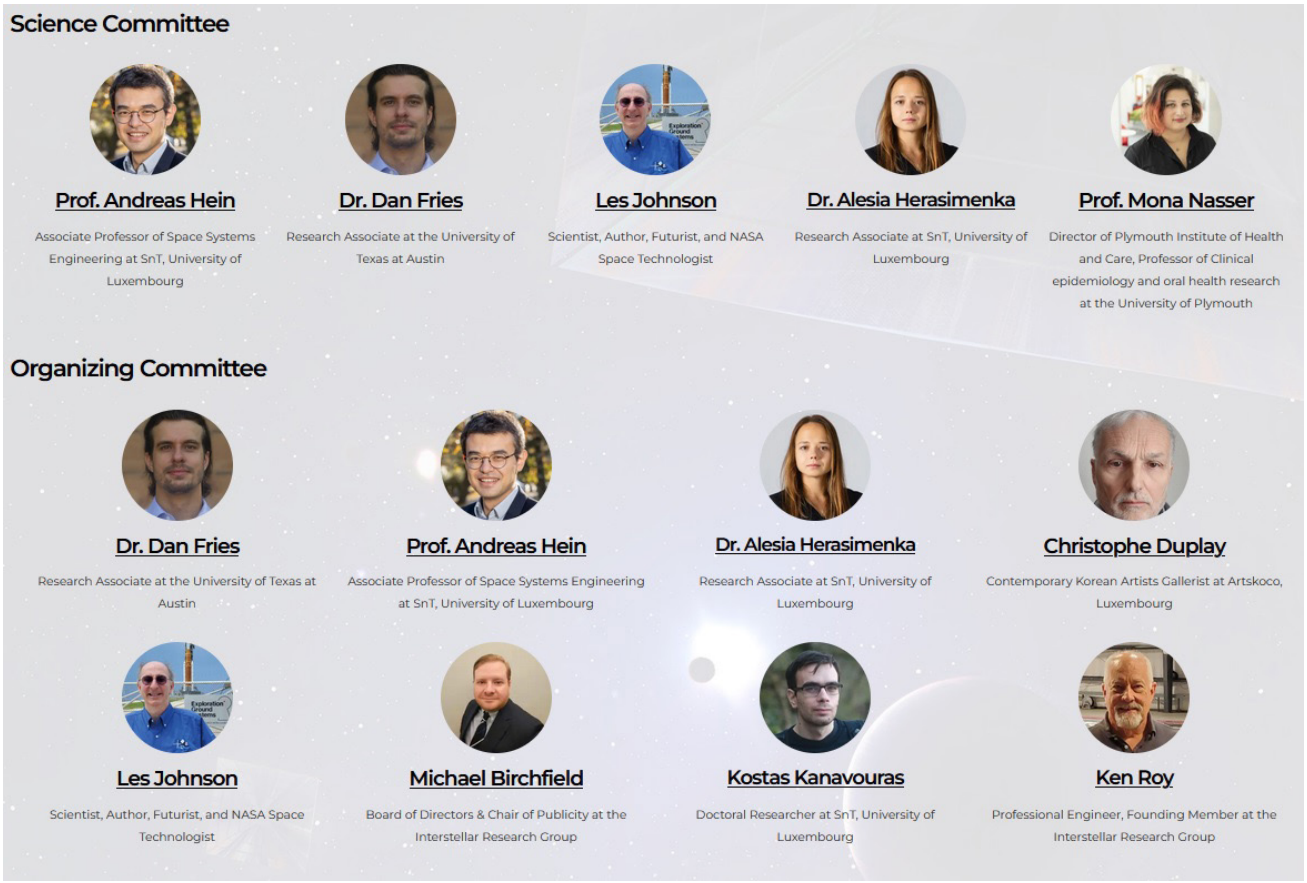
First European Interstellar Symposium

The Abstracts

The First European Interstellar Symposium will be held at the European Convention Center Luxembourg on 2nd – 5th December 2024.
The Symposium website is irg.space/first-european-interstellar-symposium

OVERALL AGENDA

The Day 1 Pre-conference Monday 02/12/2024, from 09.00 includes Registration and Introductory seminars on various topics related to interstellar travel: interstellar propulsion, environmental life support systems, interstellar communication, space law and an Opening Reception 17:00 – 20:00.
Day 2 Tuesday 03/12/2024 starts at 08.10 for Registration with Symposium main business from 08.40. Lunch 12:30 – 14:00 and concludes with the First Working Track ending at 17.30. There is a Public Outreach Event 20:00 – 21:30.
Day 3 Wednesday 04/12/2024 starts at 08.45 for Registration with Symposium main business from 09.00. Lunch 12:30 – 14:00 and concludes with the Second Working Track ending at 17:50. There is a Gala Dinner and Lightning talks 18.00-20.00 and another public event, a Science Fiction Authors Night, with Les Johnson (NASA, US), Brandon Q Morris, Joshua T Calvert.
Day 4 Thursday 05/12/2024 is the last day. It starts at 08.45 for Registration with Symposium main business from 09.00. Lunch 12:00 – 13:00, the Working Tracks Outbrief concluding 14.30 and an afternoon visit to Luxembourg space companies.
The full agenda can be found at irg.space/first-european-interstellar-symposium/agenda/



ABSTRACTS

The accepted abstracts are -

Submission #6: Ultimate Biosphere Survival: Interstellar Migration from the Post-Main Sequence Sun
In approximately 5 billion years, our Sun will start its post main-sequence evolution. The initial stage of this process, the subgiant phase, has a duration of about 100 million years. The sub-giant Sun will have a luminosity about twice that of the present-day Sun. Its radius will be about 3X the current solar radius. A more suitable phase for interstellar migrations is the horizontal branch of 500 million year duration in which the Sun's luminosity will have increased by a factor of about 100X and its radius by about 10X. At intervals of 500,000 years or less, Sun-like stars approach within one light year of the solar system. This paper investigates the feasibility of using large space habitats accelerated by graphene solar-photon sails to enable interstellar migrations of ~1,000 year duration.
Author: Gregory Matloff (Physics Dept., New York City College of Technology, CUNY)
Presenter: Gregory Matloff
Oral Presentation
Topics
* Life Support Systems and Habitats
* Potential Destinations and Astrophysics
* Propulsion

Submission #7: A Filipina Space Ethos
One of my grandparents migrated to the US from the Philippines in 1947, assimilated quickly, had children who assimilated fully, and died during my primary school years. Pinay: Culture Bearers of the Filipino Diaspora, edited by V Chattergy and P Nieva (Filipino Association of University Women, 2017) left me astonished by the adaptive skills of Filipina migrants. Are these the same adaptive skills needed for community resilience in space? It is not the colonialist's myth of the rugged pioneer, but the experiential knowledge of the displaced islander that will usefully guide human space exploration and expansion.
Authors: Jayme Johnson (Wichita State University (resigned), James Schwartz (Wichita State University
Presenters: Jayme Johnson
Oral Presentation
Topics
* Communications
* Ethics
* Life Support Systems and Habitats
* Potential Destinations and Astrophysics
* Psychology, Anthropology and Crew Health
Special Session

