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In-Space Economy in 2021 - Statistical Overview and Classification of Commercial Entities

Erik Kulu

Factories in Space, Nanosats Database, NewSpace Index, Kepler Communications
erik.kulu@factoriesinspace.com

Abstract

New in-space economy fields are emerging. The nascent space industries include human spaceflight, satellite servicing, orbital transfer vehicles, commercial space stations, in-space manufacturing, commercial landers and many others. In-space economy includes cislunar economy and Moon and Mars economies.

Factories in Space (www.factoriesinspace.com) is the largest online database of commercial entities in the emerging in-space economy, space resources and microgravity manufacturing fields. The directory was started in 2018 and is growing quickly with 400 entries at this time.

First part of the paper will define what new in-space economy is and establish classification for the companies. Literature review will be performed and glossary will be created to define the relatively new terms in a single source. Until the new industry categories are defined and accepted, activities will be named by varying methods, which makes it challenging to determine competitors and estimate market sizes. The count of high-level categories has been limited to the order of 10 for practical purposes.

Second part of the paper will present statistical overview of which companies are or aim to be active in the new in-space economy fields. While most of the commercial lander, space resources, habitat and space utilities (energy, oxygen, water, communications) enterprises are focusing on LEO and Moon, many of them will likely add Mars and deep space to their activities once launch opportunities and markets arise. Within the classifications, comparison will be made between capabilities, development status, geographical distribution and funding where available. Goal is to leave a snapshot from 2021 to be able to start discovering trends and next space market booms over the coming decade.

Keywords: in-space economy, space-based economy, beyond-Earth space economy, on-orbit economy, cislunar economy, in-space manufacturing

1. INTRODUCTION

Factories in Space has tracked new in-space economy entities since 2018. There are 400 entries as of September 2021, likely the largest public database. The initial target was microgravity applications and services, but scope was expanded when a large quantity of overlapping in-space economy or space-based economy companies started to be announced.

In-space economy means generating revenue in space using assets in orbit or beyond Earth. In-space economy is the new extraterrestrial space industries.[1] Sometimes called as space-based economy and in narrower definitions on-orbit economy, space-for-space economy, low Earth orbit economy, beyond-Earth space economy and it also encompasses cislunar economy, Moon and Mars. M. Weinzierl and M. Sarang called it as space-for-space economy and defined it as goods and services produced in space for use in space, such as mining the Moon or asteroids for material with which to construct in-space habitats or supply refuelling depots.[2] For clarity, excluding satellite constellations for terrestrial purposes and Earth-to-space launch vehicles.

New in-space economy entails space stations, commercial landers, in-space manufacturing and much more. Fields that often started emerging commercially in the 2000s and generally have had small revenues. New space economy and specifically in-space economy terms grew out to distinct the new areas and to be able to follow them without existing large space industries inflating the numbers.

Literature review was performed and studies about the broader new in-space economy seem to be relatively sparse. Butow et al. summarized state of the space industrial base in 2020, which included many of the fields.[3] Daniel Faber, CEO of Orbit Fab, has used the term.[4] The Lunar ISRU 2019 workshop was titled "Developing a New Space Economy Through Lunar Resources and Their utiliza-

tion".[5] Harrison et al. reported on the "Implications of Ultra-Low-Cost Access to Space" in 2017.[6] IDA's Corbit et al. studied global trends in on-orbit servicing, assembly and manufacturing (OSAM).[7]

Space Foundation's The Space Report found that global space economy reached $447 billion in 2020, with 80% being commercial revenues.[8,9] Euroconsult estimates that the consolidated space economy totalled $385 billion in 2020, out of which $315 billion were commercial revenues.[10] Satellite Industry Association's report prepared by Bryce Tech estimated global space economy revenues in 2020 at $371 billion.[11] P. Lionnet estimates worldwide space economy consolidated value at about $292 billion in his August 2021 discussion paper.[12] The latter being perhaps closer to reality. Most of those $300-400B estimates include government budgets, satellite TV and consumer equipment like GPS receivers. IDA report in 2020 discussed 5 forecasts for future of the space economy and found them optimistic.[13]

Fields that are undoubtedly space, also known as upstream or space infrastructure or space manufacturing sector,[12] have significantly smaller revenues. Satellite manufacturing had $12.2B and launch vehicles had $5.3B of revenues in 2020 according to Bryce Tech.[11] Euroconsult estimates that in 2020, only $9B of $385B was in commercial upstream, dividing between $4B for hardware manufacturing, $1.7B for launch services and $3B for ground segment.[10] In-space economy is even smaller than these estimates and has largely started to emerge only recently.

We need new economic drivers for spaceflight. Something new and potentially larger than any existing space industry, such as telecommunications, remote sensing, launch and research. The following are supporting macro trends for in-space economy:

- Decreasing launch costs. Now about 2-3 times less according to P. Lionnet,[14] but potentially 10-100 times lower in the future, e.g. Starship.
- Commercialization of space and LEO.
- Commercial services and infrastructure.
- ISRU and space resources advancements.
- Pollution and climate change on Earth.
- Increasing momentum for space settlements.
- NewSpace iterative mindsets and affinity for bolder risks, also from long-term investors.

First part of this paper establishes taxonomy or classification for the commercial entities in space-based economy to be able to group them. Second part presents statistical overview of the 400 surveyed in-space economy entities.

2. RISE OF NEW IN-SPACE ECONOMY

Here follows a short and non-exhaustive chronological overview of some of the latest advances and companies in the primary in-space economy fields.

2.1 Commercial Space Stations

Space Industries Incorporated was founded in the early 1980s and planned to develop a commercial space facility called the Industrial Space Facility (ISF) to be launched in the early 1990s. Reagan administration agreed to become an anchor customer with up to $700 million in funding, but the request was not approved by the US Congress.[15,16]

Bigelow Aerospace was founded in 1999 to develop expandable orbital station modules. The first free-flying technology demonstrator Genesis I was launched in 2006 and Genesis II in 2007.[17] BEAM module was launched to the ISS in 2016 under a $17.8 million NASA contract[18] and is still attached. Bigelow has developed numerous designs for large commercial space stations, space hotels and lunar bases including the BA330 and BA 2100.[17] In early 2020, SpaceNews reported that Bigelow decided not to pursue NASA competition for a commercial ISS module because of funding concerns.[19] In March 2020, Bigelow laid off all employees and it is unknown whether activities will resume.[20]

Private and cost-effective human spaceflight has always been a challenge for space stations and a relatively large expense in general. Once SpaceX demonstrated crewed flight in May 2020 (Demo-2) and NASA started seeking commercial International Space Station (ISS) modules in June 2019,[21] Bigelow seems to have been unable to take advantage of the finally positive trends and emerging ecosystem, after 20 years and well over $250 million invested.[22]

In 2007, Galactic Suite Project was announced, which planned luxury orbital getaways by 2012.[23]

In 2010, Russian company Orbital Technologies announced Commercial Space Station to be launched in 2015 in partnership with RSC Energia.[24]

Axiom Space was founded in 2016 and has raised over $150 million to date.[25] In early 2020, NASA awarded Axiom the NextSTEP contract for the first commercial ISS module.[26] The construction of the first two modules was contracted to Thales Alenia and planned to be launched in 2024 and 2025.[27] The modules will be separated into a free-flying commercial orbital platform before the ISS is deorbited.

Orion Span was founded in 2017, but fell short of their $2M crowdfunding campaign in early 2019.[28]

In February 2021, Orbital Assembly Corporation

announced plans to start building the Voyager Station with artificial gravity in 2025.[29]

In March 2021, Sierra Nevada Corporation (SNC, now Sierra Space) announced LEO space station plans with inflatable pods, which would be supplied by their Dream Chaser spaceplanes.[30]

During 2021, NASA has been seeking solutions for free-flying commercial space stations and did receive about a dozen proposals.[31,32]

Nanoracks CEO Jeff Manber has said his company has already lost business to China's Tiangong Space Station.[33] Lunar Gateway will likely have commercial services for CubeSat and microsatellite deployment and internal and external platforms for commercial payloads.

In October 2021, Nanoracks, Voyager Space and Lockheed Martin announced Starlab, a commercial space station which could launch as early as 2027.[34]

A few days later, Blue Origin and Sierra Space with Redwire Space, Boeing and Genesis announced Orbital Reef, a space station that would be ready in latter half of the 2020.[35] Sierra Space seems to be pausing its independent plans from March 2021.

