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Space Vehicle Swarm Exploration Missions: A Study of Key Enabling Technologies and Gaps

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Multi-agent robot teams and spacecraft swarms will play an important role in future space exploration missions. In this paper, we propose a comprehensive taxonomy of proposed applications of multi-agent systems in space, planetary-surface, and terrestrial domains. We identify the key enabling technologies that will enable such applications and identify the technology gaps that have to be overcome. We envisage that the broader community will strive to address these technology challenges to make multi-agent and swarm based space exploration missions a reality!
keywords: swarm, multi-agent, robots, sensor network, teams,

1. Introduction

Teams and swarms of autonomous robots and spacecraft have the potential to change the way future space exploration missions will be undertaken. A swarm of space vehicles is a collection of often smaller and simpler, autonomous vehicles that coordinate in a decentralized manner to achieve a common goal.

Present day monolithic systems (e.g. single spacecraft or rovers) could be replaced or complemented by a swarm of smaller, interconnected and coordinating assets. These swarms can increase science return by cooperatively exploring an area of interest (rovers) or make distributed measurements at sights of interest cued by a leading spacecraft (SmallSats). Spacecraft swarms can yield reduced cost and greater risk tolerance by using larger number of simpler and cheaper assets. Launch cost can also be reduced by launching assets gradually and as secondary payloads. Despite these advantages, multi-agent space exploration missions have not yet been undertaken. The main focus of this paper is to understand the key technologies that enable space exploration using teams and swarms and identify the technology gaps that have prevented mission designers from considering such systems for space exploration missions.

Specifically, the contribution of this paper is three-fold:

1. We propose a comprehensive taxonomy of proposed applications of multi-agent systems in space and planetary-surface domains. We also include terrestrial application to capture state-of-the-art enabling technologies for such systems.

Table 1: Enabling Technologies for Multi-Spacecraft and Swarm Mission Types

Domain	Mission Type	Absolute Pose Estimation (metrology)	Relative Pose Estimation (metrology)	Time Synchronization	Formation Keeping	Distributed Inter-Vehicle Communication	Modular Space Systems	Cooperative Manipulation	Distributed Estimation and Cooperative Mapping	Cooperative Motion Planning	Cooperative Task Recognition and Task Allocation	Human-Space System Interface
Space	Satellite Navigation	●[1]		●								
	Earth Observation	●	◑	●		◑			◕	◕	◕	
	Gravity Measurement	●	◕	◕	◕	◕			◕	◕		
	Distributed Aperture Telescopes	◕[2]	◑	◕	◑	◑			◑	◑	◑	
	Distributed Fractionated Spacecraft	●	◑	●		◑	◑			◑	◑	
	In-orbit Assembly and Servicing	●	◕	●	◕	◕	◑	◑		◑	◑	
	Solar Observation	◕	◑	◕	◑	◑			◕	◑		
	Planetary Exploration and Mapping	◕	◑	◕		◑			◑	◑	◑	
	Distributed Communication Array	◕	◑	◑		◑				◑		
	Interplanetary Missions	◔[4]	◔	◔		◔			◔	◔	◔	
Earth	Exploration, Mapping, and Sampling	◑[3]	◑	◕		◑			◑			
	Cooperative Lifting, and Assembly				◕			◑		◑	◑	
	Communication Infrastructure			◕		◑				◑	◑	
	Disaster Recovery/Search and Rescue								◑		◑	◑
	Reconnaissance, Patrolling and Tracking								◑	◕	◑	◑
	Urban Transportation/Delivery Systems									◑	◕	
	Entertainment		●		●							
Planetary	Exploration, Mapping and Sampling		◑	◕	◕	◑			◑			
	Cooperative Construction				◑			◑		◑	◑	
	Communication Infrastructure			◕		◑				◑	◑	
	Cooperative Computation					◑					◑	

[1] ● : the technology is mature (9 TRL)
[2] ◕ : the technology is currently under development, but quite mature (6–8 TRL)
[3] ◑ : the technology is currently under development, but not very mature (3–5 TRL)
[4] ◔ : the technology is currently not available or in conceptual stages of development (1–2 TRL)

Our proposed taxonomy is as follows:

- **Space Domain:** Satellite Navigation, Earth Observation, Gravity Measurement, Distributed Aperture Telescopes, Distributed Fractionated Spacecraft, In-orbit Assembly and Servicing, Solar Observation, Planetary Exploration and Mapping, Distributed Communication Array, Interplanetary Missions;
- **Planetary Domain:** Exploration, Mapping and Sampling, Cooperative Construction, Communication Infrastructure, Cooperative Computation;
- **Earth Domain:** Exploration, Mapping and Sampling, Cooperative Lifting, Construction and Assembly, Communication Infrastructure, Disaster Recovery/Search and Rescue, Reconnaissance, Patrolling and Tracking, Urban Transportation/Delivery Systems, Entertainment

2. We leverage the taxonomy to identify and classify the key enabling technologies that will enable such applications, as well as their current technology maturity levels. These technologies include: Absolute Pose Estimation (metrology), Relative Pose Estimation (metrology), Time Synchronization, Formation Keeping, Distributed Inter-Vehicle Communication, Modular Space Systems, Cooperative Manipulation, Distributed Estimation and Cooperative Mapping, Cooperative Motion Planning, Cooperative Task Recognition and Task Allocation, and Human-Space System Interface.
3. We identify the technology gaps that are hindering acceptance of multi-agent systems into mainstream space exploration missions, and outline critical directions for future research and technology development. This is shown in Table 1.

We envisage that the broader community will strive to address these technology challenges to make multi-agent and swarm based space exploration missions a reality!

2. Multi-Agent Systems Taxonomy

Due to their resiliency, adaptability, and low cost, multi-agent system architectures have been proposed for a variety of domains, including space exploration and Earth science. Here, we provide a brief overview of potential domains of interest for multi-agent systems and some examples of proposed missions.

Mission Domain: Space

Multi-agent missions in space can be broadly divided into two categories: *formation flying missions*, where the dynamic states of spacecraft are coupled through their control laws; and *constellation missions*, where the dynamic states of spacecraft are not coupled.[1–3] Therefore, in a formation flying mission, at least one satellite must track a desired state relative to another satellite and its tracking control law must, at the minimum, depend upon the states of this satellite. On the other hand, even though specific relative positions are actively maintained, the Global Positioning System (GPS) satellites constitute a constellation since their orbit corrections require only the individual satellite's position and velocity (dynamic states).

A recent review paper surveyed 39 multi-agent missions composed of small satellites (mass less than 10 kg) and categorized them based on their mission type (science goal, technology demonstration), status (under development, launched, completed), funding organization, and number of satellites.[4,5] This paper concluded that the technologies for Earth-based constellations missions are mature, as evident from the constellations launched by commercial companies like Planet Labs.[6–8] But the technologies for formation flying missions are still under development. Currently, the best formation flight in space by small satellites has been demonstrated by the CanX-4&5 mission.[9,10]

Here we present a comprehensive list of all multi-agent mission types within the space domain, comprising of two or more spacecraft, and discuss their key enabling technologies and technology gaps.

2.1 *Satellite Navigation*

A satnav system enables small receivers to determine their location (longitude, latitude, and altitude/elevation) to high precision (within a few meters) using radio signals transmitted from satellites. Global coverage is achieved using a constellation of ≈ 30 satellites in several orbital plans in medium Earth orbit (MEO). The satnav systems has been used for a wide variety of applications like geolocation, navigation, communication, and transportation.[11,12]

The Global Navigation Satellite System (GNSS) is composed of a number of satellite constellations:[13]

- United States' *Global Positioning System (GPS)* is an operational constellation consists of 31 satellites, each traveling in a 12-hour, 20200 km circular orbit. The satellites are positioned so that at least six satellites are observable nearly everywhere on Earth, as shown in Fig. 1.

Fig. 1: Artist's representation of the orbits of GPS satellites, which are inclined to the Earth's equator by ≈ 55 degrees. (image credit: NOAA[14])

- Russia's *GLObal NAvigation Satellite System (GLONASS)* constellation includes 24 satellites, each traveling in a 19140 km circular orbit.
- European *Galileo* constellation will consist of 30 satellites in three orbital planes at an altitude of 23222 km. Currently there are 17 operational satellites in this constellation.
- China's *BeiDou/Compass* constellation will consist of 35 satellites in both GEO and MEO. Currently there are 23 operational satellites in this constellation.
- Japan's *Quasi-Zenith Satellite System (QZSS)* will consist of three satellites in multiple orbital planes for regional positioning and time transfer.
- The *Indian Regional Navigation Satellite System (IRNSS)* will be a seven satellite constellation. The first satellite was launched in July 2013 into a geosynchronous orbit.

The key enabling technology is:

- ◦ *Relative pose estimation (metrology)* to accurately determine the position and orbit of each spacecraft. This is usually achieved by radar-based tracking from Earth and laser retroreflector arrays onboard the spacecraft.

This technology is mature for Earth-orbiting spacecraft.

2.2 *Earth Observation*

Earth science missions aim to study natural and human-induced changes in Earth's interior, land surface, biosphere, atmosphere, and oceans and understand its affect all aspects of life. Understanding these changes and their implications will enable us to build credible information products, forecast models, and other tools for making informed decisions.[15]

Multiple orbiting spacecraft can observe dynamic phenomena (weather, volcanoes, natural disasters) over an extended period of time from multiple vantage points, using multiple instruments. For example, interferometric synthetic aperture radar (InSAR) techniques can be used to measure surface deformations for geophysical monitoring of natural hazards, for example earthquakes, volcanoes and landslides.[16] Similar radio occultation of global navigation satellite system (GNSS) satellites can be used to study the atmosphere (especially ionosphere) and the effects of earthquakes and tsunamis on the ionosphere.[17,18]

A number of multi-spacecraft missions have been proposed and launched in this mission type:

- The *Afternoon Train (A-train)* is a satellite constellation of six Earth observation satellites in 1:30pm sun-synchronous orbit at an altitude of 700 km. They are spaced a few minutes apart from each other so their collective observations may be used to build high-definition three-dimensional images of the Earth's atmosphere and surface. Six satellites currently fly in the A-Train: Orbiting Carbon Observatory 2 (OCO-2), Global Change Observation Mission - Water (GCOM-W1), Aqua, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), CloudSat, and Aura,[19] as shown in Fig. 2.
- The proposed *Climate Absolute Radiance And Refractivity Observatory (CLARREO) Mission* by NASA aims to measure global climate records using state-of-the-art spectrometer observations and GNSS radio occultation. CLARREO mission requires three small satellites, each of which requires a specific orbit.[20]

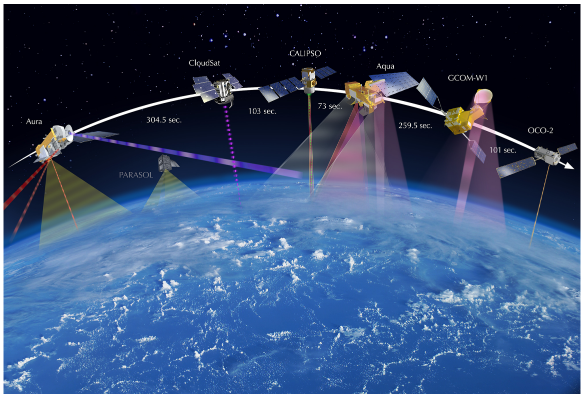

Fig. 2: Artist's representation of the A-train (image credit: NASA[19])