Submission #8: Relativistic Interstellar Flight Communications by virtue of the KLT
Nowadays the whole world uses the Fast Fourier Transform (FFT) to extract signals out of background noise, but FFT uses just sines and cosines as orthonormal time functions to, and that is an oversimplified situation. Since the discovery of the Hilbert space around 1900, however, a number of orthonormal bases in Hilbert space were used by advanced mathematicians to extract signals out of noise. During the years around World War Two, men like American Harold Hotelling, Finn Kari Karhunen, French Michel Loève and Indian Damodar Kosambi independently came up with the idea of decomposing the incoming stochastic process as an infinite sum of static random variables multiplied by orthonormal time functions. Having so done, the input autocorrelation matrix is diagonalized and the eigenvalues are the elements of the main diagonal, while each eigenfunction is corresponding to just one eigenvalue only (no degeneracy). In quantum physics that is called the eigenvalue equation of the autocorrelation operator. Thus, finding the KLT of a given stochastic process means solving the integral equation whose kernel is the autocorrelation. This author worked on the KLT while doing his PhD in mathematics at King's College London (UK) in the 1970s. He then discovered that the KLT eigenfunctions of Brownian Motion are Bessel functions J(t) and

the corresponding eigenvalues are the zeros of some derivatives of the Bessel functions. He then found that these results perfectly apply to noisy signals emitted by a special-relativistic spaceship (like StarShot).
In fact, in his first book "Telecommunications, KLT and Relativity" (1994, IPI Press, Colorado Springs, USA, website https://bis-space.com/shop/product/telecommunications-klt-relativity/) he analytically worked out several KLTs of interest to space flights and genetics aboard spaceships.
Though these mathematical calculations were published in journals like Acta Astronautica and similar journals, the topic of relativistic interstellar flight was much too ahead of time in the 1990s, and the mathematics were simply too lengthy for immediate computer implementation.
Hopefully the situation is improving now in 2024. Please, kindly read this summarizing paper:
Claudio Maccone, Relativistic Interstellar Flight Communication Theorems, Acta Astronautica, Vol. 26, No. 2, pp. 105-117, 1992.
Author: Claudio Maccone (International Academy of Astronautics (IAA, Paris, France) and INAF in Italy)
Presenter: Claudio Maccone
Oral Presentation
Topics
* Communications
Special Session

Submission #9: Antimatter Versus Fusion Deceleration Concepts for Exoplanet Exploration
Flyby probes are often used for a first glimpse, but robust exploration of exoplanets will inevitably require a propulsion system capable of deceleration into orbit around a nearby star and/or an exoplanet. Given the vast distances between stars, spacecraft cruise velocities of at least a few percent of the speed of light will need to be achieved. Deceleration from such velocities requires a propulsion system with particle exhaust velocities corresponding to kinetic energies of at least 1 MeV/nucleon. Conventional fission reactors are too heavy, and their architecture is incompatible with the emission of such energetic exhaust particles. This paper contrasts two propulsion concepts, one utilizing antimatter to induce uranium-238 fission and the other an architecture based on nuclear fusion. In both cases particles emanating from the actual nuclear reactions are focused and transmitted into space. While antimatter-based propulsion concepts have been proposed for several decades, the limited production of antimatter and its storage difficulties have retarded their development. The antimatter concept has been the subject of two past studies funded by the NASA Innovative Advanced Concepts (NIAC) program. With the exception of thermonuclear warheads, fusion reactors that output more energy than the energy input to achieve ignition have not yet been demonstrated. In this paper the suitability of several nuclear fusion channels (reactant combinations) are assessed, Onboard power systems for both concepts are also discussed. For example, a mission to the habitable planet Proxima b should have at least 100 kW for data communication back to Earth, AI-level computing, and a LIDAR system capable of studying Oort Cloud objects from both our solar system and the Centauri AB binary system. This paper describes the current state of these concepts in the context of both manned and unmanned missions to the exoplanet Proxima b. It contrasts the strengths and weaknesses of these approach in order to provide guidance to future studies.
Author: Gerald Jackson (Hbar Technologies, LLC)
Presenter: Gerald Jackson
Oral Presentation
Topics
* Power Systems
* Propulsion

Submission #10: INDUSTRIALISING EXTRASOLAR ASTEROIDS TO BUILD OUR HOME AMONG THE STARS
Background: A spectrum of interstellar exploration strategies will be essential to yield high benefits to capitalise on their high costs. To minimise costs, initial explorations will be cursory and data-limited. It is envisaged that human colony missions are the ultimate goal but such missions must be preceded by thorough robotic surveys. Furthermore, human life support will be required both in transit and at the destination. We suggest that interim missions for robotic surveys and for robotic pre-colonisation require an obvious evolution from in-transit self-repair to in-situ resource utilisation at the destination.
Objective: We examine the feasibility of building pre-colonisation assets within extrasolar systems using local resources.
Methods & Results: We have previously suggested that interstellar spacecraft will require substantial onboard self-repair to ensure their survival in-transit. Such interstellar spacecraft must be supplied with a finite range of feedstocks together with a FabLab-type manufacturing capability to build components and parts on-demand. The core of such a FabLab capability is a 3D printing facility supported by milling stations and other kinematic machines. We have demonstrated that electric motors – highly complex, multi-material components – can be 3D printed implying that the FabLabs are themselves self-repairing. To perform in-situ resource utilisation at the extrasolar system destination, further capabilities are required to generate a range of feedstocks. An industrial ecology is required to support an industrialisation process necessary for the construction of assets required for human colonists. O'Neill colonies are a fits-all solution to human habitability in extrasolar systems. This will require physical and chemical processing of local asteroidal resources. We have demonstrated the extraction of aluminium metal feedstock from anorthite minerals. Aluminium is a highly versatile multifunctional material. We expect that aluminium will be the dominant material required for constructing an O'Neill colony.
Conclusions: The payload of our ISRU-functional interstellar spacecraft constitutes a self-replicating machine. The implications for SETI are profound. Given the lack of evidence of technosignatures (in this case, evidence of artificial processing of our own asteroid objects such as extensive clay deposits), the Copernican principle forces us to the conclusion that extraterrestrial intelligence with technological means do not exist.
Author: Alex Ellery (Carleton University)
Presenter: Alex Ellery
Oral Presentation
Topic
* Advanced Materials

Submission #11: REMOTE CONTROL OF SELF-REPLICATING STARSHIPS
Background: Self-replicating starships are an inevitable evolution from interstellar starships that can self-repair in-transit. They offer the most economic means through which to explore our Galaxy at a capital cost of launching a single or a few starships. Tipler suggested that any technologically-competent extraterrestrial intelligence (ETI) would inevitable adopt this strategy. We further suggest that this strategy is logical for global defence – it provides both intelligence about potential threats in our Galactic environment and security regarding the location of our home world. Sagan suggested that no responsible ETI will adopt self-replicating starships as they are potentially uncontrollable because of their evolvability.
Objective: We propose that prevention of evolutionary change in the self-replicating starship's genetic information is feasible.
Methods: We review error detection and correction coding (EDAC) methods utilised extensively in spacecraft onboard memories to combat incident radiation. Evolutionary mutation can be prevented to any arbitrary degree through channel coding which ensures the fidelity of information through a communications channel – in this case, a vertical evolutionary channel. Biological genetic fidelity is limited by the energy cost of physical repair mechanisms but spacecraft memory-encoded binary information repair involves only bit flipping. There are two major types of EDAC and variations thereof - block coding and convolutional coding – which add redundant information. Interleaved Reed-Solomon block coding with convolutional coding is commonly implemented for reliable interplanetary data transmission, eg Voyager. Turbo coding approaches the maximum encoding efficiency dictated by Shannon's theorem. For a self-

replicating probe to spread through the Galaxy requires copying fidelity over only 24 vertical generations. We might employ deeper encoding depth at critical genetic instructions such as number of offspring and telomeric counters.
Results: Efficient channel coding can prevent mutations generated by copying errors in the genetic code of the self-replicating starship thereby preventing it from evolving.
Conclusions: The Sagan-Tipler debate regarding the existence or non-existence of ETI revolved around their deployment of self-replicating probes to permeate the Galaxy within astronomically short timescales. Sagan's retort is unfounded. Fearfulness of technology has never been much of a deterrent for humans so its application to ETI contravenes the Copernican principle.
Author: Alex Ellery (Carleton University)
Presenter: Alex Ellery
Oral Presentation
Topic
* Communications

