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Evolving Asteroid Starships: A Bio-Inspired Approach for Interstellar Space Systems

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Abstract

The hostile and unpredictable environment of deep space requires a new conceptual approach for interstellar flight, one that differs radically from any current design in aerospace. A design solution is proposed in which the starship is attached to a C-type asteroid and whose architecture evolves over time. The starship gradually mines resources of the asteroid, while at the same time using it as a shielding structure against frontal impacts. The extracted raw materials are used for cultivation of the onboard ecosystem and expansion of the starship's architecture, the latter of which is primarily conducted by mobile 3D printers. Within the bounds of its sensing horizon, the spacecraft can detect prospective high-energy particle collisions and radiation events along its upcoming flight path. Subsequently, the starship will adapt itself by changing its interior and exterior morphology. This constant evolution aims to minimize the spacecraft damage and loss of functionality, and handles the inherent unpredictability of the mission. The Delft University of Technology Starship Team (DSTART) simulates this concept using an array of different techniques. The ecosystem dynamics are approached using agent-based modeling, while the evolving architecture of the starship is approached with genetic algorithms. The starship simulation relies on four distinct timelines. A first timeline provides real-time updates on the state of the starship's regenerative ecosystem, with a focus on population sizes, mass fluxes, and radiation impact. ESA's MELiSSA project was used as a conceptual blueprint for the ecosystem. A second timeline deals with the growth of the starship architecture, taking into account material supplies, mining rates, 3D printing speeds and wear of existing structures. The third timeline forecasts the impact of future particle collisions and interstellar radiation as assessed within the sensing horizon. The fourth and final timeline is concerned with the evolution of the starship architecture as a response to this forecast. This is done by comparing the structural integrity and ecosystem health of different variations of the starship's morphology. The first results of this work will be presented, as well as an overview of the implications for space system design.
Keywords: interstellar exploration, spacecraft design, bio-inspired, evolvable, asteroid mining, 3D printing

1. Introduction

Throughout the history of space exploration, manned spaceflight systems have always been developed incrementally. It's only through a series of subsequent missions that spacecraft are gradually brought to their intended destination. Each individual mission allows for new risks to be assessed, and technologies to be added or optimized. NASA's Apollo program is a good example of this. The first 10 Apollo missions got incrementally closer to the Moon, and it was only Apollo 11 that would finally touch down on the lunar surface. Manned interstellar spaceflight, however, mandates a completely different approach, given that stars are at least 4-6 light years away and future spacecraft will most probably travel at only a fraction of the speed of light. Under these circumstances, an Apollo-style approach to reach a nearby star could take up multiple centuries. This paper explores a different design paradigm, focusing on a new evolvable spacecraft concept.

Interstellar space is a hostile, but also largely unknown environment. Cosmic radiation poses a significant risk for all biological life on board a starship. And solid interstellar dust grains may create a critical hazard for a starship traveling at a speed larger than $0.1c$ [1]. However, our knowledge about the actual nature of the local interstellar medium (LISM) is very limited [2]. As such, it is difficult for mission planners to assess specific risks and map all contingencies of a manned interstellar mission departing from our own Solar System. This high level of uncertainty creates an engineering conundrum: how to design a system that can handle future challenges that are largely unknown? This is where a bio-inspired approach comes in as a potential solution. Instead of trying to design a system that can only tackle a discrete set of expected contingencies, one can also design a system with the capacity to gradually develop itself during the mission, and evolve into more optimized configurations when previously unexpected challenges are being faced. Such bottom-up design approach is the domain of morphogenetic engineering (ME). In ME, systems are not built directly, but instead using groups of building agents, such as a swarm of construction robots. It's through designing both the properties and behaviors of the agents that a required design result can be achieved. ME is inspired by building and design processes found in nature. The self-assembled, natural world provides examples of some of the most efficient functional systems known [3]. For example, termites, ants, or wasps are capable of collectively building complex, but well-organized nests without the need for a central plan or chief architect [4]. There are several advantages to using such decentralized bottom-up approach in building [4]:

- There are fewer communication bottlenecks throughout the entire construction process.
- The use of autonomous agents creates a solution-rich space, potentially resulting in unexpected solutions.
- When many agents are used, this results in massive parallelism, and hence, increased efficiency.

