-standing experience in organizing such events, particularly in the development of standardized interfaces, file formats, validators, and benchmark sets.

Future Space Logistics

The vast majority of hypothetical space missions discussed during the seminar are from the *space logistics* domain. According to the AIAA Space Logistics Technical Committee, space logistics is “the theory and practice of driving space system design for operability and supportability, and of managing the flow of materiel, services, and information needed throughout a space system lifecycle” [3]. Yuri Shimane provided a detailed tutorial on the topic, highlighting in particular the rise of mega-constellations such as Starlink or OneWeb due to massively reduced launch costs. The design, construction, and maintenance of such structures involves various problems that can naturally be solved with tools from the constraint programming toolbox, which was presented to the participants of the seminar in a tutorial by Laurent Perron.

Routing Problems under Keplerian Dynamics

One of the actively discussed topics during the seminar was a variant of the traveling salesperson problem with moving targets, where the targets follow Keplerian dynamics [2, 4, 12]. This formulation naturally arises in applications such as in-space servicing [7], active debris removal [11], in-orbit refueling [13], and asteroid mining [5]. In contrast to these multi-rendezvous missions (the spacecraft must match position and velocity with the target), some versions only require flybys (matching only the position). A representative example discussed during the seminar was asteroid observation missions, for which Naoya Ozaki presented results on the design of flyby cycler trajectories – a promising approach for repeated asteroid visits. Participants explored how techniques like *dynamic discretization discovery* and *branch-and-price* could help to address the time-dependent nature of these problems. Additionally, discussions focused on the potential advantages of leveraging technologies such as MAX-SAT, given the highly dynamic and multi-objective characteristics inherent to these routing problems.

Orbital Facility Location Problems

Another actively discussed topic during the seminar was facility location problems in orbital environments [14]. A classical example involves placing fuel depots in orbit to support sustainable in-orbit refueling missions, where a servicing spacecraft retrieves propellant from a depot and delivers it to a client. Participants explored how such problems can be discretized to make them amenable to automated reasoning techniques. It turned out that in some cases, these problems can be treated as static – for instance, when servicing times significantly exceed orbital periods (e.g., weeks or months versus hours). However, when such assumptions cannot be made, the problem becomes highly dynamic and time-dependent, requiring more sophisticated modeling and solution approaches similar to the routing problems.

Scheduling and Packing Problems

Additional relevant problem domains were proposed during the seminar, including satellite, constellation, and fleet scheduling problems [9], as well as 3D packing problems under physical constraints such as the system's center of mass (e.g., for cargo vessel loading). While these challenges appear to be natural candidates for techniques from the constraint optimization community, they were not explored within the scope of this seminar due to lack of time.

Artificial Intelligence

The design and operation of in-space infrastructure involves constraints driven by the system's time-varying properties (e.g., transfer costs), which are often non-linear. Two approaches discussed during the seminar were: (1) *full discretization* through pre-computation, which is conceptually straightforward but computationally expensive; and (2) the use of *surrogate models*, typically neural-network-based approximators, which can be integrated into optimization frameworks. In discussions with industry experts such as Robert Luce, participants explored how such integrations could be realized and what kinds of interfaces commercial solvers should support to facilitate this interaction.

Verification and Validation of Neural Networks

Although not a central theme of the seminar, attention was drawn to the stringent safety and reliability standards that neural networks must meet to be certified for on-board use. The automated reasoning community, with its expertise in formal verification, offers promising tools to certify neural network reliability automatically. As a result, future collaborations in this domain were initiated.

Seminar Agenda

Given that this Dagstuhl Seminar brought together two distinct communities, each day began with two tutorial talks: one focused on a computer science topic and the other on a space-related topic. On the first day, Harry Holt presented a tutorial on the fundamental building blocks of (multi-)rendezvous missions, while Matti Järvisalo introduced the concept of maximum satisfiability. The second day featured the tutorials discussed in the previous section, and on the final day, Abdin Adam provided a compelling bridge between optimization techniques and space logistics.