Submission #17: Seeding life with an interstellar probe. Technical and ethical considerations
Claudius Gros, a theoretical physicist from the Institute for Theoretical Physics at Goethe University Frankfurt, proposed an idea of how robotic missions equipped with cryogenic pods with genes could be used to distribute microbial life to planets capable of supporting life but not likely to give rise to it on their own.
These kinds of interstellar robotic missions are beyond our current and near-future technological capabilities. However, there are proposals for using laser sails to send microscale probes to nearby stars within the near future. Could these kinds of microprobes be used to seed life to other worlds? Should we do this if it is technically feasible? Clearly, there are many technical problems: How do you identify suitable target planets? What organisms should we use? How do you preserve them during the long interstellar journey? How do you securely deploy organisms during the very limited time of the fly-by, and so on? Here I will make a literature review of what kind of ethical and technical problems this kind of seeding will raise.
Author: Pauli Laine (Finnish Astronautical Society)
Presenter: Pauli Laine
Oral Presentation
Topics
* Autonomous Spacecrafts
* Communications
* Ethics
* Miniaturisation and Technology Development
* Potential Destinations and Astrophysics
* Power Systems

Submission #18: To Seed or Not to Seed: The Ethical Implications of Directed Panspermia
Background - Directed panspermia involves the deliberate spread of life between planets by intelligent actors. While it was originally proposed to explain the origins of life on Earth, recent advancements in space and bio-technology suggest that humans could soon attempt this over interstellar distances – and perhaps even succeed.
Objective - Analysing the ethical impact of humans undertaking directed panspermia.
Methods - Analytic philosophy and evolutionary biology. The paper uses two of the most opposing ethical views to bracket the field of ethical theories.
Results - Panspermia is different from deliberate settlement in that humans cannot directly intervene once it is underway. Biocentric ethical theories support attempting this project to secure life's continued existence and increase its cosmic abundance. However, given its vast effects and irreversibility, directed panspermia also carries serious moral risks: if what matters is protecting and promoting the welfare of sentient beings, then attempting this project could create astronomical levels of suffering in the long-term future.

Conclusions - Taking into account normative uncertainty, the cost of waiting, and the "unilateralist curse", we argue that both views can agree on a temporary moratorium on directed panspermia.
Authors: Anders Sandberg (Institute of Futures Studies), Asher Soryl (University of Otago)
Presenter: Anders Sandberg
Oral Presentation
Topics
* Ethics
* Space Law

Submission #19: Traversable Wormholes powered by Casimir Energy with Temperature and Charge
Traversable Wormholes (TW) are solutions of the Einstein Field Equations. Even if they are not yet discovered, they represent an interesting research line especially after the discovery of Gravitational Waves. Indeed, there are proposals which consider TW as sources for Gravitational Waves. In addition to this remarkable research field, TW are also interesting because they have peculiar properties that other astrophysical objects do not have, namely they can create short-cuts between distant regions of the space-time. This amazing property can be satisfied at the price of introducing a particular kind of source dubbed as Exotic matter. We know that such a matter has not yet been discovered, however one can invoke the Casimir energy which behaves like the Exotic matter. The physics of the Casimir energy has a large plethora of applications. In this talk, we would like to propose such an energy source as a possible source powering a TW. This idea has been proposed for the first time in two pioneering papers: MS Morris and KS Thorne, Am JPhys 56, 395 (1988), "Wormholes in space-time and their use for interstellar travel: A tool for teaching general relativity" and MS Morris, KS Thorne and U Yurtsever, Phys. Rev. Lett. 61, 1446 (1988), "Wormholes, Time Machines, and the Weak Energy Condition". Also the book of M Visser, Lorentzian Wormholes: From Einstein to Hawking (American Institute of Physics, New York), 1995 is an excellent example about the physics of TW. However, we have to wait for 2019 when the candidate speaker of this talk proposed to search which kind of TW could be associated with a Casimir source. The result was published in Eur.Phys.J.C 79} (2019) 11, 951 under the title "Casimir Wormholes". A discrete degree of curiosity has been arised by such a publication (98 citations on Spires). In this talk we would like to show how some modifications on Casimir Wormholes can take the paradigm "traversable in principle" a little bit more closer to the possibility of being "traversable in practice".
Author: Remo Garattini (University of Bergamo)
Presenter: Remo Garattini
Oral Presentation
Topics
* Potential Destinations and Astrophysics
* Propulsion

Submission #20: Feasibility study of reducing interstellar travel times with groups of co-operating fuel-carrying rockets
Background
Previous rocket concepts for interstellar missions using such propulsion, which the mankind might be able to develop during the next 100 years, like projects Orion, Daedalus and Longshot have suggested travel times around 50-100 years to our nearest star systems. For example Project Daedalus had 2-stage rocket using inertial confinement fusion, which managed to reach 50-year travel time to the Barnard's star for a flyby-mission.
Objective
This feasibility study evaluates the concept of using groups of co-operating fuel-carrying rockets for reducing travel times. The payload rocket doesn't have to carry all the fuel it needs for the mission. Instead it shall meet other fuel-carrying rockets at crucial points along the way. These fuel-carrying rockets shall likewise meet other fuel-carrying rockets and use their fuel. Vessels of similar speed, direction and place can rendezvous and exchange fuel. This is especially useful for the deceleration phase of the journey, because all the fuel for deceleration don't have to be costly accelerated to very high speeds.

Methods
Using performance metrics of Project Daedalus like similar fuel / empty mass ratios of rockets and the same effective exhaust velocity some example configurations of fuel and payload carrying rockets are created. Travel times and resource requirements for a mission to Alpha Centauri system are calculated for different configurations using established science like the ideal rocket equation.
Results
With the example rocket configurations used travel time for a one-way, decelerating mission to the nearest star system is reduced from 50 - 100 years to 10 - 20 years. The resource requirements are huge, 500 - 300 000 expendable fuel carrying rockets with total masses 12,000,000 - 6,000,000,000 tons. However, the resource requirements are related to travel time: the quicker we want to go the more resources we need. Rockets needed for deceleration require tens of years of lead time before payload rocket.
Conclusions
Using the described methodology a human colonization mission to our nearest star system is possible without sleeper or freezer or hibernation ships or generation arks.
Author: Aapo Puhakka (Finnish Astronautical Society)
Presenter: Aapo Puhakka
Oral Presentation
Topics
* Autonomous Spacecrafts
* Propulsion

Submission #21: Simplified Evolutionary Neurocontrol for Lower Bound Payload Estimates of Low Thrust Solar Oberth Maneuvers to the Heliopause
Despite decades of space exploration, the very outer regions of the solar system remain largely uncharted, leaving open questions about the interaction of heliosphere and interstellar medium. One promising interstellar precursor mission architecture which can provide the challenging delta-v needed involves a Solar Oberth Maneuver (SOM) using solar electric propulsion, followed by a Jupiter gravity assist.
Devising an effective steering strategy for such a mission is challenging. Using evolutionary neurocontrol, previous research demonstrated the feasibility of flight times under 25 years (Loeb et al, 2011); yet, with the necessity of including a further Radioisotope Electric Propulsion (REP) stage. However, advancements in high-temperature solar cells might allow for SOMs even closer than 0.7 AU, and NASA's Space Launch System (SLS) for higher payload capabilities.
Previous implementations of evolutionary neurocontrollers are often sophisticated, involving artificial neural networks (ANNs) with high-dimensional inputs (up to 28 parameters) and 30-40 nodes in the hidden layer. While this allows for more optimization potential, the large input and parameter space complicates the optimization process.
The work at hand has two main objectives: i) developing a simpler evolutionary neurocontrol architecture for optimizing SOM steering strategies to achieve lower bound payload estimates and ii) using it to evaluate payload capabilities of a SOM to the heliopause with a perihelion distance of 0.3 AU, assuming a SLS launch and an advanced electric thruster with specific impulse of 6,000s and 75% thrust efficiency.
A mutation-driven evolutionary algorithm is used to optimize the steering strategy given by a neurocontroller that transforms the current spacecraft state into steering control commands.
It is shown that a neurocontroller with 4 input parameters, 10 hidden nodes and 2 output nodes suffices for lower bound assessments of payload capabilities to 200 AU within 25 years. An estimated lower bound payload of above 1,000 kg represents a significant increase in payload mass.
On the condition of sufficient maturity of the high-temperature solar cells, these results suggest feasibility of a mid-term heliopause mission without the necessity for a REP stage, thus allowing for a mission of decreased complexity and higher scientific payback.
Authors: Nadim Maraqten (Initiative for Interstellar Studies), Angelo Genovese (Initiative for Interstellar Studies), Willem van Lynden (Alma Propulsion Laboratory, University of Bologna)