Building space systems in situ, instead of launching them from Earth, has been explored for many decades. In 1980, a proposal for a self-replicating lunar factory was published by NASA [5]. A small number of initial construction robots would be sent to the lunar surface, and use the lunar regolith as a resource both for building a lunar factory and replicating themselves to speed up the construction process. More recently, there's been a multitude of studies by several space agencies in the possibility of 3D manufacturing habitats on the Moon or Mars. In Contour Crafting, the regolith is combined with a chemical binder, and the resulting paste is used to 3D print the architectural volumes [6]. The solar sintering approach gets rid of the need for a binder all together and melds the regolith particles strictly using heat [7]. Apart from regolith, water ice has also been suggested as an in situ building material [8]. In all of these examples, the main motivation to use local materials is to reduce launching mass. However, 3D manufacturing also offers the advantage of generating adaptive and response space systems. Elements can be added or changed whenever the need arises, and as such construction can be approached in a much more dynamic way.

To test the idea of a growing and evolvable asteroid starship, a computer simulation is being developed in which virtual interstellar missions can be created, and the corresponding evolution of the starship can be studied. It's a multigenerational starship with a mission time fixed at a 100 years. The following three-step methodology is used: modeling, simulation, testing. In the modeling stage the entire system architecture of the starship is being elaborated. In the simulation stage this architecture is translated into code, while in the testing stage the behavior of the system is being investigated under different conditions. The goal of the current paper is to present a high-level description of the hybrid model that is currently being developed by the DSTART research team at Delft University of Technology.

2. System description

This section provides a high-level description of the system architecture of the starship. Both the individual system elements and their relations are being described, as well as the different processes that enable the dynamic and evolvable capacities of the starship.

2.1 Assumptions

The assumptions underlying the starship model are situated within the following domains:

- propulsion system
- attitude control
- power generation and distribution system
- thermal control
- structural integrity and failure
- asteroid mining
- 3D manufacturing

Propulsion physics are not part of this study. It is assumed that an unspecified propulsion system is in place that can accelerate the starship to a maximum speed ranging between 1 to 10% of the speed of light. This is accompanied by an adequate fuel supply. Throughout the simulation, the starship follows a straight line, and no attitude control mechanisms are being used. It is also assumed there is an unspecified onboard power generation system that provides energy to all systems. Thermal control is considered less crucial because of the lack of intense stellar radiation in interstellar space, and is currently not taken into account. The integrity of the individual starship components is part of the simulation, but there are no calculations on overall structural integrity and failure. The asteroid mining is assumed to be laser-based, but is further technically unspecified. 3D manufacturing is assumed to be carried out by mobile robotic systems. The number of operational systems and the creation of additional systems are not included in this model.

2.2 Overview

The spacecraft concept that is proposed here, is that of an asteroid starship. In this concept, an asteroid gets redirected and is gradually transformed into a large-scale hybrid spacecraft, while also retaining some of the original structure of the asteroid. The idea of adapting asteroids into spacecraft originally dates back to the 60s, and was more recently also explored in Project RAMA, a 2017 NIAC study [9]. The architecture of the starship is being developed both behind and inside the asteroid (Fig. 1), using resources that are mined from the asteroid itself. The architecture is composed of individual geometric modules. The modules are being added during a growth stage, or repositioned during an evolutionary stage of the starship. Life support onboard the starship is being provided by a regenerative life-support system (RLSS) based on the MELiSSA concept of the European Space Agency.

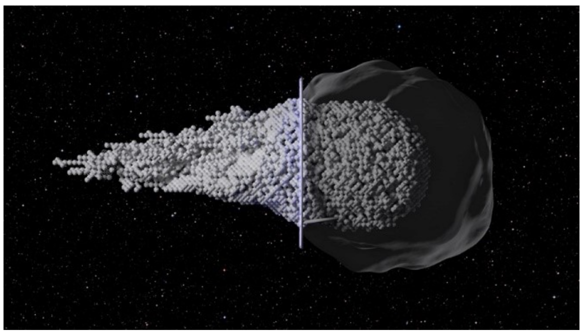

Fig. 1. Overview of the general layout of the asteroid starship. 3D modeling by Nils Faber.

