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In-Space Manufacturing - 2024 Industry Survey, Trends, Economics and Enablers

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Abstract

Discourse on in-space manufacturing (ISM) has been increasing, but recurring profitable production has yet to be demonstrated. Many products and materials have been proven to have better properties when made in space, but are they better enough? As of now the answer is known to be negative, but change is continuing, thanks to new products, processes, and decreasing upmass and downmass costs. Thus, some companies and applications may be getting near.

Since the author's 2022 paper on this topic, a report was created for NASA and ISM entities have increased from 117 to 303. Factories in Space (www.factoriesinspace.com) is the largest public database of commercial entities in the in-space economy and microgravity manufacturing fields and has over 900 total entries. First part of the paper updates the in-space manufacturing classification. Miscellaneous was added to the ISM fields of: advanced materials, biotechnology, large structures, microfabrication, novelty & luxury goods, pure substances and space food. All relevant survey entries are listed in tables for overview.

Second part of the work presents updated statistical data. Within the classifications, comparisons are made between the popularity, destinations, status, first launch years, geographical distribution and funding where available. Thanks to the previous paper, some trends can start to be deduced.

New economic activities in space have the potential to speed up space technology development and the rate of activities, creating a flywheel effect for further space utilization. In-space manufacturing could be the first industry to be moved off-Earth. Which application will be the first?

Keywords: in-space manufacturing, in-space economy, ISM, ISAM, ISRU

1. INTRODUCTION

Factories in Space has tracked new in-space economy entities since 2018.[1] There are over 900 entries as of September 2024, a considerable increase from 500 in Sept 2022. 303 entities are part of this in-space manufacturing survey, more than double compared to 117 from 2 years ago.[2]

In-space economy means generating revenue in space using assets in orbit or beyond Earth. In-space economy is the new extraterrestrial space industries. New in-space economy includes space stations, commercial landers, space infrastructure, in-space manufacturing and much more.[3]

For in-space economy to thrive, new value creation and revenue sources beyond Earth will be required. In-space manufacturing could become one of the largest industries in space and also one of the biggest customers to other in-space economy fields.[4]

In-Space Manufacturing (ISM) is a subset of in-space economy. In-Space Manufacturing is the transformation of raw or recycled materials into components, products, or infrastructure in space.[5] Wider space community may be starting to coalesce around the term ISAM[6] and then ISM is still a definable subset.

To avoid repetition as much as reasonable, please see the previous 2022 manuscript[2] for:

- Literature review
- Macro trends supporting and enabling ISM
- Benefits of in-space manufacturing
- Short history of ISM by categories
- Broader categorization: ISAM, ISRU
- Longer ISM classification and taxonomy
- Supporting services

For new readers, it would be recommended to see the 2022 paper first, followed by this for updates.

This study focuses on commercial entities in the in-space manufacturing field. First part of the paper establishes classification for the commercial entities. Second part presents statistical overview of the 303 surveyed in-space manufacturing entities.

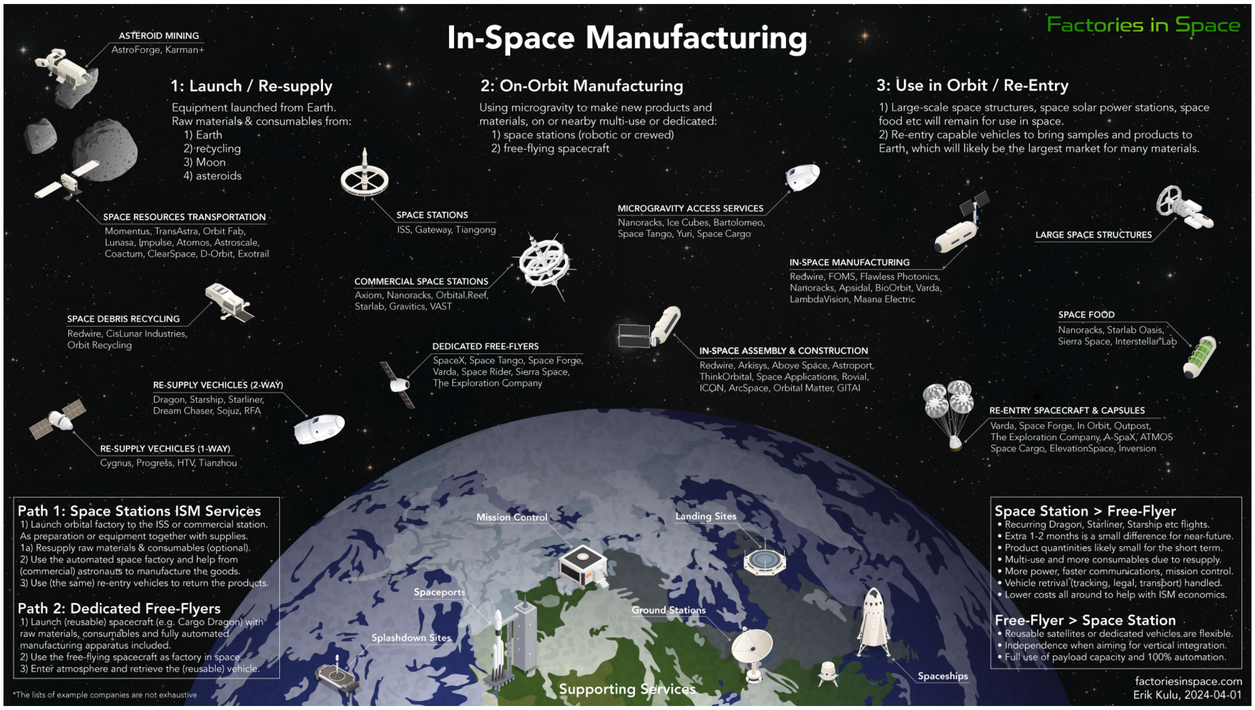

Figure 1: Illustration of In-Space Manufacturing

2. CLASSIFICATION

Figure 1 illustrates the in-space manufacturing ecosystem, methods and process.

2.1 Market Survey Criteria

The survey criteria resulting in the 303 entries:

- A planned manufacturing activity taking place beyond Earth. As defined in Section 2.
- Intent to produce specific goods, materials and/or products. Thus, some ISRU, assembly and other in-space economy fields are not included.
- Potential technologies or services without announced goods have been nominally excluded.
- Commercial entities or at minimum offering commercial services to the public markets.
- Ideally, there will also be a commercial intent to scale up the manufacturing as markets develop and increase in size in the future.
- Most data has been gathered from a large number of unstructured public sources over many years. However, some may be out of date.
- This manufacturing activity in space can either be planned, already canceled, or in some cases be a very promising technology itself.

2.2 In-Space Manufacturing Taxonomy

In-Space Manufacturing (ISM) is a process involving the fabrication, assembly, and/or integration of goods outside the Earth's atmosphere.[7,8] Alternatively, in-space manufacturing is the transformation of raw or recycled materials into components, products, or infrastructure in space.[5] As the list of in-space manufactured goods can be extremely long and likely will duplicate most terrestrial manufacturing in 100-200 years, then the categorization has been based on near-term activities as per database.

The Consortium for Space Mobility and ISAM Capabilities (COSMIC) defines ISAM as follows:[9]

- Servicing - In-space servicing involves two or more spacecraft engaging in activities that require rendezvous and proximity operations and in some instances docking.[9]
- Assembly - In-space assembly involves the construction of physical systems in space using pre-manufactured materials. The conjoining of materials to create a larger structure in space requires capabilities and technologies used for in-space servicing, such as robotic arms.[9]
- Manufacturing - In-space manufacturing involves the creation of objects and structures in space through the use of raw materials. In-space manufacturing techniques such as additive man-

ufacturing produce objects and structures for use both in-space and on the surface of celestial bodies.[9]

NASA's In-Space Servicing, Assembly, and Manufacturing (ISAM) page definitions are:[10]

- Assembly is the practice of gathering two or more parts together in space into a single, functional aggregate structure. A suite of assembly capabilities allows us to launch individual parts to space separately and bring them together, thereby overcoming the constraints of rocket fairing volume limitations. The ability to launch individual components of a large structure and robotically assemble them in space brings seemingly impossible concepts within reach. This capability allows for assembly of habitats in places further away than low-Earth orbit and opens up the door for constructing large telescopes and other platforms.[10]
- Manufacturing is the fabrication of components in space as the need arises. This capability allows for greater adaptability in dealing with unforeseen challenges and has the potential to eliminate the need to launch as many components upfront. It also allows for the production of monolithic structures, such as jointless thirty-meter truss beams. On-orbit coating and nano-manufacturing allows for surface coatings to be applied or renewed to recover optical and thermal properties.[10]

Per longer definition, in-space manufacturing is considered to be an activity that involves at least one of the following three components: fabrication, assembly, and integration:[7]

- Fabrication: The process of producing basic spacecraft or spacecraft subsystem components through 3D printing or traditional industrial methods such as welding, cutting, bending, etc.;[7] For example, 3D printing solar panels.[11]
- Assembly: Combining fabricated or pre-fabricated components into subsystems or entire spacecraft or direct complex 3D printing;[7] For example, joining the 3D printed solar panel with a stock of solar cells and wiring to form a functioning solar array.[11]
- Integration: Bringing together subsystems into one system and ensuring that the subsystems function together as such, including software; also includes potential processes associated with activities before or after upgrades, deliberate disintegration, and re-integration of subsystems into a spacecraft.[7] For example, integration could include installing the solar array onto a waiting spacecraft and incorporating it with its power system.[11]

Additional alternative definitions for in-space manufacturing, which are worth capturing:

- Space manufacturing is the production of tangible goods beyond Earth.[12]
- Space manufacturing involves the production of manufactured goods in an environment outside a planetary atmosphere.[13] "In economics, goods are items that satisfy human wants and provide utility. A common distinction is made between goods, which are transferable, and services, which are not transferable. Commercial and personal goods as categories are very broad and cover almost everything a person sees from the time they wake up in their home, on their commute to work to their arrival at the workplace."[14]
- Space manufacturing is the processing of materials in space to take advantage of the unique characteristics of space. For space manufacturing to become a reality, much research and development is needed to identify a wide range of opportunities, which are unique to space, technically feasible, economically feasible, and attractive to investors.[15]
- As of 2019, NASA Marshall Space Flight Center categorized manufacturing processes based on operational use scenario and the application of the parts being manufactured. In-space manufacturing is currently defined as manufacturing in an intravehicular (crew) environment. ISM takes place inside a pressurized habitat structure and is primarily focused on logistics reduction and on-demand manufacturing of spares.[16]
- ISM is an umbrella term for a variety of technologies, processes, and architectures, which deliver a desired component or system to a spacecraft outside of the Earth-launch paradigm.[11]

Synonyms of In-Space Manufacturing:

- Off-Earth Manufacturing,[17] Orbital Manufacturing, In-Space Fabrication,[18] In-Situ Manufacturing.[18]
- Space Manufacturing and Space-Based Manufacturing.[19]

- In-Orbit Manufacturing - Term "in-orbit" refers to the part of orbital space around Earth up to geostationary Earth orbit (GEO) as place of manufacture.[7]
- In-Space Manufacturing for Earth - In narrower definition it means making products and materials in microgravity, which cannot be made on Earth, or which are better.
- In-Space Production - ISS National Lab has started to use this term.[20]
- Materials Processing in Space - The term used in the earlier decades of space exploration. Many older reports and articles are findable with that keyword. Materials processing in space (MPS) is the science, which takes advantage of the microgravity condition found in space to produce improved materials such as pure and uniform crystals, containerless processing and new pharmaceutical products.[21]
- Microgravity Manufacturing and Microgravity Processing - Alternative name for in-space manufacturing. However, parabolic flights and drop towers have been excluded from this study.

2.3 Destinations of In-Space Manufacturing

Factories in Space divides ISM into 3 large areas by destinations, targets or locations:

1. **Earth** - In-space manufactured goods and products intended to be brought back to Earth for sale and use in terrestrial markets. Sometimes called space-for-Earth, Earth-return and return-to-Earth ISM applications. The value-added in-space processing must outweigh the cost of transportation and the use of a space factory.[8,22]
2. **Space** - In-space manufactured goods, building materials and infrastructure, which will remain in space. Sometimes called space-for-space ISM or ISM-for-space.
3. **Surface** - also known as surface manufacturing or surface construction.[23] Space manufactured goods, building materials and infrastructure, which will be taken to the surfaces of other celestial bodies like Moon, Mars or asteroids or situations where the manufacturing activity happens on the surface.

2.4 Methods of In-Space Manufacturing

1. Dedicated free-flying spacecraft - including small reusable satellites, capsules and spaceplanes with re-entry capability.
2. Space stations - including the ISS and upcoming commercial space stations such as Axiom.
3. Suborbital flights - some microgravity manufacturing can happen during short flights but it is not expected to become a leading method.

Not included in this survey:

- Parabolic flights
- Drop towers
- Earth-based microgravity simulators

2.5 Fields and Categories of In-Space Manufacturing

The following are the primary fields of in-space manufacturing applications in alphabetical order. Miscellaneous has been added since 2022. They are based on existing or near-term activities.