Presenter: Nadim Maraqten
Oral Presentation
Topics
* Propulsion

Submission #22: Advancing Interstellar Exploration: Integrating Technological, Ethical, and Socio-political Dimensions
Background: Interstellar exploration necessitates a convergence of technical innovation and profound ethical inquiry. This work synthesizes advancements in propulsion systems, sustainable habitats, and life support alongside the ethical, sociopolitical, and philosophical questions that arise as humanity extends its reach beyond the solar system.
Objective: To present a multidisciplinary framework that integrates technological advancements with ethical and sociopolitical considerations, ensuring that humanity's expansion into the cosmos is guided by foresight, equity, and collective well-being.
Methods: This study draws from three key research areas: (1) advancements in propulsion technologies and sustainable Mars settlement strategies, and (2) the development of closed-loop life support systems and habitat construction using in-situ resources, and (3) ethical frameworks for responsible exploration, addressing the moral, legal, and governance challenges of interstellar travel.
Results: The integration of MFPD and sustainable habitat technologies promises significant reductions in travel times and resource dependency, making interstellar travel feasible within our lifetime. Closed-loop life support systems, incorporating bioregenerative processes, ensure sustainable human presence in space. Ethical frameworks emphasize the preservation of extraterrestrial ecosystems and the rights of potential extraterrestrial life forms, advocating for an inclusive and equitable approach to space exploration.
Conclusions: Interstellar exploration is not merely a technical challenge but a philosophical journey. This synthesis of science and ethics offers a blueprint for navigating the unknowns of space with wisdom and integrity, ensuring that humanity's interstellar aspirations reflect the best of human values. This talk aims to lay the foundation for a responsible and sustainable future among the stars by fostering a multidisciplinary dialogue.
Author: Florian Neukart (University of Leiden; Terra Quantum AG)
Presenter: Florian Neukart
Oral Presentation
Topics
* Ethics
* Life Support Systems and Habitats
* Power Systems
* Propulsion
* Psychology, Anthropology and Crew Health

Submission #26: A top-down instructed bottom-up production method for space exploration utilising in-situ resources
Current astronomical and remote sensing methods are fundamentally limited in their capacity to obtain comprehensive information from other star systems. Direct visits are necessary to gather detailed data, but interstellar travel to the object of interest, constrained by relativistic effects, is prohibitively energy-expensive when carrying mass over durations feasible within a human lifespan. Our understanding of other star systems remains superficial, confined to remotely sensed observations.
Given these constraints, one way to overcome them is to build the information observation and communication system on-site with the resources at hand. While technological components for self-assembling and in-situ resource utilization (ISRU) systems exist, integrating these parts to find the adjacent possible is lacking.
This approach involves encoding and inscribing matter with construction instructions, enabling the self-assembly of complex structures using locally available resources.
Our study aims to assess the feasibility and implications of this bottom-up production method in the context of interstellar missions.

We employ a multidisciplinary systems engineering methodology to integrate existing technologies and processes. Our approach models the self-assembly process, starting from the creation of a "seed" that contains the necessary instructions. This seed autonomously initiates the construction process, using local materials and energy sources available within the interstellar environment. We aim to quantify the potential savings in energy, mass, and time compared to traditional top-down methods and the direct transportation of finished products.
Our preliminary findings suggest that the bottom-up construction method may significantly reduce the energy and mass required for interstellar missions. By enabling on-site production, this approach could offer a more efficient alternative to current methods. We also explore the feasibility of encoding complex construction plans into the seed and the practical challenges of sourcing and utilizing local materials in an extraterrestrial environment.
This research demonstrates the potential of a top-down instructed bottom-up production method for space exploration. Future research could focus on applying the approach to other, perhaps terrestrial, use case.
Authors: Matthias Frenzl (Complex Structures Research Collaboration), Abhimanyu Shanbhag (Complex Structures Research Collaboration)
Presenters: Abhimanyu Shanbhag, Matthias Frenzl
Oral Presentation
Topics
* Advanced Materials
* Autonomous Spacecrafts
* Miniaturisation and Technology Development
Special Session

Submission #27: From Interplanetary to Interstellar: Current Status of Exploration using Space Sails And Required Developments
Background
Following the symposium "Large area structures & light" by the Deep Space Exploration Program at the University of Tokyo and the Breakthrough Initiatives in September 2023, an international working group was established. It focuses on identifying synergies among space sail technologies as a pathway towards practical interplanetary and interstellar missions.
Objective
The objective of this study is to answer two questions. Firstly, how big is the technological gap between present state-of-the-art space sailing and future proposed interstellar missions? Secondly, what are the major risk areas, and how can eventual bottlenecks be overcome?
Methods
These questions are addressed through a focus on three planned missions with different Technology Readiness Levels, different types of stakeholders and different destinations: Solar Cruiser, Project Svarog and Breakthrough Starshot. Gaps between these missions and currently achievable technologies on subsystem- and system-levels are assessed using the Advancement Degree of Difficulty (AD2) scale, and potential ways forward are proposed. A database of parameters achievable with present technologies is obtained from prior work by the authors.
Results
When comparing mission requirements with the current state-of-the-art, the maximum scaling of key parameters such as total sail loading and deployed area required by Solar Cruiser, Project Svarog and Breakthrough Starshot are generally found to be factors of 3, 10 and 600 respectively. It is however noted that the amount of risk of advancing the technology to the required level grows significantly when stepping from Solar Cruiser to Project Svarog and to Breakthrough Starshot. Key risk areas for each mission are mapped out, with attitude control, sail material, shape accuracy and subsystem integration being identified as major risk areas. Alternatives to technologies in these high-risk areas are summarized.
Conclusions
It is concluded that although linear extrapolation predicts that the outlined missions should be feasible

with development of current technology, bottlenecks may arise in areas of high risk. It is highlighted that testing of high-risk components in intended environments is essential for lowering the AD2 levels. Moreover, cross-sectoral collaboration and cross-pollination between different types of space sails as well as other technologies is highlighted as a key to finding alternatives to high-risk technologies.
Authors: Debdut Sengupta (Imperial College London), Maximilien Berthet (University of Tokyo), Onur Çelik (Delft University of Technology), Andreas M Hein (University of Luxembourg), Ken Fujino (University of Tokyo), Koki Tanaka (University of Tokyo)
Presenter: Debdut Sengupta
Oral Presentation
Topics
* Advanced Materials
* Autonomous Spacecrafts
* Communications
* Miniaturisation and Technology Development
* Potential Destinations and Astrophysics
* Power Systems
* Propulsion

Submission #29: Interstellar communications among future human colonies
This study evaluates the feasibility and crucial importance of establishing interstellar communication among future human colonies dispersed across approximately 60 stellar systems, using an approach based on numerical calculation. We specifically focus on the reciprocal exchanges of communications, employing gravitational lensing to amplify signals across vast distances. We assess several critical parameters necessary for effective communication, including antenna gain, signal-to-noise ratio (SNR), bit error rate (BER), and channel capacity at both microwave and optical frequencies. Additionally, we examine the challenges posed by stellar corona noise.
Our analysis includes a comprehensive exploration of different communication configurations. We conclude that dual gravitational lenses offer the most effective strategy for microwave transmissions, providing optimal signal amplification. For optical transmissions, the effectiveness of using two gravitational lenses is comparable to that of a single lens.
Furthermore, we have evaluated potential data compression algorithms suitable for these long-range communications to optimize bandwidth and reduce transmission times.
To add a practical dimension to our theoretical study, we analyze and derive the optimal sequence of stellar colonization, which could guide future expansion strategies.
Our findings highlight the significant advantages of advanced gravitational lensing-based communication systems in maintaining a shared culture, ensuring technological progress, and fostering mutual enrichment between Earth and its interstellar colonies. Despite the inevitable time delays and potential for cultural divergence over huge distances, these communication strategies hold the promise of keeping both civilizations connected and advancing in unison.
Authors: Nicolò Antonietti, PhD (INAF), Claudio Maccone, PhD (IAA), Luca Derosa, PhD (iMEX.A), MEng Domenico Caliendo (iMEX.A)
Presenter: Nicolò Antonietti, PhD
Oral Presentation
Topic
* Communications

Submission #31: Interstellar Precursor Missions with Advanced FEEP Ion Thrusters

One of the most challenging technologies needed to make interstellar precursor missions practicable is the propulsion system. Several "breakthrough propulsion" concepts have been proposed, but no conclusive results offering a near-term solution to the problem have so far emerged. It is therefore realistic to assume that such solutions, if any, are probably decades away from implementation. It is thus prudent to consider outer-solar system missions employing extensions of existing technologies.