2.2 Asteroid Mining (Space Resources)

The first wave of commercial asteroid mining has already come and gone.[36]

Planetary Resources (Arkyd) was founded in 2009 by high-profile backers with the intention to mine asteroids for profit. CubeSats were launched in 2014, 2015 and 2018, and over $50M of capital was raised.[37] There were plans to create mid-wave infrared Earth Observation constellation for near-term revenue generation,[38] but the company was sold in 2018 after failing to raise further funding.[39,40]

Deep Space Industries (DSI) was founded in 2013 with the goal of prospecting and extracting space resources and raised over $3.5 million.[36] In the end, they were unable to launch a demonstration mission, business model was pivoted to deep-space smallsats and water-based thrusters, and the company was sold to Bradford Space in late 2018.[41]

There are others, including Asteroid Mining Corporation[42] in the UK and Origin Space from China, latter of which launched a test spacecraft in 2021.[43]

At the end of 2020, NASA selected four companies to collect space resources and transfer ownership to the agency: Lunar Outpost, Masten Space Systems, ispace Europe and ispace Japan, paying from $1 to $15000 for small amounts of lunar regolith.[44]

2.3 Surface Habitats

The Lunar Resources Company (now The Moon Society) designed a commercial Lunar Settlement plan in the 1990s called The Artemis Project.[45] Started in 1993, the first description and architecture was published in 1995 in Analog Magazine.[46]

Mars One organization was announced in 2012 and planned to send a crewed mission to Mars on a one-way ticket to establish a human settlement in 2023.[47] After many controversies[48] and much scepticism, the project eventually failed to attract enough funding and went bankrupt in 2019.[49]

The overall trends and technological capabilities were not there, thus making the plans too early at the time. As of 2021, SpaceX's Starship and NASA's Artemis program are starting to provide a much more favourable environment.

2.4 Commercial Landers

In 1998, SpaceDev claimed to be the world's first commercial space exploration and development company and intended to launch the first privately financed spacecraft to land on another planetary body. It was selling rides for scientific instruments to a near Earth asteroid with the intention to sell that data as commercial products.[50]

The $20M Google Lunar XPrize was announced in 2007. The goal was to land a private robotic spacecraft on the Moon, travel at least 500 meters and transmit high-definition video. The initial deadline of 2012 was extended multiple times until 2018, when the challenge ended with no winner.[51,52]

Beresheet was a lander from Israel's non-profit SpaceIL and their entry to XPrize, which as of 2021 is the only one which has been launched, and which made an unsuccessful landing attempt in 2019.[53] While most of the other XPrize finalists are still active with missions booked, none have launched after more than 3 years from the initial deadlines.

In 2018, NASA launched the Commercial Lunar Payload Services Program (CLPS) to use commercial lander services for science and technology payloads.[54] In May 2019, Astrobotic was awarded $79.5M, Intuitive Machines $77M and OrbitBeyond $97M.[55] Launches were supposed to happen in 2020-2021, but are now 2022 at the earliest. OrbitBeyond later asked to be released from the contract.[56] In 2020, NASA awarded $75.9M to Masten for for a mission in 2022.[57] Also in 2020, NASA awarded Astrobotic $199.5M to deliver the VIPER rover to the Moon.[58] In 2021, NASA awarded CLPS contract worth of $93.3M to Firefly Aerospace to deliver a suite of 10 payloads to the Moon in 2023.[59]

2.5 Commercial Rovers

The first wave of in-space economy companies happened in the late 1990s and early 2000s during the first wave of communications constellations and Internet companies.

BlastOff! Corporation operated from 1999 to 2001, peaked at 50 employees and planned to send a robotic lander and rover to the Moon in 2001.[60] TransOrbital got permission for the first private Moon landing in 2002 and planned to send an imaging satellite and a time capsule as early as 2003.[61]

Google Lunar XPrize kicked off the development of plethora of rovers, because one requirement was to travel 500 meters and capture HD-video.[51]

Astrobotic was awarded $5.6M in 2019 by NASA to develop MoonRanger rover, which could fly in 2022 on Masten XL-1 lander.[62] In 2018, Astrobotic announced that it established CubeRover subsidiary in Luxembourg,[63] but does not seem to have happened and website now redirects to Astrobotic.

2.6 Commercial Cargo

In 2004, NASA awarded Kistler, which by that time was in bankruptcy, a $227 million contract for a fully reusable launch vehicle K-1's flight data. SpaceX protested and argued that other companies should have been given the opportunity to compete. NASA cancelled the award after it became clear that the Government Accountability Office (GAO) would rule in favor of SpaceX.[64,65]

NASA Commercial Orbital Transportation Services (COTS) consisted of two phases. Phase 1 was demonstrations and Phase 2 was a competition for cargo services to support the ISS. NASA payments were made only upon completion of progress milestones.[66,67] SpaceX and Rocketplane-Kistler were selected in August 2006.[68] The agreement with Kistler was terminated in September 2007 after it failed to complete financial and technical milestones.[69] A competition was held to select a new partner, which resulted in the selection of Orbital Sciences Corporation (OSC) in February 2008.[66]

In 2008, NASA announced the Commercial Resupply Services (CRS-1) awards. SpaceX received $1.6 billion for 12 cargo Dragon flights and $1.9 billion went to Orbital Sciences for eight Cygnus flights.[70] SpaceX performed the first demo mission to ISS in 2012 and Orbital in 2014. In December 2015, NASA extended CRS-1 to twenty flights for SpaceX and ten flights to Orbital ATK.[71]

Second CRS-2 contracts were awarded in January 2016 to Orbital ATK, SpaceX (Dragon-2) and SNC (Dream Chaser) for flights starting in 2019 and lasting through 2024. Cygnus and Cargo Dragon have been flying since 2019-2020. The first SNC Dream Chaser Demo-1 launch is planned for 2022 on a Vulcan rocket, which has not flown yet.[72]

SpaceX was awarded one-way cargo transportation services called Gateway Logistics Services in March 2020 for the Lunar Gateway, using a new Dragon XL launched on Falcon Heavy.[73] As of April 2021, the formal contract start has been delayed.[74]

Chinese startup Interspace Explore is developing reusable spacecraft capable of supplying China's Tiangong space station with a first small-scale demonstration mission planned for 2022.[75]

2.7 Commercial Human Spaceflight

At least two firms entered into negotiations to buy and operate a fifth Space Shuttle in 1980s.[76,77]

In 2009, Excalibur Almaz announced they will be using Soviet Almaz reusable space capsules to launch tourists to orbit and Moon. Flights were first planned to start in 2013 and later pushed to 2015. The company went defunct around 2016.[78–80]

Space Adventures has sent 7 space tourists, or space flight participants, on 8 flights to the ISS between 2001-2009 using Sojuz.[81] In 2011, Space Adventures announced that one ticket for a circumlunar Sojuz mission in 2015 had been sold at a price of $150 million.,[82,83] but that mission has not come to fruition. Commercial visits to the ISS will continue in December 2021 using Sojuz, with a two-week mission including Yusaku Maezawa.[84] Space Adventures have also announced a free-flying SpaceX Crew Dragon capsule mission.[81]

In 2013, two-time space tourist Dennis Tito announced Inspiration Mars foundation and a private Mars flyby mission in 2018.[85] Trouble started when a mission study showed that commercial vehicles would not be suitable and NASA's SLS (Space Launch System) would be required plus extensive support.[86] In 2014, liftoff was rescheduled to 2021,[87] but the organization became dormant in 2015.

Commercial Crew Development (CCDev) Phase 1 awards were announced in early 2010 with funding for concept and technology development.[88] The final phase of CCDev program concluded in September 2014.[89] SpaceX was awarded $2.6 billion and Boeing was awarded $4.2 billion.[90] SpaceX performed the first uncrewed flight in 2019, crewed demo flight in 2020 and has performed 2 operational missions.[91] Boeing's Starliner performed a partially successful first mission in December 2019,[92] while the second uncrewed test has been delayed to 2022,[93] and the earliest crew mission to late 2022 or 2023.[94]

In 2016, SpaceX announced plans for a circumlunar mission paid by Yusaku Maezawa with the Crew Dragon flying on Falcon Heavy.[95] In 2018, the plans were switched to Starship with the lunar flyby mission "dearMoon" currently scheduled for 2023.[96]

In September 2021, Inspiration4 mission performed a 3-day flight on SpaceX Crew Dragon, which did not have any professional astronauts on-board.[97] There have been all-civilian and private missions before, but they always had at least one professional astronaut part of the crew, making this the first all private sector and citizen mission.