2.3 Spacecraft elements

2.3.1 Asteroids

Carbonaceous or C-type asteroids are considered the most suitable for the proposed model because they contain compounds that are useful both for biological life support and for architectural building. The water and organics of the asteroid [10,11] can be used to expand the RLSS and the crew population. In line with the existence of carbonaceous meteorites with high metal contents (the CH group) [12], a C-type asteroid with a significant amount of metals could be selected. In this way, both the carbon and the metals can be used to 3D manufacture the architectural modules. Asteroids with a size of a few hundred meters diameter are considered for our current concept. It is important to choose a size that is big enough to provide the right amount of resources, but as small as possible to facilitate propulsion. Apart from being a resource, the asteroid also doubles up as a frontal shield, protecting the rest of the spacecraft both from particle impacts and cosmic radiation.

2.3.2 Modules

A modular architecture approach was chosen because this allows for a flexible morphology (Fig. 2). Modules can be added, removed and repositioned, and as such, the overall spatial and functional organization of the starship can be adjusted to changing needs. The truncated octahedron is used as standard volume. This is a space-filling polyhedron with 14 sides to connect with surrounding modules. All modules have the same standard size with an edge length of 5 meters, and a maximum diameter of the entire volume of 14.1 meters.

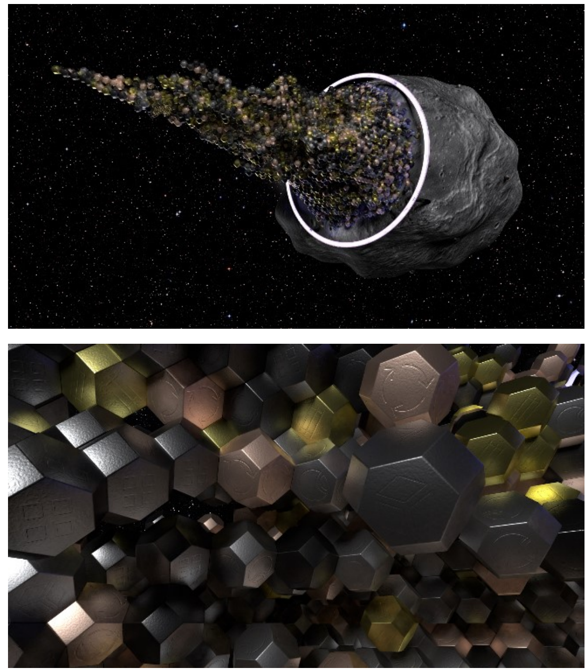

Fig 2. Top: The tail section of the starship with its modular architectural layout [13]. Bottom: Architectural modules manufactured using different materials extracted from the asteroid. The debossed symbols indicate different module functions. 3D modeling by Nils Faber.

In order to maximize building capabilities, a differential 3D manufacturing approach is used. Depending on the available supplies of refined compounds, different architectural volumes can be manufactured using different materials. This could be for example carbon, aluminum or copper. The thickness and material structure of the module walls is then adjusted to attain the same overall structural and radiation protection properties. At this point, each module is manufactured out of one single material. In a later stage of this study, multi-material 3D manufacturing will be considered.

Nine different module types were defined, each with their own functionality:

- regenerative life support module
- habitation module
- mining module
- ore storage module
- processing module
- refined materials storage module

- manufacturing module
- radiation shielding module
- collision shielding module

When creating new modules, specific proportions between different modules are being used as a guideline what to print. It is assumed that 1 habitation module provides space for 6 inhabitants. This including the fraction of shared social spaces for all crew members. Taking into account the volume that the MELiSSA system currently uses, it is estimated that the RLSS equipment in 1 biological life support module could keep 6 people alive. This means that for every new habitation module needed for an expanding crew population, 1 additional RLSS module needs to be manufactured. These are preliminary estimates, and further calculations are needed to establish more precise figures.

Next to the nine module types, remote sensors are also part of the starship design. These are positioned at the front of the asteroid, and are essential to gauge upcoming environmental challenges, and as such, provide essential information for the evolution of the starship. Technically, they are characterized by a specific sensing horizon. The array of remote sensors has a high level of redundancy to compensate for the loss of equipment due to particle impacts or damaging radiation events.