A key propulsion parameter to enable interstellar precursor exploration is the specific impulse; in order to reduce the propellant mass, and consequently the spacecraft mass, to reasonable values, the specific impulse must be much higher than the maximum specific impulse presently achieved by the most efficient ion thrusters.

Field Emission Electric Propulsion (FEEP) offers several unique features: very high specific impulse (> 7,000 s), the most efficient way of carrying propellant (namely in solid state as Indium melts at ~ 157°C), very low thermal losses as the emitter electrode is kept just above 157°C.

Over the past two decades, Fotec GmbH and Enpulsion GmbH have developed and refined FEEP technology based on porous tungsten emitter crowns, elevating it to a well-established space propulsion solution. More than 150 thrusters have been successfully deployed and are currently operational in space. Ground tests have demonstrated that these thrusters can operate for over 50,000 hours with minimal performance degradation. This remarkable lifetime is a critical attribute for the success of interstellar precursor missions.

Recent advancements have led to the successful fabrication and operation of a 2D array of emission points with a single extractor. This achievement is an important stepping stone towards the feasibility of the concept proposed in our previous work (Genovese et al, JBIS, 68, 2015), paving the way for the development of advanced FEEP ion thrusters with high thrust density and ultra-high specific impulse as high as 30,000s.

Furthermore, a short-term interstellar precursor mission based on the present FEEP technology is proposed. Finally, a more challenging mid-term mission could be enabled by the advanced FEEP concept described in this work.

Authors: Nembo Buldrini (FOTEC Forschungs- und Technologietransfer GmbH, Viktor Kaplan-Strasse, Wiener Neustadt, 2700 Austria), Angelo Genovese (Initiative for Interstellar Studies i4is Germany)
Presenters: Nembo Buldrini, Angelo Genovese

Oral Presentation

Topic

* Propulsion

Submission #32: Deployment strategies for 3D interstellar solar sails

In order to send solar sails beyond the outer solar system, significant improvements regarding the sail velocity must be achieved. To improve the velocity, the total spacecraft mass needs to be reduced. A first step is to implement aerographite (density of 0.18 kg m^-3), a new type of sail material, proposed by Heller in 2020. The next step would be to improve the deployment system. Until now, conventional motor driven metal booms unfold the sails. By removing the booms and motors, the velocity improves. Without the stabilizing booms the sail collapses under the photon pressure in the close vicinity of the sun (preceding simulations). Yet, a low solar orbit is necessary for maximum sail performance. Therefore, an alternative stabilizing strategy is required.

First, the sail will not have a conventional two-dimensional shape, but rather a three-dimensional rotational body shape. This gives the sail a self-stabilizing geometry under the influence of solar radiation and wind. The shapes can be eg semi-spheres, cone-like, funnel- or horn-like. These shapes are to be tested initially in a smaller scale in a vacuum, whilst being irradiated by a solar simulator and being exposed to a neutral plasma stream to simulate the solar wind.

Secondly, alternative deployment mechanisms are required to unfold the sail and stabilize it. So far, we investigate the use of shape memory alloys (SMA), embedded in the sail material, as well as the integration of unipolar electrets to use the Coulomb forces between them for unfolding. The SMA can be activated either passively by solar radiation or actively by Joule-heating. We test multiple methods to embed the SMA, eg weaving the SMA into the material. Furthermore, by using infrared radiation heating under vacuum conditions, the passive deployment can be tested. The active deployment can be tested by applying a voltage to the SMA. The electrets are produced by shielding free charges on a metal core with a dielectric sheath against the environment. This process is validated by measuring the surface potential of the electret.
Future strategies will include the investigation of the interaction between the aerographite and the space environment.
Authors: Julius Karlapp (Dresden University of Technology), Martin Tajmar (Dresden University of Technology)
Presenters: Julius Karlapp, Martin Tajmar
Poster
Topics
* Advanced Materials
* Propulsion

Submission #33: Interstellar Precursor Missions by Combining Laser-Powered Electric Propulsion with an Oberth Maneuver
Interstellar precursor missions require advanced propulsion systems with very high specific impulses in order to reduce the propellant mass to acceptable values and consequently being able to reach the high delta-v needed. Electric propulsion technology can be scaled up to very high specific impulses (Isp » 5.000s). However the power needed for the same thrust is also increasing together with the mass of the power source, which puts a limit to the maximum delta-v achievable with a certain Isp.
A breakthrough in power source specific mass is needed in order to enable missions with very high Isp (< 1 kg/kW); this breakthrough could be realized having the power source not on-board, as with Laser-powered Electric Propulsion (LEP), where the needed power is beamed to the spacecraft from an external laser source. In this case the on-board power source is limited to a light-weight photovoltaic receiver/converter. However, the laser source must be very large in order to accelerate the spacecraft long enough to reach the needed final speed, as the laser spot size on the spacecraft is inversely proportional to the laser aperture and directly proportional to the increasing distance.
In order to avoid laser sources with a km-size aperture, the laser-powered spacecraft acceleration could be imparted during a close sun powered fly-by by a relatively small laser array placed near the sun. Furthermore, this mission architecture would take advantage of the so-called Oberth-effect, as adding Δv within the sun's gravitational well increases the gain in final spacecraft kinetic energy.
This paper gives an assessment on the feasibility of the described propulsion architecture and proposes a preliminary design for an interstellar precursor mission.
Authors: Angelo Genovese (Initiative for Interstellar Studies i4is Germany), Nembo Buldrini (FOTEC Forschungs- und Technologietransfer GmbH, Viktor Kaplan-Strasse 2, Wiener Neustadt, 2700 Austria)
Presenter: Angelo Genovese
Oral Presentation
Topic
* Propulsion

Submission #34: Biological and mechanical reproduction strategies for interstellar exploration and settlement

Crewed interstellar flight requires bioregenerative life support for several reasons. The limited resources that can be brought on board at departure make continuous recycling imperative. To maintain the crew's health, a diet that includes at least some fresh food is indispensable. Biological organisms, being regenerative by nature, can be easily regrown in case of failure, unlike mechanical systems that depend on spare parts and repairs. A major key to the success of bioregenerative life support is effective in situ biological reproduction (ISBR). Organisms must properly reproduce in space conditions to sustain the functionality of the entire bioregenerative system. It can be argued that technological self-reproduction is another imperative for interstellar flight. Because of the limited knowledge of the interstellar medium and its long-term impact on terrestrial biology and technology, interstellar flight is highly uncertain. This uncertainty calls for an adaptable, self-organizing spacecraft architecture that can dynamically respond to unforeseen challenges.