- The joint *Taiwan-U.S. Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC)/Formosa Satellite Mission 3 (FORMOSAT-3) Mission* consisting of a constellation of six microsatellites, was launched in April 2006 into 800 km orbit. Using the GPS radio occultation technique, the satellites measure the global atmosphere with high precision, accuracy, and vertical resolution in all weather and over both land and ocean.[21]

- NASA's *Time History of Events and Macroscale Interactions during Substorms (THEMIS)* is a constellation of five satellites launched in February 2007 to study energy releases from Earth's magnetosphere that intensify auroras near Earth's poles as shown in Fig. 3.[22]

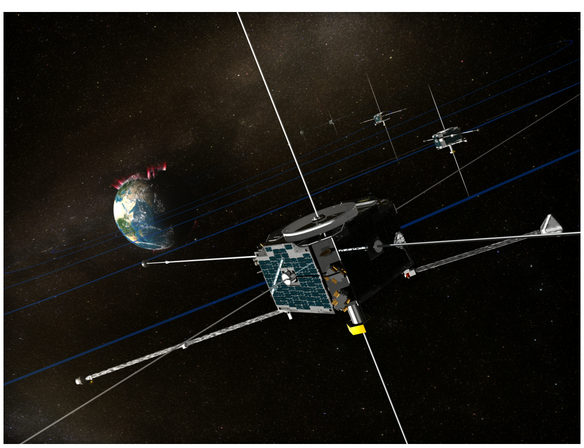

Fig. 3: Artist's representation of the THEMIS constellation in orbit (image credit: NASA[23])

- ESA's *Cluster II* mission, launched in July-August 2000, is composed of four identical spacecraft flying in a tetrahedral formation to study the Earth's magnetosphere over the course of nearly two solar cycles.[24]

- ESA's *Swarm* constellation consists of three satellites launched in November 2013 to study the geomagnetic field (multi-point measurements) and its temporal evolution.[25]

- DLR's *TerraSAR-X* spacecraft, launched in June 2007, and DLR's *TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X)* spacecraft, launched in June 2010 fly in a closely controlled formation with 250–500 m inter-satellite distance to generate high-resolution global digital elevation models as shown in Fig. 4.[26]

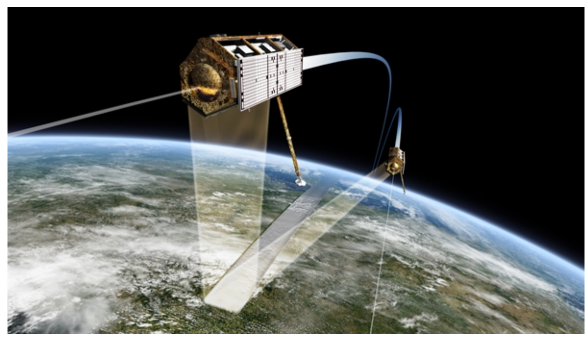

Fig. 4: Artist's representation of the TerraSAR-X and TanDEM-X spacecraft generating an accurate three-dimensional image of Earth (image credit: DLR[27])

- NASA's *Magnetospheric MultiScale Constellation (MMS)* is composed of four identical spacecraft flying in a tetrahedral formation, launched in March 2015, to study the Earth's magnetosphere.[28]

- Planet Labs is an American company that owns the largest number of Earth-orbiting imaging satellites in space:[8]

  – *Flock* constellation consists of ≈ 150 Dove satellites,

  – *RapidEye* is a five-satellite constellation,

  – *SkySat* constellation consists of ≈ 10 satellites,

  and aims to provide up-to-date information relevant to climate monitoring, crop yield prediction, urban planning, and disaster response.[6,7,29]

- NASA's *Cyclone Global Navigation Satellite System (CYGNSS)* is a constellation of eight microsatellites, launched in December 2016, to improve prediction of extreme weather (storms, hurricanes, etc.)[30]
- Stanford University's *Orbiting Picosatellite Automatic Launcher (OPAL)* mission successfully ejected six picosatellites from a single spacecraft in January 2000, in order to simultaneously sample a volume of space for magnetic field measurements.[31]
- NASA's *Space Technology 5 (ST5)* constellation mission launched three microsatellites in March 2006 in order to map the intensity and direction of magnetic fields within the inner magnetosphere.[32]
- JPL's *Sensorweb* project coordinated existing orbital assets (namely, NASA's Terra, Aqua, and EO-1 satellites), leveraging Terra and Aqua's medium-resolution MODIS cameras to identify phenomena of interest (e.g. active volcanoes and flooding) and autonomously commanding high-resolution observations on EO-1's high-resolution and hyperspectral instruments in response.[33,34]

The key enabling technologies are:

- *Absolute pose estimation (metrology)* and *time synchronization* to accurately determine the position and time of measurements. This is usually provided by the GNSS system.

The large number of missions is a testament to the fact that the technologies need for this mission type are mature.

2.3 Gravity Measurement

Measuring the mass distribution and gravity anomalies of Earth or Moon enables scientists to understand its internal structure and minute changes on its surface or interior. On Earth, such data enables studying the thinning of ice sheets, the flow of underground water, effects of earthquakes and landslides, the slow currents of magma inside Earth, etc. On Moon, such data enables studying the lunar crust, lithosphere, inner core, the asymmetric thermal evolution of the Moon, etc. In order to perform such measurements, two identical spacecraft are put in the same polar orbit and a microwave ranging system is used to accurately measure changes in the speed and distance between them.

A number of missions of this type have been launched:

- The *Gravity Recovery and Climate Experiment (GRACE) Mission* by NASA and DLR is composed of two spacecraft (GRACE-1 and GRACE-2).[35] These spacecraft were launched into 500 km polar orbit in March 2002. The two identical spacecraft were about 220 km apart, and the ranging system was sensitive enough to detect separation changes as small as 10 micrometers.[36] Due to its tremendous success in collecting high quality data over 15 years, its successor the *GRACE Follow On Mission* was launched in May 2018,[37] as shown in Fig. 5.

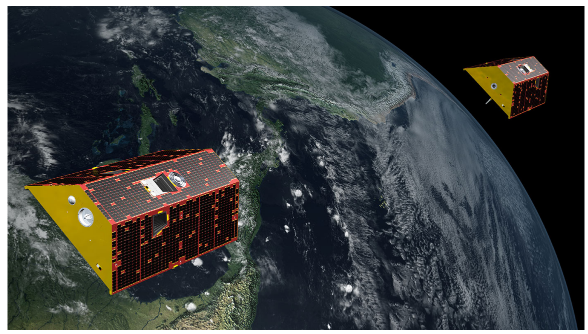

Fig. 5: Artist's representation of the GRACE Follow On Mission (image credit: NASA[38])

- NASA's *Gravity Recovery and Interior Laboratory (GRAIL) Mission* aimed to map the gravitational field of the Moon to determine its interior structure. The two small spacecraft GRAIL A (Ebb) and GRAIL B (Flow) were launched on September 2011, and reached lunar orbit in December 2011 – January 2012,[39] as shown in Fig. 6. After collecting high-quality data for a year, the two spacecraft impacted the Lunar surface in December, 2012.[40]

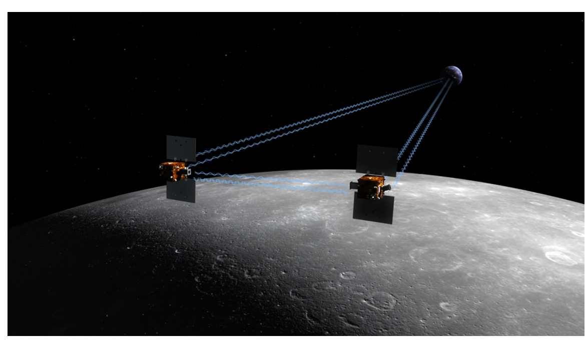

Fig. 6: Artist's representation of the GRAIL Mission (image credit: NASA[41])

- ESA's *Laser Interferometer Space Antenna (LISA)* mission consists of three spacecraft, arranged in an equilateral triangle with 2.5×10^6 km sides, and aims to detect gravitational waves from astronomical sources.[42]

The key enabling technologies are:

- *Absolute pose estimation (metrology)* and *time synchronization* to accurately determine the position and time of measurements. This is usually provided by the GNSS system.
- *Relative pose estimation (metrology)*, which is provided by the microwave ranging system.

These technologies are quite mature.

2.4 Distributed Aperture Telescopes

Astronomy and astrophysics missions aim to study celestial bodies (e.g., black holes, extra-solar planets, galaxies) and phenomena (e.g., primordial radiation, evolution of the universe) that are found beyond our solar system using instruments to detect electromagnetic radiation and high-energy particles emitted by these bodies.[43]

Space-based interferometry using distributed apertures is an important technique within astronomy and astrophysics missions. In this technique, electromagnetic waves (wavelengths from 100m (radio) to 100nm (optical)) from different apertures observing the same target are superimposed in order to cause interference and extract information. The resolution of the interferometer improves with increasing inter-satellite distance (baseline). Ground-based optical interferometry is performed at the Keck observatory (Hawaii, US), European Southern Observatory (Chile), Large Binocular Telescope Observatory (Arizona, US), Mount Wilson Observatory (California, US), Lowell Observatory (Arizona, US), and other places.[44] A number of space-based optical interferometry missions have been proposed, but none have flown till date:

- NASA's *Terrestrial Planet Finder (TPF) mission* composed of five spacecraft in a precision formation operating near the second Sun-Earth Lagrange point, as shown in Fig. 7, to search for Earth-like planets orbiting other stars and probe their atmospheres for indications of life.[45,46] TPF was the successor to NASA's *Space Interferometry Mission (SIM)*, which was canceled in 2010.
- NASA's *New Worlds Mission* is a proposed project comprising a starshade, which a large occulter shown in Fig. 8, flying in formation with a space telescope to block the light of nearby stars in order to observe their orbiting exoplanets.[47]

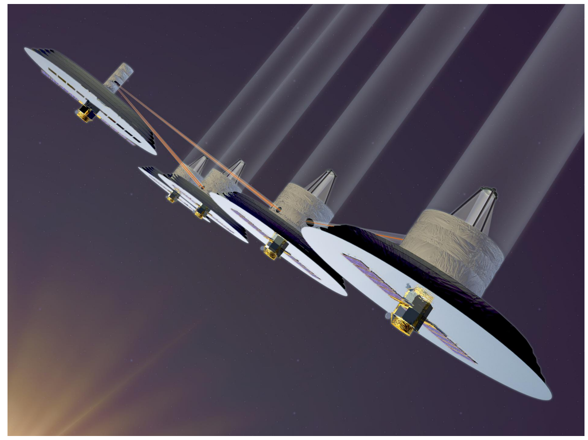

Fig. 7: Artist's representation of the TPF Mission (image credit: NASA[46])