NASA announced Artemis program in 2019 to send the first woman and the next man to the Moon by 2024 and to develop a sustainable human presence on the Moon by 2028.[98] NASA announced competition for the Human Landing System (HLS) in 2019, which would perform the human lunar landing in 2024. In the first study phase announced in April 2020, Blue Origin was awarded $579M, Dynetics $253M and SpaceX $135M.[99] In April 2021, SpaceX won the $2.89 billion contract with Starship for the first return lunar landing mission.[100] Further regular flights, after the first, will have a new competition and possibly 2 service providers to be selected. In September 2021, NASA awarded NextSTEP awards for a total of $146M for further sustainable human lander technology development.[101]

2.8 Re-Entry Capsules

Small re-entry capsules for on-demand return from space (stations) is a decades old idea with many missions flown.[102] The idea had more support during the retirement of the Space Shuttle when the ISS was supplied with expendable Progress, ATV and HTV and only a limited downmass capability existed with Sojuz capsules. With the recent emergence of regular commercial crew and returnable cargo flights every 2-3 months, the practical necessity and business case to save approximately a month of time for a considerably more cost has not been proven. Similar unproven case is with dedicated (reusable) satellites for microgravity manufacturing and research.[103]

VBK-Raduga was a reentry capsule that flew 9 or 10 flights between 1990-1994, returning materials from Mir.[104] In 2000, European Space Agency (ESA) with international partners tested inflatable re-entry technology with the ISS payload download seen as one promising application due to the Space Shuttle costs.[105] Around 2005, ESA and EADS (Airbus) studied PARES (Payload Retrieval System) that would have been launched from the expendable Automated Transfer Vehicle (ATV) and could bring back 220 kg with a design that was 70 cm in diameter and 2.28 m in length.[106]

Small re-entry capsules were commonly used for military Earth observation satellites to return the film. Soviet lunar sample return missions had a small re-entry capsule and performed the first 3 successful robotic missions in 1970-1976. BREM-SAT 2 was studied around 1996 and planned be capable of re-entry using a deployable heat shield.[107] The next extraterrestrial samples were returned on Genesis, Stardust, Hayabusa, Hayabusa2 and Chang'e 5 missions while OSIRIS-REx is ongoing and many planned including Martian sample-return.

Foton and Foton-M are a Russian series of spacecraft with re-entry capsules. First mission was in 1985 and the last mission was performed in 2014.[108]

In 2014, NASA awarded Terminal Velocity (SpaceWorks) SBIR Phase 1 and Phase 2 contracts for low-cost small payload return with a capsule-series called RED (Reentry Device, RED-25, RED-4U).[109–111] The data recorder version RED-Data2 flew in 2017 on Cygnus OA-7.[112]

In 2015, Shackelton Energy signed an agreement with CASIS to develop Oryx series of aerobraking reentry capsules for on-demand rapid return of time critical experiments from the ISS.[113] The project and company is likely now dormant.

Around 2018, Intuitive Machines advertised their URV (Universal Reentry Vehicle) capable of returning cargo from LEO and Moon, but it has since been removed from the official website.[114]

HTV Small Re-entry Capsule (HSRC) performed a successful demonstration returning cargo from the ISS in November 2018, but has not flown again. The capsule has a mass of 180 kg and is 85 cm in diameter and 66 cm in height with internal volume of 30 litres and 20 kg payload capacity.[115]

New commercial solutions in development include Varda Space and Space Forge.

2.9 In-Space Manufacturing

Microgravity Research Associates was founded in 1979 for the purpose of engaging in materials processing in space. It planned to grow crystals in space, starting with gallium arsenide. The high-quality gallium arsenide crystals could be used to make chips that would be much faster than silicon chips.[116]

Many space manufacturing experiments were performed on Skylab in 1973. First Space Manufacturing Conference was in 1977. The early 1980s was the first age of in-space manufacturing with many studies published for profitable materials as part of the beginning of regular Space Shuttle flights and

for future usage of the planned Freedom Space Station.[117–124] None of those forecasts came true.

Optical fibre ZBLAN was started to be publicly touted as the first profitable product made in space in about 2016-2017.[125–127] One of the first studies about ZBLAN manufacturing in microgravity was released in 1995.[128] News already in 1998 estimated ZBLAN commercial potential at $2.5 billion.[129] NASA's has awarded optical fiber related contracts to FOMS, Physical Optics Corporation, Apsidal and DSTAR starting from 2016.[130–133] Made in Space launched internally funded ZBLAN demonstration missions in 2017 and 2019.[134,135] FOMS reported high-quality production on ISS in 2019.[136] Flawless Photonics is developing ZBLAN production system in Luxembourg.[137] After all the news, progress seems slower than expected in the recent years and Made In Space is focusing elsewhere,[138] but it could also be because of secrecy.

Made in Space, founded in 2010, has been testing large-scale in-space assembly and construction technologies and additive manufacturing. They launched first 3D printer to ISS in 2014.[139] In 2019, NASA awarded $73.7M for Archinaut One to manufacture 10-meter beams and unfurl solar arrays.[140]

There are many commercial services on the ISS to perform experiments, demonstrate payloads and potentially in-space manufacturing processes. For example, Nanoracks Nanolab, Space Applications Services ICE Cubes, Airbus Bartolomeo, Space Tango CubeLab. In addition to many upcoming.

Varda Space was founded in 2020 and is developing reusable satellites with re-entry capability for in-space manufacturing and other services.[141] Space Forge, founded in 2020, is working on re-usable ForgeStar satellites with return-to-Earth capability for microgravity on demand.[142]

2.10 In-Space Transportation (Space Tugs)

There was a time when the Space Shuttle was planned to be the only launch vehicle of the United States and thus an upper stage would have been required for many types of spacecraft to get to their final orbits. Already by 1972, NASA and DOD had studied a variety of upper stage approaches including expendable stages and recoverable space tugs, which included in-orbit servicing.[143]

By 1984, several companies had developed upper stage vehicles designed to place payloads in high orbit. McDonnell Douglas and General Dynamics manufactured the Payload Assist Module and the Centaur. Boeing and Orbital Systems Corp were developing similar upper stage vehicles.[76]

Studies and proposals continued.[144,145] In 1986, TRW was awarded contract for one orbital manoeuvring vehicle, because NASA viewed space tugs as essential components of the proposed Freedom Space Station to retrieve and return satellites.[146] McManus et al studied over a hundred possible orbital transfer vehicle designs in 2003.[147]

Space tugs are now one of the most popular new in-space economy fields thanks to the popularity of nano- and microsatellites and low-cost rideshare missions. Spaceflight (Andrews Space) announced SHERPA in 2012 and first mission was planned for 2014, but happened in 2018.[148,149] Momentus was founded in 2017 to provide last-mile transportation service for satellites. They raised over $140 million and then went public through SPAC, but are currently solving legal and regulatory troubles.[150] In September 2021, SpaceX founding member Tom Mueller announced Impulse company with the goal to provide agile economical access to any orbit.[151]

2.11 Satellite Servicing

The first satellite servicing was performed in 1984 to Solar Maximum Mission spacecraft during the Space Shuttle mission STS-41-C.[152]

Mission Extension Vehicle (MEV) concept got started around 2010 in ViviSat.[153,154] After mergers, the project continued in Orbital ATK and then in SpaceLogistics, which is a subsidiary of Northrop Grumman.[155] First commercial servicing mission MEV-1 launched in 2019 and attached to Intelsat-901 in geostationary orbit in 2020.[156] MEV-2 launched in 2020 and attached to Intelsat 10-02 in 2021.[157] As of 2021, Space Logistics is preparing to launch a new servicing vehicle with a robotic arm that will install propulsion jet packs on dying satellites. Six undisclosed customers have signed up to get their satellites serviced by the Mission Robotic Vehicle (MRV), projected to launch in 2024.[158]

MDA announced servicing spacecraft concept in early 2010.[159] In 2017, a subsidiary called Space Infrastructure Services was created and majority was sold to Finance Technology Leverage.[160]

Astroscale, known for debris removal, but generally a satellite servicing company, was founded in 2013 and has raised over $191 million.[161,162]

Orbit Fab, founded in 2018 and offering refuelling services in space, is planning to launch a propellant tanker payload on Spaceflight Sherpa-ES orbital transfer vehicle to geostationary orbit, with the launch projected for late 2022 or early 2023.[163]

As of 2021, work is ongoing to establish satellite servicing standards and regulations.[164–166]

3. MARKET SURVEY

3.1 Survey Criteria

The survey criteria, which has resulted in the 400 entries currently and increasing, is the following:

- Belongs to the in-space economy, as defined in the next section of classifications and subcategories.
- More precisely "new in-space economy". For example, excluding launch vehicles, unless they are also meant for interplanetary flight like Starship; excluding satellite manufacturing, unless they will be reusable; excluding satellite fleets and constellations around Earth; and more.
- Commercial entities or at minimum offering commercial services to the public markets.

3.2 In-Space Economy Classification

One goal of this paper is to establish taxonomy or classification for the commercial entities in in-space economy to be able to group them. Until such categories are defined and widely accepted, the activities will be called with different names as per personal preferences, which makes it more challenging to determine competitors and estimate market sizes. The categories have been limited to 10 to make the graphs more practical to read, but this will likely change in the future.

The following classification is preliminary and author expects it to improve greatly thanks to feedback, independent iterations and especially over the upcoming years as the new space-based industries emerge and become established.