1. **Advanced Materials**
2. **Biotechnology**
3. **Large Structures**
4. **Microfabricated Goods**
5. **Miscellaneous**
6. **Novelty & Luxury Goods**
7. **Pure Substances**
8. **Space Food**

This list is expected to significantly expand in the coming decades but at this time there do not seem to be enough existing or planned commercial activities to warrant separate fields. Some possibilities for next categories may include:

- Vehicles - rovers, drones, re-entry capsules, space tugs, etc.
- Spare parts and tools, etc.
- Equipment - medical, etc.
- Household items - furniture, art, etc.

2.5.1 Advanced Materials

Advanced materials made in microgravity have also been called unique materials or exotic materials. They may include ZBLAN[24] and other exotic glasses, superalloys,[25] optical crystals,[26] covetic materials, superconductors, carbon nanotubes, bulk metallic glass and many more. Most preferred and likely initial market for them could be on Earth thanks to existing industries and supply chains.

2.5.2 Biotechnology

Biotechnology field collects potential biomedical in-space manufacturing applications such as medicine, stem cells,[25] tissue engineering,[25] 3D bioprinting,[25] organ growth,[27] pharmaceuticals[25] and many more.

2.5.3 Large Structures

Large-scale structures will ultimately enable and lead to the construction of unprecedented space structures and platforms.[28] All areas related to building for space.[27] It can include booms, building materials, additive manufacturing, infrastructure, megastructures, additive construction,[25] in-space construction,[25] in-space assembly, space-based solar power, space stations and many more.

2.5.4 Microfabrication

Orbital microfabrication field includes microfabricated and nanofabricated goods such as semiconductors,[25] solar cells, thin-films,[25] ultra-thin coatings and many more, which are all microfabrication concepts or processes. Microfabrication is a more general term compared to orbital microfabrication because the manufacturing may also happen on planetary surfaces.

2.5.5 Miscellaneous

A catch-all for ISM products such as spare parts or whole spacecraft, which do not fit well under other categories.

2.5.6 Novelty & Luxury Goods

Luxury and novelty goods such as jewellery, art, wine, coffee and beer, have started to see an increased traction as space-flown goods. D. F. Robertson wrote about backhauling novelty items to Earth on returning capsules as a potential way to make new space businesses happen as inspired from the trucking industry.[29]

Looking back to centuries ago at how silk trade and spice trade started and what long-term impact they had to global economy, then luxury goods made in space could similarly help to kickstart in-space economy and in-space manufacturing. More practical and industrial goods would follow later once science develops, launch costs decrease even further and technology readiness increases.

2.5.7 Pure Substances

Pure substances such as water, oxygen, hydrogen, propellants, metals, can also be a result of in-space manufacturing. This was previously called raw materials. Recycling processes would be included here also. For example, M. Moraguez had an application of Recycling Orbital Debris as Feedstock.[30]

These fields are commonly defined as ISRU, which can still fall under the definition of ISM as “fabrication” of raw material stock from mined or extracted resources.[11] Mass production of materials or processing can be considered manufacturing when compared to Earth-bound analogues but other authors sometimes exclude it.[7]

2.5.8 Space Food

Space food will be a large industry to supply fresh food to workers, settlers and tourists, both in-space and on Moon, Mars and beyond.[31] Aesthetic reasons also for psychological well-being.[32] Relevant keywords or synonyms are space agriculture, space farming, deep space food, hydroponics, etc.

There is potentially a considerable overlap with vertical farming technologies and related benefits on Earth. Terrestrial revenues from food growing systems, which were initially developed for microgravity and for limited resources in space like electricity, water and nutrients, could help with the economic sustainability of in-space manufacturing companies until a larger number of people are living and working beyond Earth.

2.6 Processes or Technologies of In-Space Manufacturing

The following list of example ISM processes and technologies is not exhaustive. Many of these processes can produce different types of goods in various ISM fields. Goal is to expand on this in the future.

- Additive Manufacturing
- Aeroponics & Hydroponics
- Bioprinting
- Bioreactor
- Containerless Processing
- Electrolysis
- In-Space Assembly
- Recycling
- Tissue Engineering
- Vacuum Deposition

Example technologies not included in this study:

- Asteroid mining and lunar mining, unless there is an in-situ manufacturing component.
- Not all NASA-funded additive manufacturing technologies have been included. There preferably should be an announced commercial intent to do the manufacturing activity in space.

2.7 Types of Goods & Outputs for In-Space Manufacturing

Example types of goods or end products that could be manufactured in space are (non-exhaustively):

- ZBLAN optical fiber
- Optical crystals
- Perfect spheres
- Human organs
- Human implants
- Pharmaceuticals
- Fresh food
- Lab-grown meat
- Semiconductors, microchips
- Solar cells
- Solar arrays
- Spare parts
- Tools
- Building materials
- Long booms
- Antennas
- Propellants
- Bulk metallic glass
- Carbon nanotubes
- Superconductors
- Artificial-gravity space habitats
- Space-based solar power
- Very large space telescopes
- Particle colliders/accelerators
- Space elevator
- Mass drivers

Example goods not included in this study:

- Space-flown goods. Purely space-flown items are not included. Nevertheless, long-term microgravity environment can itself have an effect and for example ageing process can be considered a manufacturing activity on Earth.
- Bottled wine - 12 bottles of wine were sent to space by Space Cargo Unlimited, brought back to Earth after 1 year, and one of them was expected to sell for about $1M at an auction.[33]
- Space beer made from space-flown yeast or hops, which has been demonstrated multiple times.

3. ECOSYSTEM OVERVIEW 2024

Please find the 303 commercial entities organized by the high-level categories in table format in Section APPENDIX A: Ecosystem Overview by Categories. They have been discovered as part of the in-space manufacturing survey up to September 2024.

This section describes notable events, news and publications relevant for ISM and each of the 8 categories. Historical overview for each category can be found in the previous paper.[2]

3.1 Selected General Updates Since 2022

There has not been enough focus on "manufacturing". ISAM term covers Servicing, which gets most of the attention and funding. The world needs more focus and funding to practically solve assembly and manufacturing challenges. Robotic arms do cover assembly and there are many, but much more development is needed for activities with them.

Wright et al. (2022) published "An Analysis of Publicly Available Microgravity Crystallization Data: Emergent Themes Across Crystal Types", also know as the "Butler Study". The databases are freely available and have continued to be updated.[34]

The Consortium for Space Mobility and ISAM Capabilities (COSMIC) was founded in 2023 and is a US-wide coalition to invigorate domestic ISAM capability. Its mission is to make ISAM a routine part of space architectures and mission lifecycles.[35]

DARPA and M. Nayak released six hypotheses for accelerating the lunar economy (SHALE), which include (3) Creating large silicon wafers for microsystems on the Moon, (4) Biomanufacturing to accelerate lunar construction, (5) New concepts to increase refinement rates in low gravity.[36]

NASA released Low Earth Orbit Microgravity Strategy in August 2024, where ET-3 is to demonstrate advanced manufacturing techniques and nondestructive evaluation in microgravity and ET-4 is to demonstrate in-space assembly of structures to enable increasingly complex mission concepts.[37]

The 2023 ISAM State of Play document was released. It is a survey of past, present, and near future ISAM capabilities across industry and government agencies. It is the third release of the document and provides significant updates, including the addition of 26 new ISAM technologies, 50 ISAM-related facilities, and 88 ISAM developers.[10]

European Space Policy Institute (ESPI) publised "On-orbit Servicing, Assembly, and Manufacturing - State of Play and Perspectives on Future Evolutions" in 2023.[38]

Seraphim Space forecast that just as the low-cost launch has reshaped the space sector over the last decade, they anticipate that the advent of low-cost, frequent return-to-Earth capabilities will have a similar impact over the next decade.[39]

In Vast's announcement of Haven-1 Lab, Redwire and Yuri were named as inaugural partners.[40]

In-orbit servicing, assembly and manufacturing is included in the UK's Space Industrial Plan 2024.[41]

Europe's STARFAB project started in 2024 with goals to elaborate a viable concept of in-space automated warehouse facility supporting ISAM applications, explore relevance of robotic technologies in such a facility, and define a roadmap and exploitation prospects for ISAM applications.[42]

In no order, selected publications are:

- "Benefits of In-Space Manufacturing Technology Development for Human Spaceflight," Moraguez and Weck (2020).[43]
- "Factories-in-Space for Servicing, Assembly, & Manufacturing," Malshe et al., 2023.[44]
- "Goods beyond earth: Cheaper manufacturing in space," James (2022).[45]
- "Factory in Space: Considerations and Feasibility for Low Earth Orbit," Abdulhamid et al., 2024.[46]
- "Exploring space manufacturing: designing a lunar factory for space-bound products in the new space economy," Francesco et al., 2024.[47]
- "Orbital Reef and commercial low Earth orbit destinations—upcoming space research opportunities", Zea et al., 2024.[48]
- "An Economic Case for Distributed, On-Demand Down-Mass Systems in Low Earth Orbit (2024)," Kunsa et al., 2024.[49]

3.2 Advanced Materials (Updates Since 2022)

Flawless Photonics produced 11.8 km ZBLAN on the ISS in 2024. NASA's In Space Production Applications program is now supporting a new preform manufacturing experiment by Flawless Photonics, Australia's University of Adelaide, Axiom Space and Visioneering Space.[50,51]

Varda planned to manufacture ZLBAN in 2021[52] but it is assumed that the project was canceled or paused, because the co-founder D. Marshall with ZLBAN background left in 2022[53] and recent focus has been on pharmaceuticals.

DSTAR Communications has been working on halide optical fibers, which have even wider wavelength range than ZLBAN.[54]

BEAM Collective was founded. The Beyond Earth Advanced Materials (BEAM) Collective is the world authority on microgravity-based manufacturing of advanced materials—materials that require extreme process parameters (e.g., high temperatures, high pressures, toxic chemicals).[55]

3.3 Biotechnology (Updates Since 2022)

Varda launched first commercial re-entry capsule in June 2023 and landed in Utah in February 2024 and first results on producing crystals of ritonavir (an HIV medication) were considered positive.[56–58]

Redwire announced successful bioprinting of live human heart tissue on its 3D BioFabrication Facility (BFF) on the ISS. On the same flight that returned heart tissue samples, Redwire received a batch of space-flown crystal experiments from its Pharmaceutical In-space Laboratory (PIL-BOX) platform.[59]

DARPA'S B-SURE project has been studying microbial biomanufacturing, where microorganisms could perform functions such as recycling, food and pharmaceutical production, mining, and other processes. The goal is to combine local materials, such as lunar regolith.[60,61]

The Space Omics and Medical Atlas (SOMA) package of manuscripts, data, protocols, and code represents the largest-ever compendium of data for aerospace medicine and space biology. Over 100 institutions from >25 countries worked together for a coordinated 2024 release of molecular, cellular, physiological, phenotypic, and spaceflight data.[62]

There are several new microgravity simulator startups. For example, Litegrav, which is the ground-based platform provider for 2024 Boryung's Humans in Space program.[63]

Space Tango launched a new middeck locker facility on NG-21 mission. The Microgravity-based Automated Manufacturing and Bioprocessing Outpost (MAMBO) provides a high throughput solution to enable in-space manufacturing capability.[64]

A selection of manuscripts:

- Santomartino et al. (2023) proposed and highlighted a series of microbial biotechnologies suited to establish sustainable processes for in situ resource utilization and loop-closure.[65]
- "Bioprinting of Cardiac Tissue in Space: Where Are We?," Tabury et al., 2023.[66]
- "Bioprinting in Microgravity," Sarabi et al., 2022.[67]

3.4 Large Structures (Updates Since 2022)

Ignoring robotic arm activities, there are many. Services and activities, not common technologies. Robotic arm and docking interfaces are too common, relevant but in-direct. Space welding however would apply. Handling does not matter, has to be a manufacturing activity. Some repairs and servicing could be considered manufacturing, but many projects tend to overstate their scope.