The Evolving Asteroid Starships (E|A|S) project is a theoretical study exploring the gradual transformation of an asteroid into an interstellar craft using asteroid mining and in-space manufacturing, facilitated by swarm robotics with self-replicating capabilities. This project addresses the challenges of bioregenerative life support and self-organizing spacecraft architecture through a complex adaptive systems approach and computer modelling. Two models have been developed: an agent-based model (ABM) for the bioregenerative life support system and a discrete event simulation (DEVS) for the self-organizing spacecraft architecture. These models allow for the investigation of long-term system behavior and the testing of different space travel scenarios. Both systems exhibit chaotic behavior, where small differences in stochastic parameters, such as bioreactor efficiencies or module lifetimes, lead to divergent outcomes. The challenge is to design strategies that can mitigate potential catastrophic deviations by eg, integrating redundancies and applying distributed decision-making. Such strategies can help to maintain system stability, avoid chaotic attractors, and support multigenerational growth.

Authors: Angelo Vermeulen (Delft University of Technology), Arpi Derm (SEADS), Alvaro Papic, Igor Nikolic (Delft University of Technology), Frances Brazier (Delft University of Technology)

Presenter: Angelo Vermeulen

Oral Presentation

Topics

* Autonomous Spacecrafts
* Life Support Systems and Habitats

Submission #39: Pentagonal Photonic Crystal Mirrors: Scalable Lightsails with Enhanced Acceleration via Neural Topology Optimization

The Starshot Breakthrough Initiative aims to send one-gram microchip probes to Alpha Centauri within 20 years, using gram-scale lightsails propelled by laser-based radiation pressure, reaching velocities nearing a fifth of light speed. This mission requires lightsail materials that challenge the fundamentals of nanotechnology, requiring innovations in optics, material science and structural engineering. Unlike the microchip payload, which must be minimized in every dimension, such lightsails need meter-scale dimensions with nanoscale thickness and billions of nanoscale holes to enhance reflectivity and reduce mass.

Our study employs neural topology optimization, revealing a novel pentagonal lattice-based photonic crystal (PhC) reflector. The optimized designs shorten acceleration times, therefore lowering launch costs significantly. Crucially, these designs also enable lightsail material fabrication with orders-of-magnitude reduction in costs.

We have fabricated a 60 x60 mm2, 200 nm thick, single-layer reflector perforated with over a billion nanoscale features; the highest aspect-ratio nanophotonic element to date. We achieve this with nearly 9,000 times cost reduction per m2. Starshot lightsails will have several stringent requirements but will ultimately be driven by costs to build at scale. Here we highlight challenges and possible solutions in developing lightsail materials - showcasing the potential of scaling nanophotonics for cost-effective next-generation space exploration.
Authors: L Norder (Delft University of Technology), S Yin (Brown University), MHJ de Jong (Delft University of Technology), H Aydogmus (Delft University of Technology), F Stallone (Delft University of Technology), PM Sberna (Delft University of Technology), MA Bessa (Brown University), RA Norte (Delft University of Technology)
Presenter: L Norder
Oral Presentation
Topics
* Advanced Materials
* Miniaturisation and Technology Development
* Propulsion

Submission #40: Towards optical levitation of centimeter scale photonic crystal lightsails
The quest for interstellar travel presents one of the most formidable challenges in modern science and engineering, primarily due to the need for propulsion systems capable of achieving relativistic speeds. Traditional chemical and nuclear propulsion methods are inadequate for these requirements, prompting exploration into alternative technologies such as laser propulsion. This approach leverages photon pressure to accelerate spacecraft to significant fractions of the speed of light, necessitating the development of ultra-lightweight, highly reflective structures. Due to required radiation pressure, achieving levitation at macro scale poses important challenges in the fields of optomechanics and nanofabrication, as these structures have to be optimized both for their mass and optical properties, generally resulting in designs with extreme aspect ratios with almost perfect reflectivity.
Here, we demonstrate our initial results and roadmap for achieving macroscopic scale optical levitation as a critical step towards the realization of laser-propelled spacecraft for interstellar travel. The focus is on the development, optimization and characterization of high aspect ratio photonic crystal membranes designed for stability and efficiency under high-intensity laser illumination.
Using cutting-edge nanofabrication techniques, we fabricate SiN photonic crystal lightsail membranes with extreme aspect ratios (1 cm/200 nm) optimized via neural network algorithms. Our novel fabrication-measurement scheme ensures these membranes are released and measured within an Inductively Coupled Plasma - Reactive Ion Etching (ICP-RIE) system, avoiding exposure to atmospheric pressure and external forces that could compromise their integrity. The photonic crystal lightsail membranes are subsequently subjected to continuous strong radiation pressure (400 W - 1,070 nm) to assess their mechanical integrity and dynamic stability.
We present our progress on achieving and characterizing the macroscale optical levitation and share our future plans with the goal of demonstrating the feasibility of stable levitation of macroscopic structures using a single laser, paving the path for this previously unexplored regime of optomechanics. These results will be essential for realizing the dream of interstellar travel, providing a feasible pathway to propel spacecraft beyond our solar system within human lifetimes.
Authors: Ata Keşkekler (TU Delft), Lucas Norder (TU Delft), Richard Norte (TU Delft)
Presenter: Ata Keşkekler
Poster
Topics
* Advanced Materials
* Autonomous Spacecrafts
* Miniaturisation and Technology Development
* Propulsion

Submission #41: Should Military Issues be Incorporated in Interstellar Missions?
Is there a need to think about military issues in relation to interstellar travel? I argue yes, based on a couple of primary lines of historical and current research.
First, all indications we have are that the universe is a 'life form eat life form' place. Predator-prey relations exist not just in the natural world but also in the realm of state politics. It is not just about resources either, conflict can and does arise over ego, fear, markets and many other reasons. The net is that based on our one-planet dataset, war is ubiquitous and thus countries must defend themselves (in some way or another).
Closely related to existential competitiveness is the question of an extraterrestrial's disposition. We have zero evidence that more advanced civilizations will be peaceful or benign. For that matter researchers also frequently assume monolithic ETs that speak and act with one voice, again without evidence. This implies that there could be a lack of civilizational agreement on how to treat humanity if encountered.
Second, there is no such thing as an unarmed interstellar-capable ship. At a minimum, from sheer kinetic energy, to main drive systems to electromagnetic communication systems powerful enough to work over interstellar distances, a starship can be a weapon. The unintentional mis-use of these systems or the energy of a starship might be interpreted as hostile acts. Avoiding these situations must be a paramount part of any mission.
For reasons cited it would thus be negligent not to think, plan for and incorporate some level of military practice into any interstellar ships including not just human or AI-crewed ships, but microprobes as well.
Author: Ken Wisian (University of Texas at Austin)
Presenter: Ken Wisian
Oral Presentation
Topics
* Autonomous Spacecrafts
* Ethics
* Space Law

Submission #42: Optimal Solar Sail Trajectories for Fast Deep Space Missions
Solar sail missions hold considerable promise for expeditions to the outer reaches of the solar system and interstellar travel due to their propellantless character. One approach to achieving high velocities involves utilizing a solar flyby (gravity and photonic assist) to accelerate the sail away from the solar system. Recent attention has focused on aerographene, an ultra-lightweight material with a density of 0.16 kg/m3, offering significantly improved performance potential compared to conventional materials like mylar or kapton. However, aerographene's complete absorptive nature poses challenges for controllability of the sail, eg the ability to arbitrarily change its trajectory.
In this study, we propose an optimal control approach to find a trajectory maximizing the excess velocity of a solar sail towards the farthest regions of the solar system, leveraging a solar flyby. We address the challenge of temperature constraints, crucial for preventing material degradation near the Sun. This involves incorporating constraints on both the state variable (distance from the Sun) and control variable (orientation of the sail) to manage surface temperature fluctuations. Specifically, while proximity to the Sun may be necessary for gravitational and photonic assists, it also risks excessive heating, necessitating adjustments to sail orientation to mitigate temperature effects.
To solve this optimal control problem with combined constraints, we employ a multiple shooting method with a constrained arc. We derive optimality conditions using Pontryagin's principle and analyse the Hamiltonian dynamics to formulate an optimal control problem tailored to ideal, ie perfectly reflective, solar sails.
Furthermore, continuation techniques are employed to assess the impact of degraded sail performance (with a less reflectivity coefficient) on trajectory variations. This exploration aims to determine the feasibility of interstellar missions solely with aerographene sails.
This comprehensive study offers insights into optimizing solar sail trajectories, addressing key challenges for ambitious deep space exploration missions. By integrating theoretical analysis, numerical simulations, and innovative design concepts, we advance our understanding of solar sail dynamics, laying the groundwork for future interstellar exploration endeavours.

