Optimal Strategies for Exploring Near-by Stars

LEAD FEATURE

Johannes Lebert

In Principium 32, February 2021, David Gahan suggested ways in which intergalactic civilisations might meet at a "Treffpunkt"*. Here Johannes Lebert explores the more immediate problem which we will face once the basic technologies of interestellar probes have been achieved - How do we route our explorers to achieve optimal research results at minimum expenditure of effort? More about this in Johannes' Author's Introduction below.

Note that all references appear at the end of this article.

Author's Introduction

Last year, I decided to break the travel restrictions due to the pandemic and to leave our solar system to explore close-by stars. The result of my journey is documented in my Master Thesis with the title Optimal Strategies for Exploring Near-by Stars [1]. My thanks go to my supervisors Andreas Hein and Martin Dziura, who gave me the possibility to work on this specific topic and John Davies, who offered me the opportunity to present a summary of my work here.

Motivation and Thesis Objective

Driven by exoplanet discoveries and the ongoing progress in related technologies, the idea of interstellar travel and exploration has gained momentum in the recent decade. However, while there are already various suggestions for probe concepts (eg [2], [3]) and considerations on relevant technologies, only few, limited research activities on suitable exploration strategies exist (eg [4], [5]). The overarching objective of this thesis is to develop strategies for the exploration of star systems in the solar neighbourhood (approximately 1,000-10,000 stars), based on optimization algorithms, taking advantage of current knowledge of nearby star systems and interstellar spacecraft.

* *AMiTe Treffpunkt - A proposal for communication between Kardashev Type IIb civilisations* David F Gahan, P32, Feb 2021 i4is.org/wp-content/uploads/2021/06/AMiTe-Treffpunkt-Principium32-print-2102221659-opt.pdf

Interstellar Exploration as an Optimisation Problem

As part of the thesis, the planning of interstellar exploration strategies is categorized as **bi-objective multi-vehicle open routing problem with profits:**

- **Bi-objective:** There are two objectives which are the mission return (J_1) and the mission duration (J_2). The mission return is the sum of all rewards provided by the stars which have been visited during the mission. The mission duration is equal to the overall travel time of the probe - if the mission consists of several probes, the probe which has the longest overall travel time is considered. The optimization aims to maximize the mission return while keeping the mission duration minimal.
- **Multi-vehicle:** Several probes can be used to explore different stars simultaneously.
- **Open:** Probes are not required to return to Earth once the mission is completed but can choose arbitrarily where to end their trip.
- **Routing Problem with Profits:** We assume the stars as a set of locations with each of it providing a certain reward or score S_i. From this set, a subset needs to be selected and arranged as a route in a way which optimizes the given objectives (see Figure 1).

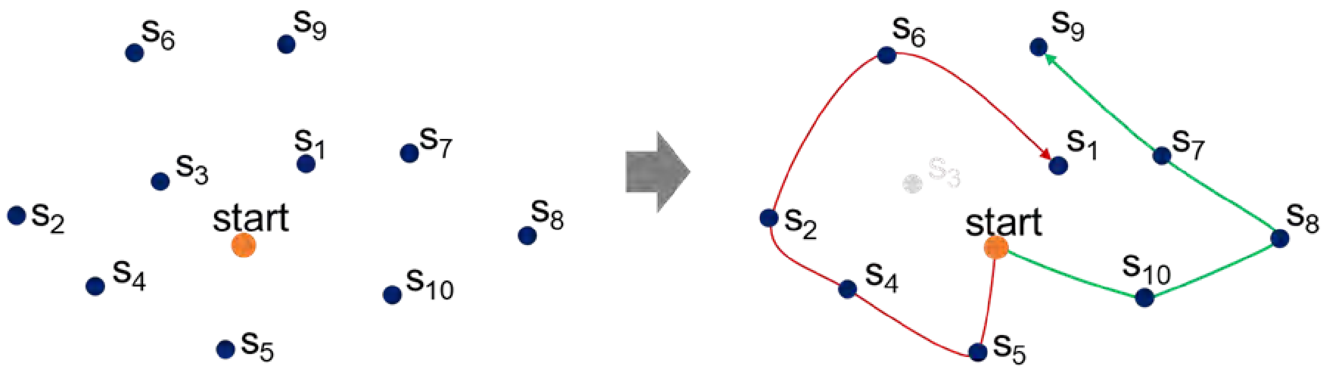

Figure 1: Visualization of the multi-vehicle open routing problem with profits.

