The Space Optimization Competition: Third Edition

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ABSTRACT

The organizers of the third *Space Optimization Competition* (SpOC)[1] give a brief overview of the competition. We lay out the timeline and discuss administrative decisions. As was common in previous editions, the competition consists of three problems. We present them swiftly and provide their scientific background and motivation.

CCS CONCEPTS

• **Applied computing → Aerospace**.

KEYWORDS

Genetic Computation, Optimization, Computational Challenge

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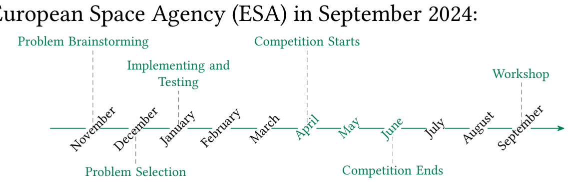
1 HISTORY AND TIMELINE

The *Space Optimization Competition (SpOC)* was established in 2022 by the European Space Agency's Advanced Concepts Team (ESA's ACT) with the goal of bridging aerospace research with the scientific community of evolutionary algorithms. It renders problems relevant to the space industry in an appealing *futuristic* setting, which allows participants from various domains to solve these challenges with tools familiar to them. The first edition of the competition was themed around the design of multi-rendezvous missions to mine the asteroid belt. Over 40 teams from 11 countries took up this challenge and advanced tools useful for early mission planning. In the second edition of SpOC in 2023, participants were asked to design algorithms that help to solve three optimization problems needed to establish a colony in a distant galaxy. Thirty teams and over 100 newly registered users from 11 countries developed the details for these futuristic colony plans. Shortly after the second edition was concluded with a workshop in September 2023, we began the planning of the third edition. We generated a pool of over ten possible and challenging problems, from which we selected the three most promising ones in December. From January to March 2024 we implemented and tested these challenges and constructed an overarching storyline. As in the previous years, the competition is held from April to June and is concluded with a workshop at the European Space Research and Technology Centre (ESTEC) of the European Space Agency (ESA) in September 2024:



2 THE STORY: ORBITAL MEGASTRUCTURES

The sci-fi story that envelops the challenges of SpOC 3 plays more than 200 years in the future, where our descendants plan to reach humanity's next evolutionary leap with the construction of a gigantic multi-generational starship in orbit. While a multi-generational starship is, of course, currently just a spark of imagination, in-orbit assembly is an active field of research [3] with applications in the construction of large space telescopes [11] or space-based solar power within the solaris project of the European Space Agency.

3 PROBLEM 1: TORSO DECOMPOSITIONS

The first problem of SpOC 3 is concerned with the computation of *torso decompositions* [6], which in our story is linked to the organization of the megastructure. A *torso* of a graph G (with vertex set $V(G)$ and edge set $E(G)$) for a set $X \subseteq V(G)$ is a graph torso(G, X) with $V(\text{torso}(G, X)) = X$ that contains an edge $\{u, v\}$ if and only if there is a u-v-path in G whose internal vertices are not in X. It turned out to be desirable for applications in optimization and verification to have *large* torsos of *small* treewidth [1]. This bi-objective optimization problem is equivalent to the following task: Given a graph G with $V(G) = \{0, \dots, n-1\}$, find a bijection $\pi\colon V(G) \to V(G)$ and a number $t \in \{0, \dots, n-1\}$ such that:

The Size of the Torso is Maximized: the last $n - t$ elements of the permutation π define the torso, so minimizing t maximizes the size of the torso;

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[1] https://github.com/esa/SpOC3

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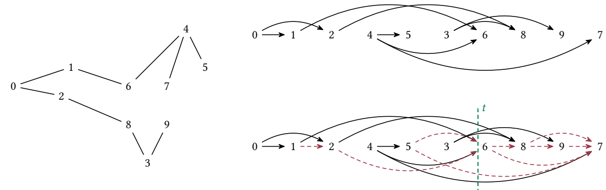
The Treewidth of the Torso is Minimized: A completion is obtained by scanning the nodes ascending with regard to π while completing the neighbors into cliques and orienting all introduced edge according to π. The width of the torso is the maximum degree within the last $n - t$ elements.

The following example shows a graph G on the left, a bijection π and the implied orientation (top right), as well as the introduced edges in red (bottom right). The size of the torso is 4 and its width 2:



The participants were asked to produce a Pareto-front as set of pairs (π, t) that correspond to different torso decompositions of varying size $(n - t)$ and width (defined by π).

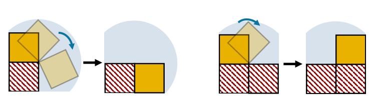
4 PROBLEM 2: INTERFEROMETRIC MISSION

The second problem is about assembling a constellation of satellites equipped with telescopes to perform interferometric measurements. Multiple telescopes are often used to synthetically simulate a large aperture. In order to obtain the highest possible resolution, the constellation needs to follow the mathematical structure of Golomb patterns [7]. An optimal Golomb pattern consists of distinct displacements (called baselines) between each telescope on the plane normal to the observation direction. Hence, the objective is to find each satellite's initial position and velocity with respect to a mothership such that the entire constellation forms as many distinct baselines as possible. The participant's solution will be evaluated by computing the amount of unique baselines at three different times ($t \in \{0, 1, 2\}$ periods of the mothership) and on three different observation planes (XY, XZ and YZ).