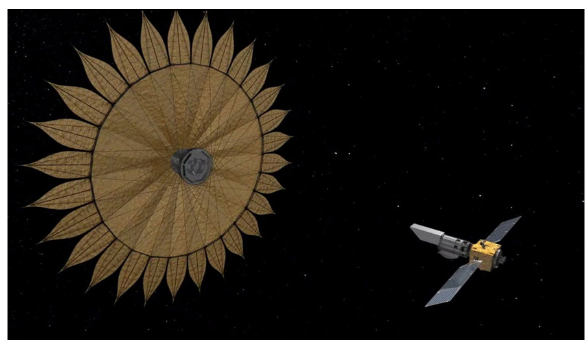

Fig. 8: Artist's representation of the Starshade and space telescope (image credit: NASA[47])

- The Netherlands' *Orbiting Low Frequency Array (OLFAR)* will be composed of a swarm of nanosatellites in lunar orbit, carrying antennae in the band from around 30 kHz to 30 MHz, to observe the universe in this scientifically-interesting and largely-unexplored radio frequency bands to detect signals originating from the yet unseen "Dark Ages" ranging from the Big Bang until around 400 million year after.[48,49]
- ESA's *Darwin* mission was composed of four or five space telescopes, flying in formation as an astronomical interferometer, to search for Earth-like planets around other stars and analyze their atmospheres for chemical signatures of life.[50]
- JPL's *RELIC* project provides a set of tools for

end-to-end optimization of space-based interferometry missions, assisting mission planners the design of orbits and constellation geometries and automatically assessing science returns and overall operability of a given mission.[51,52]

A number of formation flight technology demonstration missions have been proposed and launched:

- Sweden's *Prototype Research Instruments and Space Mission technology Advancement (PRISMA)* mission demonstrated formation flying in space in June 2010 using two satellites (140 kg Mango satellite and 40 kg Tango satellite).[53,54]
- The University of Texas at Austin's *Formation Autonomy Spacecraft with Thrust, Relnav, Attitude and Crosslink (FASTRAC)* mission launched two microsatellites in November 2010 in order to demonstrated enabling technologies for satellite formations like on-orbit micro-thrust capability, relative navigation, attitude determination, and satellite crosslink communications.[55]
- The *Japan Canada Joint Collaboration Satellites – Formation Flying (JC2Sat-FF)* mission aims to demonstrate autonomous formation flight with aerodynamic drag control and GPS-based relative navigation using two microsatellites.[56]
- The University of Toronto's *Canadian Advanced Nanospace eXperiment-4&5 (CanX-4&5)* demonstrated satellite formation flying, with sub-meter tracking error accuracy, in space in June 2004.[9,10]

The key enabling technologies are:

- *Relative pose estimation (metrology)* to measure inter-satellite distances to a fraction of wavelength over multi-kilometer baselines. This is currently possible for radio and far-IR wavelength, but very difficult for near-IR and optical wavelengths.
- *Time synchronization* across multiple spacecraft, which can be achieved using GNSS near Earth and atomic clocks.
- *Formation keeping* is necessary for observing the same astronomical targets.
- *Distributed inter-vehicle communication* to send the signals/data to centralized location (or spacecraft) for automated analysis.

The technologies for precision metrology and formation flying are not yet mature. Moreover, ground-based experimental setups are needed to test and validate these technologies.

2.5 *Distributed Fractionated Spacecraft*

A fractionated spacecraft is a spacecraft architecture where the functional capabilities of a conventional monolithic spacecraft are distributed across multiple modules, which interact through inter-satellite communication links. The modules of a fractionated spacecraft are largely heterogeneous and perform distinct functions like the various subsystem elements of a traditional satellite.[57] DARPA had proposed the System F6 mission concept, but it was later canceled.[58,59]

The key enabling technologies are:

- *Distributed Inter-satellite communication* because it is the main technology that binds all the spacecraft together.
- *Modular space systems*, which enable higher resilience to failures and ease of deployment/upgrades.

Modular spacecraft architecture, which can be housed in different spacecraft, is not mature.

2.6 *In-orbit Assembly and Servicing*

Autonomous assembly, construction and servicing in space will be a game-changing technology that will enable a wide range of applications, like construction of the next-generation space station and science telescopes in Earth orbit, space debris removal or reuse, and construction of spacecraft for Solar System exploration in Earth or Moon orbit. Novel spacecraft architectures, that are too fragile to survive launch loads or need the weightless environment for assembly, can be built in space. Recent advances like 3D printing onboard the International Space Station (ISS)[60] and development of construction robots like Archinauts,[61] shown in Fig. 9, have made this type of mission within the grasp of modern-day technology.

A number of missions of this type have been launched:

- NASA's *Orbital Express* mission demonstrated safe and cost-effective technologies to autonomously service satellites in orbit, including short range and long range autonomous rendezvous, capture and berthing, on-orbit electronics upgrades, on-orbit refueling, and autonomous fly-around visual inspection using a demonstra-

Fig. 9: Artist's representation of Made In Space's Archinaut spacecraft 3D-printing and assembling satellite reflectors in space. (image credit: Made In Space[61])

tion client satellite.[62] The system consisting of two spacecraft, Autonomous Space Transport Robotic Operations (ASTRO) and Next Generation Satellite and Commodities Spacecraft (NEXTSat) shown in Fig. 10, were launched in March 2007 and successfully completed all demonstrations.

- Surrey Satellite Technology Ltd's *RemoveDEBRIS* mission aims to demonstrate various space debris removal technologies like capturing CubeSat DebrisSat1 using a net, vision-based navigation, firing a harpoon at a deployed target, and deploying a dragsail for air braking. This mission was launched in April 2018.[63]

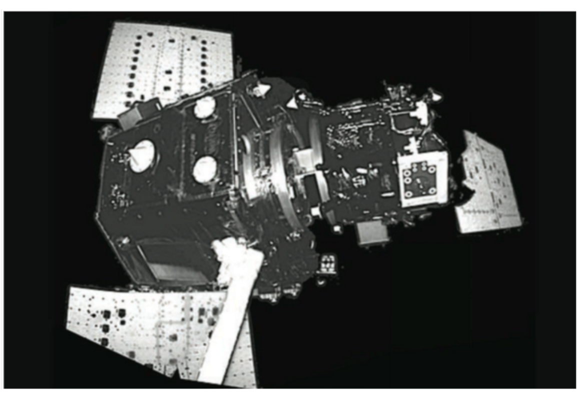

Fig. 10: Orbital Express' ASTRO and NEXTSat spacecraft in orbit, without the separation ring. (image credit: NASA[64])

We envisage that a swarm of autonomous small satellites will be the most likely construction workforce in space, due to advantages like highly reconfigurable behaviors, low cost, scalability, and resilience to failures. The key enabling technologies are:

- ◦ *Relative pose estimation (metrology)* to measure inter-satellite distances to ensure smooth collision-free motion and docking. This is currently achievable using COTS sensors like LIDARs.
- ◦ *Formation keeping* is necessary for moving the structures and docking.
- ◦ *Distributed Inter-satellite communication* is needed to generate and follow a common construction plan across all satellites.
- ◦ *Cooperative manipulation*, which includes techniques for grasping and manipulation of structures.

The main technology gaps are robotic assembly and formation flying.

2.7 Solar Observation

The aim of heliophysics missions is to study the Sun-Earth system and the Sun's interaction with the solar system.[65,66] A number of multi-spacecraft missions have been proposed for such observations:

- NASA's *Solar Terrestrial Relations Observatory (STEREO) Mission* is composed of two identical spacecraft, which were launched in October 2006 into orbits around the Sun that cause them to respectively pull farther ahead of and fall gradually behind the Earth. The two spacecraft STEREO-A (ahead) and STEREO-B (behind) continue to separate from each other at a combined rate of approximately 44 degrees per year. This enables stereoscopic imaging of the Sun and solar phenomena, such as coronal mass ejections. In September 2012, the two SETERO spacecraft along with the Solar Dynamics Observatory (SDO) spacecraft in GEO observed the entire Sun for the first time,[67] as shown in Fig. 11. Contact with SETERO-B spacecraft was lost since October 2014.

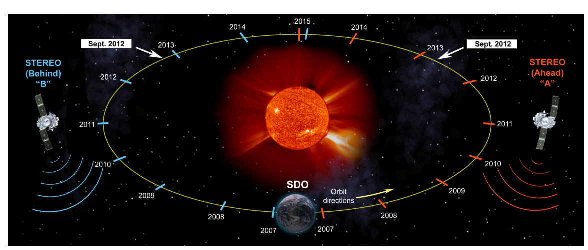

Fig. 11: Artist's representation of the relative positions STEREO spacecraft. (image credit: NASA[67])

- NASA's *Geospace Dynamics Constellation (GDC)* is a mission concept recommended by the Heliophysics decadal survey to study the coupling between the magnetosphere and the upper atmosphere (ionosphere/thermosphere system), and how that coupled system responds to external energy input.[65] GDC will use six identical satellites that will be spread individually into equally-spaced low Earth orbital planes, thus providing simultaneous multi-point measurements at 12 local times.
- ESA's *Project for On-Board Autonomy-3 (PROBA-3)* will be composed of two independent spacecraft flying in formation with the ability to accurately control their attitude and separation. The primary mission is solar coronagraphy, where the smaller spacecraft is maneuvered to occult the Sun.[68]

The key enabling technology is:

- *Absolute pose estimation (metrology)* to accurately determine the position and orbit of the spacecraft. This is usually achieved using the Deep Space Network (DSN).

This technology is mature for Earth-orbiting and deep space spacecraft.

2.8 *Planetary Exploration and Mapping from Space*

The aim of planetary science missions is to study the planets, moons, and small bodies (asteroids, comets, etc.) in our solar system to understand their origin and evolution and to understand the origins of life.[69,70] Majority of planetary science missions till date involve a single spacecraft (e.g. Voyager, Galileo, Juno, Dawn, Mars Reconnaissance Orbiter).