Generally, the score of a star system can be adjusted depending on the mission interests (eg according to its probability to host (habitable) exoplanets) but for now it is assumed that each star system has the same score ($S_i = 1$). Hence, the mission return will be equal to the number of stars that are visited during the mission.

Modelling and Optimization Algorithm

Probe, Mission Architecture and Star Model

All probes are launched at the same time from Earth and limited to performing flyby manoeuvres. Furthermore, they are assumed to travel along straight-lined trajectories at an average velocity of 10 % of the speed of light, which is in line with suggestions from literature (eg [4]). Other parameters, such as mass or propulsion technology, are not considered.

The used star data is taken from the **Gaia Data Release 2** (available online through the Gaia Archive [6]), which is currently considered to be the most complete and accurate star database*.

To eliminate spurious data sources, a filtering is applied, which follows the suggestions from Lindegren *et al* [7]. The resulting star model is shown in Figure 2. It contains **10,000 stars** and represents a spherical domain with a radius of roughly **110 light years** around the solar system. The stars are assumed to maintain fix positions, which can be shown to be a valid simplification within this context for mission timeframes up to 7,000 years.

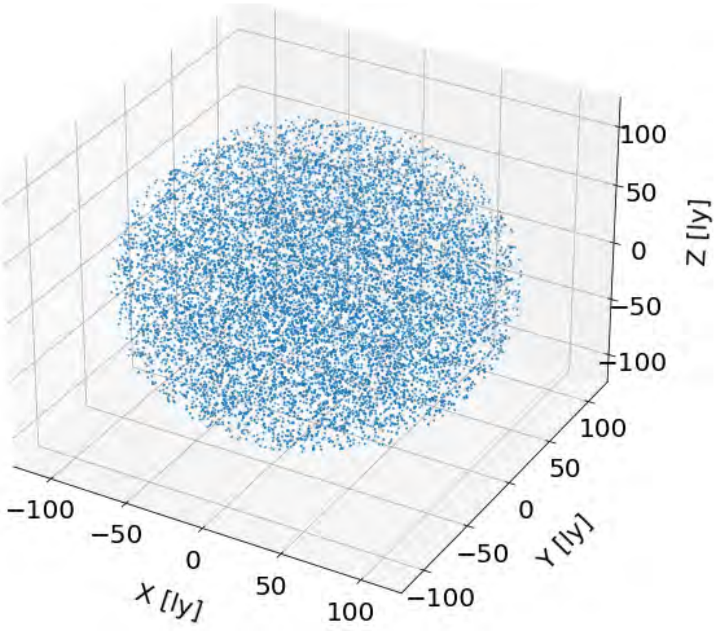

Figure 2: Star model based on Gaia DR2.

The Optimization Algorithm

To solve the described problem, a **hybrid genetic algorithm** presented by Bederina and Hifi [8] is selected. Genetic algorithms are a very intuitive optimization approach, as they try to imitate the process of natural evolution, which consists basically of reproduction and survival of the fittest. The required genetic encoding is shown in Figure 3: Exploration missions are represented by chromosomes while each gene embodies a sequence of stars or travel route which is assigned to a probe. For more details and explanations on the workflow and mechanisms of the algorithm please refer to the thesis document [1].

To improve the convergence behaviour the genetic algorithm is combined with a local search operation. The local search is applied in regular intervals to all current solutions to improve routes individually (eg by swapping two stars from the same route). That is why this method is referred to as hybrid genetic algorithm.