5 PROBLEM 3: PROGRAMMABLE CUBES

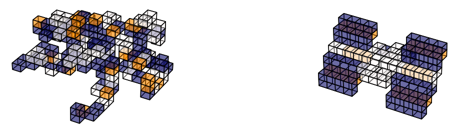
The third problem relates to the programming of an *ensemble of reconfigurable cubes* [8] to form into target structures as accurately and fast as possible. In our story, this is linked to the construction of a massive interstellar generation ship, which is to be constructed in orbit. Although this scenario is a sci-fi dream, it ties into active research on autonomous (self-)assembly of multi-robot systems [2, 9, 12] as well as large-scale space infrastructures such as habitats and spacecraft components [4, 5, 10].

The cubes can change their position by rotating along each other, thus allowing the ensemble to form a variety of complex structures. Such structures are characterized by the number of cubes they are composed of, the location of each cube in 3D space, and the type of cubes – representing different functional components, e.g., cubes with and without solar arrays. A cube can move along the ensemble in two different ways, *pivoting* (left) and *traversal* (right):



In addition, a cube can only move when it does not physically collide with any other cube during its motion and when the ensemble does not become disconnected while moving the cube. Only the rotation axis (x, y, or z) and rotation direction (*counter-clockwise* and *clockwise*) have to be specified in the code provided in the challenge to initiate cube movements, as the type of movement (*pivoting* or *traversal*) is automatically determined (see also [12]).

This challenge requires participants to provide a list of commands to transform three different cube ensembles from an initial configuration (left) into a target structure (e.g. the ISS, right):



The command lists are composed of tuples indicating the index of the cube to be moved and the maneuver to be applied. Three problem cases were provided in this challenge: the construction of the ISS, the JWST, and the U.S.S. Enterprise NCC-1701.

The score of a solution is composed from two objectives. The primary objective is to maximise the overlap of the cube ensemble with the target configuration, i.e., maximise the ratio of cubes that are in a correct location given their cube type. The secondary objective is to minimise the number of commands used.

6 CONCLUSION AND FUTURE EDITIONS

We thank all the participants for their impressive work and vital contributions, which have helped the SpOC community grow year after year. We also thank GECCO for the fruitful cooperation and hope that we can continue to build bridges between the space sector and the evolutionary algorithms community in the future.

REFERENCES

[1] M. Bannach and M. Hecher. 2024. Structure-guided Cube-and-conquer for MaxSAT. In *NFM 2024*. Springer.

[2] E. Bray and R. Groß. 2023. Recent Developments in Self-Assembling Multi-Robot Systems. *Current Robotics Reports* 4, 4 (2023), 101–116.

[3] T. Chen, H. Wen, H. Hu, and D. Jin. 2017. On-orbit assembly of a team of flexible spacecraft using potential field based method. *Acta Astronautica* 133 (2017).

[4] A. Ekblaw and J. Paradiso. 2019. Self-Assembling Space Habitats: TESSERAE design and mission architecture. In *IEEE Aerospace Conference*. IEEE.

[5] C. Gregg, D. Catanoso, O. Formoso, I. Kostitsyna, M. Ochalek, T. Olatunde, I. Park, F. Sebastianelli, E. Taylor, G. Trinh, et al. 2024. Ultralight, strong, and self-reprogrammable mechanical metamaterials. *Science Robotics* 9, 86 (2024).

[6] D. Marx, B. O'Sullivan, and I. Razgon. 2010. Treewidth Reduction for Constrained Separation and Bipartization Problems. In *STACS*.

[7] N. Memarsadeghi, R. Joseph, J. Kaufmann, and B. Lee. 2022. Golomb Patterns, Astrophysics, and Citizen Science Games. *IEEE Access* (2022).

[8] Martin Nisser, Dario Izzo, and Andreas Borggraefe. 2017. An electromagnetically actuated, self-reconfigurable space structure. *Transactions of the Japan Society for aeronautical and space sciences* 14 (2017), 1–9.

[9] M. Nisser, Y. Makaram, F. Faruqi, R. Suzuki, and S. Mueller. 2022. Selective Self-Assembly using Re-Programmable Magnetic Pixels. In *IROS*.

[10] C. Pirat, P. Ribes-Pleguezuelo, F. Keller, A. Zuccaro Marchi, and R. Walker. 2022. Toward the autonomous assembly of large telescopes using CubeSat rendezvous and docking. *Journal of Spacecraft and Rockets* 59, 2 (2022).

[11] Y. She, S. Li, Y. Liu, and M. Cao. 2020. In-orbit robotic assembly mission design and planning to construct a large space telescope. *Journal of Astronomical Telescopes, Instruments, and Systems* 6 (2020), 18 pages.

[12] C. Sung, J. Bern, J. Romanishin, and D. Rus. 2015. Reconfiguration planning for pivoting cube modular robots. In *ICRA*.