Multi-spacecraft missions enable simultaneous observations of the same phenomena from multiple angles or simultaneous multi-point observations, both of which are crucial to our scientific understanding of the bodies. A number of multi-spacecraft planetary science missions have been proposed and launched till date:

- NASA's *Cassini* spacecraft carried ESA's *Huygens* lander, which landed on Saturn's largest moon Titan. After separation in December 2004, as shown in Fig. 12, Cassini and Huygens simultaneously studied the clouds, atmosphere, and surface of Titan.[71]
- NASA's *Deep Impact* spacecraft released an impactor on comet Tempel 1 in July 2005 to expose materials on its surface, which revealed a number of new findings about comets and their composition including evidence of water ice and organic materials.[73]

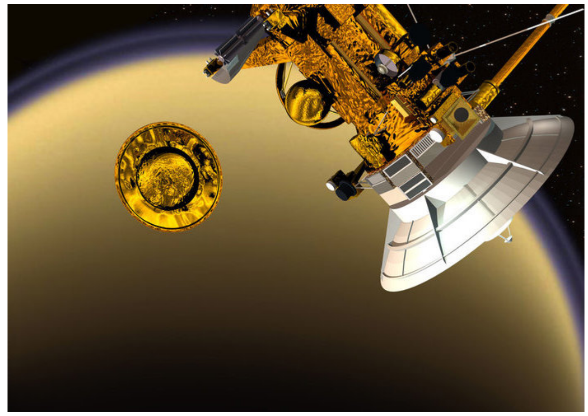

Fig. 12: Artist's representation of the Cassini and Huygens separation near Titan. (image credit: NASA[72])

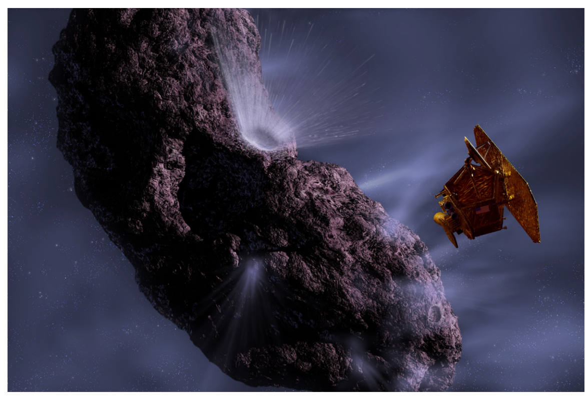

Fig. 13: Artist's representation of impactor striking the comet Tempel 1 while the Deep Impact observes it. (image credit: NASA[73])

- ESA's *Rosetta* spacecraft carried ESA's *Philae* lander to comet 67P/Churyumov–Gerasimenko to image the comet surface and determine its composition. In November 2014, Philae touched down on the comet, as shown in Fig. 14, but had difficulties during landing.[74]
- JAXA's *Hayabusa2* spacecraft carried four rovers (JAXA's ROVER-1A, ROVER-1B, ROVER-2, and DLR/CNES's Mobile Asteroid Surface Scout (MASCOT)) to the near-Earth asteroid 162173 Ryugu for in-situ investigation of the asteroid's surface as shown in Fig. 15.[75] Note that JAXA's *Hayabusa* spacecraft also car-

Fig. 14: Artist's representation of Rosetta spacecraft and Philae lander at comet 67P/Churyumov–Gerasimenko. (image credit: NASA[74])

ried the MINERVA (MIcro-Nano Experimental Robot Vehicle for the Asteroid) mini-lander, but it was lost into space at the time of separation.[76]

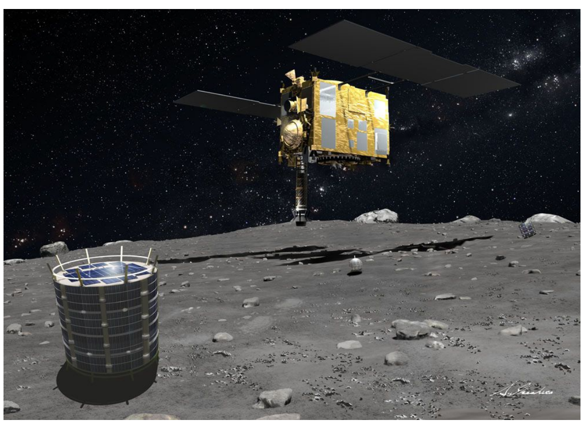

Fig. 15: Artist's representation of rovers hopping around on asteroid Ryugu's surface while Hayabusa2 spacecraft samples the surface. (image credit: JAXA[75])

The key enabling technologies are:

- *Absolute pose estimation (metrology)* to accurately determine the position and orbit of the spacecraft. This is usually achieved using the Deep Space Network (DSN).
- *Distributed inter-satellite communication* is needed to coordinate across multiple spacecraft and rovers.

These technologies are mature.

2.9 Distributed Communication Array

High-bandwidth communication with spacecraft in deep space using Deep Space Network (DSN) is becoming an issue because of the growing number of assets in deep space (at Mars, other planets, moons, and small bodies, etc.) and the growing capability of assets in collecting and sending scientifically useful data. The current paradigm of using existing spacecraft (e.g. MRO and Maven) as communication relays to store and send high-bandwidth data to DSN is further adding to this bottleneck. One approach to mitigate this communication bottleneck is to launch communication-only spacecraft and setup a network of relay stations across the Solar System.

The data rate from a spacecraft to DSN directly scales with the effective isotropic radiated power (EIRP). A single communication-only spacecraft needs to have large solar panels for high EIRP, but this will lead to large costs and complexity. Instead, a number of smaller spacecraft with modest solar panels could outperform the single monolithic spacecraft (i.e., transmit higher EIRP) while cost less. Moreover the multiple spacecraft will provide higher resilience to failures and the enable to constellation/swarm to grow over multiple launches. Note that the smaller spacecraft need to transmit coherently so that phase difference error between signals from different spacecraft is minimized.[77] NASA recently launched the twin communications-relay CubeSats, *Mars Cube One (MarCO)*, to demonstrate deep space communication capability using small spacecraft.[78] Currently there are no planned missions of this type, but this is a key enabling technology that would keep JPL at the forefront in deep space communications.

The key enabling technologies are:

- *Relative pose estimation (metrology)* is necessary to measure inter-satellite distances to a fraction of Ka/X-band wavelength over 100-meter baselines. This is currently achievable using COTS sensors like LIDARs, but not ready for application in deep space.
- *Time synchronization* across multiple spacecraft, which can be achieved using atomic clocks and exchange of radio messages.
- *Formation keeping* is necessary for observing the same target and synchronizing transmitted signals.
- *Distributed inter-satellite communication* is needed to generate and follow a common com-

munication plan across all satellites.

All the above technologies are not mature, and ground-based experimental setups are needed to test and validate these technologies.

2.10 Interplanetary Missions

Humanity's quest to explore the universe is boundless, and inter-planetary travel is the next frontier. The Voyager spacecraft are already exploring the boundary of heliosphere in interstellar space.[79] The Breakthrough Starshot project aims to send multiple ultra-light nanocrafts, miniature spacecraft with lightsails, to the Alpha Centauri which is 4.37 light years away.[80] Using a ground-based light beamer, the nanocraft will travel at $\approx 10\%$ light speed. The scientific and technical community need to solve a number of challenges to make this project a reality.[81]

Mission Domain: Earth surface, atmosphere, and water bodies

2.11 Exploration, Mapping, and Sampling

Multi-robot systems can be used to support Earth science research by collecting spatially and temporally correlated measurements of quantities of interest (e.g. atmospheric properties, concentrations of chemicals, or multi-spectral images), enabling scientists to build high-quality spatio-temporal maps and inform numerical models for applications including weather prediction, tracking of methane emissions, marine biology and study of ocean currents, and geology.

Compared to single-agent architectures, multi-agent systems offer the ability to collect *temporally correlated* information, an enabling factor for the study of time-varying phenomena such as ocean currents, atmospheric phenomena, and glacial erosion. A secondary advantage is the ability of multi-agent architectures to conduct a testing campaign significantly faster compared to a single-agent architecture. Compared to static sensor networks, multi-agent systems can be reconfigured on the fly, enabling *adaptive* sampling strategies; are self-deploying; and can be reused for multiple missions.

A number of multi-agent architectures carrying sample-collection devices,[82] ground-penetrating radars (e.g. JPL's proposed DASHER mission), seismometers, multi-spectral cameras, and gas spectrometers have been proposed and deployed. As an example, Figure 16 shows a deployment of multiple underwater gliders for ocean sampling along the California coast.

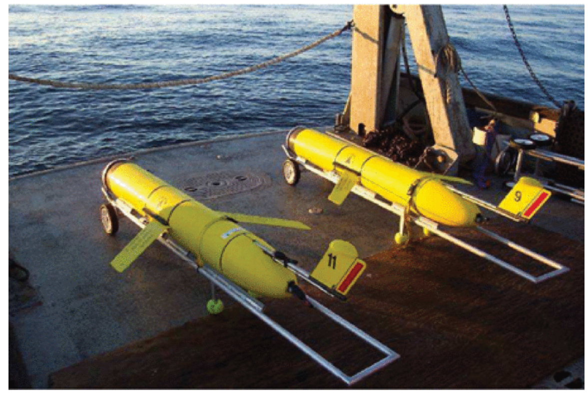

Fig. 16: A fleet of ten Slocum underwater gliders was used for ocean sampling in the Adaptive Sampling and Prediction (ASAP) project. (image credit:[82])

The key enabling technologies are:

- *Distributed estimation and cooperative mapping* is necessary to build maps of quantities of interest in real-time and enable adaptive sampling strategies; a number of algorithms for this application are available, and several of them have been tested in the field.
- *Distributed inter-vehicle communication* is required to support cooperative estimation and mapping. The problem is highly challenging for underwater and underground applications; possible remedies are discussed in Section 2.13.
- *Time synchronization* enables measurements collected by different agents to be correlated. The required precision is highly problem-specific, ranging from minutes or hours for direct sampling of slow-changing phenomena to sub-nanosecond for applications leveraging distributed RADAR.
- *Relative pose estimation* allows the information samples to be correlated in time and space, and
- *Absolute pose estimation* allows them to be registered with a world map. The precision requirements can vary widely, from hundreds of meters for direct observation phenomena with large geographic scale to sub-cm for RADAR and RF sensing applications.

2.12 Cooperative Lifting, Construction, and Assembly

Groups of terrestrial and flying robots can cooperate to move and assemble large structures, coordinating to transport and handle parts and sub-assemblies that would be too big or heavy for an individual robot. Cooperative lifting, construction, and assembly is the norm for non-autonomous construction projects; enabling such tasks to be performed *autonomously* holds promise to greatly reduce the time and cost required for construction.

Figure 17 and Figure 18 show examples of cooperative lifting and cooperative construction respectively.

Fig. 17: Multi-UAV cooperative lifting. From[83]

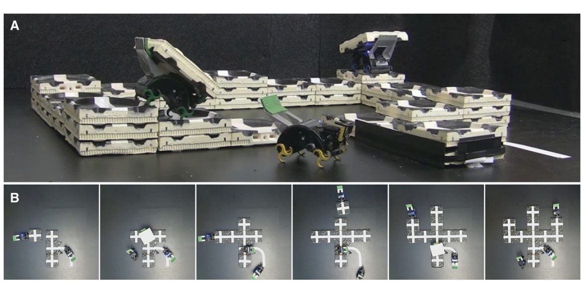

Fig. 18: Independent autonomous robots with purely onboard sensing collectively work on prespecified structures. From[84]

The key enabling technologies are:

- *Cooperative manipulation*, required to move parts and assemblies that are too large for a single robot to handle - an active area of research in the robotics community.
- *Cooperative motion planning* and
- *Formation keeping* to coordinate the motion of multiple vehicles grasping the same part or assembly.
- *Cooperative task recognition and task allocation* to map a high-level assembly task to a set of grasping and motion tasks for the robots - also an active area of research.

2.13 Communication Infrastructure

Autonomous robots can act as communication relay for other robots, carrying radio repeaters and planning their motion so as to ensure that all vehicles have a reliable connection to each other and/or to a ground station. Use of multi-agent systems as communication repeaters is an *enabling technology* for robot operation in communication-denied environments such as underground caves. For surface-based and aerial applications, already-in-place communication infrastructure (e.g. cellular and satellite communication networks) can be used in lieu of robot radio relays; however, dedicated relays can offer lower latency (and potentially lower cost) compared to satellite data links, and they can be deployed in areas where no cellular connectivity is available with much lower cost and higher operational flexibility compared to dedicated infrastructure. Finally, use of robots as communication relays is an enabling factor for planetary and Small Solar System Body exploration: such applications are discussed in Section 2.20.