2.3.3 RLSS

A regenerative life-support system (RLSS) is of great importance to keep the starship crew members alive. Relying on single-use food, water and oxygen supplies is highly inefficient and technically impossible for such a long journey. Therefore, the starship must create its own supplies by making use of the available waste streams of the crew. Mimicking nature, where regeneration is key to keep ecosystems alive, is the solution to surviving long-duration interstellar travel. ESA's Micro-Ecological Life Support System Alternative (MELiSSA) is one of the various attempts to design a closed-loop system which supplies the crew member with oxygen, water and food.

MELiSSA takes its inspiration from a typical lake ecosystem and conceptualizes this by means of 5 different compartments [14]. All compartments are interconnected and have different functions within the system, converting the waste products of the astronauts into edible plants and algae, fresh water and clean air (Fig. 3). The first three compartments (CI, CII, CIII) are bioreactors that convert human feces and non-edible plant parts into plant fertilizer and CO_2. Two food production systems (CIVa, CIVb) provide the astronauts with fresh produce and edible algae. This results in a vegetarian diet combining a wide variety of crops with the algae species *Arthrospira* (also known as Spirulina), addressing the different nutritional needs of the crew. The last compartment is the crew compartment (CV).

So far, MELiSSA has only been tested on a lab scale, without full closure of the entire metabolic loop. The complete system has yet to be tested under the levels of demand and stress experienced during an actual space mission. This means there is little insight in how the system would behave if put under the demands of a long-duration multigenerational space mission, as proposed in this study. Among the possible issues the system would have to face, are the needs of a crew whose numbers increase over time, and the hazards that characterize deep space such as harmful cosmic radiation. The MELiSSA simulation that has been created for this study will enable us to precisely investigate these kinds of issues (see subsection 3.2).

2.4 Spacecraft architecture

The architecture of the starship is developed in a cone-shaped volume behind the asteroid to maximize the protective effect of the asteroid. The size of the cone depends on the diameter of the asteroid and the safety angle that is selected (Fig. 4). Because of the mining and extraction procedures, the asteroid is gradually being hollowed out. This empty space is subsequently filled up with 3D manufactured modules. The architecture thus develops itself in two opposing directions: inside the asteroid, and away from it, as a 'tail'.

2.5 Processes

2.5.1 Ecosystem dynamics

The human population is allowed to expand during the interstellar journey. As a consequence, the RLSS needs to expand accordingly, and the different populations of microorganisms and plants need to increase. The ecosystem dynamics in this study is primarily described in function of population sizes and compound concentrations.

In each of the five MELiSSA compartments, compounds are transformed by living organisms. In this study, the mass flow of the four most common elements (carbon, hydrogen, oxygen, and nitrogen) is being investigated. These four atoms appear in different types of compounds which are continually being converted into other types of molecules through the metabolic processes of the five compartments. The output of each compartment is used by at least one other compartment as input, through a web of intersecting metabolic interactions. In describing