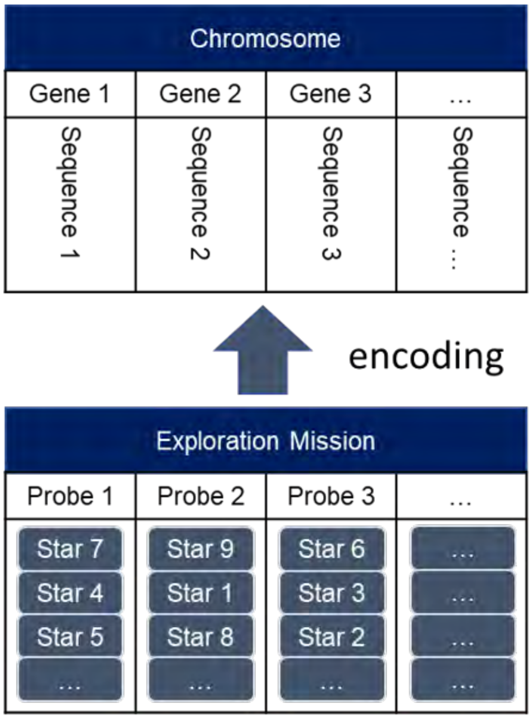

Figure 3: Genetic encoding

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* Note that there is already an updated Data Release (Gaia DR3), which was not available yet during this thesis.

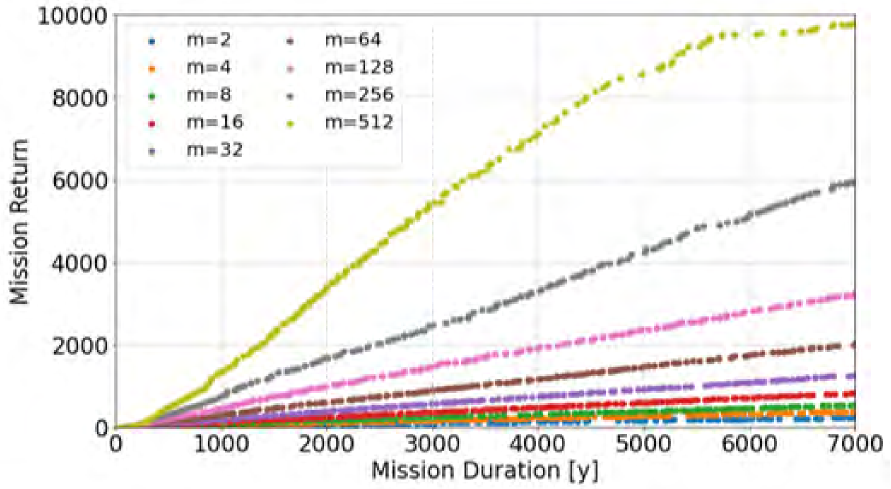


Figure 4: Optimization results for different probe numbers (model with 10,000 stars).

Optimization Results

Several optimization runs are performed whereby between each run maximum probe number m is doubled, starting with m=2. The resulting solutions are plotted in Figure 4 where the missions are evaluated with respect to both optimization objectives. Different runs (and thus different probe numbers) are indicated by different colours, each dot represents one possible exploration mission.

From Figure 4 one can observe that the mission return (which we assumed equal to the number of explored stars, just as a reminder) increases almost linearly with mission duration. For a given mission duration, the mission return can be increased by launching more probes. After doing some further analysis, both observations can be condensed in the following scaling law, which puts mission return J_1, mission duration J_2 and probe number m into relation:

$$J_1 \sim J_2\, m^{0.6}$$

As J_1 grows only with $m^{0.6}$, **the beneficial impact of additional probes on the mission return diminishes with increasing probe numbers**. This phenomenon is similar to the concept of diminishing returns in economics, which denotes the effect that an increase of the input yields progressively lower or even reduced increase in output.