Figure 19 shows an experimental deployment of robots acting as communication relays to support exploration of an underground mine.

The key enabling technologies are:

- *Cooperative task recognition and task allocation* to decide which agents should act as communication relays.
- *Cooperative motion planning* to identify suitable locations where the relay agents should position themselves.
- *Distributed inter-vehicle communication* to route packets appropriately from their origin to their intended destination in dynamic network topologies.

Fig. 19: Robots can act as communication relays in communication-denied environments. Image from[85]

- *Time synchronization* to enable TDMA access control protocols.

2.14 *Disaster Recovery and Search & Rescue*

Teams of UAVs and UGVs can cooperate to quickly and cooperatively map a disaster zone (e.g. a collapsed building) so as to provide rescuers with situational awareness; they can also autonomously explore large geographical regions, detect potential casualties, and relay information to rescuers, enabling fast exploration of large regions (a critical capability for wildland search and rescue).

Compared to individual vehicles, multi-agent robotic systems can explore a given area significantly faster, a critical consideration for search and rescue operations.

Urban search and rescue is a prime application for multi-agent robotic systems, as shown by the immense amount of interest from the scientific and industrial community[86–95]

The key enabling technologies are:

- *Cooperative task recognition and task allocation* to efficiently explore the environment and assign unexplored regions to suitably-equipped agents.
- *Distributed estimation and cooperative mapping* to collectively build a map of the environment.
- *Human-robot interfaces* to efficiently relay large amounts of information from many vehicles to a small number of human operators.

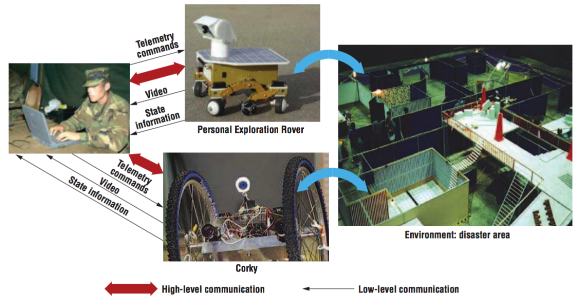

Fig. 20: Multi-robot teams with humans in the loop for disaster recovery (from[91])

2.15 *Reconnaissance, Patrolling and Tracking*

Teams of UAVs, AUV, and UGVs can be used to patrol high-value regions and targets (e.g. harbors, sensitive facilities, and convoys), detecting and tracking intruders. Availability of multiple, possibly heterogeneous agents is critical to ensure persistent coverage. Coordination between different classes of vehicles is a key capability for these applications, as it enables the multi-agent system to exploit the unique capabilities of each vehicle: for instance, a fast and lightweight UAV can be used to intercept and assess unknown intruders, whereas a slower but better-equipped UGV can be leveraged for in-depth inspection and interdiction. Reconnaissance, patrolling, and tracking are naturally well-suited to multi-agent systems: accordingly, such systems have seen deployment in the field,[96] (see Figure 22).

The key enabling technologies are very similar to those required for disaster recovery and SAR (Section 2.14). In addition,

- *Cooperative motion planning* may be required for agents to closely track an unidentified or suspect vehicle.

2.16 *Urban Transportation/Delivery Systems*

Fleets of autonomous vehicles hold promise to revolutionize urban transportation by providing on-demand transportation services for people and goods at lower cost compared to private vehicles and taxi systems – a mode of transportation known as Autonomous Mobility-on-Demand. Autonomous Mobility-on-Demand holds promise to deliver a significant reduction in transportation costs, lower demand for parking infrastructure, lower pollution, and

Fig. 21: 6: Entrants in the 2010 MAGIC reconnaissance and SAR competition. Left: from.[93] Right: from[94]

less traffic;[97] Autonomous transportation systems were the subject of a JPL Blue Sky Study in 2015.[98]

The key enabling technologies are:

- *Cooperative task allocation*, to efficiently allocate transportation requests to agents.
- *Cooperative motion planning* to enact congestion-aware routing policies that do not increase (and, ideally, reduce) traffic congestion.

2.17 *Entertainment*

Finally, swarms of hundreds to thousands autonomous quadcopters have been used for large-scale "light show" displays consisting of choreographed formation maneuvers (Figure 23).

The key enabling technologies are:

- *Relative pose estimation* to estimate the agents' relative locations.
- *Formation keeping.*

Mission Domain: Planetary/Moon surfaces, atmosphere, and water bodies

Exploration of the surfaces, atmospheres, and water bodies of other planets is central to JPL's mission.

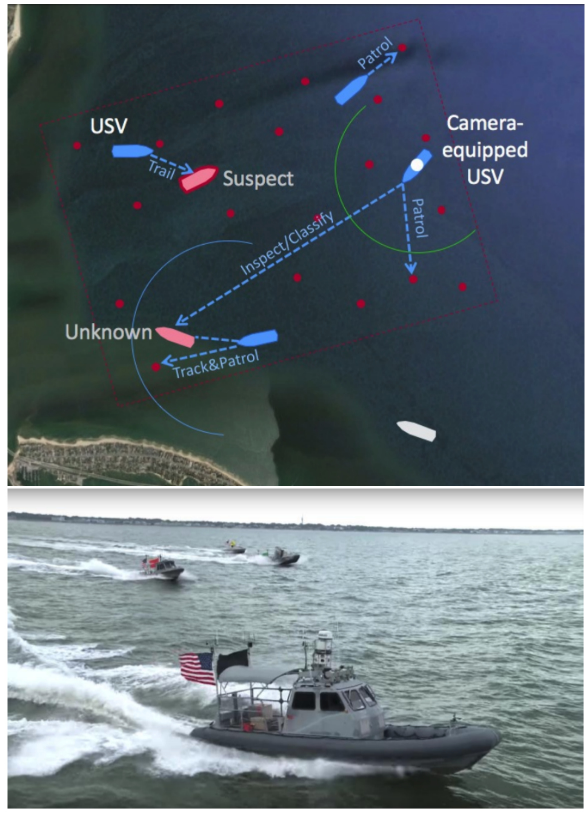

Fig. 22: A multi-AUV team performing a harbor patrol mission (from[96])

While many proposed applications of multi-agent systems to this domain have strong parallels to Earth-based applications, space-based systems present two key differences with terrestrial ones.

On the one hand, lack of existing infrastructure make multi-agent robotic systems more attractive for space-based application compared to terrestrial ones; for instance, robotic systems are the primary (if not only) solution for communication relays and construction on planetary surfaces. On the other hand, light-speed delays and scarce DNS availability impose strict requirements on the autonomy and resilience of multi-agent systems deployed on other planets, making many partially-supervised solutions (widely used for Earth applications) unsuitable.

2.18 *Exploration, Mapping and Sampling*

Groups of multiple robots can collect spatially and temporally correlated data quickly and effectively, providing scientists with high-quality information on surface and sub-surface geology and chemistry, airborne particulates, and weather patterns. A number

Fig. 23: INTEL's Drone Light show at the 2018 PyeongChang Winter Olympics

of multi-agent and multi-sensor missions for planetary explorations have been proposed, including:

- multi-static ground-penetrating radar platforms which could reconstruct 3D maps of the planetary crust and map sub-surface voids (e.g., JPL's proposed DASHER project);
- seismometers to assess the composition of planetary bodies' cores by observing the propagation of seismic waves (e.g., early concepts for INSIGHT),
- spectrometers to track the diffusion of airborne chemicals,
- camera-equipped rovers to map sub-surface voids (e.g., JPL's PUFFER and Mars Caves projects),
- airborne platforms that act as scouts for ground robots (e.g., Mars Helicopter),
- and meteorological stations (e.g., the Printable Spacecraft platform concept[99]).

These applications greatly differ in size and weight (ranging from large ground robots weighing tens of kilograms to sub-gram vehicles and sensors) and mobility requirements (spanning flying robots, wheeled vehicles, and static sensor networks. However, they all share certain key requirements, including:

- Autonomy: the platforms should be able to operate for hours to days with no humans in the loop;
- *Relative pose estimation* and
- *Formation keeping*: the vehicles should be able to assess and, in many applications, control their relative location to a high degree of accuracy.
- *Distributed estimation and cooperative mapping* to build real-time maps of the observed quantities and enable adaptive sampling strategies.
- *Time synchronization.* the vehicles must have access to synchronized clocks to time-stamp the collected data. Synchronization accuracy can vary from minutes (for slow-changing phenomena) to sub-ns (for radio science, and in particular multi-static RADAR).
- *Distributed inter-agent communication*: in order to cooperate and relay data to Earth, the agents must establish and maintain a communication network. To support geographically-distributed agents, the communication mechanism may need to support reconfigurable multi-hop communications – a novel requirement for space applications, where the communication topology is generally single-hop or (in the case of rover-orbiter relays) well-defined in advance.

2.19 Cooperative Construction

Permanent human manned outposts on Solar System bodies will require large amounts of infrastructure to provide astronauts with shelter and resources. Ideally, such infrastructure should be in place *before* the astronauts land.

Construction and assembly are often highly parallelizable: accordingly, they are ideal applications for multi-robot systems. Cooperation between multiple vehicles enables the construction of large structures beyond the capabilities of a single rover – a critical consideration, since the maximum mass and volume of an individual rover is constrained by launcher capabilities.

Several multi-robot cooperative construction systems have been proposed: in particular, JPL's CAMPOUT architecture for cooperative assembly allows multiple robots to lift and move large structures, e.g. beams,[100] and USC's Contour Crafting system for lunar construction (Figure 25) "prints" full-scale buildings by extruding specially formulated concrete-like materials.[101]

The key enabling technologies are similar to those for Earth-based cooperative construction (Section 2.12) and include:

- *Cooperative manipulation*, required to move parts and assemblies that are too large for a single robot to handle
- *Cooperative motion planning* and
- *Formation keeping* to coordinate the motion of multiple vehicles grasping the same part or assembly.

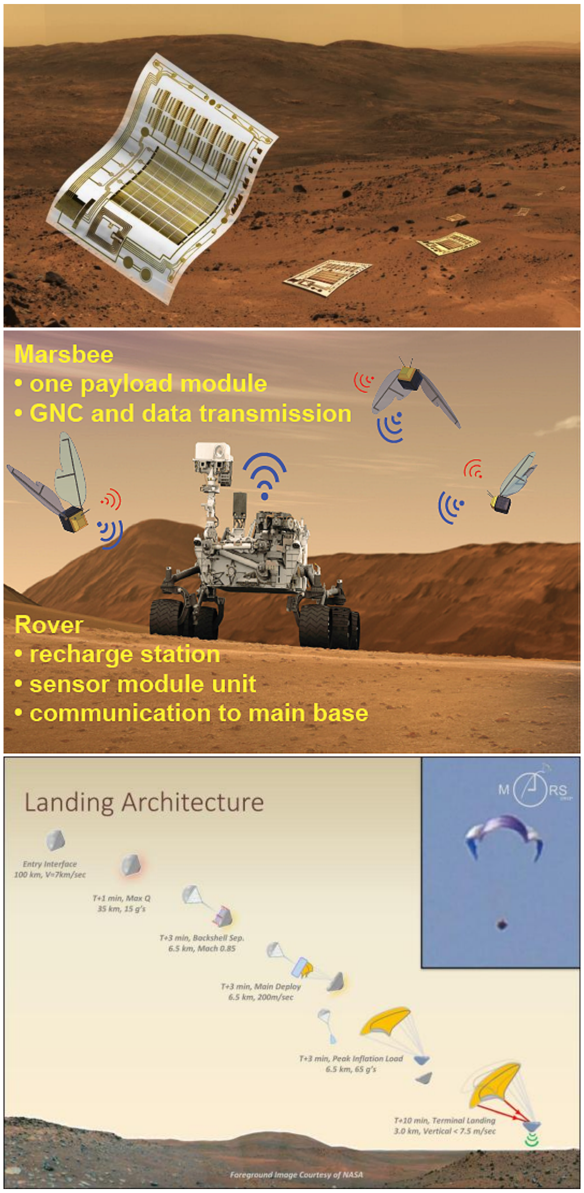

Fig. 24: Printable Spacecraft, MarsBee, and MARS-DROP systems for mapping and sampling.