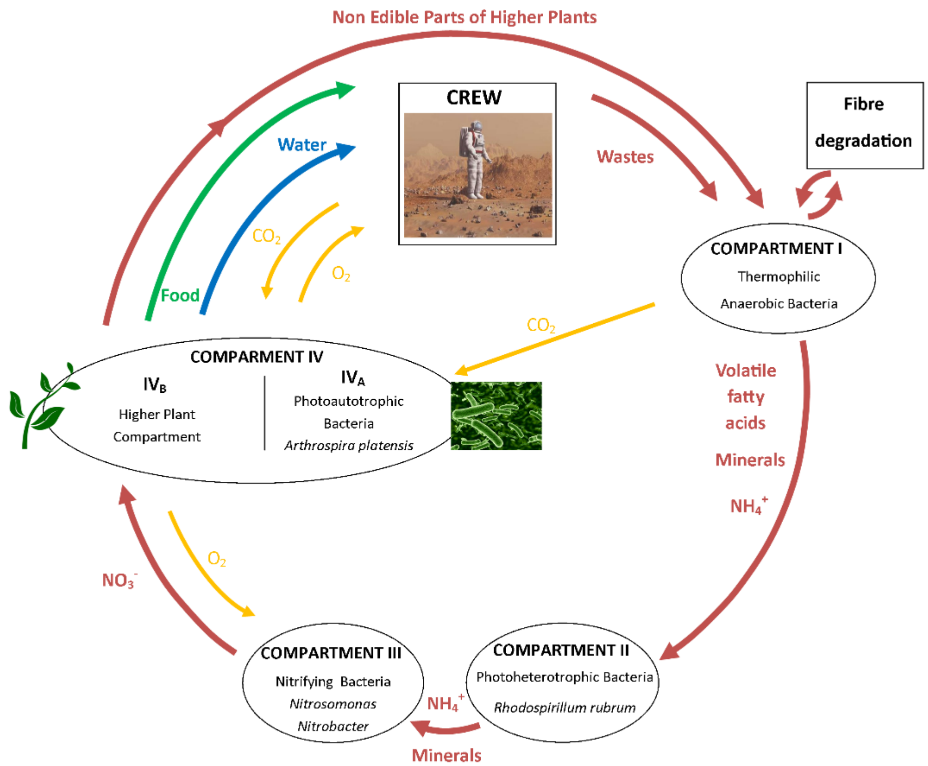

Fig. 3. MELiSSA regenerative life support system with its five main compartments and major mass flux directions. Diagram by MELiSSA/ESA.

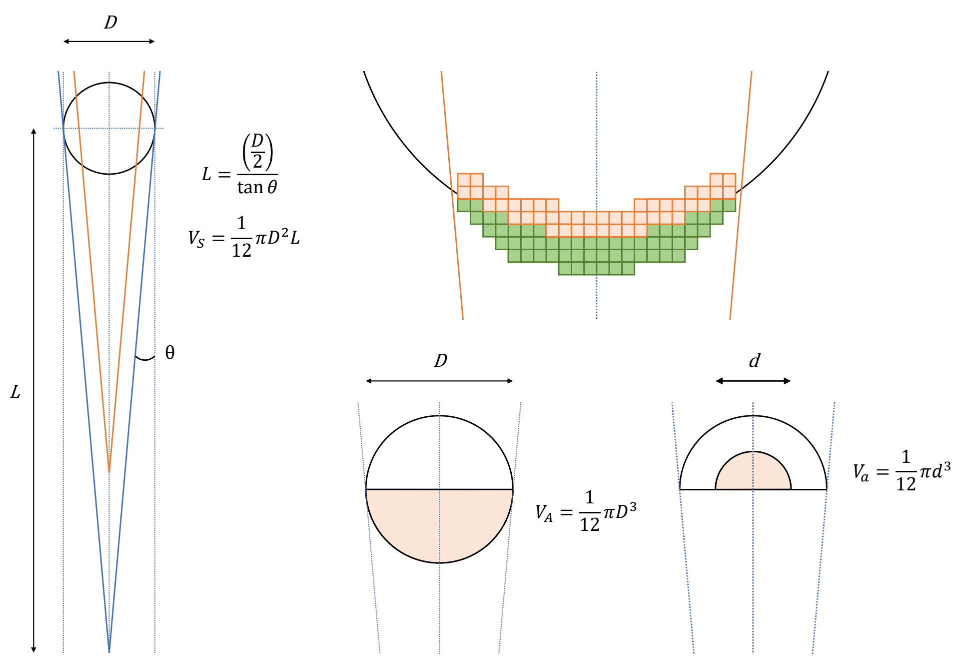

Fig. 4. The starship architecture is partially developed inside a conical volume behind the asteroid. The asteroid itself is gradually being mined and hollowed out. In the excavated space new architectural modules are being built. D = diameter of the asteroid; d = diameter of the posterior hollowed out part of the asteroid; θ = safety angle to reduce the chance of particle or radiation impact; L = maximum length of the starship architecture; V_A and V_a = volumes of the excavated asteroid materials.

these interactions, it is essential that all used equations are stoichiometrically balanced, and that the cycles of all four elements are closed. In other words, in a steady state condition, all the molecules which are produced have the be consumed.

The population size of each compartment determines the speed at which the different compounds are being processed. To prevent an accumulation of a compound in one of the compartments, balancing all the sizes of the compartments is necessary. Otherwise, this accumulation will cause a shortage of other compounds further down the loop, endangering the survival of the entire system.