Authors: Alesia Herasimenka (University of Luxembourg), Lamberto Dell'Elce (Centre Inria de l'Université Côte d'Azur), Andreas Hein (University of Luxembourg)
Presenter: Alesia HERASIMENKA
Oral Presentation
Topics
* Advanced Materials
* Propulsion

Submission #43: Astrosociological design of protocols for encounters with extraterrestrial life
Background
The paper attempts to lay the ground work for safe and trustworthy encounters with alien civilisations through simple protocols that AIs are trained to execute and offers three new 'laws of robotics' derived from them with which to inculcate artificial sentience and replace other efforts in that direction, for example, the notorious three laws of robotics first suggested by the fiction writer Isaac Asimov.
Objective
The paper considers how a sociobiologically determined set of bioethics can be fashioned into a set of universal protocols with which encounters with extraterrestrial life may be managed. These protocols will be simplified into an alphanumeric formula to capture the essential levels of trust for useful communications and suggest how the incorporation of AI into communications will overcome the prejudices likely to be present in exchanges with ETIs and to provide a basis for expecting an alien counterparty to possess similar ethical protocols to generate trust.
Methods
It examines three bioethics and within each considers a hierarchy of dynamical trust parameters. The three bioethical principles are derived from the concept of strangeness in the visual cognitive dimension to inclusive fitness, from environmental logic and from an initial neutral communication protocol designed to avoid revealing too much about Humanity. A simple alphanumeric code is generated to annotate the degree of trust present in an encounter with an ETI. From a hierarchy of trust levels it can be shown how interactions may proceed for Humans during encounters with all life, microbial or intelligent, organic or artificial.
Results
With the trust levels within the three bioethics the necessity for a deceitful presentation of Human nature becomes clear. An agnostic protocol of first interaction is derived in which generative language text models can replace other mathematical and logical astrolinguistic proposals for extra terrestrial communications like LINCOS and can be applied to communication even under potential risks in untrustworthy alien encounters.
Conclusions
Communication with ETIs must begin with a known level of deceit in order to build trust. Developing common mathematical or science languages will be the least productive way of communicating with ETIs.
Authors: Andrew Kennedy (Project Chronolith), Stella Grania Kennedy Kennedy-Whitaker (none)
Presenter: Andrew Kennedy
Oral Presentation
Topics
* Communications
* Ethics

Submission #45: The use of Textiles as a processing form for space applications
Since the dawn of human history, we have sought a fundamental necessity for survival: the hut or the cave as a form of protection. This fundamental aspect of human existence has remained constant throughout history, but the way we think about living has evolved. The resumption of space travel, has made the prospect of living in space become a tangible possibility, revolutionizing the way we think of life. If the house meets the needs of the occupants on Earth the habitat does so in space. This challenge addresses various factors that must be considered when building in an extreme environment. This factor represents a significant challenge for the selection of materials that are optimal for use in space. The use of in situ materials will be a necessity for the construction of habitats on a planetary surface, given that regolith is the most abundant material on it but it is also necessary to consider the use of textiles.
The behaviour of the textile as a form of processing will provide a variety of solutions to the space challenges. One example is the possibility of creating moon fibre from regolith, which could be used as a building material in future lunar bases. The selection of materials for use in space is a crucial decision, but equally important is the manner in which these materials are employed. The choice may fall upon hard or solid structures or alternatively, flexible or mouldable materials. The choice of the most suitable solution is contingent upon the specific applications or requirements, which may include the facilitation of communication, the transport, the production of components, or the construction of habitats. For this ongoing research, a series of experiments will be conducted to assess the applicability of different textiles for the use of outer space habitats.
This approach will lead to a more comprehensive understanding of the potential for construction in space. Whether used alone, in combination with other materials such as regolith or as a form of processing textiles offer a multitude of properties that are essential for a space-based operations.
Authors: 1. MSc Linda Cortes Satizabal (Institut für Textiltechnik der RWTH Aachen University), Dr.-Ing. Kira Heins (Institut für Textiltechnik der RWTH Aachen University), Dr.-Ing. Christian Boltersdorf (Institut für Textiltechnik der RWTH Aachen University), Univ.-Prof. Prof hc Dr-Ing Dipl.-Wirt.-Ing. Thomas Gries (Institut für Textiltechnik der RWTH Aachen University)
Presenters: MSc Linda Cortes Satizabal, Institut für Textiltechnik der RWTH Aachen University, Dr.-Ing. Kira Heins, Institut für Textiltechnik der RWTH Aachen University, Dr.-Ing. Christian Boltersdorf, Institut für Textiltechnik der RWTH Aachen University
Poster
Topics
* Advanced Materials
* Life Support Systems and Habitats
Special Session

Submission #47: Project Hyperion: Systems Architecting of an Interstellar Generation Ship
Background
Project Hyperion is a conceptual study of a hypothetical interstellar generation ship. Since 2023, the Hyperion team has been working on organizing an interdisciplinary design competition on the habitat of the generation ship. Design competitions have proven to be an effective means of generating a variety of designs to explore a novel design space. The highly interdisciplinary nature of generation ship habitats, spanning architecture, engineering, and social sciences makes it a particularly challenging design problem.
Objective
This talk presents the system architecting process to define the Project Hyperion competition, which includes the steps of defining the context, system boundaries, system and sub-system-level requirements and constraints.
Methods
We use concepts from architecture (functional spaces), social sciences (cultural invariants), and engineering (habitat geometries, bioregenerative life support systems) to combine them into an integrated socio-technical framework, where the focus is on the interdependencies between the features of the habitat and the society's structure.

Results
We present the first results from the competition and where the designs are situated in the design space. Designs with unusual positioning are also presented.
Conclusions
We conclude that an iterative approach to define competitions and an analysis of the resulting designs may efficiently steer the process of converging towards a baseline architecture for a generation ship habitat.
Authors: Andreas M Hein (Initiative for Interstellar Studies), Yazgi Demirbas Pech (Initiative for Interstellar Studies), Cameron Smith (University of Arizona), Dan Fries (Initiative for Interstellar Studies), Claas Olthoff (University of Stuttgart), Steve Summerford, Maciej Rebisz (Independent)
Presenter: Andreas M Hein
Oral Presentation
Topics
* Life Support Systems and Habitats
* Miniaturisation and Technology Development
* Psychology, Anthropology and Crew Health

Submission #48: Project Lyra: Opening up the space between the stars - Missions to Interstellar Objects and Nomadic Worlds
Background
It is frequently believed that the space between the stars is empty. The interstellar community is firmly grounded in this belief and is predominantly focused on missions to other star systems. Today, we know that the space between the stars is not empty but is populated by a plethora of objects. While interstellar dust has been known for many decades, more recently, larger objects have been discovered, such as interstellar objects and nomadic worlds.
Objective
We present a variety of mission architectures to interstellar objects and nomadic worlds and thereby explore propulsion technology – trip time limits over a variety of distance requirements.
Methods
We use the Optimum Interplanetary Trajectory Software (OITS) to find optimal trajectories for various interstellar objects alone. Furthermore, we use Technology Readiness Levels (TRL) for comparing propulsion system performance with maturity.
Results
We find that chemical propulsion in combination with a solar Oberth manoeuvre and/or flybys (in particular the Passive Jupiter Gravity Assist (PJGA)) reaches its limits at a distance of roughly 500 AU, if the maximum trip time is set at about 80 years. For reaching nomadic worlds, which may have average distances of 10^3 to 10^4 AU, precursor versions of interstellar-capable propulsion systems are needed, such as laser sails and fusion propulsion.
Conclusions
We conclude that existing propulsion systems, combined with flyby maneuvers are viable for reaching interstellar objects up to hundreds of AU distance, which is in a similar range as the putative Planet Nine. However, nomadic worlds (hundreds of km in diameter) are likely only reachable via interstellar-capable propulsion systems. The presented results have important implications for future propulsion system roadmaps, which should also focus on the development of interstellar-capable propulsion systems.
Authors: Andreas M Hein (Initiative for Interstellar Studies), Adam Hibberd (Initiative for Interstellar Studies), Manasvi Lingam (Florida Institute of Technology), Marshall Eubanks (Space Initiatives), Dan Fries (Initiative for Interstellar Studies), Robert Kennedy (Institute for Interstellar Studies), Jean Schneider (Paris Observatory)