Voyager and Nanoracks launched Outpost Mars Demo-1 (OMD-1) on SpaceX's Transporter 5 rideshare flight. It was the first demonstration of metal cutting in space using friction milling to cut corrosion-resistant steel found in space debris. The OMD-1 operated as a hosted payload aboard an upper stage of the SpaceX rocket. OMD-1 was supported by Maxar, who developed a robotic arm that used a commercial friction milling end-effector, which uses a cutting tool operating at high rotations per minute to soften the metal in such a way that a cut is made while reducing on-orbit debris. The experiment's arm and metal samples were contained inside an enclosure, ensuring that no debris would escape.[68]

ThinkOrbital demonstrated electron beam welding on a suborbital mission in May 2024 and an orbital mission is planned for later in 2024.[69,70]

ESA's SOLARIS program to develop technologies relevant for space-based solar power has funding challenges, unfortunately, and many envisioned projects have not come to fruition. Nevertheless, many companies in the space solar field are working on in-space assembly of large structures. In 2024, ESA published a UK-specific call for €3M to develop in-space assembly methods and tools.[71]

Funded by ESA, Airbus and AddUp developed and launched the first metal 3D printer to space in 2024. By early August 2024, the first sample was ready for an ISS astronaut to retrieve.[72]

Thales Alenia has been studying data centres in space and Lumen Orbit published a whitepaper.[73,74]

On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) mission was cancelled in 2024 due to continued technical, cost, and schedule challenges. A broader community evolution away from refueling unprepared spacecraft has also led to a lack of a committed partner. However, it may be brought back.[75] It had a payload called Space Infrastructure Dexterous Robot (SPIDER). SPIDER planned to assemble seven elements to form a functional 3-meter antenna and test Ka-band transmission.[76,77]

Orbital Matter launched their first 3D printer to space in 2024 on a CubeSat called Replicator, but the satellite does not seem to be operational.[78]

Hassell published "Lunar Master Plan: Moon base" for the European Space Agency[79]

Ethos emerged from stealth to melt regolith to build lunar landing pads with oxygen as by-product.[80]

OHB developed the IMPERIAL 3D printer, which can additively manufacture parts larger than itself.[81]

Lockheed Martin published "A Vision for Humanity's Future in Space - Lockheed Martin's Water-Based Lunar Architecture"[82]

DARPA's Novel Orbital and Moon Manufacturing, Materials, and Mass-efficient Design (NOM4D) program aims to develop the foundations of building robust, precise structures in space. The program comprises two technical areas. The first plans to develop and demonstrate foundational materials, manufacturing processes, and designs to enable the in-orbit fabrication of robust, resilient, and high-precision structures. The second technical area will investigate innovative designs that take advantage of the ability to manufacture in space, yet enable precise, mass-efficient future space structures that withstand maneuvers, eclipses, damage, and thermal cycles inherent to the space environment.[83] HRL Laboratories was elected as one of eight industry and university research teams for the program.[84]

Selected works and manuscripts:

- "Exploring space manufacturing: designing a lunar factory for space-bound products in the new space economy," Francesco et al., 2024.[47]
- Hoffmann and Elwany published "In-Space Additive Manufacturing: A Review" in 2022.[85]
- "Robotic technologies for in-orbit assembly of a large aperture space telescope: A review," Nair et al., 2024.[86]
- "3D printing in space: from mechanical structures to living tissues," Mao et al., 2024.[87]
- L. David presented "How can we build landing and launch pads on the moon?" The Lunar Surface Innovation Consortium (LSIC) held a Moon launch and landing facilities workshop in July 2024.[88]
- Numerous other research on 3D printing in space.[89–91]

3.5 Microfabricated Goods (Updates Since 2022)

The Workshop on Semiconductor Manufacturing in the Space Domain took place in March 2023 at Stanford. Author presented the "In-Space Manufacturing of Semiconductors – History and Future Vision". A comprehensive whitepaper was published "Semiconductor Manufacturing in Low-Earth Orbit for Terrestrial Use," Frick et al., 2023.[92]

Jessica J. Frick and Debbie G. Senesky also founded Astral Materials, and have received SBIR Ignite Phase I and Phase II grants.[93]

NASA Marshall Space Flight Center (MSFC) has been working with Intel and others on Space Enabled Advanced Devices and Semiconductors (SEADS). The NASA On Demand Manufacturing of Electronics (ODME) overall project goal is to develop and demonstrate the feasibility of a low-gravity, on-demand manufacturing system for semiconductor electronic devices on the ISS). As part of that goal, ODME is partnering with various groups (Intel/NAU/Fujifilm/TEL/Axiom Space) on the development of an high-precision inkjet printer.[94, 95]

Current manufacturing methods usually require costly facilities, hundreds of masks, and complex process flow such as lithography, etching, deposition, and thin film growth. Electrohydrodynamic (EHD) printing technology is a promising alternative process providing a non-contact (defect reduction), direct printing (mask-less) method, and etching-free process for semiconductor electronic manufacture. The microgravity environment provides the beneficial effects in EHD printing technology (from ink preparation and manufacturing to applications and product stages) that can provide better trench filling conformity, and less voiding defects for advanced sub-µm semiconductor manufacturing in a zero-gravity environment. Parabolic flights have been completed in 2021, 2022 and 2024 and more planned.[94, 95]

Redwire's MSTIC payload launched to the ISS on the Crew-7 mission in 2023. Manufacturing of Semiconductors and Thin-Film Integrated Coatings (MSTIC) examines how microgravity affects thin films that have a wide range of uses.[96]

One of the six DARPA lunar economy hypotheses is silicon wafer manufacturing.[36]

3.6 Miscellaneous (Updates Since 2022)

The U.S. Space Force awarded a $1.6 million SpaceWERX contract to a team led by Arkisys to demonstrate robotic assembly of a three-axis stabilized satellite with the robotic arm on the Arkisys Port Module.[97]

Maurel et al. (2023) discuss "What Would Battery Manufacturing Look Like on the Moon and Mars?" including 3D printing batteries.[98]

3.7 Novelty & Luxury (Updates Since 2022)

Starbase Brewing was founded and aims to be the first brewery on Mars.[99]

Interstellar Lab plans to grow a rose (flower) on the Moon as soon as 2026.[100]

A withdrawn paper from IAC 2024 proposed to make diamonds in space.[101] The space diamonds idea has been on the Factories in Space since 2018.[102]

3.8 Pure Substances (Updates Since 2022)

NASA's Break The Ice Challenge concluded during 2024. Terra Engineering won the first place and Starpath Robotics was second.[103]

The joint UK-Canada £1.2 million Aqualunar Challenge launched in 2024 to support development of water-purifying technologies for the Moon and 10+8 finalists have been selected.[104–106]

In Sept 2024, NASA announced LunaRecycle Challenge, which is also expected to kick-start many relevant companies.[107]

Starparth raised $12M in 2024.[108] They are estimating that the cost to build a mass scale propellant production system on the Moon will cost significantly less than $100M.[109]

Karman+ shared their Master Plan in 2024.[110]

CisLunar Industries shared ther plans for 5000 kg Lunar Space Foundry.[111]

One of the six DARPA lunar economy hypotheses is low-gravity resource extraction.[36]

3.9 Space Food (Updates Since 2022)

Deep Space Challenge concluded in 2024. The U.S. winner and recipient of the $750,000 grand prize was Interstellar Lab. Two runners-up Nolux and SATED received $250,000. Solar Foods from Finland was the international winner and Ecoation won the Canada track.[112]

Came across Monje et al. (2019) publication "New Frontiers in Food Production Beyond LEO."[113] Santhoshkumar et al. (2023) published "3D Printing for Space Food Applications: Advancements, Challenges, and Prospects."[114]

Redwire's commercial Greenhouse has not launched as of yet.[115]

4. STATISTICAL OVERVIEW 2024

This sections covers the statistical overview of the 303 entries in the database to analyse which types of commercial entities are or aim to become active in the emerging in-space manufacturing fields.

4.1 Destinations

Figure 2 shows the destinations, targets or locations of in-space manufactured goods as defined in Section 2.3. Most products or constructions are planned to remain in space with 160 activities out of 303. This is followed by the surfaces of Moon, Mars and other planetary bodies with 86 activities.

The smallest amount of commercial activities in the database (57) are aiming to return in-space manufactured products to Earth for sale in terrestrial markets. This is interesting, because existing, nearer-term, and larger markets are thought to be on Earth and that expectation has partially started a wave of startups pursuing small re-entry capsules and end-to-end microgravity access services.

In the previous study, the counts in the same order were 54, 35 and 28.[2]

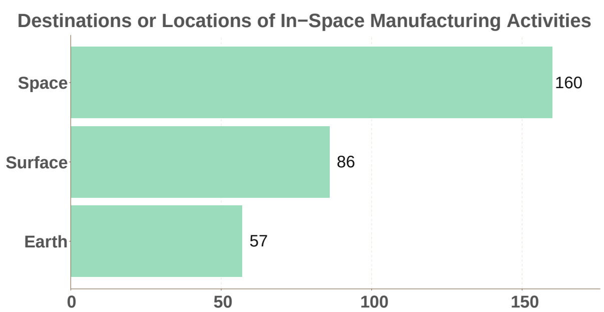

Figure 2: Targets & Locations of In-Space Manufactured Goods or Activities

4.2 Destinations with Categories

Figure 3 shows the destinations together with in-space manufacturing fields as defined in Section 2.5. Goods intended to be flown back to Earth are dominated by advanced materials, biotechnology and microfabrication applications. Followed by novelty & luxury goods with all the fields present.

The largest in-space manufacturing categories from ISM-for-space, where the output will remain in space, are space food and large-scale structures but otherwise again varied.

In the case of ISM-for-surface, where in the most cases the manufacturing activity will also happen on the same planetary surface, they are still considered "in-space" or beyond-Earth manufacturing. Surface ISM applications are also very mixed, but the largest new category is pure substances. Likely due to better access to and processing of raw or recycled resources in order to produce of water, oxygen, metals, propellants and other substances. Large-scale structures is also a frequent category here due to the upcoming need to build facilities and infrastructure on Moon and Mars.

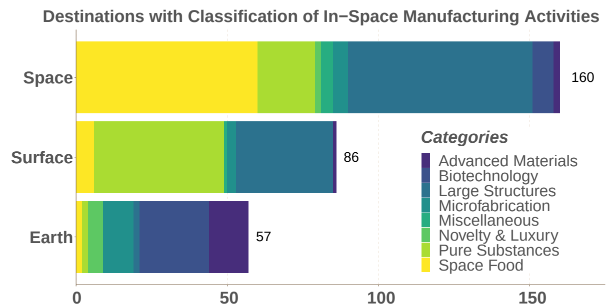

Figure 3: Destinations with ISM Fields for In-Space Manufacturing Companies

4.3 Destinations with Status

Figure 3 shows the destinations or locations together with the status of the in-space manufacturing commercial activity. None are considered "active", which would entail regular commercial production of the same product. Up to 30% in each category can be considered canceled or dormant, and the percentage likely will increase in the near-term.

Majority of ISM activities are in early, concept, or development stages. It is interesting to note that no commercial demonstrations have been performed on planetary surfaces (MOXIE is partial) but the situation will improve once commercial Moon landers will start to achieve successful lunar landings.

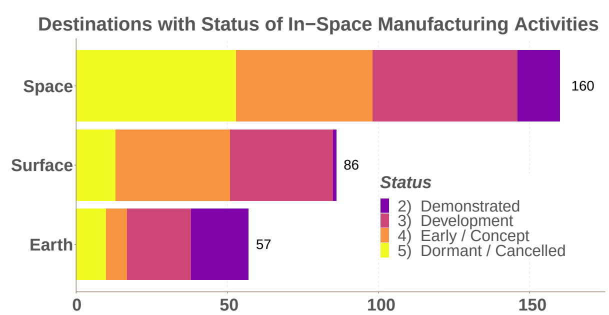

Figure 4: Destinations with Statuses for the In-Space Manufacturing Activities

4.4 Fields or Categories

Figure 5 shows the classification of ISM activities as defined in Section 2. Generally, there is only one primary category per company but for example Redwire has been included 12 times. This reiterates that the 303 entries in the database are not strictly separate commercial entities but rather separate in-space manufacturing activities.

Large structures is the most popular field with 95 entries followed by space food with 68, pure substances with 64, biotechnology with 30, microfabricated goods with 18 and advanced materials for Earth with 16 entries. Novelty & luxury goods with 7 entries and miscellaneous are the least common ISM activities at this time.

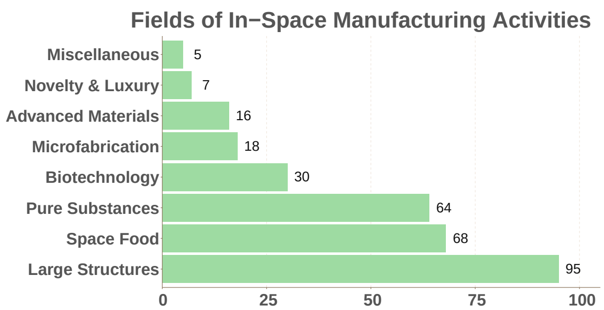

Figure 5: Fields or Categories of In-Space Manufacturing Companies

4.5 Fields with Status

Figure 6 lists the fields of in-space manufacturing entities together with the status categories.

There are no active recurring in-space manufacturing entities making products and materials for Earth or space. Space beer from Japan was set as "Recurring/Active", because it was made from space-grown barley multiple times but not in the recent years. In this case, growing yeast can be considered a manufacturing activity and more applicable compared to space-flying hops.

Some other products and materials have been demonstrated. Redwire (Made in Space) fabricated ZBLAN[116] in 2017 and 2019. FOMS demonstrated ZBLAN manufacturing in 2019.[117] Flawless Photonics did so in 2024.[50] In 2022, Redwire manufactured optical crystal in space and sold it commercially.[26]

Overall, as seen from the chart 6, many commercial organizations are in the early stages of development and often the progress could be limited only to a website and to a tiny team. The situation should improve in the next years thanks to the emergence of multiple small re-entry spacecraft, Axiom Space Station and ESA's Space Rider spaceplane, all of which are likely to result in more microgravity manufacturing experiments, demonstrations and perhaps regular activities too.

It is currently unknown which are going to be the first recurring in-space manufactured goods and when but many more demonstrations and limited sales are likely. There still seems to be a long path for the ISM-for-Earth markets to emerge and for commercial in-space manufacturing activities to become recurring.