Because of the multiple intersecting interactions, the MELiSSA loop is a complex system displaying emergent behavior. Concentrations of different compounds vary over time, even in steady-state conditions and with a stable human population. This variable availability can have a significant impact on the population sizes of the different microorganisms and plants. The goal is to design a system in which these variations remain within acceptable boundaries and do not endanger the survival of the crew. When the human crew size is growing, more resources (sourced through asteroid mining) are added to the RLSS loop, and the populations of microorganisms and plants expand accordingly.

2.5.2 Asteroid mining

In order to support a gradually growing crew size, the RLSS needs to be expanded and more space needs to be provided. This is handled through 3D manufacturing using a range of compounds extracted from the asteroid. Asteroid mining is currently considered a potential major future economic activity in space, and several private companies are currently looking into its technical and economic feasibility. Hypothetical laser-based mining technology is used with a specific mining rate. The amount of mined ore and extracted chemicals is constantly kept track of. Mining starts at the back, on the surface of the asteroid using mining modules. These modules excavate a space which is identical to a module. That space is subsequently transformed into new mining module, while the old module gets a new function. Consequently, the architecture of the starship develops itself gradually inside the asteroid. The maximum available volume for mining is the first half of the asteroid plus an interior part of the remaining half (Fig. 4). The thickness of the remaining asteroid shell depends on the structural integrity of the material.

2.5.3 Architectural growth

The expansion of the starship architecture is primarily a response to the gradually increasing crew size, and consequently, to an increased need for RLSS. If, at a certain moment during the journey, more compounds are needed, mining activity will need to go up, together with storage, refining and manufacturing capabilities. This also implies an architectural expansion. A hypothetical mobile 3D manufacturing technology is used to create the modules. A differential 3D printing approach is used in which, depending on which extracted materials are available, different modules can be printed out of different materials (e.g. aluminum, copper foam, carbon fiber). The thickness of the module walls can be varied in order to obtain the same radiation and/or impact protection. It is assumed that the walls of the modules will wear out over time, due to particle impacts and radiation (energy absorption) [15]. It is therefore important to replace the modules at regular time intervals, especially the ones located at the outer edges of the starship. These modules are then recycled and added to the amount of refined materials that is available for 3D manufacturing.

2.5.4 Environmental impact

The interstellar medium poses two major physical challenges that are difficult to predict: dust particle impacts and cosmic radiation. Even though the density of dust particles in the LISM is very low [2], a significant amount can be encountered during a relatively short time span because of the high velocity of the spacecraft. Also, precisely because of that high spacecraft velocity, even an impact with a small particle can cause significant damage.

Cosmic radiation and particle impacts can have a detrimental effect on both the onboard regenerative life support system and the starship's architecture. When radiation levels get too high, this will be lethal for at least a part of the populations of microorganisms and plants that make up the RLSS [16]. As already mentioned, particle impacts, and to a lesser degree radiation, will gradually wear down shielding and module walls. As such, the shielding and other modules will have to be replaced after being exposed for a prolonged period of time.

In order to assess the environmental impact of the LISM, two types of onboard environmental sensors being used: local and remote. The data from the local sensors are used to calculate real-time effects. The data from the remote sensors are used to assess upcoming effects, and are crucial to deciding when and how the starship's configuration should be evolved.

2.5.5 Architectural evolution

The starship's architecture is conceived as a reconfigurable system in which modules can be disconnected and relocated. This allows for changing the overall morphology of the spacecraft, and for functionally reorganizing the spacecraft. For example, if strong radiation is expected from a particular side, more shielding can be moved to that location, and modules that are more sensitive (such as habitation and RLSS) can be moved to a different spot. Such evolvability is crucial to maximize the resilience of the starship and the survival of its inhabitants.

The sensing horizon of the remote sensors is limited, and substantial dangers posed by the upcoming interstellar medium can only be detected from a certain point in time onward. Once the decision has been made that an evolution of the starship's layout is necessary, there's a limited time-frame in which the different steps of the starship's reconfiguration can take place. First, a better configuration needs to be calculated. This process should be limited in time, and still allow for the execution of the reconfiguration process. If additional modules need to be manufactured, this also needs to be taken into account. As such, the limited time that is available for adjustment is a crucial constraint in calculating a more optimized configuration of the starship.