Figure 1 illustrates the in-space economy fields.

The in-space economy categories are:

1. Human Spaceflight & Landers
2. Cargo Transportation & Landers
3. Surface Spacecraft
4. Space Stations & Habitats
5. Surface Habitats & Structures
6. In-Space Manufacturing
7. Space Resources
8. Space Utilities
9. In-Space Transportation
10. Miscellaneous

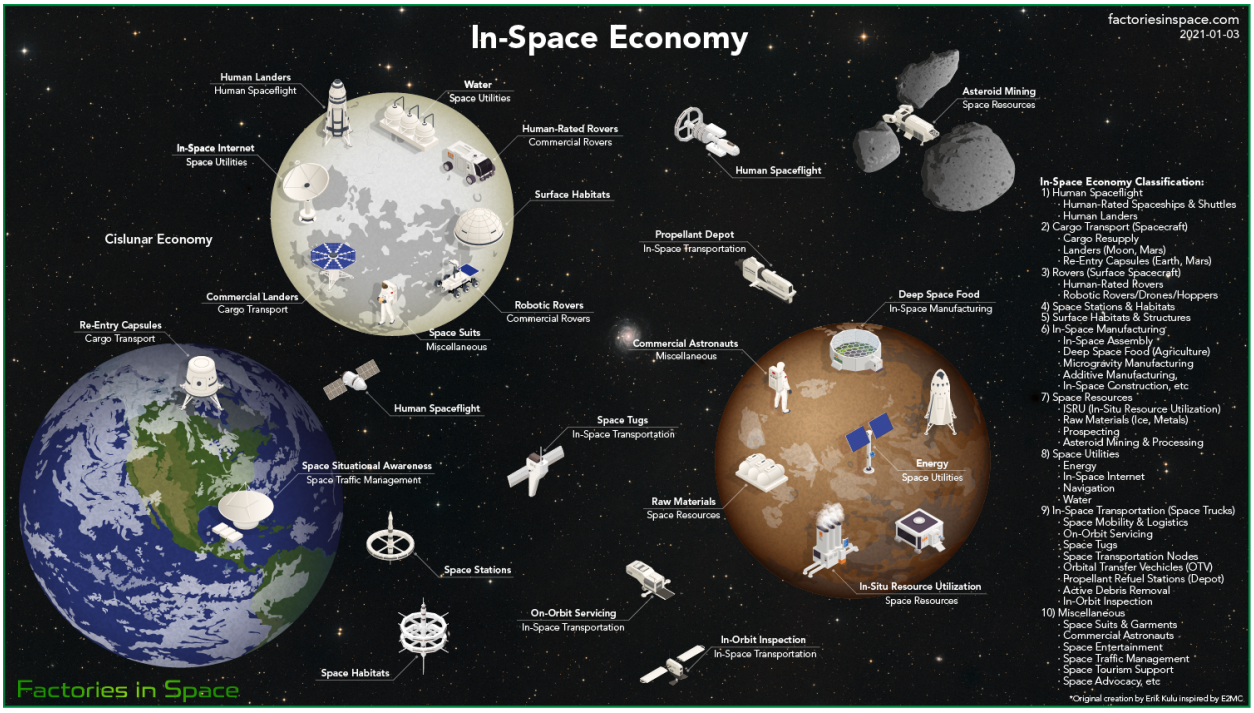

Figure 1: In-Space Economy

4. IN-SPACE ECONOMY GLOSSARY

Here follows the terminology and definitions for the primary classifications. The following list of keywords, alternative terms, applications and fields is not exhaustive. Feedback is very welcome and author expects the terminology to evolve greatly as in-space economy markets develop.

1. **Human Spaceflight & Landers** - Space vehicles designed for any kind of human flight. Also referred to as crewed spaceflight.[167] It is a separate category due to difficulty level, but could be merged in the future.
    - Human-Rated Spacecraft, Spaceships & Shuttles - Minimum criteria is an orbital flight in LEO.[167] Includes space transport ships to Moon, Mars and beyond.
    - Human-Rated Landers - Moon and Mars landers and reusable shuttles.
2. **Cargo Transportation & Landers** - Spacecraft transporting goods from and to Earth, Moon and Mars.
    - Cargo Resupply - Space station cargo resupply services.
    - Landers - Commercial non-reusable Moon, Mars and asteroid robotic landers.
    - Reusable Satellites - Spacecraft with launch and re-entry capability that could be used for activities near Earth and Mars.
    - Reentry Capsules (Earth, Mars) - Dedicated re-entry capsules of which many have been in development and one flown by Russia. This and previous might re-emerge to service in-space manufacturing.
3. **Surface Spacecraft** - Spacecraft working on the surface or near the surface of a planetary body. Includes rovers, drones and hoppers.
    - Rovers - Wheeled or rolling robotic vehicles on the Moon. To be used for exploration, prospecting and transportation.
    - Drones - Rocket-powered flight on the lunar surface to reach difficult locations or winged and rotary aircraft on Mars, Venus and Titan for example.
    - Hoppers - Hopping might become a transportation method on Moon and asteroids.
    - Human-Rated Rovers - Sub-set of rovers designed for human-use, often larger scale and stricter safety requirements.
4. **Space Stations & Space Habitats -** Free-flying space stations and even larger space habitats. Can be called space platform, orbital colony, space colony and space settlement. May be located in orbit around the Earth, Moon, Mars, Venus and in Lagrange points. Could be a rotating space station to achieve artificial gravity.[168] Merriam-Webster defines space station as a large artificial satellite designed to be occupied for long periods and to serve as a base.[169] K. Kennedy et al defined space habitats as a recreation of the Earth environment for the purpose of sustaining human life, and that habitats are pressurized crew volumes including laboratories, living quarters, and maintenance facilities.[170]
5. **Surface Habitats & Surface Structures -** alternatively surface facilities. Facilities on the surface of Moon and Mars for habitation, storage and manufacturing. Structures can include physical infrastructure, antennas, various plants, factories and more.
6. **In-Space Manufacturing** (ISM) - alternatively Off-Earth Manufacturing[171] and Space-Based Manufacturing.[172] ISM divides into 2 large areas. First area is manufacturing products in microgravity for Earth, which will be brought back to be sold on terrestrial markets. Second area is manufacturing large-scale space structures that will remain in space.
    - Microgravity & ISS Flight Service - Service providers to access microgravity environment, which can be facilities on the ISS and upcoming space stations, or dedicated free-flyer spacecraft.
    - In-Space Manufacturing - In narrower definition it means making products and materials in microgravity, which cannot be made on Earth, or which are better.
    - In-Space Production - Same as the narrow definition of in-space manufacturing. ISS National Lab has started to actively use this term.[173]
    - Space Food or Deep Space Food - Space agriculture will be a large industry to supply fresh food to workers, settlers and tourists, both in-space and on Moon, Mars and beyond.
    - Microgravity Manufacturing - Alternative name for in-space manufacturing and in-space production.

- In-Space Construction - Large-scale construction in space and on Moon and Mars.
- In-Space Assembly (ISA) - Subset of in-space construction, which will likely be the first step before the very large-scale end-to-end construction in space. Xue et al. defines ISA as the assembly activities completed in the target orbit and extraterrestrial space, which is to assemble modules in space in order to form a larger functional element, or to recombine one or more structures after separation.[174]
- Additive Manufacturing - Subset of in-space construction, also 3D printing.
- Parabolic and Suborbital Flights - Some microgravity manufacturing can happen during short flights and due to that has been included here for completeness.

7. **Space Resources** - Deals with the prospecting, mining, beneficiation, processing, ISRU and recycling of natural or artificial resources in space, incl. Moon, Mars and asteroids.[1,175]

   - ISRU (In-Situ Resource Utilization) - Any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration.[1] Encompasses exploration, mine planning, mineral processing, metallurgy and sale of off-Earth resources.[1]
   - Prospecting - Determining the composition of asteroids, moons and planets with mining and ISRU in mind using remote sensing and in-situ measurements.
   - Space Mining - Also Off-World Mining[176] and includes Moon and Mars mining. Extracting and collecting the raw resources from planetoids or planetary surfaces.[177]
   - Asteroid Mining - Sub-set of space mining focused on asteroids in space together with basic processing to reduce the mass of materials to be transported.
   - Lunar Resources - Subset of space resources.
   - Raw Materials - Selling processed materials like ice, water, oxygen and metals.
   - Recycling - Reprocessing artificial objects including satellites and spent rocket stages into raw materials or reusing parts of them for new missions.
   - Processing or Beneficiation - Separating valuable minerals from waste rock.

8. **Space Utilities** - alternatively In-Space Utilities. There will exist distinctive supply chains and physical infrastructure for common goods like energy, internet, navigation and water.