To foster collaboration and interaction, the seminar contained a *problem session* on the first day. Zhong Zhang introduced the *Global Trajectory Optimization Competition*, while Giacomo Acciarini and Manuel López-Ibáñez presented various formulations of the *traveling salesperson problem under Keplerian dynamics*. Following this session, participants engaged in breakout groups to explore the proposed challenges in more depth. These sessions focused on three main topics: (1) the use of MAX-SAT and *dynamic discretization discovery* for solving time-dependent routing problems (chaired by Max Bannach), (2) the integration and support of *non-linear constraints in modern solvers* (chaired by Robert Luce), and (3) the computational aspects of a *future mission to the Saturn system*, including how a spacecraft might leverage its moons for gravitational braking (chaired by Laurent Beauregard).

Additionally, two sessions of *inspiring talks* were organized, giving young researchers the opportunity to share ideas from their current work and spark new discussions. Robyn Natherson spoke about challenges in *low-thrust trajectory design*, Chit Hong Yam addressed issues in *sustainable lunar logistics*, and Thorsten Ehlers presented on *trajectory optimization at DLR*. These space-focused insights were complemented by contributions from the computer science community: Anna Latour discussed *reasoning under uncertainty*, Alexandra Lassota analyzed *structural properties of integer programs*, and Stefan Szeider explored *synergies between language models and constraint reasoning*. As is tradition at Dagstuhl, some of the most engaging conversations took place during the Tuesday hike, which provided an informal yet productive setting for deeper interdisciplinary exchanges.

Future Work

As the primary objective of this seminar was to raise awareness of the tools and challenges developed within the computer science and space communities in recent years, much of the time was dedicated to presenting these resources rather than solving specific problems. A natural next step is a more solution-oriented workshop, focused on developing algorithms for concrete applications using techniques from the automated reasoning community. To facilitate this collaboration, participants expressed a clear desire for standardized interfaces, file formats, and benchmark sets.

Moreover, due to the limited duration of the seminar, many important topics could only be touched upon briefly or not at all. These include cargo packing, reliability analysis of constellations under uncertainty, sustainability aspects, applications to planetary defense, and satellite traffic management. These areas present promising directions for future interdisciplinary exploration.

References

- 1 Global Trajectory Optimisation Competition. https://sophia.estec.esa.int/gtoc_portal/, 2024. Accessed: 11.04.2024.
- 2 Adam Abdin. Strategic Management of On-Orbit Servicing: Leveraging Operations Research Methods for Enhanced Mission Planning and Scheduling. In *18th International Conference on Space Operations*, 2025.
- 3 AIAA Space Logistics Technical Committee. Definition of Space Logistics. <https://www.aiaa-sltc.org/>, 2024. Accessed: 06.09.2025.
- 4 Max Bannach, Giacomo Acciarini, and Dario Izzo. On the Keplerian TSP and VRP: Benchmarks and Encoding Techniques. In *International Astronautical Congress*, 2024.
- 5 A. Bellome, J.P. Sánchez, J.C. García Mateas, L. Felicetti, and S. Kemble. Modified Dynamic Programming for Asteroids Belt Exploration. *Acta Astronautica*, 215:142–155, 2024.
- 6 Jeremias Berg, Matti Järvisalo, Ruben Martins, Andreas Niskanen, and Tobias Paxian. MaxSAT Evaluation 2024: Solver and Benchmark Descriptions. 2024.
- 7 Alec J Cavaciuti, Joseph H Heying, and Joshua Davis. In-space Servicing, Assembly, and Manufacturing for the New Space Economy. *Aerospace Center for Space Policy and Strategy*, pages 2022–07, 2022.
- 8 ESA. SpOC. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Help_make_an_orbital_megastructure_with_genetic_computation, 2024. Accessed: 08.04.2024.
- 9 Benedetta Ferrari, Jean-François Cordeau, Maxence Delorme, Manuel Iori, and Roberto Orosei. Satellite Scheduling Problems: A Survey of Applications in Earth and Outer Space Observation. *Comput. Oper. Res.*, 173:106875, 2025.
- 10 Marijn JH Heule, Markus Iser, Matti Järvisalo, and Martin Suda. Proceedings of SAT Competition 2024: Solver, Benchmark and Proof Checker Descriptions. 2024.
- 11 Dario Izzo, Ingmar Getzner, Daniel Hennes, and Luís Felismino Simões. Evolving Solutions to TSP Variants for Active Space Debris Removal. In *Proceedings of the Genetic and Evolutionary Computation Conference, GECCO 2015, Madrid, Spain, July 11-15, 2015*, pages 1207–1214, 2015.
- 12 Manuel López-Ibáñez, Francisco Chicano, and Rodrigo Gil-Merino. The Asteroid Routing Problem: A Benchmark for Expensive Black-Box Permutation Optimization. In *International Conference on the Applications of Evolutionary Computation (Part of EvoStar)*, pages 124–140. Springer, 2022.
- 13 Daria Malyh, Sergey Vaulin, Victor Fedorov, Ruslan Peshkov, and Mikhail Shalashov. A Brief Review on in-orbit Refueling Projects and Critical Techniques. *Aerospace Systems*, 5(2):185–196, 2022.
- 14 Yuri Shimane, Nicholas Gollins, and Koki Ho. Orbital Facility Location Problem for Satellite Constellation Servicing Depots. *Journal of Spacecraft and Rockets*, 61(3):808–825, 2024.