3. Simulation description

3.1 Assumptions

There is a range of assumptions specific to the simulation. These are complementing the assumptions that are listed in section 2.1, and deal more precisely with how things are being calculated and which values are used. Key assumptions are listed below.

- The starship starts its journey with an initial human population of 50-100 people.
- Chemical compounds are equally distributed throughout the asteroid.
- Mining and processing rates are assumptions that can be varied in simulation experiments.
- 3D manufacturing time of the internal infrastructure of modules is not considered.
- The remote sensors measure upcoming environmental challenges with a lower resolution than the local sensors.
- Several assumptions have been made in the MELiSSA agent-based model (ABM): for example, all compounds are stored in central reservoirs directly accessible for those agents that need them.

3.2 Objective

There are two main objectives of the simulation study.

- Mapping the behavior of the proposed starship concept under different circumstances.
- Understand under which circumstances the starship can complete a mission with structurally sound modules, an adequate internal life support system, and no loss of human life.

3.3 Overview

The starship simulation relies on four distinct timelines. A first timeline provides real-time updates on the state of the starship's regenerative ecosystem, with a focus on population sizes, mass fluxes, and radiation impact. As explained before, ESA's MELiSSA project was used as a conceptual blueprint for the ecosystem. A second timeline deals with the growth of the starship architecture, taking into account material supplies, mining rates, 3D printing speeds and wear of existing structures. The third timeline forecasts the impact of future particle collisions and interstellar radiation as assessed within the sensing horizon. The fourth and final timeline is concerned with the evolution of the starship architecture as a response to this forecast. This is done by comparing the structural integrity and ecosystem health of different variations of the starship's morphology. Fig. 5 shows how all these timelines are interconnected.

The challenges mentioned above require developing a multi-paradigm simulation study. That is, the starship is considered as a meta-model combining a series of formalisms (Table 1). First, the ecosystem dynamics are approached through agent-based modeling (ABM). This allows us to model and simulate on a low level with high granularity and high ontological correspondence. Moreover, due to the focus of ABM on interactions between agents, emergent complex patterns can be studied. Second, the starship requires tracking that is common for discrete event system specification (DEVS) modeling. For example, location in space, travel time, etc. Particle collisions also create discrete events that change the state of a starship object. Thirdly, the mining process, 3D printing and wear of modules, as well as radiation effects, have a continuous nature, and therefore they are modeled as differential equation system specification (DESS). Finally, genetic algorithms provide us with an opportunity to define an objective function, optimize it, and then based on the outcome, restructure the starship architecture. This dynamic evolutionary approach is used to increase the resilience of the system, and handle anticipated (but originally unforeseen) challenges observed in the starship's sensing horizon.

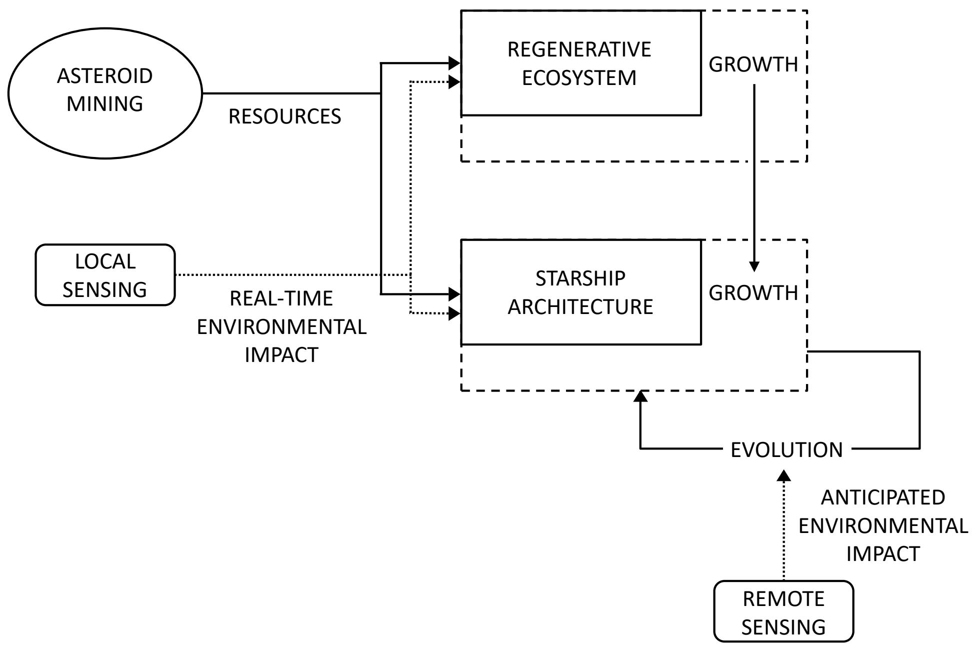

Fig. 5. Diagram showing an integrated view of the four different timelines used in the simulation. See subsection 3.3 for further details.