Presenter: Andreas M Hein
Oral Presentation
Topics
* Miniaturisation and Technology Development
* Potential Destinations and Astrophysics
* Power Systems
* Propulsion
Special Session

Submission #50: Integrating Interstellar Research and STEM Education: Pioneering the Future of Space Travel
Background
The Limitless Space Institute (LSI) is at the forefront of pioneering advancements in interstellar research and education. Through the funding of groundbreaking research through the LSI Grants and Fellowship program, significant advancements have been made in the power and propulsion of spacecraft, and our comprehensive STEM education and outreach programs, we are committed to inspiring and educating the next generation of explorers and the workforce that will establish our home among the stars.
Objective
Our primary objective is to present the latest advancements in interstellar research funded by LSI and to showcase our robust STEM education initiatives. We aim to illustrate how integrating interstellar concepts into classrooms worldwide can inspire and educate the future workforce necessary for achieving interstellar travel. By participating in the European Interstellar Symposium, we seek to highlight the importance of early exposure to interstellar travel concepts to foster a generation capable of realizing these ambitious goals.
Methods
Research Initiatives:
• Target Population: Research teams and institutions focused on interstellar travel.
• Program Content: Funding and support for innovative research projects, including theoretical and experimental approaches to propulsion, power generation, and autonomous systems.
• Evaluation Method: Regular progress reviews, peer-reviewed publications, and collaborative workshops to assess the impact and feasibility of the research.
STEM Education and Outreach:
• Target Population: Global citizens passionate about inspiring the next generation of explorers who will "go incredibly fast".
• Program Content: Development of curriculum and educational materials that integrate interstellar travel concepts, hands-on activities, virtual experiences and in person trainings both in the host country and Houston, Texas.
• Evaluation Method: Surveys, feedback forms, and performance metrics from participating schools and educational institutions to measure engagement and learning outcomes.
Results
Through the LSI Grants and Fellowship program, funded research around the world has yielded significant advancements in spacecraft power and propulsion technologies. Our support on the educational front, our programs have reached thousands of students globally, igniting interest in STEM fields and providing them with a foundational understanding of interstellar travel. Feedback from educators indicates a high level of engagement and enthusiasm among students, with many expressing a newfound interest in pursuing careers in space exploration and related fields.

Conclusions
The findings from our research and educational initiatives demonstrate the vital role of early exposure to interstellar concepts in inspiring the next generation. Integrating these concepts into K-12 education not only fosters a deeper interest in STEM but also prepares a skilled workforce capable of tackling the challenges of interstellar travel. Our participation in the European Interstellar Symposium aims to further these efforts by fostering collaboration and knowledge exchange among the multi-disciplinary community dedicated to building our home among the stars.
By bridging the gap between current research and education, the Limitless Space Institute is paving the way for a future where interstellar travel is not just a dream but a reality.
Author: Kaci Heins (Limitless Space Institute)
Presenter: Kaci Heins, Executive Director
Oral Presentation
Topic
* Propulsion

Submission #56: Interstellar Astrometric Navigation
Background
Interstellar spacecraft need to know their position and velocity at various points in their mission in order to make course corrections, and to switch on/off propulsion, instruments, or communications. Given their large distances from Earth, spacecraft must be able to navigate autonomously.
Objective
I develop a model to determine the 3D position and 3D velocity of a spacecraft using measurements of the angular separations of stars.
Methods
The Gaia survey has provided accurate stellar positions and velocities relative to the solar system barycentre (SSB). A spacecraft at some other arbitrary position and velocity can observe the same stars, but at different angular positions due to parallax, aberration, and proper motion. This can be inverted: By measuring the relative angular positions of the stars, the 3D position and 3D velocity of the spacecraft relative to the SSB can be inferred, here using a Monte Carlo approach. The model requires measurements of only the angular separations between pairs of stars (no absolute measurements), as done historically with a sextant. The model takes into account special relativity and light travel time. An accurate onboard clock is not required as the approximate SSB time is also inferred. Stellar radial velocity measurements may be used in addition or instead to achieve similar results. I demonstrate the performance using simulated spacecraft data together with real astrometric data.
Results
Using 20 bright, nearby stars and assuming an angular measurement accuracy of 10 mas (milliarcseconds), the position of a spacecraft can be determined to within 0.03 au and its velocity to 20 m/s.
The accuracy improves linearly with the accuracy of the angular separation measurements. Increasing the number of stars or taking multiple measurements over time improves the determination further.
Conclusions
While not as accurate as pulsar navigation in the solar vicinity, the astrometric method works in deep space many parsecs from the Sun, where pulsar navigation would also have to accommodate parallaxes. Astrometric navigation can also be used for initialization, combined with pulsar navigation, or used as a backup system.
This work builds on that published by the author in [PASP 133:074502 (2021)](https://iopscience.iop.org/article/10.1088/1538-3873/ac0774).

Author: Coryn Bailer-Jones (Max Planck Institute for Astronomy)
Presenter: Coryn Bailer-Jones
Oral Presentation
Topics
* Autonomous Spacecrafts
* Miniaturisation and Technology Development

Submission #57: Macro-Environmental and Technology Readiness Assessment for Interstellar Travel Infrastructure

Background

Habitats on Earth are part of a larger macroenvironment that provides infrastructure, supplies, and services, alongside the microenvironment within each habitat. When designing for human space travel, all macro and micro aspects are considered. Deep space design includes everything from the transportation to the buildings, devices, and breathable air. Therefore, the concept of the macroenvironment includes infrastructure systems beyond individual mission requirement. Given the limited human space travel experience, further ventures into space require increased involvement. What does an infrastructure plan on the Moon look like, and how does that compare to supporting deeper missions in the solar system and interstellar travel? Answering such questions aids in designing for extended space travel and envisioning long-term infrastructure and maintenance strategies.

Objective

This paper outlines and assess the (i) main survival and functional elements needed for sustainable space travel across various destinations and mission types, from cislunar to interstellar, (ii) quantities and interconnected requirements, (iii) the technology status, and (iv) the anticipated timeline for achieving the technology readiness.

Methods

The tables and matrices present basic elements including space and terrain routes, energy systems, and supplies like food, water, and gases, comparing their use for single missions versus their role as infrastructure for multi-missions. The assessment charts the requirements and technology readiness for cislunar, planetary, and interstellar trips. The evaluation involves referencing previous studies related to the sequence and technological requirements for both achieved and anticipated travel such as ISP and Road Map to the Stars. Additionally recent documented advancements in space travel since 2015 are used for comparison and to project the future pace of space exploration utilizing aggregated design items such as Starship Gliina System.

Results & Conclusion

In extended space travel, the complexity of designing macroenvironmental and infrastructural requirements grows significantly. The assessment of the components' requirements shows an exponential increase in magnitude as travel distances and intervals expand. That aligns with the trajectory of technological readiness capability timelines. Such realistic guidelines enhance the design of infrastructure and maintenance components, improving resilience, longevity, maintainability, and maintenance protocols while decreasing the burden of involving several macroenvironment elements in each mission.

Author: Antoine G Faddoul (Tony Sky Designs Group)
Presenter: Antoine G Faddoul
Oral Presentation
Topic
* Life Support Systems and Habitats