2 Table of Contents

Executive Summary

<i>Max Bannach, Johannes Klaus Fichte, Dario Izzo, and Inês Lynce</i>	81
---	----

Overview of Talks

The Keplerian Traveling Salesperson Problem <i>Giacomo Acciarini</i>	86
Optimization in Future Space Logistics <i>Abdin Adam</i>	86
Trajectory Optimization at DLR <i>Thorsten Ehlers</i>	87
Tutorial Talk on Multi-Rendezvous Missions <i>Harry Holt</i>	87
Tutorial on Maximum Satisfiability <i>Matti Järvisalo</i>	87
What do we do with Integer Programs in Theory? <i>Alexandra Lassota</i>	88
Which Variables Matter? Structure-based Sensitivity Analysis for Reasoning Under Uncertainty <i>Anna Latour</i>	88
An Exact Framework for Solving the Space-Time Dependent TSP <i>Manuel López-Ibáñez</i>	89
The Asteroid Routing Problem: a Benchmark for Expensive Black-Box Permutation Optimization <i>Manuel López-Ibáñez</i>	89
Reachability-Informed Low-Thrust Trajectory Design: Progress and Challenges <i>Robyn Natherson</i>	90
Asteroid Flyby Cycler Trajectory Design Using Deep Neural Networks <i>Naoya Ozaki</i>	91
Tutorial Talk on CSP <i>Laurent Perron</i>	91
Tutorial Talk on Future Space Logistics <i>Yuri Shimane</i>	92
Neural Meets Symbolic: Synergies Between Language Models and Constraint Reasoning <i>Stefan Szeider</i>	92
Challenges of Sustainable Lunar Logistics <i>Chit Hong Yam</i>	92
Global Trajectory Optimization Competition (GTOC) – GTOC12 Asteroid Mining <i>Zhong Zhang</i>	93

Participants	94
-------------------------------	----

3 Overview of Talks

3.1 The Keplerian Traveling Salesperson Problem

Giacomo Acciarini (ESA / ESTEC – Noordwijk, NL)

License © Creative Commons BY 4.0 International license
© Giacomo Acciarini

Joint work of Max Bannach, Giacomo Acciarini, Dario Izzo

Main reference Max Bannach, Giacomo Acciarini, Dario Izzo: “On the Keplerian TSP and VRP: Benchmarks and Encoding Techniques”, International Astronautical Congress, Milan, 2024.

URL <https://openresearch.surrey.ac.uk/esploro/outputs/99927464502346>

This talk addresses a central challenge in space mission design and logistics: planning interplanetary trajectories for missions that must rendezvous with multiple bodies, such as in active debris removal, in-orbit servicing, or asteroid belt exploration. The problem is captured by the Keplerian Traveling Salesperson Problem (KTSP), an extension of the classical TSP that incorporates the orbital motion of targets. In contrast to the standard TSP, the KTSP features time-dependent and asymmetric transfer costs.