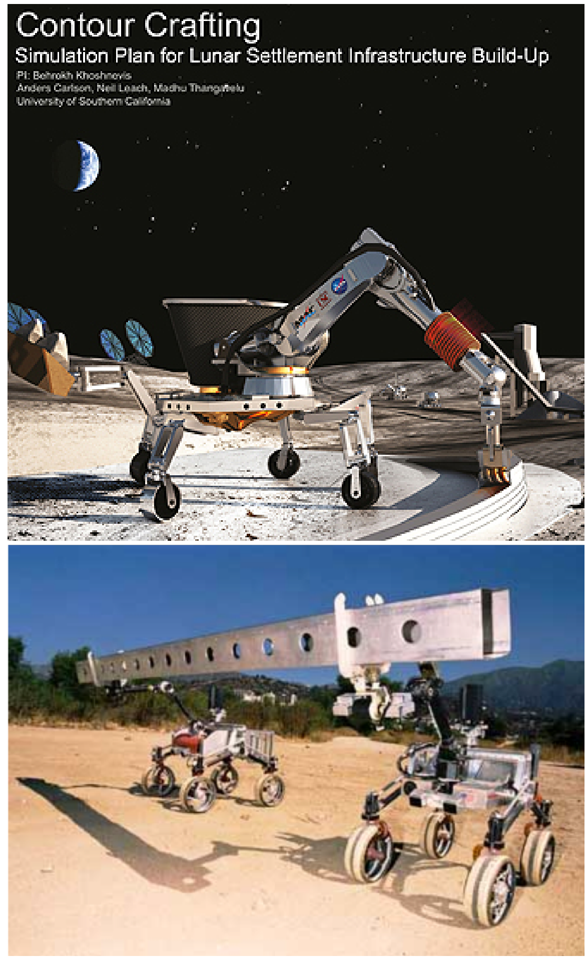

Fig. 25: Left: USC's Contour Crafting concept (from[101]). Right: JPL's CAMPOUT cooperative construction architecture (from[100]).

- *Cooperative task recognition and task allocation* to map a high-level assembly task to a set of grasping and motion tasks for the robots.

2.20 *Communication Infrastructure*

Autonomous agents can act as radio relays for other agents, enabling robots and sensors to transmit data to a base station or Earth relay in scenarios where single-hop communication is impossible. The concept of using spacecraft as communication relays has a rich heritage in planetary exploration: in particular, Mars orbiters Mars Reconnaissance Orbiter, Mars Odyssey, and MAVEN are equipped with transceivers that routinely relay communications from ground rovers to the Deep Space Network's antennas[102] (Figure 26), enabling Mars rovers rovers to transmit information to Earth at high data rates without carrying large high-gain antennas.

The concept is is being further extended in the InSight mission, due to land on Mars in November 2018. InSight is accompanied to Mars by two CubeSats, named MarCO-A and MarCO-B, which will be will be used to relay real-time information to Earth during the probe's Entry, Descent and Landing sequence (Figure 27)

This paradigm is especially promising for mobile rover operations in challenging terrains and environments, where individual rovers may not have a line-of-sight path to either a base station, an overhead orbiter, or Earth. For instance, JPL's PUFFER mission concept proposes using a group of mobile wheeler rovers as robotic relays to enable operations beyond line-of-sight of a ground station in rough terrain and in sub-surface voids (shown in Figure 28).

The key enabling technologies are similar to those required by Earth-based robotic communication infrastructure (Section 2.13), including:

- *Cooperative task recognition and task allocation* to decide which agents should act as communication relays.
- *Cooperative motion planning* to identify suitable locations where the relay agents should position themselves.
- *Distributed inter-vehicle communication* to route packets appropriately.
- *Time synchronization* to enable TDMA access control protocols.

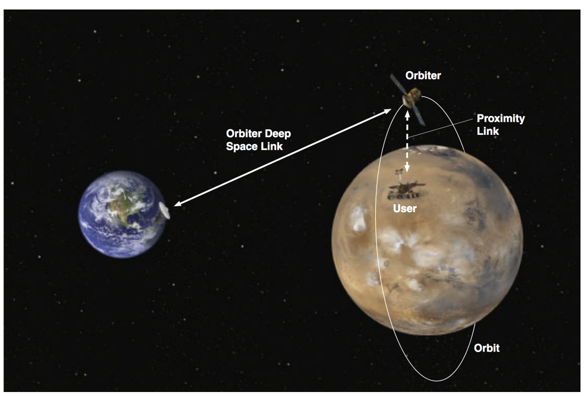

Fig. 26: Mars orbiters act as relays for ground rovers, enabling data transmission at high data rates without requiring large antennas on ground assets (from[102]).

2.21 *Cooperative Computation*

The computational capabilities of planetary exploration robots are often highly limited due to limited availability of radiation-hard computing equipment. Furthermore, robotic agents in the same mission can have highly heterogeneous computation capabilities: for instance, the Mars 2020 rover will be equipped with a RAD750 processor, whereas the Mars Helicopter daughter-craft will carry a vastly more capable Qualcomm Snapdragon processor. A proposed concept of operations, spearheaded by JPL's MOSAIC project, is to enable robotic agents to *share* their computational capabilities, leveraging available communication links to assign computational tasks to agents with unused computational capabilities. Such a paradigm could, for instance, enable small rovers with limited computation to perform complex computational tasks such as visual odometry by delegating heavy computations to a high-performance spaceflight computer (HPSC) hosted in a base station or even in a passing orbiter. Figure 29 shows a graphical depiction of the concept.

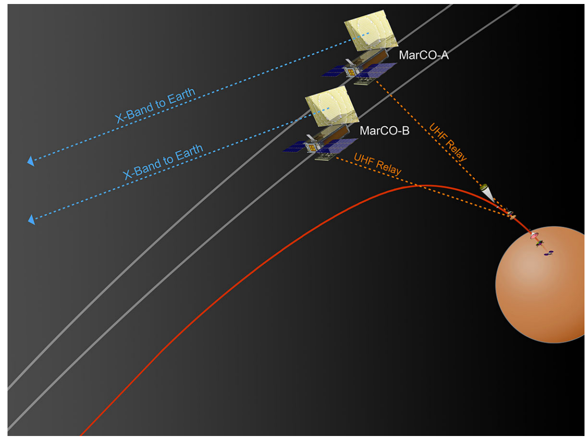

Fig. 27: Artist's conception of the MarCO cubesats relaying information from InSight to Earth during EDL.

Key enabling technologies include:

- *Cooperative task recognition and task allocation* to allocate computation tasks to agents.
- *Distributed inter-vehicle communication* to enable agents to exchange information on the inputs and outputs of computation tasks.

3. Enabling Technologies and Gaps

Several technologies are key to realizing the benefits of multi-agent systems. In this report, we focus on enabling technologies that are *uniquely* relevant to multi-agent systems; in other words, we do not include technologies that are required by *individual* vehicle autonomy, e.g. single-agent motion planning, even though those technologies are a prerequisite for the deployment of autonomous multi-agent systems. Table 1 lists the enabling technologies for different multi-spacecraft missions and their technology development maturity.

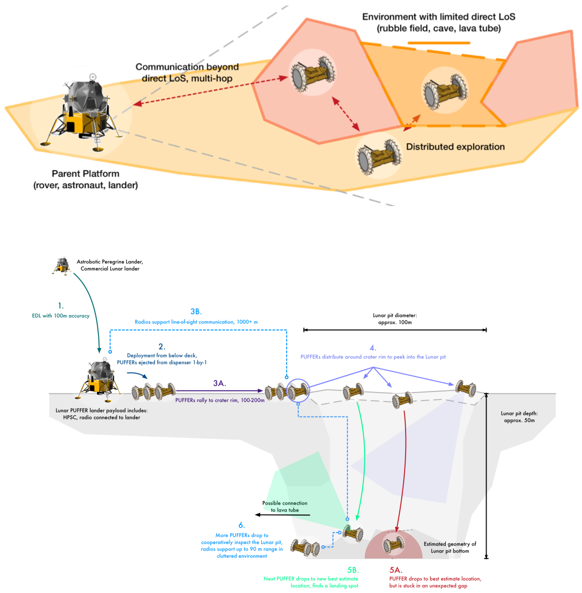

Fig. 28: PUFFER concept of operations: PUFFERs act as relays to enable beyond line-of-sight operations in challenging terrain (left) and in sub-surface cavities (right).

3.1 *Absolute Pose Estimation (metrology)*

Absolute pose estimation enables agents to estimate their location in an absolute reference frame (e.g. with respect to Earth or an orbiting body). This technology is central to many multi-agent challenges, enabling agents to correlate their measurements and observations to an absolute reference frame and point instruments to specific locations. For applications from the Earth surface through Low Earth orbit, GNSS constellations provide real-time absolute pose estimation to sub-meter resolution, and the pose of spacecraft in the Solar System can be estimated to a high degree of accuracy through Deep Space Network observations and extensive modeling; conversely, solutions for absolute localization underwater and in subterranean environments are an active area of research.

3.2 *Relative Pose Estimation (metrology)*

Relative pose estimation allows agents to estimate their position with respect to other agents; it is fundamental sub-routine for application requiring agents to interact with each other (e.g. through formation keeping and cooperative manipulation). Precision requirements can range from multiple meters (for sampling of macroscopic phenomena) to mm-level (e.g., for radio and RADAR applications). Relative pose

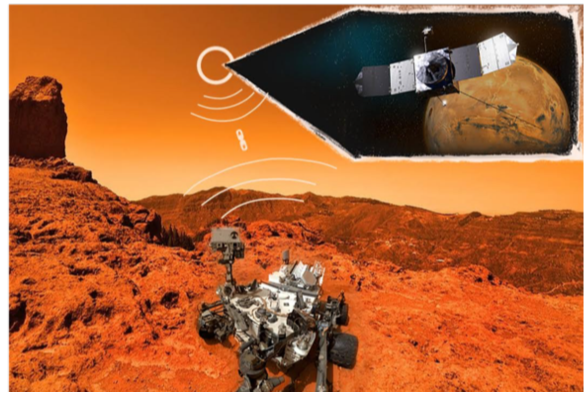

Fig. 29: Robotic agents can share computational capabilities, enabling novel concepts of operation and heterogeneous computation architectures.

estimation can be achieved from absolute pose estimation and information exchange over arbitrary baselines; over short baselines, RF, structured light, and vision can deliver very high accuracy.