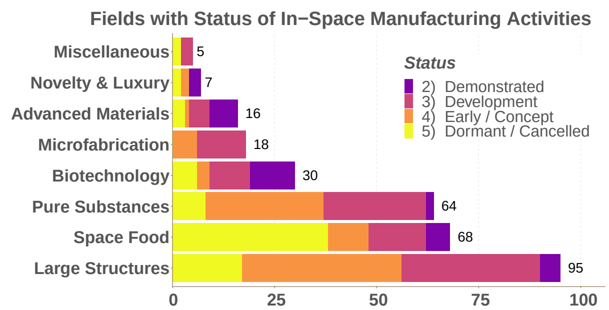

Figure 6: ISM Fields with Status for In-Space Manufacturing Companies

4.6 Fields with Destinations

Figure 7 lists the fields of in-space manufacturing entities together with the destinations. Depending on the priorities for in-space manufactured goods, this chart may help to focus technology development in certain areas.

The fields of advanced materials, biotechnology, microfabrication, and novelty & luxury goods are terrestrial market centric. While growing food in space and building large-scale structures are more space-centric. Pure substances, large structures and space food are most common on planetary surfaces at this time.

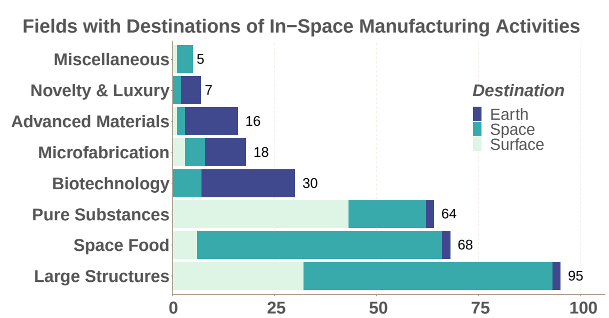

Figure 7: ISM Fields with Destinations for In-Space Manufacturing Companies

4.7 Fields/Categories with Processes & Technologies

Figure 8 lists the fields together with processes or technologies of in-space manufacturing entities.

Additive manufacturing and assembly dominate for large structures. While aeroponics & hydroponics are very popular for growing food in space.

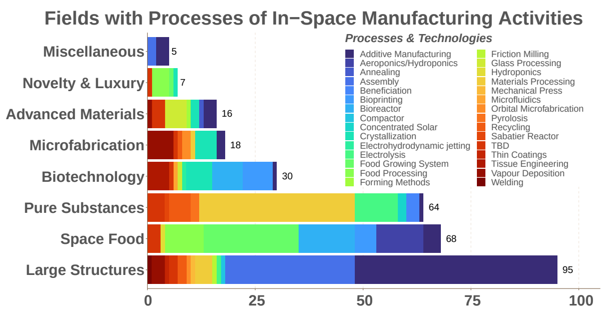

Figure 8: ISM Fields with Processes & Technologies for In-Space Manufacturing Companies

4.8 Processes & Technologies with Categories

Figure 9 lists the processes or technologies of in-space manufacturing activities together with the ISM fields. This figure is preliminary and more work is required to research, define and set the categories for processes and technologies. Due to the early nature of many activities, these are often not publicly shared or known.

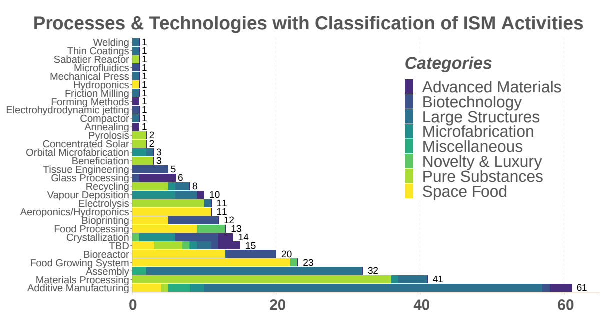

Figure 9: ISM Processes & Technologies with Fields for In-Space Manufacturing Companies

4.9 Processes & Technologies with Status

Figure 10 lists the processes or technologies of in-space manufacturing activities with the statuses.

Some additive manufacturing, crystal growing, bioreactor, glass processing and tissue engineering technologies have been demonstrated.

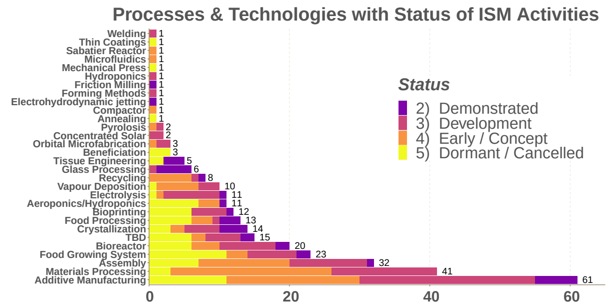

Figure 10: ISM Processes & Technologies with Status for In-Space Manufacturing Companies

4.10 Processes & Technologies with Destinations

Figure 11 lists the processes or technologies of in-space manufacturing activities together with the destinations of goods or locations of manufacturing.

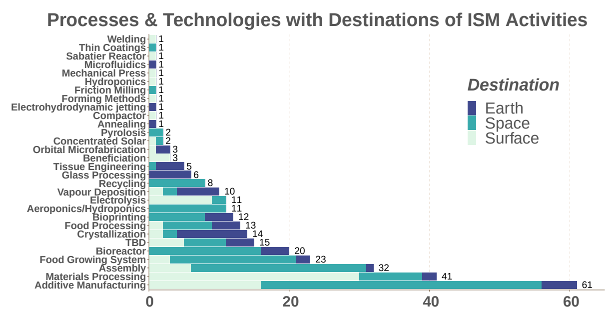

Figure 11: ISM Processes & Technologies with Destinations for In-Space Manufacturing Companies

4.11 Founded with Classification

Figure 12 plots the founding dates of all entries in the database together with the in-space manufacturing fields. The founding year of a company may not be correlated to the start of the ISM activity. Founding of a company also does not correlate to a successful long-term business nor to performing demonstration missions because many activities will become dormant or get cancelled before.

Starting from 2016 and continuing, there has been a large increase of ISM activities. Space food, advanced materials and pure substances fields stand out but other categories are present too. This timeline coincides with the first Starship announcements and successful re-usability of Falcon 9, because both are aiming to lower costs of space access, which could enable the business cases of in-space manufacturing. NASA's Artemis announcement in 2019 and new funding opportunities have also increased the interest, because these programs will be creating new markets for many in-space economy fields.

The peak in 2021 is due to the Deep Space Food Challenge by NASA and Canadian Space Agency. This is a great example of how competitive challenges can start commercial activities in a space industry, similar to how Google Lunar X Prize stimulated startups for lunar landers and rovers. NASA's Break The Ice Challenge concluded in 2024 and UK and Canada's Aqualunar Challenge started.[103,105]

Two years ago, there was a small continued decline after 2017, but they have been back-filled.

Author forecast in 2022 that successful Starship missions to orbit, return to the Moon, commercial space stations, and small re-entry capsules will kick off another in-space manufacturing startup founding wave in about 2-3 years. Two years has now passed and many startups may be in stealth, but more likely it will take 2-3 years more.[31]

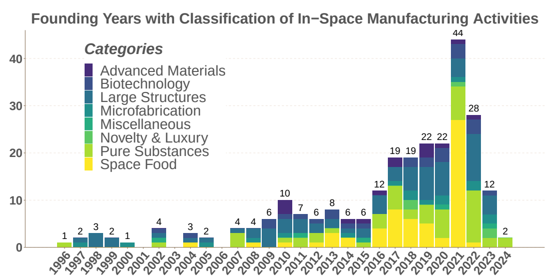

Figure 12: Founding Years with Classification for In-Space Manufacturing Entities

4.12 Founded with Status

Figure 12 plots the founding dates of in-space manufacturing companies together with the status.

The recently founded companies, especially in relation to the Deep Space Food Challenge, are still in early and concept design phases. It often takes years of time and effort to raise the funding, build an experiment module and launch it to space, and such demonstration is only the first step towards recurring in-space manufacturing activities.

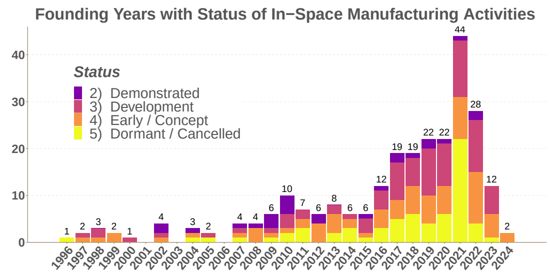

Figure 13: Founding Years with Status for In-Space Manufacturing Entities

4.13 Funding with Classification

Figure 14 shows in-space manufacturing categories with funding amounts in the defined ranges. The funding amounts are per company and they are not always fully used for ISM, which makes this analysis challenging. "Not applicable" has been used for companies with multiple entries but that also does not give the full picture about each category.

"Yes, amount TBD" often means an established company but it is publicly unknown how much are they investing into in-space manufacturing, likely a considerable amount. "Unknown" category is for companies who have not announced any funding. For them, it is often the case that based on their activities, social media and employee count, they likely only have small amounts or no funding.

There are many engineering companies with relevant grants, but it is likely they will never spin-off in-space manufacturing as products or services.

Over $1 billion in private and awarded funding have received Relativity and Sierra Space. Over $100 million in funding have to raised Made in Space (Redwire) and Aleph Farms. Between $50-100M in private funding has raised for example Varda Space Industries. Between $10-50M in funding have e.g. Space Forge, Solar Foods and Space BD. Between $5-10M in funding have for example Interstellar Lab and Maana Electric.

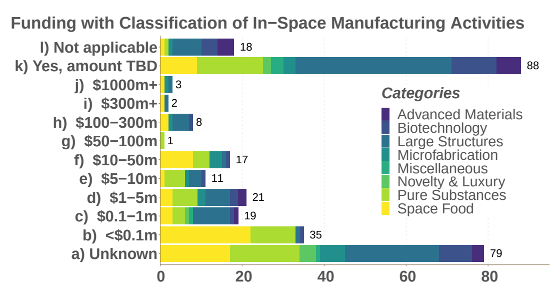

Figure 14: Funding Levels with Classifications for In-Space Manufacturing Companies

4.14 First Launches

First missions in space related to in-space manufacturing activities have been gathered on Figure 15. Knowingly cancelled and dormant companies have been marked separately. The approach here is to keep the last publicly announced year in the database until such date passes even when it becomes unrealistic, and then move it forward in the beginning of the following year. The log of changes among the launch years will help to track delays.

"Not announced" are companies that do not seem to have publicly announced a launch year for their first ISM demonstrations or activities in space. The very large quantity of such entities, 166 out of 303, matches with the large number of idea and early stage companies, or primarily technology development projects, which still have to be followed by flight model developments. At least 67 are already dormant and/or canceled too, likely more.

The first launch also does not correlate to the start of a recurring commercial activity. Many of these initial demonstrations can be scientific in nature, often primarily funded by grants, and very commonly also be one-off.

In 2015, Argotec flew espresso machine to space.[118] In 2017, SpacePharma launched their first biotechnology experiment CubeSat.[119]

In 2018, Made in Space launched first ZBLAN demonstration,[120] Tethers Unlimited launched plastic recycling system[121] and 3D Bioprinting Solutions launched a bioprinter.[122]

2019 saw the launches for Aleph Farms, Braskem, DoubleTree by Hilton, Flawless Photonics, FOMS (Fiber Optic Manufacturing in Space),[117] Sierra Space, Techshot (Redwire) and Zero G Kitchen.

In 2020, LambdaVision, OxEon Energy (involved in MOXIE) and Redwire's Ceramic Manufacturing module were launched.

In 2022, Space Crystals sent 36 samples to the ISS to figure out the how to grow DNA-infused crystals in orbit.[123] 2022 also include Apsidal, Cedars-Sinai, Mercury Systems (Physical Optics Corporation, POC), Nanoracks (Voyager Space), Nature's Fynd, Strauss Group.

In 2023, the following were involved in a launch to space Eascra Biotech, MakerHealth, Odyssey SpaceWorks, Redwire, Sachi Bioworks and Varda.

In 2024, Airbus, GITAI, Redwire (MSTIC), Orbital Matter (Replicator) have launched payloads to orbit but not all are yet demonstrated.

Still current marked for 2024 are AMi Exploration (ARCA Space), Argo Space, Arkisys, Encapsulate, Eta Space, EXPLOR Biologics, OHB, Planetoid Mines Company, Takasago Thermal Engineering, ThinkOrbital, but many lilely delayed

Planned for 2025 are Above Space (Orbital Assembly, Above: Orbital), DCubed, Dewey Scientific, Extremo Technologies, Helios, Interstellar Lab, Space Forge, Stellar Luxuries.

Planned for 2026 are ICON, Karman+ and Starpath Robotics. Planned for 2027 are MDA Space, Off-World, Solar Space Technologies. Planned for 2035 is Shimizu's lunar space solar power facility.