An analysis of the route structure (visualized in Figure 5 for two solutions with different probe number but similar mission return) reveals strong differences depending on the probe number:

High probe number missions focus on the immediate solar neighbourhood and consist mainly of single-target routes whereas low probe number missions are built of longer routes which include also more distant stars. This could explain the lower efficiency of high probe numbers revealed through the scaling law before: With each additional probe being launched, the distance to the nearest star which is still unexplored increases. Accordingly, with higher probe numbers more distant transfers are required to provide the same mission return while lower probe numbers enable a quite efficient routing due to the shorter transfers.

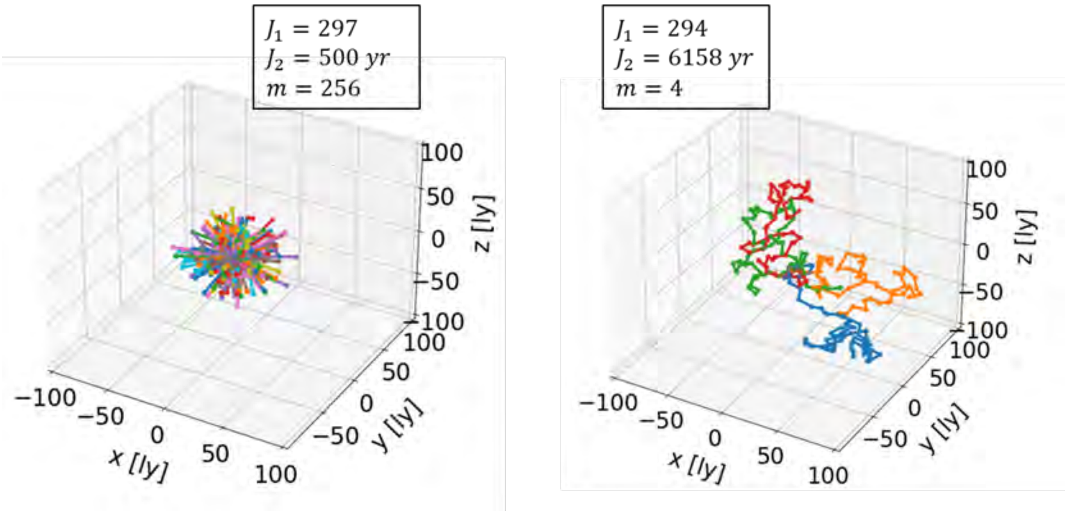
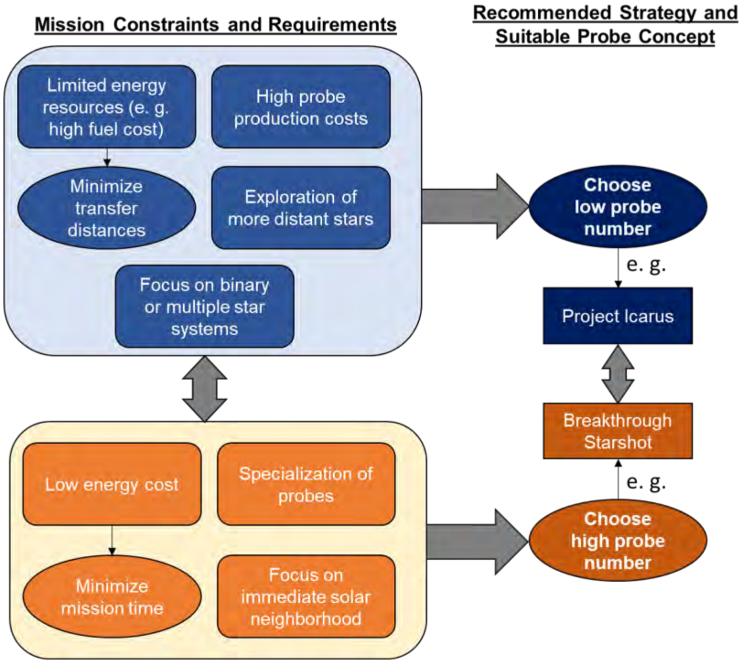