3.3 *Time Synchronization*

Time synchronization enables multiple agents to perform as a single transmitter or receiver large-aperture antenna; it also allows agents to temporally correlate their measurements and samples. Distributed radio applications can require synchronization with sub-ns accuracy, an extremely stringent requirement; several technologies exist that hold promise to achieve such precision, but their integration in multi-agent systems is an active area of development.

3.4 *Formation Keeping*

Formation keeping allows agents to control their position relative to other agents and enables groups of agents to move as a group. The problem of formation keeping has seen a high level of interest in the scientific community; nevertheless, for many applications, it remains an active area of research due to stringent metrology requirements and/or limited sensing and communication capabilities.

3.5 *Distributed Inter-Vehicle Communication*

Distributed inter-vehicle communication is an enabling technology for virtually all applications requiring agents to actively coordinate. While the physical layer of multi-agent communications is well understood, technologies and algorithms for packet routing in large, time-varying networks is challenging and an active area of research; coding techniques for distributed multi-vehicle communication in underground and underwater environments, where bandwidth is highly limited, are also under active development.

3.6 *Modular Space Systems*

Modular space systems consist of multiple subsystems, launched separately, that are assembled or connected in orbit or in situ. Such systems allow designers to deploy systems larger than what a single launch vehicle can accommodate; in addition, they enable individual subsystems to be upgraded or replaced. This technology encompasses both subsystems that are physically assembled and subsystems interacting through wireless links (e.g. DARPA's proposed System F6), and is not mature.

3.7 *Cooperative Manipulation*

Cooperative manipulation encompasses two key technologies required for autonomous construction and assembly, namely:

- Multi-agent grasping, i.e. the ability to engage a part or assembly with an end effector;
- Assembly, i.e. the ability to connect and disconnect parts and assemblies with each other and accommodate the change in the parts' mass and inertia resulting from connection or disconnection.

3.8 *Distributed Estimation and Cooperative Mapping*

Distributed estimation and cooperative mapping enables agents to cooperatively build a global model of a quantity of interest (specifically, in the case of mapping, a global map of the environment they operate in). To do so, agents must be able to (i) calibrate and register their sensor readings with other agents' information and (ii) fuse the readings to form a global world model. The problems of distributed estimation and cooperative mapping have been heavily studied, but they remain an area of active research.

3.9 *Cooperative Motion Planning*

In many applications, agents must coordinate their motion plans to ensure collision avoidance and optimally utilize a shared spatial resource. Several approaches to the cooperative motion planning problem have been proposed in the scientific literature; nevertheless, the problem remains actively studied.

3.10 *Cooperative Task Recognition and Task Allocation*

Cooperative task recognition and task allocation enable agents to:

- recognize tasks that should be performed based on environmental cues observed by the agents, and
- assign such tasks according to the agents' states and capabilities.

Both problems are active areas of research in the robotics community.

3.11 *Human-Space System Interface*

Multi-agent system must often operate under human supervision. A key open challenge that must be overcome in order to enable adoption and scalability of such systems is to allow a small number of operators to control large numbers of asset by (i) presenting relevant information about the *system* state and (ii) allowing operators to effectively command the *system*'s behavior, as opposed to individual vehicles.

4. Conclusions

Multi-spacecraft and swarm missions could change risk-posture of future space exploration missions by affording loss of one or more agents without compromising the whole missions, and also allow concurrent measurements and scientific explorations that are not possible using a monolithic architecture, e.g. interferometry using formation flying spacecraft, scientific exploration of comets and asteroids using a swarm fly-by, or exploration of moon and mars lava tubes using a swarm of small rovers. In order to achieve technological readiness for such missions, we need to address the technology gaps identified in this paper, such as:

- Resource-aware and network-aware autonomous task identification and task allocation for robot teams.
- Algorithms for optimizing what and when to communicate among assets, given the costs of the communication and the benefits of coordination.
- Relative localization / team member pose estimation from on-board sensors and subject to computational and network conditions of small spacecraft.

- On-board risk awareness and incorporation of risk into mission and motion planning.
- Mission planning and scheduling that accounts for multiple dynamic assets; synchronization and/or distribution of plans.
- Autonomy and network software systems designed explicitly to coordinate multiple spacecraft.
- Human interfaces and autonomy software designed for an updated operations paradigm; overall, great individual autonomy will be needed as human sequencing for all agents is likely too cumbersome / impractical.
- Smaller and cheaper communications and sensor equipment, shifting the focus from individual robustness to redundancy.

In particular, we recommend the development of a hardware and software infrastructure for such multi spacecraft missions by pursuing the following tasks:

- Development of flight software designed from the ground up to allow multi-robot and multi-spacecraft coordination and operations.
- Defining a modular SmallSat common bus capable of carrying a variety of sensors to enable Multi-Agent Multi-Mission operations.
- Pursuing a technology demonstration mission consistent of 4-5 spacecraft, verifying key technologies required for such missions.
- Pursuing technology demonstrations with medium sized swarm of rovers and aerial vehicles.

We envisage that the broader community will strive to address these technology challenges to make multi-agent and swarm based space exploration missions a reality!

Acknowledgments

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References

[1] D. P. Scharf, F. Y. Hadaegh, and S. R. Ploen, "A survey of spacecraft formation flying guidance and control (part I): Guidance," in *Proc. Amer. Control Conf.*, Denver, CO, June 2003, pp. 1733–1739.

[2] ——, "A survey of spacecraft formation flying guidance and control (part II): Control," in *Proc. Amer. Control Conf.*, Boston, MA, June 2004, pp. 2976–2985.

[3] F. Y. Hadaegh, B. Acikmese, D. S. Bayard, G. Singh, M. Mandic, S.-J. Chung, and D. Morgan, *Adventures on the Interface of Mechanics and Control*. Duluth, GA: Tech Science Press, 2012, ch. Guidance and Control of Formation Flying Spacecraft: From Two to Thousands, pp. 327–371.

[4] S. Bandyopadhyay, R. Foust, G. P. Subramanian, S.-J. Chung, and F. Y. Hadaegh, "Review of formation flying and constellation missions using nanosatellites," *J. Spacecraft and Rockets*, vol. 53, no. 3, pp. 567–578, 2016.

[5] S. Bandyopadhyay, G. P. Subramanian, D. Morgan, R. Foust, S.-J. Chung, and F. Y. Hadaegh, "A review of impending small satellite formation flying missions," in *53rd AIAA Aerospace Sciences Meeting*, Kissimee, FL, Jan. 2015, aIAA 2015-1623.

[6] Planet Labs. Planet Pulse. URL: https://www.planet.com/pulse/ [cited 2020-02-10].

[7] C. Boshuizen, J. Mason, P. Klupar, and S. Spanhake, "Results from the planet labs flock constellation," in *AIAA/USU Conference on Small Satellites*, Logan, UT, Aug. 2014.

[8] C. Foster, J. Mason, V. Vittaldev, L. Leung, V. Beukelaers, L. Stepan, and R. Zimmerman, "Constellation phasing with differential drag on planet labs satellites," *Journal of Spacecraft and Rockets*, vol. 55, no. 2, pp. 473–483, 2017.

[9] G. Bonin, N. Roth, S. Armitage, B. Risi, and R. Zee, "The CanX-4&5 formation flying mission: A technology pathfinder for nanosatellite constellations," in *AIAA/USU Conference on Small Satellites*, Logan, UT, Aug. 2013.

[10] eoPortal. CanX-4&5 (Canadian Advanced Nanospace eXperiment-4&5). URL: https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/canx45 [cited 2020-02-10].

[11] B. Hofmann-Wellenhof, H. Lichtenegger, and J. Collins, *Global positioning system: theory and practice*. Springer Science & Business Media, 2012.

[12] B. W. Parkinson, P. Enge, P. Axelrad, and J. J. Spilker Jr, *Global positioning system: Theory and applications, Volume II*. American Institute of Aeronautics and Astronautics, 1996.

[13] National Aeronautics and Space Administration. Global Navigation Satellite System (GNSS) Overview. URL: https://cddis.nasa.gov/Techniques/GNSS/GNSS_Overview.html [cited 2020-02-10].

[14] National Oceanic and Atmospheric Administration. What Is the Global Positioning System? URL: https://celebrating200years.noaa.gov/transformations/gps/side1.html [cited 2020-02-10].

[15] National Academy of Sciences. Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. URL: http://www.nap.edu/catalog.php?record_id=11820 [cited 2020-02-10].

[16] D. Massonnet and K. L. Feigl, "Radar interferometry and its application to changes in the earth's surface," *Reviews of Geophysics*, vol. 36, no. 4, pp. 441–500, 1998.

[17] A. J. Mannucci, B. D. Wilson, D. N. Yuan, C. H. Ho, U. J. Lindqwister, and T. F. Runge, "A global mapping technique for gps-derived ionospheric total electron content measurements," *Radio Science*, vol. 33, no. 3, pp. 565–582, 1998.

[18] J. Artru, V. Ducic, H. Kanamori, P. Lognonné, and M. Murakami, "Ionospheric detection of gravity waves induced by tsunamis," *Geophysical Journal International*, vol. 160, no. 3, pp. 840–848, 2005.

[19] National Aeronautics and Space Administration. The Afternoon Constellation. URL: http://atrain.nasa.gov/ [cited 2020-02-10].

[20] ——. CLARREO project. URL: https://clarreo.larc.nasa.gov/ [cited 2020-02-10].

[21] R. A. Anthes, P. A. Bernhardt, Y. Chen, L. Cucurull, K. F. Dymond, D. Ector, S. B. Healy, S.-P. Ho, D. C. Hunt, Y.-H. Kuo *et al.*, "The COSMIC/FORMOSAT-3 mission: Early results," *Bulletin of the American Meteorological Society*, vol. 89, no. 3, pp. 313–334, 2008.

[22] eoPortal. THEMIS (Time History of Events and Macroscale Interactions during Substorms) / ARTEMIS. URL: https://directory.eoportal.org/web/eoportal/satellite-missions/t/themis [cited 2020-02-10].

[23] NASA. THEMIS in orbit. URL: http://www.nasa.gov/mission_pages/themis/multimedia/themis_artist.html [cited 2020-02-10].

[24] European Space Agency. Cluster II Operations. URL: http://www.esa.int/Our_Activities/Operations/Cluster_II_operations [cited 2020-02-10].

[25] eoPortal. Swarm (Geomagnetic LEO Constellation). URL: https://directory.eoportal.org/web/eoportal/satellite-missions/s/swarm [cited 2020-02-10].

[26] German Aerospace Center. TanDEM-X – the Earth in Three Dimensions. URL: http://www.dlr.de/eo/en/desktopdefault.aspx/tabid-5727/10086_read-21046/ [cited 2020-02-10].

[27] DLR. TanDEM-X - the Earth in three dimensions. URL: https://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10378/566_read-426/#/gallery/345 [cited 2020-02-10].