The talk presents a rigorous formalization of the KTSP together with a benchmark suite that includes globally optimal solutions, providing a basis for comparison with heuristic methods. A time-unfolding technique reformulates the continuous orbital dynamics as a discrete optimization problem in a time-expanded network, making the benchmark accessible to the discrete optimization community without prior expertise in celestial mechanics. An alternative formulation as an integer linear program is also introduced, using Interval-based Dynamic Discretization Discovery to capture the time-dependent structure of orbital transfers.

To enable practical comparisons and foster research in the field, exact methods are complemented with initial solution heuristics, improvement strategies, and preprocessing routines, and compared to heuristics like beam search and variants of the 2-opt algorithm. The overall framework demonstrates how complex multi-body rendezvous problems, ranging from asteroid exploration to on-orbit servicing and debris removal, can be systematically addressed within a rigorous optimization setting.

3.2 Optimization in Future Space Logistics

Abdin Adam (CentraleSupélec – Gif sur Yvette, FR)

License © Creative Commons BY 4.0 International license
© Abdin Adam

The continued expansion of space activities is giving rise to a new class of logistical challenges, where the effective management of orbital assets is critical to the resilience, adaptability, and sustainability of space infrastructure. Missions such as satellite refueling, repair, debris removal, and life-extension will increasingly rely on carefully optimized planning and coordination across multiple timescales. These missions introduce distinctive challenges in modeling, optimization, and decision-making, as they must reconcile resource limitations, orbital dynamics, operational feasibility, and uncertainty inherent to the space environment. Operations research (OR) provides a rigorous methodological basis for addressing such problems, combining mathematical modeling with analytical and computational techniques. We discuss OR frameworks relevant to space logistics and future space missions management, including deterministic optimization, stochastic programming, robust optimization, sequential decision-making, and associated decision analysis methods. We further illustrate how these approaches can be integrated with automated reasoning and intelligent algorithms to support mission planning across different temporal and operational scales.

References

- 1 Ho, K. (2024). Space logistics modeling and optimization: Review of the state of the art. *Journal of Spacecraft and Rockets*, 61(5), 1417–1427. American Institute of Aeronautics and Astronautics.
- 2 Abdin, A. (2025). Strategic Management of On-Orbit Servicing: Leveraging Operations Research Methods for Enhanced Mission Planning and Scheduling. In *Proceedings of the 18th International Conference on Space Operations*.
- 3 Bannach, M., Acciarini, G., & Izzo, D. (2024). On the Keplerian TSP and VRP: Benchmarks and Encoding Techniques. In *Proceedings of the International Astronautical Congress*.

3.3 Trajectory Optimization at DLR

Thorsten Ehlers (DLR – Hamburg, DE)

License © Creative Commons BY 4.0 International license
© Thorsten Ehlers

In this talk I will show some optimization problems that were solved in the institute for air transport at DLR. While the main focus of our institute is on the aerospace side, it is highly relevant for us to use the right optimization algorithms, e.g. in evaluating operational concepts for new aircraft.

3.4 Tutorial Talk on Multi-Rendezvous Missions

Harry Holt (ESA / ESTEC – Noordwijk, NL)

License © Creative Commons BY 4.0 International license
© Harry Holt

The objective of this talk was to introduce the field of multi-rendezvous/encounter missions in astrodynamics to a non-expert audience. After covering some of the building blocks in orbital mechanics, such as propagation, orbital elements and reference frames, we discussed the constraints imposed by different encounters and propulsion systems. Lambert’s problem was introduced for solving two-impulse transfers, and direct encodings were presented for deep-space manoeuvres, multi-impulse trajectories, low-thrust trajectories, and gravity assists. Finally, space-specific methods for solving the outer combinatorial part were presented, including pruning approaches and approximating the cost function.