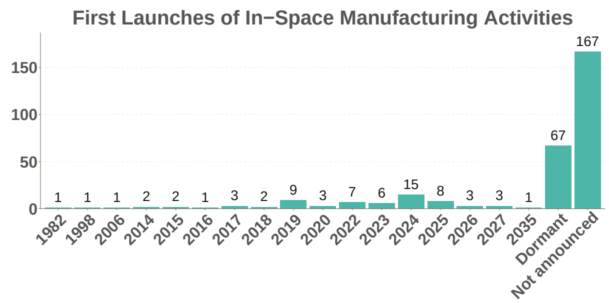

Figure 15: First Launch Years of In-Space Manufacturing Activities and Demonstrations

4.15 Geographical Distribution

Distribution of in-space manufacturing companies by headquarters locations is on Figure 16.

172 of the 303 ISM activities are based in the United States. Followed by 28 activities in the UK, 20 activities in Germany and Canada, 9 in Italy and Japan, 8 in France and 7 in Australia, 6 in Luxembourg, Poland and Israel, 3 in Belgium, but otherwise only 1-2 in other marked countries on the map.

The United States is also in the first place by the quantity of commercial entities and missions flown among in-space economy companies,[31] small launchers,[124] satellite constellations[125] and nanosatellites.[126] With in-space manufacturing being one of the most leading edge, risky and futuristic space industries, such lead and popularity is then expected.

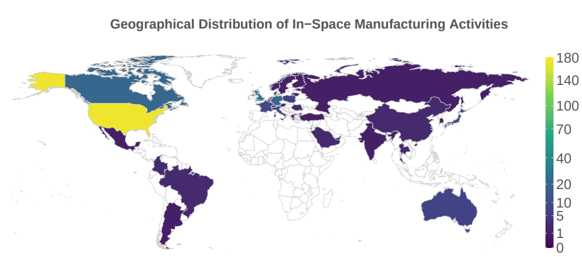

Figure 16: Map of In-Space Manufacturing Activities Headquarters

5. DISCUSSION & CONCLUSIONS

Statistical overview of 303 commercial activities for in-space manufacturing has been presented. Short history of in-space manufacturing and longer literature review has been written in the previous manuscript from 2022.[2]

In-Space Manufacturing (ISM) is a process involving the fabrication, assembly, and/or integration of goods outside the Earth's atmosphere.[7,8] Alternatively, in-space manufacturing is the transformation of raw or recycled materials into components, products, or infrastructure in space.[5]

The in-space manufacturing activities are divided into 8 categories: advanced materials, biotechnology, large structures, microfabricated goods, miscellaneous, novelty & luxury goods, pure substances and space food. Most common are space food and large-scale structures. This categorization will expand and change considerably in the coming decades when all types of goods and infrastructure will be made in space.

ISM companies have also been sorted by 3 main destinations or targets for the space-made goods: Earth, space and planetary surfaces.

There are no recurring in-space manufacturing products or activities as of September 2024. Several companies have performed demonstrations but no regularly active in-space production of specific goods is known. ZBLAN manufacturing in space has been demonstrated several times but regular production has not started and the future is unknown. Redwire announced an optical crystal in 2022 as the first sale of an in-space fabricated product. Instead, the first commercial space-made product was likely the latex spheres in the mid-1980s.

Finding the potentially profitable space-fabricated products and materials seems to be the biggest challenge for the in-space manufactured goods market targeted for Earth to take off. Research has been active for many decades but more fundamental research & development and quantitative studies are likely required to find the commercializable paths.

Microgravity manufacturing has to be analyzed in the context of full life-cycle cost, economies of scale and new technological processes. Some goods may be better when made in space but it is rarely quantified whether they are better enough to warrant the higher cost, which inherently arises due to space transportation, facilities and astronauts. Quantitative and comparative technical and market pricing studies for almost all microgravity applications seem to be missing or not yet made public.

There is an increasing number of service providers supporting in-space manufacturing such as Cargo Dragon, commercial ISS facilities, ESA's Space Rider, and many small re-entry capsules. However, already existing or planned space stations and transport capabilities should be lower cost when compared to accessing microgravity on dedicated on-demand solutions such as spaceplanes or re-entry capsules. Comparatively, the high-value materials worthwhile to be produced in space have been much slower to emerge and are difficult to forecast, thus the market size for supporting services for in-space manufacturing is unclear. The emergence of so many service providers likely cannot be explained purely by market forces. It might be comparable to building railways and large buildings but then not having a complete plan for their full utilization. Nevertheless, easier access to microgravity should help to spur the innovation, with many space station and re-entry capsule teams exploring applications on their own.

For ISM-for-space, where the outputs will remain in space, many first demonstrations are planned in the next 2-3 years. Commercial applications such as long antenna booms and solar arrays made in space could follow. This area has challenges with large initial investment requirements, market size and growth uncertainties, and many unproven technologies. However, government grants and awards should help to overcome it in the next years. Space-based solar power is also gaining new momentum.[127]

For ISM on planetary surfaces, successful missions of commercial lunar landers in the next 1-3 years should also pave the wave for first technology demonstrations. Then crewed return to the Moon should be followed by a rapidly increasing cadence of ISM activities on the lunar surface.

To conclude, in-space manufacturing has the potential to become one of the biggest space industries in the future just as manufacturing is a major broad industry on Earth but more fundamental research and quantitative studies are likely needed to find the promising commercial microgravity applications.

For future readers, the online-accessible database of commercial entities and related figures are expected to be updated multiple times per year on Factories in Space website (www.factoriesinspace.com).

Acknowledgments

The previous version of this work in 2022 received financial support and input from the In-Space Manufacturing Group from Space Technology Development Branch at NASA/George C. Marshall Space Flight Center.

6. APPENDIX A: Ecosystem Overview by Categories

The tables are sorted first by the in-space manufacturing process & technology and then alphabetically by the company name.

6.1 Advanced Materials

Table 1 lists the in-space manufacturing entities among the unique materials field. About 7 of them are or have worked on ZBLAN, which is currently the most common application. Some overlap with microfabricated goods is possible.

Table 1: In-Space Manufacturing Companies for Advanced Materials

Name	Destination	ISM Field	ISM Process/Tech	ISM Goods	Status	Founded	First Launch
Nanoarmor	Earth	Advanced Materials	Additive Manufacturing	Thermal tiles, Ceramics	Development	2016	Not announced
Redwire	Earth	Advanced Materials	Additive Manufacturing	Ceramics, Spare Parts	Demonstrated	2010	2020
ACME Advanced Materials	Earth	Advanced Materials	Annealing	Silicon Carbide Wafers	Dormant, Cancelled	2014	Dormant
GOEPPERT	Earth	Advanced Materials	Crystallization	Semiconductors, Molybdenum disulfide	Development	2017	Not announced
Varda Space Industries	Earth	Advanced Materials	Crystallization	ZBLAN	Dormant, Cancelled	2020	Dormant
MoonFibre	Surface	Advanced Materials	Forming Methods	Fibre-Reinforced Composites, Composites, Thermal Insulation, Filter	Development	2019	Not announced
Apsidal	Earth	Advanced Materials	Glass Processing	ZBLAN, Optical Fibers, Glass	Demonstrated	2019	2022
Flawless Photonics	Earth	Advanced Materials	Glass Processing	ZBLAN	Demonstrated	2017	2019
FOMS (Fiber Optic Manufacturing in Space)	Earth	Advanced Materials	Glass Processing	ZBLAN	Demonstrated	2015	2019
Mercury Systems (Physical Optics Corporation, POC)	Earth	Advanced Materials	Glass Processing	ZBLAN	Demonstrated	1985	2022
Redwire (Made in Space)	Earth	Advanced Materials	Glass Processing	ZBLAN, Glass, Optical Crystals	Demonstrated	2010	2017
Faraday Technologies	Space	Advanced Materials	Metallurgical Synthesis	Covetic materials	Development	1991	Not announced
Alva	Earth	Advanced Materials	TBD	Electroluminescent materials	Development	2021	Not announced
DSTAR Communications	Space	Advanced Materials	TBD	ZBLAN, Optical Fibers, Solar arrays	Development	2019	Not announced
Interstellar Space Technologies	Space	Advanced Materials	TBD	TBD	Early, Concept	2022	Not announced

6.2 Biotechnology

Table 2 lists the commercial in-space manufacturing entities under the broad biotechnology field and grouped by the process & technology. While many processes are similar to the ones used for space food then goods here are commonly non-edible.

Table 2: In-Space Manufacturing Companies for Biotechnology

Name	**Destination**	**ISM Field**	**ISM Process/Tech**	**ISM Goods**	**Status**	**Founded**	**First Launch**
3D Bioprinting Solutions (In-vitro)	Earth	Biotechnology	Bioprinting	Human organs	Dormant, Cancelled	2013	2018
Allevi (3D Systems)	Space	Biotechnology	Bioprinting	Human organs	Dormant, Cancelled	2014	Dormant
Encapsulate	Earth	Biotechnology	Bioprinting	Organ-on-chip, Tissue-on-chip	Development	2019	2024
Greiner Bio-One	Space	Biotechnology	Bioprinting	Cell Cultures	Development	1868	Not announced
LambdaVision	Earth	Biotechnology	Bioprinting	Retinal implant	Development	2009	2020
nScrypt	Earth	Biotechnology	Bioprinting	Implants	Demonstrated	2002	2019
Prometheus Life Technologies	Space	Biotechnology	Bioprinting	Tissue-on-chip, Organoids	Development	2022	Not announced
Space Applications Services	Space	Biotechnology	Bioprinting	Soft tissue	Development	1987	Not announced
Astronika	Space	Biotechnology	Bioreactor	Food, Oxygen	Early, Concept	2013	Not announced
Blue Horizon	Earth	Biotechnology	Bioreactor	Microorganisms	Development	2021	Not announced
Ecoatoms	Earth	Biotechnology	Bioreactor	Biomaterials	Development	2020	Not announced
EXPLOR Biologics	Earth	Biotechnology	Bioreactor	TBD	Development	2018	2024
Helix Space	Earth	Biotechnology	Bioreactor	Biomaterials, Biomolecules, Nutrients	Development	2021	Not announced
Kayser Space	Space	Biotechnology	Bioreactor	Lab-grown meat	Early, Concept	2015	Not announced
MakerHealth	Space	Biotechnology	Bioreactor	Drugs, Pharmaceutics	Demonstrated	2009	2023
BioOrbit	Earth	Biotechnology	Crystallization	Pharmaceutics, Drugs	Development	2023	Not announced
EOS (Electrophoresis Operations in Space)	Earth	Biotechnology	Crystallization	Pharmaceutics	Dormant, Cancelled	1980	1982
Merck Research Laboratories	Earth	Biotechnology	Crystallization	Pharmaceutics, Crystals	Demonstrated	2004	2014
Sachi Bioworks	Earth	Biotechnology	Crystallization	Drugs, Pharmaceutics	Demonstrated	2019	2023
Space Origami	Earth	Biotechnology	Crystallization	Crystals	Dormant, Cancelled	2018	Dormant
Varda Space Industries	Earth	Biotechnology	Crystallization	Pharmaceutics, Drugs, TBD	Demonstrated	2020	2023
Eascra Biotech	Earth	Biotechnology	Electrohydrodynamic jetting	Nanomaterials	Demonstrated	2022	2023

Continued on next page

Table 2: In-Space Manufacturing Companies for Biotechnology (Continued)

Redwire	Earth	Biotechnology	Glass Processing	Pharmaceutics	Development	2010	Not announced
Frontier Space Technologies	Earth	Biotechnology	Microfluidics	Biomaterials	Early, Concept	2021	Not announced
Odyssey SpaceWorks	Earth	Biotechnology	TBD	TBD	Demonstrated	2022	2023
Cedars-Sinai	Earth	Biotechnology	Tissue Engineering	Stem cells	Demonstrated	1902	2022
Numa Biosciences (Nortis)	Space	Biotechnology	Tissue Engineering	Organ-on-chip, Tissue-on-chip	Dormant, Cancelled	2011	2019
Redwire (Techshot)	Earth	Biotechnology	Tissue Engineering	Human organs, Biomaterials, Soft tissue	Demonstrated	1989	2019
Space Labs (BioGravity)	Earth	Biotechnology	Tissue Engineering	Cell Cultures	Dormant, Cancelled	2020	Dormant
SpacePharma	Earth	Biotechnology	Tissue Engineering	Pharmaceutics	Demonstrated	2012	2017

6.3 Large Structures

Table 3 lists the commercial in-space manufacturing entities under the large structures and in-space construction fields while grouped by technology & process. Most common technologies and processes are related to additive manufacturing, in-space assembly and vacuum deposition.