Table 1. Different formalisms that are combined in the proposed hybrid simulation. A selection of system and process examples is added.

Formalism or proposed algorithm	System or corresponding process
DESS	Asteroid mining
	Cosmic radiation
	Wear of architectural modules
	Local and remote sensing
DEVS	3D manufacturing of architectural modules
	Particle impacts
	Loss of architectural modules caused by particle impacts
ABM	Regenerative life support system
Genetic algorithms	Starship evolution

ABM = agent-based modeling; DEVS = discrete event system specification; DESS = differential equation system specification.

To perform this study, several software packages are under consideration, such as NetLogo, Simio, and Vensim. AnyLogic can be used to connect all formalisms into one single hybrid model. Since simulation packages for all formalisms have recently been announced in Python, the hybrid model could also be created entirely in Python.

4. Discussion

This simulation concept shows that it's possible to create a framework to test emergent behavior of a complex system such as an interstellar spacecraft. With the current concept, system design choices can be tested, and new design possibilities can be explored. The biological focus within the system's design offers several advantages. First and foremost, it results in dynamic and adaptive system with an increased resilience in comparison to fully pre-designed spacecraft. The implementation of an onboard regenerative life support system points to the future of deep-space exploration where spacecraft need to be fully autonomous. Using an existing RLSS of a space agency such as ESA has several advantages. It increases the fidelity of the simulation, and its results can be benchmarked against existing data. So far, most of the effort in this study has been devoted to the MELiSSA agent-based model. A detailed requirements analysis was carried out with input from researchers from the MELiSSA consortium (Claude-Gilles Dussap, Polytech Clermont Ferrand; Christophe Lasseur, ESTEC). The ABM was written in NetLogo, and the resulting simulation has already been (partially) validated by Siegfried Vlaeminck from Ghent University, also a collaborator in the MELiSSA consortium. First results indicate there's a high level of flow conservation (Table 2).

The next steps in creating the hybrid simulation are focused on continuing the development of the ABM, and on starting the programming of the mining and architecture processes. Once the MELiSSA ABM is fully validated and operational, the model will be thoroughly tested to obtain a full understanding of its behavior (in steady state). Subsequently, design principles will be identified and explored that increase the resilience of this ABM. In parallel with the ABM development, detailed requirements analyses for the DEVS, DES and genetic algorithm simulations will be performed. Once this has been completed, the actual coding of the DEVS, DES and genetic algorithm simulations can begin.

Table 2. Flow conservation rates in the current version of the MELiSSA ABM. These are preliminary figures obtained via an iterative process that guaranteed a supply of minimum requirements to the human crew. Based off that constraint, agent populations in each compartment would increase in number (e.g., plant plots or bioreactors), backward from compartment IV to I, so as to adjust their combined capacities to the required outputs.

Compound	Consumed (g)	Produced (g)	Flow	Delta
Bacterial protein	13828	13828	100.0%	0.00
Fecal protein	1148	1148	100.0%	0.00
Carbohydrates	7486	7486	100.0%	0.00
Lipids	1912	1912	100.0%	0.00
Food (higher plants)	3600	3600	100.0%	0.00
Food (algae)	400	400	100.0%	0.00
Acetate	20501	20501	100.0%	-0.01
Butyrate	3008	3008	100.0%	-0.01
HNO_3	2228	2228	100.0%	-0.07
NH_3	3487	3494	99.8%	6.90
CO_2	13703	13788	99.4%	85.92
H_2O	17602	17564	100.2%	-37.95
O_2	12186	12186	100.0%	0.00
H_2	1018	1027	99.2%	8.18
Total	102107	102170	99.9%	62.95

Acknowledgments

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