3.5 Tutorial on Maximum Satisfiability

Matti Järvisalo (University of Helsinki, FI)

License © Creative Commons BY 4.0 International license
© Matti Järvisalo

Main reference Fahiem Bacchus, Matti Järvisalo, Ruben Martins: “Maximum Satisfiability”, pp. 929–991, IOS Press, 2021.

URL <http://dx.doi.org/10.3233/FAIA201008>

We provide a high-level overview of maximum satisfiability (MaxSAT), covering basics on encoding problems as MaxSAT, the algorithmic approaches implemented in modern MaxSAT solvers, and pointers to further recent developments in MaxSAT solving.

3.6 What do we do with Integer Programs in Theory?

Alexandra Lassota (TU Eindhoven, NL)

License  Creative Commons BY 4.0 International license
© Alexandra Lassota

This talk will give you a little snippet on the TCS side of integer programs: What are some of us actually doing? What are our challenges? What are our accomplishments?

3.7 Which Variables Matter? Structure-based Sensitivity Analysis for Reasoning Under Uncertainty

Anna Latour (TU Delft, NL)

License  Creative Commons BY 4.0 International license
© Anna Latour

Real-world problems typically contain a lot of structure that we can exploit to solve them fast in practice. For example: in many problems that reason about uncertainty, we can capture the problem in a decision diagram, and use that DD's structure to not only prune the search space of strategies, but also efficiently integrate over scenarios to evaluate the quality of a strategy.

For a satellite constellation for Earth observation design problem, we recently showed that we can improve upon the state of the art by framing the original problem as a computationally harder problem, but with an exponentially smaller encoding. Thanks to the speed of solvers for high-complexity problems in practice, we can make orders of magnitude improvement in the size of the problems that we can solve. This is all thanks to smartly leveraging the structure of the problem. We are currently working on how to apply this trick to different (and in some cases more realistic) variants of the problem.

The next step is to increase our capabilities of optimisation under uncertainty by applying structure-based approaches to sensitivity analysis. The classical approach to identifying how sensitive your decisions are to the exact value of certain input parameters relies on simulations. These are computationally expensive, might miss important sensitivities due to their probabilistic nature (and hence provide statistical guarantees at best), and can typically only handle one parameter at a time.

I propose a new method that is based on the logical structure of the problem, instead. Advantages include that you get the interaction of variables for free and that you get access to formal verification technology.

3.8 An Exact Framework for Solving the Space-Time Dependent TSP

Manuel López-Ibáñez (University of Manchester, GB)

License © Creative Commons BY 4.0 International license
© Manuel López-Ibáñez

Main reference Isaac Rudich, Quentin Cappart, Manuel López-Ibáñez, Michael Römer, Louis-Martin Rousseau: “An Exact Framework for Solving the Space-Time Dependent TSP”, 2024

URL <https://doi.org/10.48550/arXiv.2312.01404>

Many real-world scenarios involve solving bi-level optimization problems in which there is an outer discrete optimization problem, and an inner problem involving expensive or black-box computation. This arises in space-time dependent variants of the Traveling Salesman Problem, such as when planning space missions that visit multiple astronomical objects. Planning these missions presents significant challenges due to the constant relative motion of the objects involved. There is an outer combinatorial problem of finding the optimal order to visit the objects and an inner optimization problem that requires finding the optimal departure time and trajectory to travel between each pair of objects. The constant motion of the objects complicates the inner problem, making it computationally expensive. This paper introduces a novel framework utilizing decision diagrams (DDs) and a DD-based branch-and-bound technique, Peel-and-Bound, to achieve exact solutions for such bi-level optimization problems, assuming sufficient inner problem optimizer quality. The framework leverages problem-specific knowledge to expedite search processes and minimize the number of expensive evaluations required. As a case study, we apply this framework to the Asteroid Routing Problem (ARP), a benchmark problem in global trajectory optimization. Experimental results demonstrate the framework’s scalability and ability to generate robust heuristic solutions for ARP instances. Many of these solutions are exact, contingent on the assumed quality of the inner problem’s optimizer.