   - Energy - Includes space-based solar power, nuclear power and wireless transmission. Electrical energy will likely have a more centralized infrastructure on Moon and Mars. Currently often served by independent solar panels, but solar power stations could supply other satellites and vehicles and outposts on the ground. Caltech recently announced they got a $100 million donation in 2013 to form the Space-based Solar Power Project.[178]
   - In-Space Internet - Communications will be a critical infrastructure throughout the solar system and on the surfaces of Moon and Mars.
   - Navigation - Navigation in space and on Moon and Mars. Possibly required for future landers and surface vehicles.
   - Water - Water in space and on Moon and Mars, to be used for human consumption, air and propellant.

9. **In-Space Transportation** - Could be called Space Trucks as a utility vehicle comparison. There are many similarities between the following sub-categories, because all of the spacecraft must be capable of significant orbital velocity changes. It is very likely that same entities will offer multiple services thanks to the underlying technologies. Similar to terrestrial applications, where trucks and pick-ups can serve multiple roles depending on the choice of payload, all requiring only small modifications. Key difference with Cargo Transportation is that these vehicles will stay in space and do not have reentry and/or landing capability.

   - On-Orbit Servicing (OOS) - Spacecraft with the means to go nearby other spacecraft and dock with them for propellant loading, orbital repositioning or to stay attached and augment capabilities. J. P. Davis et al. defines OOS as on-orbit activities conducted by a space vehicle that performs up-close inspection of, or results in intentional and beneficial changes to, another resident space object. These activities include non-contact support, orbit modification (relocation) and maintenance, refuelling and commodities replen-

ishment, upgrade, repair, assembly, and debris mitigation.[179]

- Satellite Maintenance - Alternative term for in-space servicing.[180]
- In-Orbit Inspection - Sub-set of on-orbit servicing. Spacecraft capable of travelling nearby to other spacecraft and inspecting them for damages and status.
- Orbital Transfer Vehicle (OTV) - Spacecraft capable of transporting other spacecraft between different orbits. Capabilities can vary greatly. Starting from small altitude and inclination changes in LEO, to taking spacecraft from LEO to GEO, and to Moon, Mars and further.
- Space Tugs - Alternative name for Orbital Transfer Vehicles.
- Space Transportation Node - Alternative name for Orbital Transfer Vehicles.
- Orbital Manoeuvring Vehicle - Alternative term for OTVs and Space Tugs.[181]
- Propellant Reload Station - Includes propellant refuel stations, propellant depots, orbital refuelling, and propellant tankers.[163] As Elon Musk noted, propellant reloading is correcter term compared to refuelling, because propellant is a combination of fuel and oxidizer.[182]
- Active Debris Removal (ADR) - Spacecraft with the means to go nearby other spacecraft and help them de-orbit faster.
- Reusable Satellites - Sharing many technologies with OTVs and spacecraft in general. Uniqueness will be on modular exchangeable payloads changed in space.
- Space Mobility, Space Logistics - Another terms for In-Space Transportation that might become widely used. AIAA defines space logistics as the science of planning and carrying out the movement of humans and materiel to, from and within space combined with the ability to maintain human and robotics operations within space.[183]

10. **Miscellaneous** - Supporting and connected services to the in-space economy, which largely would not exist without it. Some of them may not strictly generate revenue in space.

    - Space Suits & Garments - Space suits and space clothing will be required for every astronaut, settler and tourist.
    - Commercial Astronauts - Privately employed and trained astronauts to help with large-scale commercial activities in space and on the surfaces.[184,185]
    - Space Tourism, Suborbital Space Tourism - Wider terms encompassing human spaceflight and habitation services. Suborbital Space Tourism companies have been included under miscellaneous. Space tourism is considered to be one of the potential customer segments for multiple in-space economy fields in the future.
    - Space Tourism Support Activities - Space tourists, but also commercial astronauts, will require some training and support for the foreseeable future. This can also include space-themed experiences on Earth.
    - Space Entertainment - In-space economy will likely start a new form of entertainment, where the activities will happen in space. Starting with variations of or new types of sports, space casinos, performance shows, and other entertainment activities.
    - Space Advertising and Marketing - Advertisements in space, Moon and Mars.
    - Space Traffic Management - Very active and common human spaceflight activities between Earth, Moon, Mars and space stations will likely need some coordination. This also includes Space Situational Awareness (SSA), which US Air Force now calls Space Domain Awareness (SDA).[186]
    - In-Orbit Computing - Both edge computing and server farms in space.
    - Space Robotics - Can be covered by in-space construction, in-space manufacturing, surface spacecraft and satellite servicing, but also robotic humanoid robots.
    - Moon and Mars Remote Sensing - Imaging in different wavelengths for choosing landing and base sites, cartography and resource mapping.
    - In-Space Infrastructure - Wider term that would encompass many of the top-level categories like transportation, utilities and stations. No companies in the data have this classification currently and has been only listed for completeness. S. P Sharma and C. Moore define in-Space infrastructure as consisting of the systems and services operating in Earth's neighbourhood to facilitate commerce, exploration, and scientific discovery.[187]

5. 2021 STATISTICAL OVERVIEW

Here follows the statistical overview of the 400 entries included in this new in-space economy survey of commercial space entities.

5.1 Classifications

Figure 2 shows the classification of new in-space economy companies. Generally, there has been only one primary category per company, but it will have to be expanded soon.

Human spaceflight and space stations are expensive and technologically challenging to develop, and as such it is difficult to enter this market, which has resulted in a small number of entities.

In-space transportation with 57 entries is the most popular due to a rapid increase in orbital transfer vehicle (space tug) startups. This category also includes satellite servicing, active debris removal and propellant reloading, because of the large overlap in spacecraft technologies.

In-space manufacturing with 80 entries includes the ISS-based and other microgravity testing service providers, and thanks to that is the most popular category. There are only a few actual and regular in-space manufacturing entities making products and materials for Earth or space. This category also includes numerous companies which have performed demonstrations, done research or made limited quantity of novelty products such as space whisky and space beer.

5.2 Status with Classification

Figure 3 plots the same classification as Figure 2 and adds status indicators. In the human spaceflight category, SpaceX is active.

In general, a 1/3 of entities are in dormant, concept or early stages. Another 1/3 are in active development. Approximately 10% of companies have launched some technologies to orbit and thanks to that they can be given demonstrated status.

In-space manufacturing is active, because of large amount of the ISS and other microgravity service providers which are actively offering services. There are currently no known companies manufacturing the same product regularly in space.

Northrop Grumman, D-Orbit and Spaceflight are active in the in-space transportation category because they have launched their space tugs for servicing or satellite deployment.

Miscellaneous includes multiple non-hardware or space advocacy organizations that are active.

5.3 Founded

Figure 4 lists the founding dates of all entities in the database. Founding of a company does not correlate to a successful long-term business and before that to performing demonstration missions, because many will become dormant before being ready.

Between 2008-2010, SpaceX succeeded in launching rockets to orbit. CubeSats started to be taken seriously around the same time. The amount of new