Table 3: In-Space Manufacturing Companies for Large Structures

Name	**Destination**	**ISM Field**	**ISM Process/Tech**	**ISM Goods**	**Status**	**Founded**	**First Launch**
AI Spacefactory	Surface	Large Structures	Additive Manufacturing	Surface Habitats	Development	2017	Not announced
Airbus	Space	Large Structures	Additive Manufacturing	Radiation shield, Tools, Equipment, Antennas , Spacecraft	Demonstrated	1970	2024
Anisoprint	Space	Large Structures	Additive Manufacturing	Spare Parts, TBD	Development	2015	Not announced
Astroport Space Technologies (XArc, Exploration Architecture)	Surface	Large Structures	Additive Manufacturing	Building Materials, Bricks, Landing Pad	Development	2020	Not announced
Automated Dynamics	Space	Large Structures	Additive Manufacturing	Boom	Early, Concept	1984	Not announced
Blueshift (Outward Technologies)	Surface	Large Structures	Additive Manufacturing	Spare Parts, Building Materials, Oxygen	Development	2017	Not announced
Branch Technology	Space	Large Structures	Additive Manufacturing	Structures	Early, Concept	2014	Not announced
Cislune	Surface	Large Structures	Additive Manufacturing	Propellant, Roads, Landing Pad	Development	2021	Not announced
DCUBED (Deployables Cubed)	Space	Large Structures	Additive Manufacturing	Solar arrays, Boom	Development	2019	2024
Fabrisonic	Space	Large Structures	Additive Manufacturing	Structures	Development	2011	Not announced
Gradel	Space	Large Structures	Additive Manufacturing	TBD	Early, Concept	2008	Not announced

Continued on next page

Table 3: In-Space Manufacturing Companies for Large Structures (Continued)

H-CAM (Hellenic Center for Additive Manufacturing)	Space	Large Structures	Additive Manufacturing	Structures	Development	2022	Not announced
Hassell Studio	Surface	Large Structures	Additive Manufacturing	Surface Habitats	Early, Concept	1938	Not announced
ICON	Surface	Large Structures	Additive Manufacturing	Surface Habitats	Development	2016	2026
Ierus Technologies	Space	Large Structures	Additive Manufacturing	Structures	Early, Concept	2008	Not announced
Infinity Space	Space	Large Structures	Additive Manufacturing	TBD	Early, Concept	2012	Not announced
International Scientific Technologies	Surface	Large Structures	Additive Manufacturing	Structures, Surface Habitats, Bricks	Early, Concept	2002	Not announced
Kilncore	Surface	Large Structures	Additive Manufacturing	Thermal tiles	Early, Concept	2020	Not announced
L3Harris (Eagle Technology)	Space	Large Structures	Additive Manufacturing	Antennas	Development	1998	Not announced
LavaHive	Surface	Large Structures	Additive Manufacturing	Surface Habitats	Dormant, Cancelled	2015	Dormant
Linc Research	Surface	Large Structures	Additive Manufacturing	Landing Pad	Early, Concept	2012	Not announced
Lodestar Space	Space	Large Structures	Additive Manufacturing	TBD	Dormant, Cancelled	2022	Dormant
Magna Parva (Kleos Space, In-Space Manufacturing)	Space	Large Structures	Additive Manufacturing	Boom	Dormant, Cancelled	2005	Dormant
Mainstream Engineering Corporation	Space	Large Structures	Additive Manufacturing	Thermal tiles	Early, Concept	1986	Not announced
Masten Space Systems (Rocket M, Astrobotic)	Surface	Large Structures	Additive Manufacturing	Landing Pad	Early, Concept	2004	Not announced
Mitsubishi Electric	Space	Large Structures	Additive Manufacturing	Antennas	Development	1921	Not announced
OHB	Space	Large Structures	Additive Manufacturing	Boom, Spare Parts	Demonstrated	1958	2024
Opterus	Space	Large Structures	Additive Manufacturing	Trusses, Boom	Development	2019	Not announced
Optomec	Space	Large Structures	Additive Manufacturing	Spare Parts	Early, Concept	1982	Not announced
Orbital Composites	Space	Large Structures	Additive Manufacturing	Solar arrays, RF antennas, Segmented optics, Mirrors	Development	2018	Not announced
Orbital Matter	Earth	Large Structures	Additive Manufacturing	Boom, Solar arrays	Development	2022	2024
Planetoid Mines Company	Surface	Large Structures	Additive Manufacturing	Boom, Landing Pad, Antennas	Early, Concept	2009	2024
Raven Space Systems	Space	Large Structures	Additive Manufacturing	Re-entry Capsule, Thermal tiles	Dormant, Cancelled	2020	Dormant
Redwire	Surface	Large Structures	Additive Manufacturing	Landing Pad, Roads	Development	2020	Not announced
Redwire	Earth	Large Structures	Additive Manufacturing	Optical Crystals, Crystals	Demonstrated	2010	2023
Redwire (Made in Space)	Space	Large Structures	Additive Manufacturing	Tools, Spare Parts	Demonstrated	2010	2016
Redwire (Made in Space)	Space	Large Structures	Additive Manufacturing	Boom, Antennas , Solar arrays	Early, Concept	2010	Not announced
Relativity Space	Surface	Large Structures	Additive Manufacturing	Surface Habitats	Early, Concept	2016	Not announced
Solideon (Additive Space Technologies)	Surface	Large Structures	Additive Manufacturing	TBD	Early, Concept	2022	Not announced
Space Copy	Surface	Large Structures	Additive Manufacturing	Structures, Infrastructure	Early, Concept	2022	Not announced

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Table 3: In-Space Manufacturing Companies for Large Structures (Continued)

Space Foundry	Space	Large Structures	Additive Manufacturing	Spare Parts, Printed electronics, Antennas	Development	2019	Not announced
Tethers Unlimited (ARKA, Amergint Technology)	Space	Large Structures	Additive Manufacturing	Boom, Antennas , Trusses, Solar arrays	Dormant, Cancelled	1994	2018
TGV Rockets	Space	Large Structures	Additive Manufacturing	Spare Parts	Development	1998	Not announced
Treddy	Space	Large Structures	Additive Manufacturing	Structures, Spare Parts	Early, Concept	2019	Not announced
Ultra Tech Machinery (The HEH Group)	Space	Large Structures	Additive Manufacturing	Spare Parts	Dormant, Cancelled	1986	Not announced
United Space Structures	Space	Large Structures	Additive Manufacturing	Surface Habitats	Dormant, Cancelled	2009	Dormant
Above Space (Orbital Assembly, Above: Orbital)	Space	Large Structures	Assembly	Space Station	Early, Concept	2018	Not announced
ArcSpace	Space	Large Structures	Assembly	Structures	Development	2022	Not announced
Astrea (Astreia)	Surface	Large Structures	Assembly	Surface Habitats	Dormant, Cancelled	2019	Dormant
Awake Aerospace	Space	Large Structures	Assembly	Space Station	Early, Concept	2020	Not announced
BAE Systems	Space	Large Structures	Assembly	TBD	Early, Concept	1999	Not announced
Bechtel	Surface	Large Structures	Assembly	Surface Habitats, Landing Pad	Early, Concept	1898	Not announced
Cosmic Robotics	Surface	Large Structures	Assembly	Structures, Infrastructure	Development	2023	Not announced
GIKEN	Surface	Large Structures	Assembly	Structures	Development	1967	Not announced
GITAI	Space	Large Structures	Assembly	Structures, Solar arrays	Development	2016	2024
HRL Laboratories	Space	Large Structures	Assembly	Antennas , Solar arrays	Development	1997	Not announced
International Electric Company	Space	Large Structures	Assembly	Space Solar Power	Early, Concept	1999	Not announced
KINETIK Space	Space	Large Structures	Assembly	TBD	Development	2022	Not announced
Kiteleon Technologies	Space	Large Structures	Assembly	TBD	Dormant, Cancelled	2020	Dormant
Light Mirror	Space	Large Structures	Assembly	Mirrors	Early, Concept	2019	Not announced
Lockheed Martin	Space	Large Structures	Assembly	TBD	Development	1912	Not announced
Longhurst Engineering	Space	Large Structures	Assembly	TBD	Dormant, Cancelled	2010	Dormant
Lunar Outpost	Space	Large Structures	Assembly	Structures	Development	2017	Not announced
Maxar (SSL)	Space	Large Structures	Assembly	Antennas	Dormant, Cancelled	1957	Dormant
MDA Space	Space	Large Structures	Assembly	Structures	Early, Concept	1957	2027
Moliri Space Energy	Space	Large Structures	Assembly	Structures, Space Solar Power	Early, Concept	2023	Not announced
OffWorld	Surface	Large Structures	Assembly	Oxygen, Hydrogen	Development	2016	2027
Orbital Outpost X (Space Villages)	Space	Large Structures	Assembly	Space Station	Dormant, Cancelled	2021	Not announced
ROVIAL	Space	Large Structures	Assembly	Spacecraft	Development	2021	Not announced
Shimizu Corporation	Surface	Large Structures	Assembly	Equipment	Development	1804	Not announced
Solar Space Technologies	Earth	Large Structures	Assembly	Space Solar Power	Early, Concept	2019	2027

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Table 3: In-Space Manufacturing Companies for Large Structures (Continued)

Space Applications Services	Space	Large Structures	Assembly	Space Solar Power	Early, Concept	1987	Not announced
Space Applications Services	Space	Large Structures	Assembly	Space Station	Early, Concept	1987	Not announced
Space Quarters	Space	Large Structures	Assembly	Structures	Early, Concept	2022	Not announced
Spacebilt (SkyCorp)	Space	Large Structures	Assembly	Spacecraft, Space Tug, Vehicle	Early, Concept	1998	Not announced
SpaceCrane	Space	Large Structures	Assembly	Structures, Infrastructure	Dormant, Cancelled	2022	Dormant
ThinkOrbital (Think Orbital)	Space	Large Structures	Assembly	Space Station	Development	2021	2024
Astronika	Surface	Large Structures	Compactor	Landing Pad, Roads	Early, Concept	2013	Not announced
Nanoracks (Voyager Space)	Space	Large Structures	Friction Milling	TBD	Demonstrated	2009	2022
Honeybee Robotics (Blue Origin)	Surface	Pure Substances,Large Structures	Materials Processing	Water, Oxygen, Hydrogen	Development	1983	Not announced
NANOARC	Surface	Large Structures	Materials Processing	Building Materials	Early, Concept	2013	Not announced
Physical Sciences	Surface	Large Structures	Materials Processing	Structures	Development	1973	Not announced
Thales Alenia Space	Space	Large Structures	Materials Processing	Spare Parts	Demonstrated	2007	2015
Uplift Aerospace	Surface	Large Structures	Materials Processing	Bricks	Dormant, Cancelled	2020	Not announced
Luna Innovations	Surface	Large Structures	Mechanical Press	Building Materials, Bricks	Dormant, Cancelled	1990	Not announced
Shimizu Corporation	Surface	Large Structures	Orbital Microfabrication	Space Solar Power	Early, Concept	1804	2035
Orbit Recycling	Space	Large Structures	Recycling	Building Materials	Early, Concept	2018	Not announced
Sira Space	Space	Large Structures	Recycling	Satellite, Infrastructure	Early, Concept	2023	Not announced
Arundal Astronautics	Space	Large Structures	TBD	TBD	Dormant, Cancelled	2016	Dormant
Futura	Surface	Large Structures	TBD	Landing Pad	Development	2023	Not announced
ABM Space	Space	Large Structures	Thin Coatings	Solar sail	Dormant, Cancelled	2011	Dormant
Lunar Resources	Surface	Large Structures	Vapour Deposition	Solar arrays, ZBLAN, Mirrors, Wire	Early, Concept	2018	Not announced
Rhea Space Activity (RSA)	Space	Large Structures	Vapour Deposition	Mirrors	Early, Concept	2018	
ZeCoat Corp	Space	Large Structures	Vapour Deposition	Mirrors	Early, Concept	2011	Not announced
Nanoracks (Voyager Space)	Surface	Large Structures	Welding	Bricks	Development	2009	Not announced

6.4 Microfabricated Goods

Table 4 gathers the commercial activities under the in-space manufactured microfabricated goods field. The most common goods are in-situ fabricated solar cells and semiconductors.

Table 4: In-Space Manufacturing Companies for Microfabrication

Name	**Destination**	**ISM Field**	**ISM Process/Tech**	**ISM Goods**	**Status**	**Founded**	**First Launch**
ATLANT 3D Nanosystems	Space	Microfabrication	Additive Manufacturing	Printed electronics, Microchips	Development	2018	Not announced
Hummink	Space	Microfabrication	Additive Manufacturing	Printed electronics, Composites	Development	2020	Not announced
JPM Silicon	Surface	Microfabrication	Crystallization	Solar cells	Development	2010	Not announced
Maana Electric	Surface	Microfabrication	Crystallization	Solar cells, Solar arrays	Development	2017	Not announced
United Semiconductors	Earth	Microfabrication	Crystallization	Semiconductors, Crystals	Development	2005	Not announced
UniversityWafer	Earth	Microfabrication	Crystallization	Microchips	Early, Concept	1997	Not announced
Blue Origin	Space	Microfabrication	Materials Processing	Solar cells, Building Materials, Alloys, Mirrors	Development	2000	Not announced
Astral Materials (Astral Forge)	Earth	Microfabrication	Orbital Microfabrication	Semiconductors	Development	2023	Not announced
LatticeXX (LatticeX)	Earth	Microfabrication	Orbital Microfabrication	Silicon Carbide Wafers	Development	2014	Not announced
Lunexus Space	Space	Microfabrication	Recycling	Solar cells	Early, Concept	2022	Not announced
Space Forge	Earth	Microfabrication	TBD	Wafers, Microchips, TBD	Development	2019	2025
Starflight Dynamics	Earth	Microfabrication	TBD	TBD	Development	2023	Not announced
Astrobotic	Surface	Microfabrication	Vapour Deposition	Solar cells	Early, Concept	2008	Not announced
Intel	Earth	Microfabrication	Vapour Deposition	Printed electronics, Semiconductors	Development	1968	Not announced
Microgravity Research Associates	Earth	Microfabrication	Vapour Deposition	Microchips	Dormant, Cancelled	1979	Dormant
NanoPrintek	Earth	Microfabrication	Vapour Deposition	Printed electronics	Early, Concept	2022	Not announced
Nebula Interplanetary Systems	Earth	Microfabrication	Vapour Deposition	Microchips	Early, Concept	2021	Not announced
Redwire (Made in Space)	Earth	Microfabrication	Vapour Deposition	Semiconductors	Development	2020	2024

6.5 Miscellaneous

Table 5 lists the commercial in-space manufacturing activities marked with the miscellaneous field as defined by their primary application and customer segments.