3.9 The Asteroid Routing Problem: a Benchmark for Expensive Black-Box Permutation Optimization

Manuel López-Ibáñez (University of Manchester, GB)

License © Creative Commons BY 4.0 International license
© Manuel López-Ibáñez

Main reference Manuel López-Ibáñez, Francisco Chicano, Rodrigo Gil-Merino: “The Asteroid Routing Problem: A Benchmark for Expensive Black-Box Permutation Optimization”, in Proc. of the Applications of Evolutionary Computation, pp. 124–140, Springer International Publishing, 2022.

URL https://doi.org/10.1007/978-3-031-02462-7_9

Inspired by the recent 11th Global Trajectory Optimisation Competition, this paper presents the asteroid routing problem (ARP) as a realistic benchmark of algorithms for expensive bound-constrained black-box optimization in permutation space. Given a set of asteroids’ orbits and a departure epoch, the goal of the ARP is to find the optimal sequence for visiting the asteroids, starting from Earth’s orbit, in order to minimize both the cost, measured as the sum of the magnitude of velocity changes required to complete the trip, and the time, measured as the time elapsed from the departure epoch until visiting the last asteroid. We provide open-source code for generating instances of arbitrary sizes and evaluating solutions to the problem. As a preliminary analysis, we compare the results of two methods for expensive black-box optimization in permutation spaces, namely, Combinatorial Efficient Global Optimization (CEGO), a Bayesian optimizer based on Gaussian processes,

and Unbalanced Mallows Model (UMM), an estimation-of-distribution algorithm based on probabilistic Mallows models. We investigate the best permutation representation for each algorithm, either rank-based or order-based. Moreover, we analyze the effect of providing a good initial solution, generated by a greedy nearest neighbor heuristic, on the performance of the algorithms. The results suggest directions for improvements in the algorithms being compared.

3.10 Reachability-Informed Low-Thrust Trajectory Design: Progress and Challenges

Robyn Natherson (University of Colorado Boulder, US)

License  Creative Commons BY 4.0 International license
© Robyn Natherson

Joint work of Robyn Natherson, Daniel J Scheeres

Main reference Robyn Natherson, Daniel J Scheeres: “Reachability-informed missed thrust design”. In AAS/AIAA Astrodynamics Specialist Conference, number AAS 25-609, 2025.

URL https://www.researchgate.net/publication/395012227_Reachability-Informed_Missed_Thrust_Design_AAS_25-609

Low-thrust propulsion enables deep space exploration at a fraction of the fuel cost. However, these systems require significantly longer thrust arcs compared to those with conventional chemical propulsion systems. Burn durations can span days, weeks, or even months. The extended thrusting periods of low-thrust systems increase the likelihood that a spacecraft anomaly will overlap with a planned burn, causing the spacecraft to deviate from its nominal trajectory. This is referred to as the missed thrust problem. Without robust trajectory design, losses from missed thrust jeopardize mission objectives, especially when flight paths include encounters with celestial bodies.

My doctoral research focuses on how to leverage reachability results to design robust transfers accounting for missed thrust. Reachability results can be formulated in two ways, forwards and backwards. My work specifically utilizes backwards reachable sets, or controllable sets. Controllable sets characterize the region of full-state initial conditions which can reach a target within a finite time. Typically, designing for missed thrust involves an iterative process where candidate transfers are tested for robustness and updated until design constraints are satisfied. However, applying reachability theory to study the missed thrust problem would allow the entire solution space to be studied at once, avoiding this tedious process. I will discuss the use of a reachability framework to compute a robustness metric, the missed thrust recovery margin (MTRM). The MTRM is the amount of time a spacecraft can coast away from a nominal trajectory before the target becomes inaccessible. By sampling points on a controllable set, we map the robustness of regions in phase-space visualized with a heatmap. The goal is to leverage this reachability information to design flight paths through regions that have inherently high MTRM.