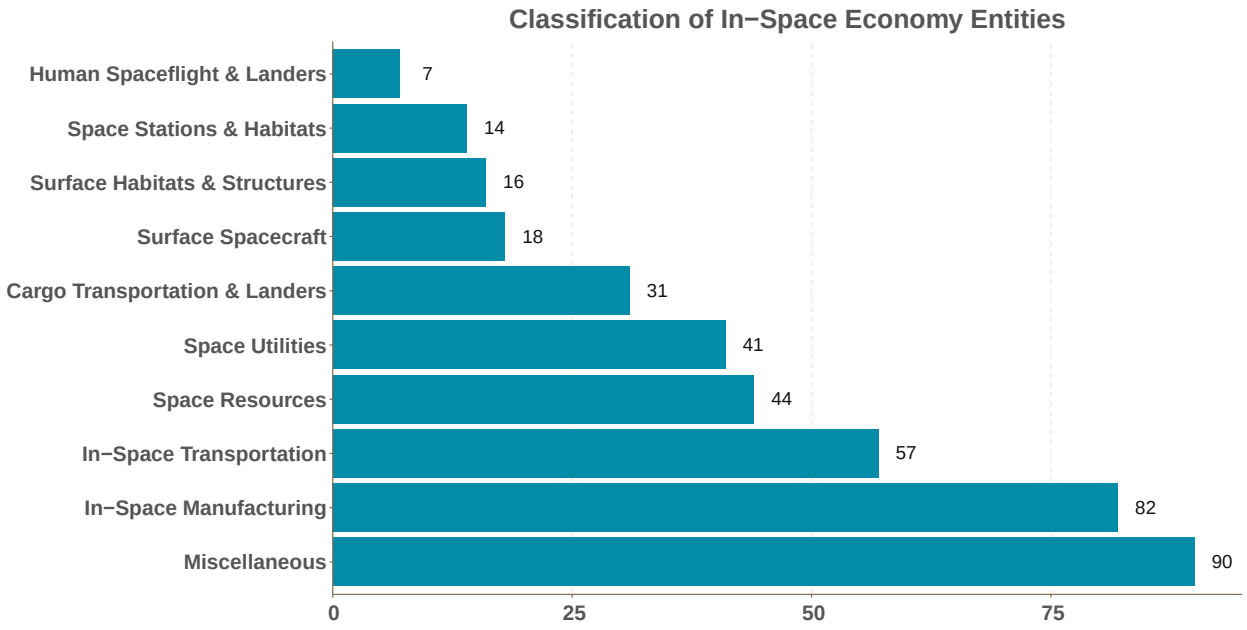

Figure 2: New In-Space Economy Applications

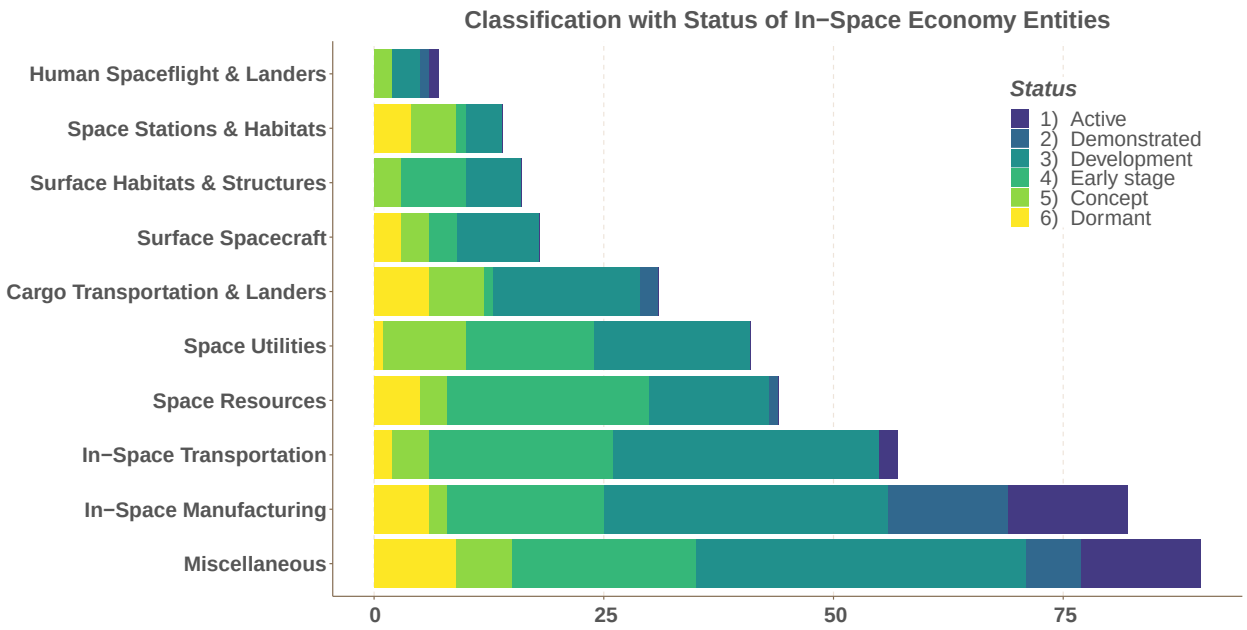

Figure 3: New In-Space Economy Status

space companies being created has increased rapidly in the recent years when compared to 10 years ago.

This figure shows well the arrival of NewSpace. The peak in 2018 and subsequent decline could be explained by as a mix of the following points. First, there was a boom of some sorts, which has slowed down in terms of very new startups, because there are similar graphs for nanosatellite, constellation and launcher companies.[188,189] Funding boom is continuing though. Second, because many of those new in-space fields do not have existing markets, some potential new actors might be in waiting mode, because they want to see what happens financially and technically to existing companies. Third, startups could be in stealth mode or very early stage and as such I have not become aware of them yet. They will likely partially backfill.

The new wave of companies founded between 2017-2019 is likely correlated to SpaceX's Starship and NASA's Artemis program announcements, because of the very high payload capacity and low-cost rideshare missions improve the business cases, while returning to the Moon is creating new markets for many in-space economy fields.

Bryce Tech report about start-up space companies also shows a decline in new companies, but they only track the ones with announced investments.[190]

While there was a decline, author forecasts that successful Starship missions to orbit and return to the Moon will kick off another startup founding wave in about 2-3 years.

5.4 Founded with Status

Figure 5 lists the founding dates of all entities in the database together with the status categories. As seen from the chart, many commercial organizations are in the early stages of development and often the progress could be limited only to a website and a small partially committed team.

The highest year of 2018 also has the largest amount of dormant companies. 2018 also sees the highest amount of concept and early stage companies, with only about 30% in active development as of now.

Only a small percentage of companies have performed orbital demonstrations or are active, which shows there is still a long path for the market to emerge and for many in-space economy services to become commonplace.

5.5 Founded with Classification

Figure 6 plots the founding dates of all entities in the database together with the classification.

Blue Origin was founded in 2000 and SpaceX was founded in 2002. Google Lunar XPrize was announced in 2007,[51] which inspired many lunar lander and lunar rover companies that were founded in the following years.

Starting from 2017 and still continuing, there has been a large increase of in-space transportation companies, which include space tugs, debris removal and satellite servicing. Possibly coinciding with the

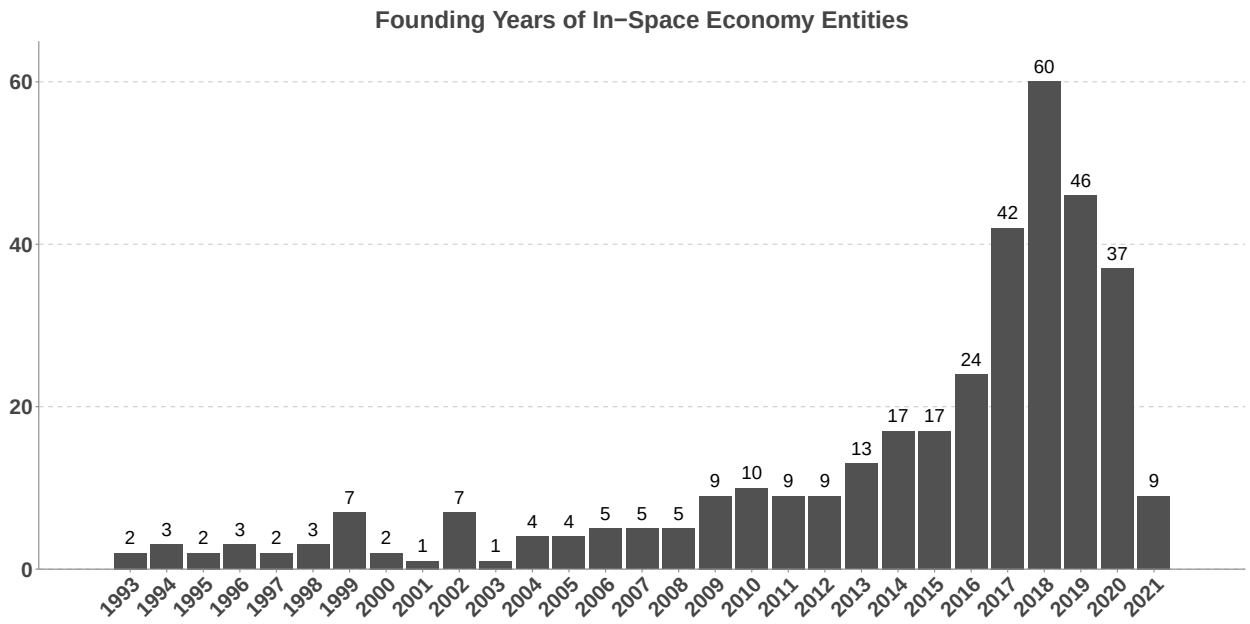

Figure 4: New In-Space Economy Status

first public Starship announcements and successful re-usability of Falcon 9, because both are aiming to lower costs of space access, potentially enabling the business cases using rideshare missions.

Companies developing ISRU and surface habitats solutions have been increasing also. Likely again thanks to NASA's Artemis announcement in 2019 and SpaceX's long-term vision for Mars settlement.

5.6 Funding

Figure 7 collected funding amounts in the defined ranges. "Yes, but unknown" commonly means an established space company, but it is unknown how much are they investing in those specific new fields, but very likely a considerable amount. "Unknown" category is for companies who have not announced funding and based on their activities, social media and a number of public employees, it leaves an impression that they probably have very little funding. "Not applicable" category is for various space advocacy organizations, which are not aiming to do much technology development or own space missions, and many of them can be non-profits who do not announce fundraising round like startups.