Table 5: In-Space Manufacturing Companies for Miscellaneous

Name	Destination	ISM Field	ISM Process/Tech	ISM Goods	Status	Founded	First Launch
Photocentric	Space	Miscellaneous	Additive Manufacturing	Tools, Spare Parts	Development	2002	Not announced
Stemrad	Space	Miscellaneous	Additive Manufacturing	Radiation shield	Development	2011	Not announced
Vistacent	Space	Miscellaneous	Additive Manufacturing	Spare Parts	Dormant, Cancelled	2020	Dormant
Arkisys	Space	Miscellaneous	Assembly	Satellite	Development	2015	2024
Finite Space	Surface	Miscellaneous	Assembly	Rover	Dormant, Cancelled	2023	Dormant

6.6 Novelty & Luxury Goods

Table 6 lists the commercial in-space manufacturing activities marked with the novelty & luxury goods field as defined by their primary application and customer segments.

Table 6: In-Space Manufacturing Companies for Novelty & Luxury Goods

Name	Destination	ISM Field	ISM Process/Tech	ISM Goods	Status	Founded	First Launch
Space Craft Beer	Earth	Novelty & Luxury	Bioreactor	Beer, Yeast	Dormant, Cancelled	2021	Dormant
Space Crystals	Space	Novelty & Luxury	Crystallization	Crystals	Demonstrated	2021	2022
Sapporo	Earth	Novelty & Luxury	Food Growing System	Beer, Barley	Demonstrated	1876	2006
Hopstronautix	Earth	Novelty & Luxury	Food Processing	Beer	Dormant, Cancelled	2018	Dormant
Space Roasters	Earth	Novelty & Luxury	Food Processing	Coffee Beans	Dormant, Cancelled	2018	Dormant
Starbase Brewing	Space	Novelty & Luxury	Food Processing	Beer	Early, Concept	2023	Not announced
Stellar Luxuries	Earth	Novelty & Luxury	Food Processing	Whisky	Early, Concept	2023	2025
International Flavors and Fragrances (IFF)	Earth	Novelty & Luxury	TBD	Fragrance	Demonstrated	1833	1998

6.7 Pure Substances

Table 7 lists commercial ISM activities under the pure substances, recycling and raw materials applications sorted by the processes & technologies.

Table 7: In-Space Manufacturing Companies for Pure Substances

Name	**Target**	**ISM Field**	**ISM Process/Tech**	**ISM Goods**	**Status**	**Founded**	**First Launch**
Re:3D	Space	Pure Substances	Additive Manufacturing	TBD	Development	2013	Not announced
Packer Engineering	Surface	Pure Substances	Beneficiation	Oxygen	Dormant, Cancelled	1962	Not announced
Shackleton Energy	Surface	Pure Substances	Beneficiation	Water	Dormant, Cancelled	2007	Dormant
Solar System Resources Corporation	Space	Pure Substances	Beneficiation	Helium-3	Early, Concept	2020	2028
Space Industries	Surface	Pure Substances	Beneficiation	Helium-3, Water, Hydrogen, Oxygen, Infrastructure, Structures	Dormant, Cancelled	2018	Dormant
L'Garde	Surface	Pure Substances	Concentrated Solar	Oxygen	Development	1971	Not announced
Northrop Grumman	Space	Pure Substances	Concentrated Solar	Metals	Development	1994	Not announced
Airbus	Surface	Pure Substances	Electrolysis	Oxygen, Metals	Early, Concept	1970	Not announced
Eta Space	Surface	Pure Substances	Electrolysis	Hydrogen, Oxygen	Development	2019	2024
Exoterra	Space	Pure Substances	Electrolysis	Hydrogen, Oxygen	Dormant, Cancelled	2011	Dormant
Helios	Surface	Pure Substances	Electrolysis	Oxygen, Metals	Development	2018	2025
Honda Motor Co	Surface	Pure Substances	Electrolysis	Water, Propellant	Development	1948	Not announced
Metalysis	Space	Pure Substances	Electrolysis	Oxygen	Development	2016	Not announced
OxEon Energy	Surface	Pure Substances	Electrolysis	Ice, Hydrogen, Oxygen	Demonstrated	2017	2020
Paragon Space Development Corporation (Final Frontier Design)	Surface	Pure Substances	Electrolysis	Water, Oxygen	Development	2010	Not announced
Skyre	Surface	Pure Substances	Electrolysis	Hydrogen, Oxygen	Development	2007	Not announced
Takasago Thermal Engineering	Surface	Pure Substances	Electrolysis	Water, Oxygen	Development	1923	2024
778 Labs	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2019	Not announced
AMi Exploration (ARCA Space, Asteroid Mining Program)	Earth	Pure Substances	Materials Processing	Water	Early, Concept	2022	2024
Argo Space	Surface	Pure Substances	Materials Processing	Water	Development	2022	2024
AstroForge	Earth	Pure Substances	Materials Processing	Platinum-group metals	Development	2022	Not announced
Austere Engineering	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2020	Not announced
Canadian Space Mining Corporation	Surface	Pure Substances	Materials Processing	Water, Oxygen	Early, Concept	2020	Not announced
Cimbus	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2024	Not announced
Ethos Space	Surface	Pure Substances	Materials Processing	Landing Pad, Oxygen, Concrete	Development	2022	Not announced

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Table 7: In-Space Manufacturing Companies for Pure Substances (Continued)

General Galactic	Space	Pure Substances	Materials Processing	Propellant, Methane, Oxygen, Hydrogen	Development	2023	Not announced
Hanwha Systems	Space	Pure Substances	Materials Processing	Water	Development	1977	Not announced
Interlune	Surface	Pure Substances	Materials Processing	Helium-3	Development	2020	Not announced
Interstellar Mapping	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2024	Not announced
Karman+ (Karman Plus)	Space	Pure Substances	Materials Processing	Water	Development	2021	2026
Liquifer Systems Group (LIQUIFER Space Systems)	Surface	Pure Substances	Materials Processing	Propellant, Water	Early, Concept	2011	Not announced
Lotic Technologies	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2022	Not announced
MAC SciTech	Surface	Pure Substances	Materials Processing	Oxygen, Hydrogen	Early, Concept	2012	Not announced
May Marom	Surface	Pure Substances	Materials Processing	Water	Dormant, Cancelled	2019	Dormant
Microelectronica	Space	Pure Substances	Materials Processing	Oxygen, Hydrogen	Development	2022	Not announced
Minespace	Space	Pure Substances	Materials Processing	Hydrogen	Early, Concept	2022	Not announced
Minima Design	Surface	Pure Substances	Materials Processing	Water	Early, Concept	1989	Not announced
Naicker Scientific	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2021	Not announced
Nascent Semiconductor	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2021	Not announced
Perspective Space-Tech	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2021	Not announced
Pioneer Astronautics (Voyager Space Holdings)	Surface	Pure Substances	Materials Processing	Iron, Silicon	Dormant, Cancelled	1996	Dormant
RedSpace	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2023	Not announced
Sierra Space (Sierra Nevada Corp, SNC)	Surface	Pure Substances	Materials Processing	Oxygen	Development	1963	Not announced
Sixpenny Architectural Fabrication	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2012	Not announced
SpaceGold	Surface	Pure Substances	Materials Processing	Metals, Platinum-group metals	Early, Concept	2019	Not announced
SpaceTIS	Space	Pure Substances	Materials Processing	Water, Metals	Early, Concept	2017	Not announced
Starpath Robotics	Surface	Pure Substances	Materials Processing	Propellant, Water	Development	2022	2026
TDA Research	Surface	Pure Substances	Materials Processing	Oxygen	Early, Concept	2016	Not announced
Terra Luna Resources	Surface	Pure Substances	Materials Processing	Water	Development	2022	Not announced
Thales Alenia Space UK	Surface	Pure Substances	Materials Processing	Oxygen, Propellant	Early, Concept	2007	Not announced
TransAstra (Trans Astronautics Corporation)	Space	Pure Substances	Materials Processing	Water	Development	2015	Not announced
WaterPuris	Surface	Pure Substances	Materials Processing	Water	Early, Concept	2022	Not announced
Advanced Fuel Research	Space	Pure Substances	Pyrolosis	Water, Propellant, Carbon	Early, Concept	1980	Not announced
Terraxis	Space	Pure Substances	Pyrolosis	Water, Metals	Development	2020	Not announced
Braskem	Space	Pure Substances	Recycling	Plastic feed stock	Demonstrated	2002	2019
Build Beyond	Space	Pure Substances	Recycling	TBD	Early, Concept	2021	Not announced

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Table 7: In-Space Manufacturing Companies for Pure Substances (Continued)

CisLunar Industries	Space	Pure Substances	Recycling	Aluminium, Metals	Development	2017	Not announced
Space Cowboy	Space	Pure Substances	Recycling	Metals, Feedstock	Early, Concept	2022	Not announced
Widgetblender	Space	Pure Substances	Recycling	Metals	Early, Concept	2021	Not announced
Skyhaven (Reactive Innovations)	Surface	Pure Substances	Sabatier Reactor	Hydrogen, Methane	Early, Concept	2017	Not announced
Diatomic Space	Surface	Pure Substances	TBD	Oxygen, Water, Propellant	Dormant, Cancelled	2022	Dormant
Foundation Space Resources (Lunar Water Supply Company)	Surface	Pure Substances	TBD	Water	Early, Concept	2020	Not announced
Regolithix	Surface	Pure Substances	TBD	Oxygen	Development	2021	Not announced
Space Mining Technologies	Surface	Pure Substances	TBD	Water, Propellant, Oxygen, Hydrogen	Dormant, Cancelled	2017	Dormant

6.8 Space Food

Table 8 lists the commercial ISM activities collected under the space food field and grouped by the process & technology types.

Table 8: In-Space Manufacturing Companies for Space Food

Name	**Destination**	**ISM Field**	**ISM Process/Tech**	**ISM Goods**	**Status**	**Founded**	**First Launch**
ALSEC	Space	Space Food	Additive Manufacturing	Food	Dormant, Cancelled	2004	Dormant
BeeHex	Space	Space Food	Additive Manufacturing	Pizza	Early, Concept	2016	Not announced
Explaneta Space	Space	Space Food	Additive Manufacturing	Food, Art	Dormant, Cancelled	2019	Dormant
Space Zab (SpaceZab)	Space	Space Food	Additive Manufacturing	Food, Pharmaceutics	Dormant, Cancelled	2017	Dormant
Ecoation Innovative Solutions	Space	Space Food	Aeroponics/Hydroponics	Food	Dormant, Cancelled	2010	Dormant
Eden Grow Systems	Space	Space Food	Aeroponics/Hydroponics	Food	Early, Concept	2017	Not announced
Far Out Foods	Space	Space Food	Aeroponics/Hydroponics	Food	Dormant, Cancelled	2021	Dormant
GreenOnyx	Space	Space Food	Aeroponics/Hydroponics	Food	Early, Concept	2013	Not announced
Interstellar Lab	Surface	Space Food	Aeroponics/Hydroponics	Surface Habitats, Flower	Development	2019	2025
JPWORKS	Space	Space Food	Aeroponics/Hydroponics	Food	Dormant, Cancelled	1914	Dormant
LTCOP (Laboratory of Tissue Culture Ornamental Plants)	Space	Space Food	Aeroponics/Hydroponics	Food	Dormant, Cancelled	2021	Dormant
Natufia x Edama	Space	Space Food	Aeroponics/Hydroponics	Food	Dormant, Cancelled	2014	Dormant
Orbital Farm	Space	Space Food	Aeroponics/Hydroponics	Food, Seafood	Early, Concept	2018	Not announced
Sierra Space (Sierra Nevada Corp)	Space	Space Food	Aeroponics/Hydroponics	Food, Oxygen	Demonstrated	1963	2014
SIRONA NOMs	Space	Space Food	Aeroponics/Hydroponics	Food	Dormant, Cancelled	2021	Dormant
SolSys Mining	Surface	Space Food	Aeroponics/Hydroponics	Fertilizer	Development	2018	Not announced
StarLab Oasis (Nanoracks)	Space	Space Food	Aeroponics/Hydroponics	Food	Dormant, Cancelled	2021	Dormant