Challenges associated with this research include:

- Reachability computation – efficiency, accuracy, and sampling of full-state sets
- Representing reachability point-cloud data in a usable form – especially for non-convex reachability results
- Testing inside/outside of a controllable or reachable set
- Visualization of 4D or 6D full-state reachability data

Due to the missed thrust problem, robust design strategies are integral for promoting mission assurance for flight projects employing low-thrust systems. Our novel reachability-informed trajectory design approach has the potential to change how to view the missed thrust problem.

3.11 Asteroid Flyby Cyclers Trajectory Design Using Deep Neural Networks

Naoya Ozaki (JAXA – Sagami-hara, JP)

License  Creative Commons BY 4.0 International license
© Naoya Ozaki

Asteroid exploration has been attracting more attention in recent years. Nevertheless, we have just visited tens of asteroids while we have discovered more than one million bodies. As our current observation and knowledge should be biased, it is essential to explore multiple asteroids directly to better understand the remains of planetary building materials. One of the mission design solutions is utilizing asteroid flyby cyclers trajectories with multiple Earth gravity assists.

An asteroid flyby cycler trajectory design problem is a subclass of global trajectory optimization problems with multiple flybys, involving a trajectory optimization problem for a given flyby sequence and a combinatorial optimization problem to decide the sequence of the flybys. As the number of flyby bodies grows, the computation time of this optimization problem expands maliciously.

This paper presents a new method to design asteroid flyby cyclers trajectories utilizing a surrogate model constructed by deep neural networks approximating trajectory optimization results. Since one of the bottlenecks of machine learning approaches is the computation time to generate massive trajectory databases, we propose an efficient database generation strategy by introducing pseudo-asteroids satisfying the Karush-Kuhn-Tucker conditions.

The numerical result applied to JAXA's DESTINY+ mission shows that the proposed method is practically applicable to space mission design and can significantly reduce the computational time for searching asteroid flyby sequences.

3.12 Tutorial Talk on CSP

Laurent Perron (Google – Paris, FR)

License  Creative Commons BY 4.0 International license
© Laurent Perron

We present OR-Tools, the suite of Operations Research tools build at Google and exported to github.

We give a more detailed overview of the CP-SAT solver, an award winning hybrid solver using MaxSAT, CP, MIP, and Meta-Heuristics techniques.

3.13 Tutorial Talk on Future Space Logistics

Yuri Shimane (Georgia Institute of Technology, US)

License © Creative Commons BY 4.0 International license
© Yuri Shimane

Main reference Yuri Shimane, Kento Tomita, Koki Ho: “Cislunar Space Situational Awareness Constellation Design and Planning with Facility Location Problem”, *Journal of Spacecraft and Rockets*, Vol. 62(6), pp. 1938–1960, 2025.

URL <http://dx.doi.org/10.2514/1.A36361>

Space Logistics, which studies the design, operation, and maintenance of in-space infrastructures, requires reconciling combinatorial aspects of the problem with the underlying orbital mechanics. In this light, we begin by exploring the history of Space Logistics, from the Space Shuttle era to the present decade. We then explore two space-based applications of the facility location problem (FLP) in closer detail. The first example is for the placement of in-orbit servicing depots and their allocation to GNSS constellations. In this example, due to the periodicity of the depots’ candidate orbits and the difference in time scale between the servicing allocation and the orbital periods, we assume a time-independent formulation. In contrast, the second example studying the placement and sensor-tasking of a cislunar space situational awareness constellation is time-dependent, requiring a time-expanded FLP. To tackle the problem size growth with the inclusion of discretized time, we develop a Lagrangian relaxation scheme that features an analytical relaxed solution, customized heuristics for the feasible solution, and that scales linearly with the number of time-steps. We conclude by looking towards the future – areas such as coordinated space traffic management, data logistics, and planetary defense, present exciting research avenues with real-life implications for the space economy.

3.14 Neural Meets Symbolic: Synergies Between Language Models and Constraint Reasoning

Stefan Szeider (TU Wien, AT)

License © Creative Commons BY 4.0 International license
© Stefan Szeider

Integrating Large Language Models (LLMs) with traditional solving techniques creates new synergies in automated reasoning. This talk explores both (i) how LLMs can enhance SAT and constraint solving through structural analysis and search guidance and (ii) how formal reasoning can help LLMs tackle hard reasoning and optimization problems. We will present case studies exploring the practical advances and future potential of combining neural and symbolic approaches in computational reasoning.