Over $1 billion in private and awarded funding have received for example SpaceX, Blue Origin and Boeing. Over $100 million in funding have been able to raise Astrobotic, Astroscale, Bigelow Space Operations, Firefly Aerospace, ispace, Masten Space Systems, Spaceflight. Between $50-100 million in private funding have for example Axiom Space, Made In Space (Redwire), Moon Express, SpaceIL, Varda Space Industries.

5.7 Funding with Classification

Figure 8 adds categories to the funding amounts. SpaceX is represented multiple times due to various future services in development.

Some lander, rover and in-space transportation and space stations companies have accumulated large funding over $100 million.

Many companies in the in-space manufacturing and ISRU fields have recently received awards from NASA, in relation to the Artemis program.

Most surface habitat companies have gotten very little funding, but in many ways the state of the ecosystem is also early for them.

5.8 First Launches

First missions and demonstrations in space have been gathered on Figure 9.

Knowingly cancelled and dormant companies have been marked separately. "Not applicable" includes space advocacy organizations, which are not aiming to do own space missions. "Not announced" are companies that do not seem to have announced a year for their first missions or activities in space. This also correlates to the large number of idea and early stage companies, where there are too many unknowns.

5.9 Geographical Distribution

Distribution of the in-space economy companies by headquarters locations is on Figure 10.

Almost all are based in the United States. Less than 20 in Canada, UK, Germany and Australia, but otherwise only one or two in other countries. It is possible that some are missing from China.