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Table 8: In-Space Manufacturing Companies for Space Food (Continued)

Aleph Farms	Space	Space Food	Bioprinting	Lab-grown meat	Development	2017	2019
Electric Cow	Space	Space Food	Bioprinting	Food	Dormant, Cancelled	2021	Dormant
Hefvin	Space	Space Food	Bioprinting	Food	Dormant, Cancelled	2019	Dormant
KEETA	Space	Space Food	Bioprinting	Food	Dormant, Cancelled	2021	Dormant
Micro Meat	Space	Space Food	Bioprinting	Lab-grown meat	Dormant, Cancelled	2021	Dormant
Air Protein	Space	Space Food	Bioreactor	Protein food	Early, Concept	2019	Not announced
AlgaBloom International	Space	Space Food	Bioreactor	Food	Early, Concept	2014	Not announced
Alginity	Space	Space Food	Bioreactor	Food, Oxygen	Dormant, Cancelled	2018	Dormant
BigRedBites	Space	Space Food	Bioreactor	Food	Dormant, Cancelled	2021	Dormant
Canacompost Systems	Space	Space Food	Bioreactor	Composting	Dormant, Cancelled	2021	Dormant
CemVita Factory	Space	Space Food	Bioreactor	Nutrients, Pharmaceutics, Food	Dormant, Cancelled	2017	Dormant
Deep Space Entomoculture	Space	Space Food	Bioreactor	Food	Dormant, Cancelled	2016	Dormant
Eternal	Space	Space Food	Bioreactor	Food, Fungi	Development	2019	Not announced
Extremo Technologies	Space	Space Food	Bioreactor	Food, Oxygen	Development	2021	2025
Kernel Deltech	Space	Space Food	Bioreactor	Food	Dormant, Cancelled	2021	Dormant
Nature's Fynd	Space	Space Food	Bioreactor	Protein food, Fungi	Demonstrated	2012	2022
Nolux	Space	Space Food	Bioreactor	Food	Development	2021	Not announced
Solar Foods	Space	Space Food	Bioreactor	Protein food	Development	2017	Not announced
Air Company	Space	Space Food	Food Growing System	Food	Early, Concept	2017	Not announced
AMBAR	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	2021	Dormant
ASCENT Technology	Space	Space Food	Food Growing System	Food	Development	2020	Not announced
Canadensys	Space	Space Food	Food Growing System	Food	Development	2013	Not announced
Cosmic Eats	Space	Space Food	Food Growing System	Food	Early, Concept	2021	Not announced
Deep Space Ecology	Surface	Space Food	Food Growing System	Food	Dormant, Cancelled	2016	Dormant
Dewey Scientific	Earth	Space Food	Food Growing System	Hemp	Development	2018	2025
Enigma of the Cosmos	Space	Space Food	Food Growing System	Food	Development	2021	Not announced
InFynity	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	2022	Dormant
Mu Mycology	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	2021	Dormant
Naplasol (Mycorena)	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	2017	Dormant
Project MIDGE	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	2021	Dormant
RADICLE-X	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	2021	Dormant
Red Planet Farms	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	2021	Dormant
Redwire	Space	Space Food	Food Growing System	Food	Development	2020	2024
Space Lab Technologies	Surface	Space Food	Food Growing System	Food	Early, Concept	2016	Not announced
Space V (Space-V, SpaceV)	Space	Space Food	Food Growing System	Food	Development	2021	Not announced

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Table 8: In-Space Manufacturing Companies for Space Food (Continued)

Strauss Group	Space	Space Food	Food Growing System	Food	Demonstrated	1933	2022
Team PI	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	2021	Dormant
Wester Shore Associates	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	1984	Dormant
µBites	Space	Space Food	Food Growing System	Food	Dormant, Cancelled	2021	Dormant
Argotec	Space	Space Food	Food Processing	Coffee	Demonstrated	2008	2015
Bake In Space	Space	Space Food	Food Processing	Bread	Dormant, Cancelled	2017	Dormant
Budweiser (Anheuser-Busch)	Surface	Space Food	Food Processing	Beer	Development	1876	2017
Cx Bio (Connectomix)	Surface	Space Food	Food Processing	Food	Early, Concept	2021	Not announced
Hilton (DoubleTree by Hilton)	Space	Space Food	Food Processing	Cookie	Demonstrated	1969	2019
Mission: Space Food (Astreas)	Space	Space Food	Food Processing	Food	Dormant, Cancelled	2018	Dormant
Space Bread	Space	Space Food	Food Processing	Bread, Food	Dormant, Cancelled	2021	Dormant
Zero G Kitchen	Space	Space Food	Food Processing	Food	Demonstrated	2018	2019
Bistromathic	Space	Space Food	TBD	Food	Dormant, Cancelled	2021	Dormant
PeaPod Technologies	Space	Space Food	TBD	Food	Dormant, Cancelled	2021	Dormant
SolarBiotech (Noblegen)	Space	Space Food	TBD	Food	Dormant, Cancelled	2013	Dormant

APPENDIX B: NASA's 2020 Technology Taxonomy Connections

NASA's 2020 Technology Taxonomy has technical discipline of TX07 Exploration Destination Systems where the technology type TX07.2.2 In-Situ Manufacturing, Maintenance, and Repair is defined as "In-situ manufacturing, maintenance, and repair technologies manufacture items using feedstock produced from in-situ resources and recycled materials and provide system evaluation, preventive maintenance, and corrective actions for human exploration systems".[18,128] The taxonomy also has subareas for example TX07.1 In-Situ Resource Utilization, TX07.2.3 Surface Construction and Assembly, TX07.2.4 Micro-Gravity Construction and Assembly, TX12.4.1 Manufacturing Processes, etc.[18,128]

NASA's 2020 Technology Taxonomy lists many example technology types under TX12.4.1 Manufacturing Processes: additive manufacturing of metallics and nanofiber/fiber/ceramic matrix based composites (for large structures); in-space fabrication, assembly and repair; advanced casting and injection molding of metal components (including amorphous metals and metal matrix composites); subtractive manufacturing processes including wire-Electrical Discharge Machining (EDM). TX12.4.6 Repurpose Processes lists reusing vehicle tanks for habitats and storage and metals components as 3D printing feedstock. TX12.4.3 Electronics and Optics Manufacturing Process is also relevant to ISM..[18]

There is a long list of enabling and supporting technologies for ISM in the NASA's 2020 Technology Taxonomy, e.g. TX12.3.1 Deployables, Docking, and Interfaces, TX04.3.1 Dexterous Manipulation, TX04.3.2 Grappling Technologies, TX04.5.5 Capture Mechanisms and Fixtures, TX10 Autonomous Systems, TX10.1.2 State Estimation and Monitoring, TX12.3.2 Electro-Mechanical, Mechanical, and Micromechanisms, and many more.[18]

Appendix B1: Advanced Materials

NASA's 2020 Technology Taxonomy area TX12 Materials, Structures, Mechanical Systems, and Manufacturing includes technology types TX12.1.1 Lightweight Structural Materials, TX12.1.3 Flexible Material Systems, TX12.1.4 Materials for Extreme Environments, TX12.1.5 Coatings, TX12.1.6 Materials for Electrical Power Generation, Energy Storage, Power Distribution and Electrical Machines, TX12.1.7 Special Materials, TX12.1.8 Smart Materials. Many of the listed example technologies could be made in space and some might achieve better properties. For example novel low density metals, metallized films, nanomaterials, ceramic matrix composites, ultrahigh temperature ceramics, advanced alloys, amorphous metals, nanofibres, nanocomposites, graphene sheets, superconducting materials, amorphous nanocrystalline coatings, optically transparent window materials, metallic glasses, metamaterials, aerogels, etc.[18]

Appendix B2: Biotechnology

NASA's Taxonomy area TX06 Human Health, Life Support, and Habitation Systems includes technology type TX06.6.6 Maintainability and Supportability under which example technologies of "onboard biotechnology capability to deal with unforeseen medical and ecological failures" and "integrated ecological system (sewage and organic matter including anaerobic products such as methane, H2, and succinates—processing by organisms, plant growth for food and air" are related to biotechnology. Same with subarea TX06.3 Human Health and Performance where the example technologies under TX06.3.2 Prevention and Countermeasures are cell/tissue culture, animal models, and induced pluripotent stem cells.[18]

Appendix B3: Large Structures

The most relevant technology areas found from NASA's 2020 Technology Taxonomy are:

- TX07.2.2 In-Situ Manufacturing, Maintenance, and Repair technology type lists example technologies such as additive manufacturing using broad-specification feedstock from terrestrially-delivered, locally-produced, and recycled materials; subtractive manufacturing using feedstock from terrestrially-delivered, locally-produced, and recycled materials.[18]
- TX07.2.3 Surface Construction and Assembly is defined as surface construction and assembly covers technologies for construction, assembly, disassembly, and reverse assembly of surface structures, including both traditional construction, assembly, and disassembly concepts and advanced systems. Example technologies include consolidation and stabilization of regolith on large scales with microwave and concentrated solar irradiation; manufacturing of structural elements using feedstock derived from locally-produced and recycled materials; assembly of structural and environmental barrier systems from terrestrially-delivered and/or locally-derived elements.[18]

- TX07.2.4 Micro-Gravity Construction and Assembly is described as construction and assembly technologies which transform the way we manufacture, assemble, disassemble, and repair large structures in space, providing a robust space infrastructure freed from launch window scheduling, launch vehicle mass limitations, and astronaut safety concerns. Example technologies are on-orbit three dimensional (3D) manufacturing, robotic arms/manipulators and in-space truss manufacturing.[18]
- TX12.2.1 Lightweight Concepts are efficient structures and structural systems using new and innovative approaches to develop beyond-state-of-the-art mass reductions for affordable, enhanced performance, reliable, and environmentally responsible aerospace applications. Example applications are components for space vehicles and surface habitats, in-space depots and landers, solar or antenna arrays, complex precision deployables. The technologies used for these components may include either rigid construction (e.g., shell or truss structures) or expandable configurations (e.g., inflatable structures) having efficient structural geometries (e.g., hat-stiffened shells) constructed from advanced materials (e.g., polymer matrix composites) using advanced fabrication methods (e.g., additive manufacturing).[18]

Appendix B4: Microfabrication

Possibly related technologies and applications from the NASA's 2020 Technology Taxonomy include high-voltage semiconductors and passive components under technology type TX03.3.4 Advanced Electronic Parts; metallized films and solar sails under TX12.1.3 Flexible Material Systems; and films, nanofibers, nanocomposites listed under TX12.1.5 Coatings.[18]

Appendix B5: Pure Substances

NASA's 2020 Technology Taxonomy includes many relevant technology areas:

- TX07.1.2 Resource Acquisition, Isolation, and Preparation is defined as resource acquisition, isolation, and preparation technologies access, extract, isolate, concentrate, modify, and purify resource-bearing materials in preparation for further processing, which can include locally acquired materials and byproducts of mission operations that become available for recycling. Example technologies for in-space manufacturing are preparing granular regolith through grinding, crushing, sorting, and mixing; collect, filter, isolate, and accumulate resource-bearing atmospheric gases; collect, separate, and purify recyclable water and organic and inorganic by-products of mission operations; separate target resources from extraterrestrial materials and gases including beneficiation and atmospheric gas separation.[18]
- TX07.1.3 Resource Processing for Production of Mission Consumables is defined as resource processing technologies that produce mission consumables, such as water, breathable oxygen, inert gases, and propellants, from pre-processed resources. Example technologies are thermal/mechanical components and reactors to extract end-product resources from inert materials (e.g. thermal reactors for volatile extraction from regolith); chemical, electrochemical, and biological materials, catalysts, components, and reactors to extract and combine resources to produce end-products (e.g. catalytic reactors to produce methane, electrolysis devices to produce oxygen, etc.); phase-change devices to extract or distill end-product gases from by-product recycling sources (e.g. cryocoolers for gas product drying); crosscutting technologies for utilizing sources of high-temperature thermal energy for process-heating (e.g. integrated solar concentrators).[18]
- TX07.1.4 Resource Processing for Production of Manufacturing, Construction, and Energy Storage Feedstock Materials is defined as resource processing technologies that produce feedstock for in-situ manufacturing, construction, and thermal energy storage systems. Example technologies are production of granular material by grinding, crushing, sorting, and mixing; chemical, electrochemical, and biological processing to extract and combine resources to produce manufacturing feedstock (e.g. metal extraction and separation, ceramic materials extraction, plastic production, etc.); physical, chemical, thermal, and biological pretreatment of raw feedstock materials to meet purity standards required for manufacturing or construction processes.[18]

Appendix B6: Space Food

There are many relevant activities and technologies listed in the NASA's 2020 Taxonomy under area TX06 Human Health, Life Support, and Habitation Systems. For example store/prepare/consume food under subarea TX06.1.4 Habitation Systems. Technology TX06.3.5 Food Production, Processing, and Preservation is defined as food production, processing, preservation technologies include both space and Earth technologies that safely produce and handle food to reduce up-mass and retain maximum nutritional value. Example technologies for ISM are bioregenerative food system, vegetable production system, and plants habitat.[18]

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