3.15 Challenges of Sustainable Lunar Logistics

Chit Hong Yam (ispace – Tokyo, JP)

License © Creative Commons BY 4.0 International license
© Chit Hong Yam

Future lunar exploration will depend on building a sustainable logistics framework that connects data, mission components, and technologies into a coherent system. Yet critical uncertainties remain: how much and what type of lunar data is sufficient for planning? How

should interdependent mission elements – landers, habitats, power systems, and resource utilization – be prioritized? And who will coordinate logistics standards across multiple players? This talk highlights the challenges and trade-offs of sustainable lunar logistics, emphasizing the tension between incomplete knowledge and long-term commitments. Rather than presenting solutions, it frames the open questions that must be addressed before a truly sustainable lunar supply chain can emerge.

3.16 Global Trajectory Optimization Competition (GTOC) – GTOC12 Asteroid Mining

Zhong Zhang (Tsinghua University – Beijing, CN)

License © Creative Commons BY 4.0 International license

© Zhong Zhang

Main reference Zhong Zhang, Nan Zhang, Xiang Guo, Di Wu, Xuan Xie, Jia Yang, Fanghua Jiang, Hexi Baoyin: “Sustainable Asteroid Mining: On the design of GTOC12 problem and summary of results”. *Astrodyn* 9, 3–17 (2025).

URL <https://doi.org/10.1007/s42064-024-0199-3>

The 12th Global Trajectory Optimization Competition (GTOC12) focused on the challenge of asteroid mining. Teams were tasked with designing trajectories for multiple mining spacecraft departing from Earth, visiting asteroids, extracting resources, and returning the mined material to Earth. The primary objective was to maximize the total returned mass of minerals. The problem combined optimal control and combinatorial optimization. From the control perspective, spacecraft needed to rendezvous with asteroids, requiring precise position and velocity matching under a two-body low-thrust dynamical model. From the combinatorial side, teams had to decide how many spacecraft to use, which asteroids to target, in what order, and at what times. The competition highlighted the intersection of astrodynamics, optimization, and mission design. Ultimately, innovative strategies enabled the top teams to achieve impressive results. The next competition, GTOC13, will be hosted by NASA JPL.

Participants

- Giacomo Acciarini
University of Surrey –
Guildford, GB
- Abdin Adam
CentraleSupélec –
Gif sur Yvette, FR
- Carlos Ansotegui
University of Lleida, ES
- Max Bannach
ESA / ESTEC – Noordwijk, NL
- Laurent Beauregard
Telespazio – Darmstadt, DE
- Thorsten Ehlers
DLR – Hamburg, DE
- Johannes Klaus Fichte
Linköping University, SE
- Harry Holt
ESA / ESTEC – Noordwijk, NL
- Dario Izzo
ESA / ESTEC – Noordwijk, NL
- Matti Järvisalo
University of Helsinki, FI
- Alfons Laarman
Leiden University, NL
- Alexandra Lassota
TU Eindhoven, NL
- Anna Latour
TU Delft, NL
- Manuel López-Ibáñez
University of Manchester, GB
- Robert Luce
Gurobi Optimization –
Berlin, DE
- Inês Lynce
INESC-ID – Lisbon, PT
- Robyn Natherson
University of Colorado
Boulder, US
- Naoya Ozaki
JAXA – Sagamiara, JP
- Laurent Perron
Google – Paris, FR
- Yuri Shimane
Georgia Institute of Technology –
Atlanta, US
- Stefan Szeider
TU Wien, AT
- Polina Verkhovodova
Georgia Institute of Technology –
Atlanta, US
- Felix Winter
TU Wien, AT
- Chit Hong Yam
ispace – Tokyo, JP
- Zhong Zhang
Tsinghua University –
Beijing, CN