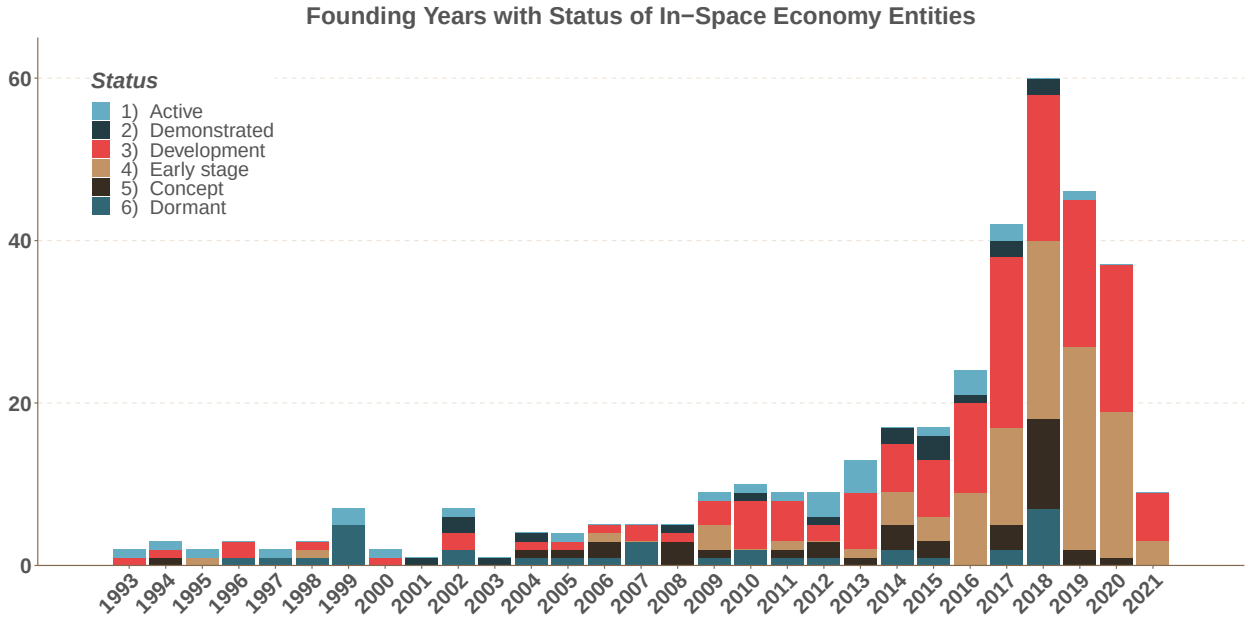

Figure 5: New In-Space Economy Status

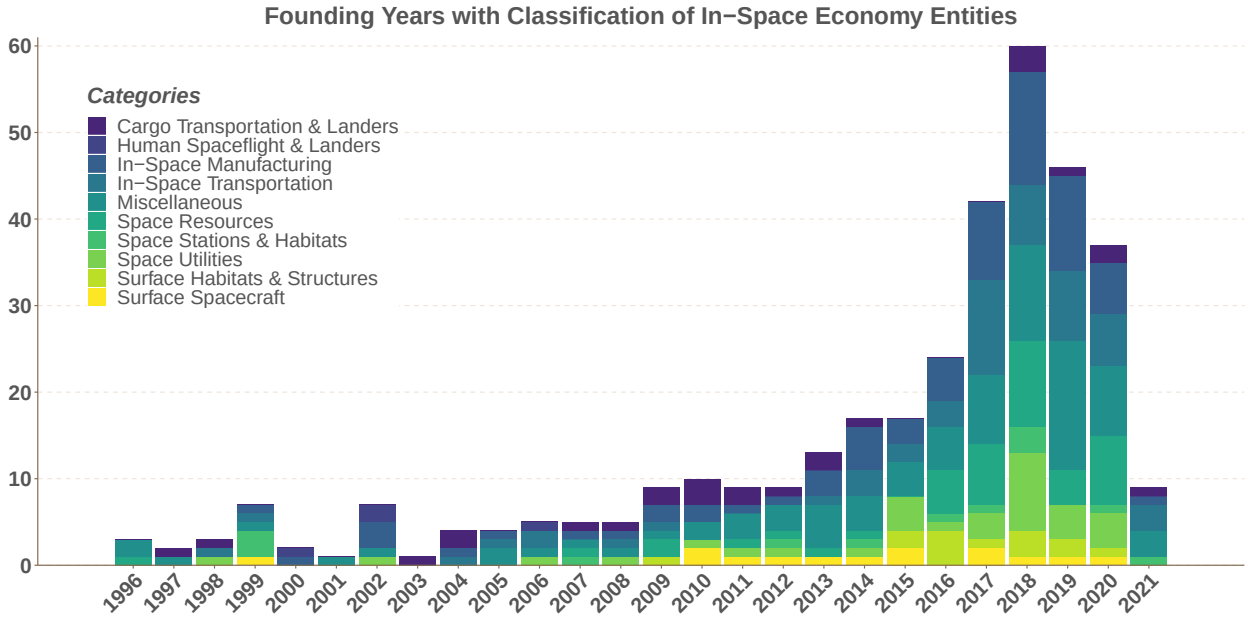

Figure 6: New In-Space Economy Status

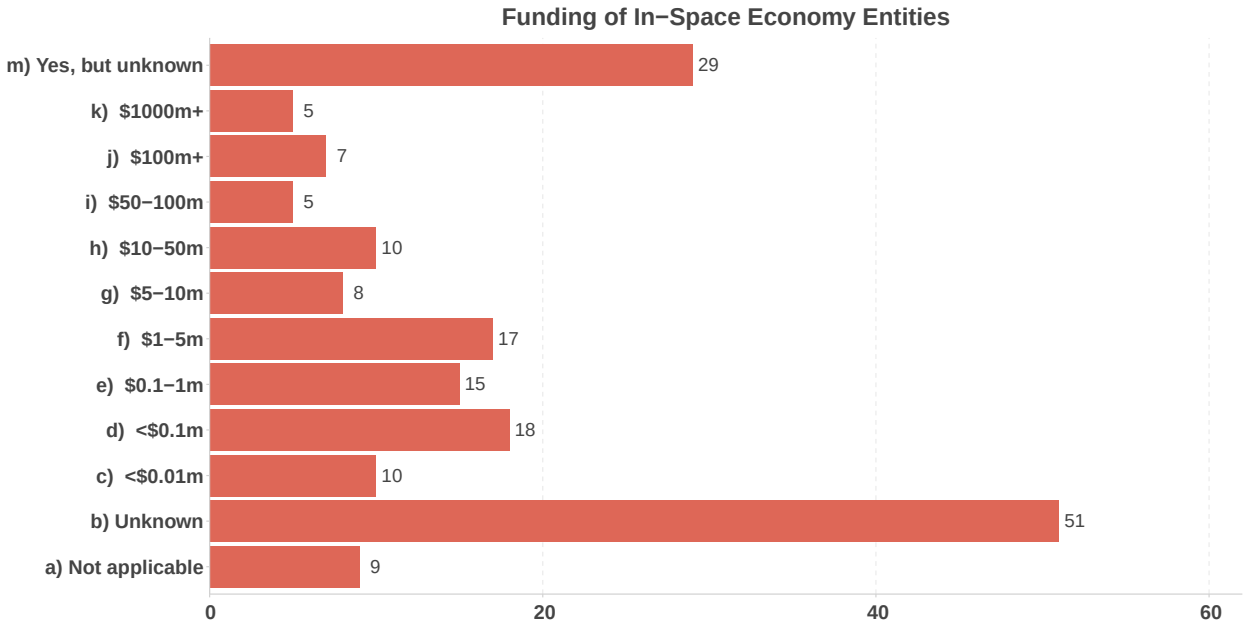

Figure 7: New In-Space Economy Status

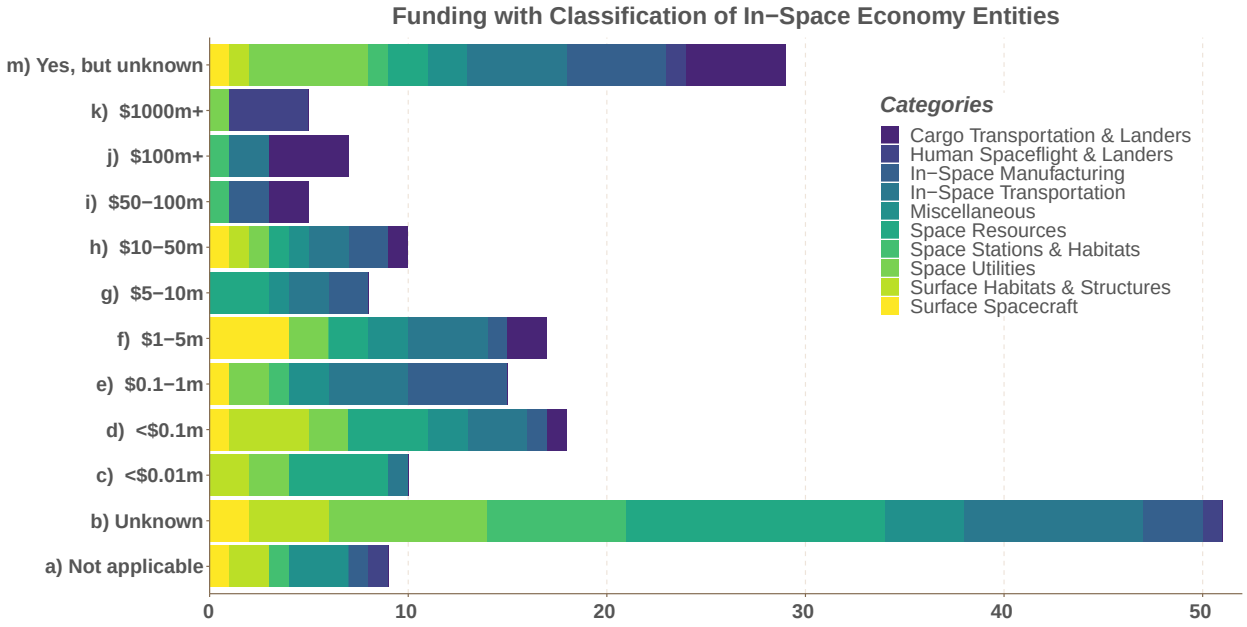

Figure 8: New In-Space Economy Status

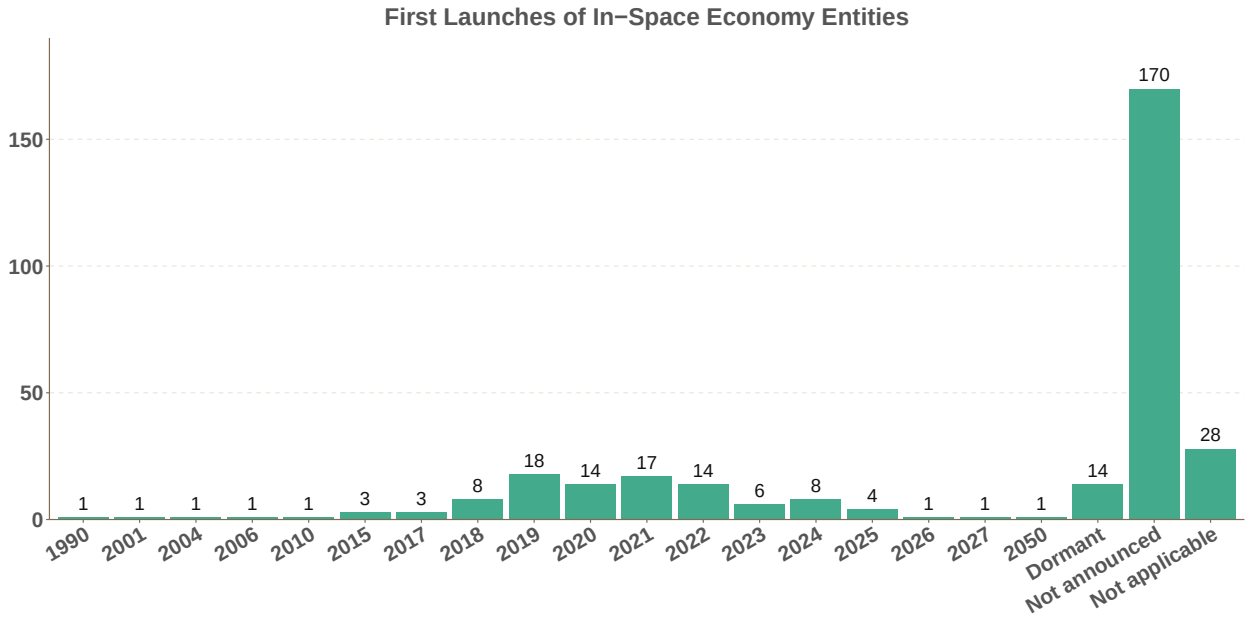

Figure 9: New In-Space Economy Status

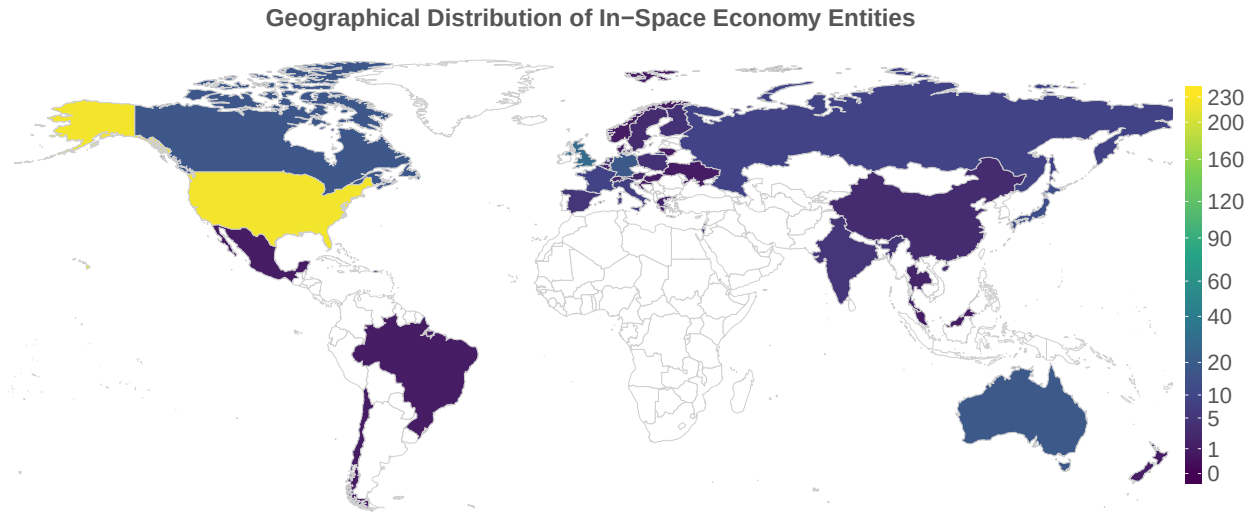

Figure 10: New In-Space Economy Map

6. CONCLUSIONS

Statistical overview of 400 in-space economy entities has been presented. Short historical overview about the primary in-space economy fields was described. All the fields were classified into a 10-category in-space economy taxonomy. Furthermore, glossary was presented, which included sub-categories, definitions and example entities and projects.

New in-space economy fields are emerging rapidly. Commercial human spaceflight has been demonstrated with Inspiration4 and NASA's crew missions to the ISS, all using SpaceX's Crew Dragon capsules. Axiom Space is actively building commercial space station modules. Commercial Moon lander and rover missions are planned to start in 2022. In-space manufacturing has already many microgravity service providers, but now the first steps have been taken towards in-space production and in-space construction. Satellite servicing has also been demonstrated. Space tugs or orbital transfer vehicles is possibly the field that is most blooming by the amount of active and starting organizations.

The goal is to start repeating this study annually as a whole or as deep dives into the classifications. The online figures and database are expected to be updated multiple times per year at minimum.

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