Figure 5: Route structure depending on probe number, each colour refers to one probe -

left: 256 available probes, right: 4 available probes

Figure 6: Strategy recommendations based on mission constraints and requirements including suitable probe concepts from literature



Conclusions with respect to Exploration Strategies

Based on the optimization results, several recommendations for exploration strategies can be derived (summarized in Figure 6): Due to the efficient routing low probe numbers are more suitable in case of limited energy resources (eg high fuel cost) and when the exploration mission is not restricted to very nearby stars. Conversely, high probe numbers enable a faster exploration of the nearest stars at the expense of less resource-optimal transfers and therefore match better with strategies based on small-scale, remotely propelled concepts (eg Breakthrough Starshot described by Parkin [3]). As further advantage, high probe numbers allow a higher specialization of the probes as each probe explores only few stars. However, according to the derived scaling law high probe numbers bear the risk of less efficient probe deployment, which is probably due to local crowding effects. Swarm-based concepts which include a mother ship that transports a fleet of smaller probes to a more distant star could help to mitigate this effect (see Figure 7).

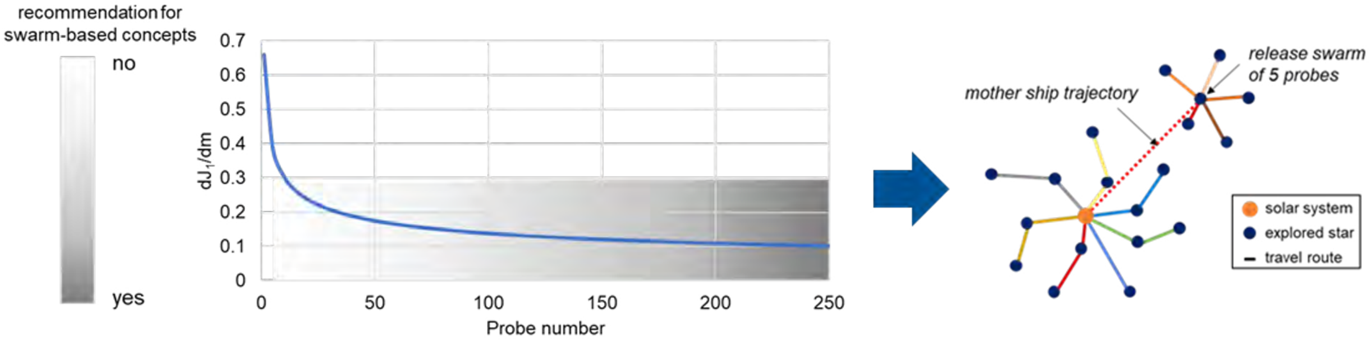


Figure 7: Left: Recommendation for swarm-based concepts based on qualitative analysis of the scaling law's first derivative (blue curve), right: Sketch of a possible mission which includes swarm-based concepts

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About The Author

Johannes Lebert has just completed a degree of Master of Science in Aerospace at the Technische Universität München (TUM). He also holds a Bachelor of Science in Mechanical Engineering (TUM) and was visiting student in the field of Aerospace Engineering at the Universitat Politècnica de València (UPV), Spain. He has worked at Starburst Aerospace (a global aerospace & defense startup accelerator and strategic advisory practice headquartered in Los Angeles, California), AMDC GmbH (a consultancy with focus on defense located in Munich) and Mainsite Technologies GmbH (an industry engineering company near Frankfurt/Main).

His thesis Optimal Strategies for Exploring Near-by Stars, the basis for this piece, is presented in support of his masters degree at TUM. His thesis supervisors were Andreas Hein (Initiative for Interstellar Studies) and Martin Dziura (Institute of Astronautics, TUM).