[28] eoPortal. MMS (Magnetospheric MultiScale) Constellation. URL: https://directory.eoportal.org/web/eoportal/satellite-missions/m/mms-observatory [cited 2020-02-10].

[29] Satellite Today. Skybox Imaging Exec Discusses Constellation Plans. URL: http://www.satellitetoday.com/technology/2014/02/11/skybox-imaging-exec-discusses-constellation-plans/ [cited 2020-02-10].

[30] eoPortal. CYGNSS (Cyclone Global Navigation Satellite System). URL: https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cygnss[cited 2020-02-10].

[31] ——. OPAL (Orbiting Picosatellite Automatic Launcher). URL: https://directory.eoportal.org/web/eoportal/satellite-missions/o/opal [cited 2020-02-10].

[32] ——. ST5 (Space Technology 5). URL: https://directory.eoportal.org/web/eoportal/satellite-missions/s/st5[cited 2020-02-10].

[33] A. G. Davies, S. Chien, J. Doubleday, D. Tran, T. Thordarson, M. Gudmundsson, A. Hoskuldsson, S. Jakobsdottir, R. Wright, and D. Mandl, "Observing iceland's eyjafjallajökull 2010 eruptions with the autonomous nasa volcano sensor web," *Journal of Geophysical Research - Solid Earth*, 2013.

[34] A. G. Davies, S. Chien, J. Doubleday, D. Tran, and D. McLaren, "The nasa volcano sensorweb: Over a decade of operations," in *International Joint Conference on Artificial Intelligence Workshop on Artificial Intelligence in Space (AI Space, IJCAI 2015)*, Buenos Aires, Argentina, July 2015. [Online]. Available: https://ai.jpl.nasa.gov/public/papers/davies_ijcai2015_nasa.pdf

[35] University of Texas at Austin. GRACE Gravity Recovery And Climate Experiment. URL: http://www.csr.utexas.edu/grace/ [cited 2020-02-10].

[36] B. D. Tapley, S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins, "GRACE measurements of mass variability in the Earth system," *Science*, vol. 305, no. 5683, pp. 503–505, 2004.

[37] B. S. Sheard, G. Heinzel, K. Danzmann, D. A. Shaddock, W. M. Klipstein, and W. M. Folkner, "Intersatellite laser ranging instrument for the GRACE follow-on mission," *Journal of Geodesy*, vol. 86, no. 12, pp. 1083–1095, 2012.

[38] Jet Propulsion Laboratory, California Institute of Technology. GRACE-FO Satellite Switching to Backup Instrument Processing Unit. URL: https://www.jpl.nasa.gov/news/news.php?feature=7236 [cited 2020-02-10].

[39] M. T. Zuber, D. E. Smith, M. M. Watkins, S. W. Asmar, A. S. Konopliv, F. G. Lemoine, H. J. Melosh, G. A. Neumann, R. J. Phillips, S. C. Solomon *et al.*, "Gravity field of the Moon from the Gravity Recovery and Interior Laboratory (GRAIL) mission," *Science*, p. 1231507, 2012.

[40] C. Edwards-Stewart, "Nasa's grail spacecraft formation flight, end of mission results, and small–satellite applications," in *AIAA/USU Conference on Small Satellites*, Logan, UT, Aug. 2013.

[41] Jet Propulsion Laboratory, California Institute of Technology. New NASA Mission to Reveal Moon's Internal Structure and Evolution. URL: https://www.jpl.nasa.gov/news/news.php?release=2007-145 [cited 2020-02-10].

[42] K. D. for the LISA Study Team *et al.*, "LISA – an ESA cornerstone mission for a gravitational wave observatory," *Classical and Quantum Gravity*, vol. 14, no. 6, p. 1399, 1997.

[43] R. D. Blandford *et al.*, *New Worlds, New Horizons in Astronomy and Astrophysics.* The National Academies Press, Washington, DC, 2010.

[44] K. G. Carpenter, R. Allen, J. Benson, D. Ciardi, W. Danchi, V. Foresto, M. Karovska, K. Mighell, J. Monnier, J. Mould *et al.*, "The future of space-based interferometry," *"Future Directions for Interferometry"*, 2006.

[45] P. R. Lawson, O. P. Lay, K. J. Johnston, and C. A. Beichman, "Terrestrial planet finder interferometer science working group report," Jet Propulsion Laboratory, National Aeronautics and Space Administration, Pasadena, California, Tech. Rep., 2007.

[46] F. Y. Hadaegh, G. Singh, B. Açikmeşe, D. P. Scharf, and M. Mandić, *The Path to Autonomous Robots.* New York, NY: Springer, 2009, ch. Guidance and Control of Formation Flying Spacecraft, pp. 25–43.

[47] Jet Propulsion Laboratory, California Institute of Technology. Starshade. URL: https://science.jpl.nasa.gov/projects/Starshade/ [cited 2020-02-10].

[48] M. J. Bentum, C. J. M. Verhoeven, and A. J. Boonstra, "OLFAR - orbiting low frequency antennas for radio astronomy," in *20th Annual Workshop on Circuits, Systems and Signal Processing*, Veldhoven, Nov. 2009.

[49] A. Budianu, A. Meijerink, and M. Bentum, "Swarm-to-earth communication in OLFAR," *Acta astronautica*, vol. 107, pp. 14–19, 2015.

[50] ESA. Darwin Overview. URL: http://www.esa.int/Our_Activities/Space_Science/Darwin_overview [cited 2020-02-10].

[51] S. Schaffer, A. Branch, S. Hernandez, and S. Chien, "Heuristic-guided orbit selection for a radio-interferometric spacecraft constellation: Summary report," in *International Symposium on Artificial Intelligence, Robotics, and Automation for Space (ISAIRAS 2018)*, Madrid, Spain, July 2018, also appears at AI in the Oceans and Space Workshop, International Joint Conference on Artificial Intelligence (IJCAI 2017). [Online]. Available: https://ai.jpl.nasa.gov/public/papers/schaffer_ijcai2017_orbit.pdf

[52] K. Belov, A. Branch, S. Broschart, J. Castillo-Rogez, S. Chien, L. Clare, R. Dengler, J. Gao, D. Garza, A. Hegedus, S. Hernandez, S. Herzig, T. Imken, H. Kim, S. Mandutianu, A. Romero-Wolf, S. Schaffer, M. Troesch, E. J. Wyatt, and J. Lazio, "A space-based decametric wavelength radio telescope concept," *Experimental Astronomy*, August 2018. [Online]. Available: https://doi.org/10.1007/s10686-018-9601-6

[53] E. Gill, O. Montenbruck, and S. D'Amico, "Autonomous formation flying for the PRISMA mission," *Journal of Spacecraft and Rockets*, vol. 44, no. 3, pp. 671–681, 2007.

[54] eoPortal. PRISMA (Prototype Research Instruments and Space Mission technology Advancement). URL: https://directory.eoportal.org/web/eoportal/satellite-missions/p/prisma-prototype [cited 2020-02-10].

[55] ——. FASTRAC (Formation Autonomy Spacecraft with Thrust, Relnav, Attitude and Crosslink). URL: https://directory.eoportal.org/web/eoportal/satellite-missions/f/fastrac [cited 2020-02-10].

[56] ——. JC2Sat-FF (Japan Canada Joint Collaboration Satellites – Formation Flying). URL: https://directory.eoportal.org/web/eoportal/satellite-missions/j/jc2sat-ff [cited 2020-02-10].

[57] O. Brown and P. Eremenko, "The value proposition for fractionated space architectures," in *Space 2006*, 2006, p. 7506.

[58] Defense Advanced Research Projects Agency. SYSTEM F6. URL: http://www.darpa.mil/Our_Work/TTO/Programs/System_F6.aspx [cited 2020-02-10].

[59] S. Cornford, R. Shishko, S. Wall, B. Cole, S. Jenkins, N. Rouquette, G. Dubos, T. Ryan, P. Zarifian, and B. Durham, "Evaluating a fractionated spacecraft system: A business case tool for DARPA's F6 program," in *Aerospace Conference, 2012 IEEE*. IEEE, 2012, pp. 1–20.

[60] Made In Space. Made In Space - Additive Manufacturing Facility. URL: http://madeinspace.us/projects/amf/ [cited 2020-02-10].

[61] ——. Made In Space - Archinaut. URL: http://madeinspace.us/archinaut/ [cited 2020-02-10].

[62] R. B. Friend, "Orbital express program summary and mission overview," in *Sensors and Systems for space applications II*, vol. 6958. International Society for Optics and Photonics, 2008, p. 695803.

[63] J. L. Forshaw, G. S. Aglietti, N. Navarathinam, H. Kadhem, T. Salmon, A. Pisseloup, E. Joffre, T. Chabot, I. Retat, R. Axthelm *et al.*, "Removedebris: An in-orbit active debris removal demonstration mission," *Acta Astronautica*, vol. 127, pp. 448–463, 2016.

[64] Jet Propulsion Laboratory, California Institute of Technology. Orbital Express. URL: https://ai.jpl.nasa.gov/public/projects/orbital-express/ [cited 2020-02-10].

[65] National Academy of Sciences. Solar and Space Physics: A Science for a Technological Society. URL: http://www.nap.edu/catalog.php?record_id=13060 [cited 2020-02-10].

[66] National Aeronautics and Space Administration. Heliophysics Missions. URL: http://sec.gsfc.nasa.gov/sec_missions.htm [cited 2020-02-10].

[67] eoPortal. STEREO (Solar-Terrestrial Relations Observatory). URL: https://earth.esa.int/web/eoportal/satellite-missions/s/stereo [cited 2020-02-10].

[68] ——. PROBA-3 (Project for On-Board Autonomy-3). URL: https://directory.eoportal.org/web/eoportal/satellite-missions/p/proba-3 [cited 2020-02-10].

[69] Committee on the Planetary Science Decadal Survey, "Vision and voyages for planetary science in the decade 2013 to 2022," National Research Council, Tech. Rep., 2011.

[70] National Aeronautics and Space Administration. Planets Focus Areas. URL: http://science.nasa.gov/planetary-science/focus-areas/ [cited 2020-02-10].

[71] D. L. Matson, L. J. Spilker, and J.-P. Lebreton, "The cassini/huygens mission to the saturnian system," in *The Cassini-Huygens Mission*. Springer, 2003, pp. 1–58.

[72] ESA. Separation of Huygens from Cassini. URL: https://www.esa.int/spaceinimages/Images/2004/12/Separation_of_Huygens_from_Cassini [cited 2020-02-10].

[73] Jet Propulsion Laboratory, California Institute of Technology. Mission to Comet Tempel 1 Deep Impact. URL: https://www.jpl.nasa.gov/missions/deep-impact/ [cited 2020-02-10].

[74] NASA Solar System Exploration. Rosetta. URL: https://solarsystem.nasa.gov/missions/rosetta/in-depth/ [cited 2020-02-10].

[75] Spaceflight 101. Hayabusa-2 – Asteroid Exploration Mission. URL: http://spaceflight101.com/spacecraft/hayabusa-2/ [cited 2020-02-10].

[76] T. Yoshimitsu, T. Kubota, and I. Nakatani, "MINERVA rover which became a small artificial solar satellite," in *AIAA/USU Conference on Small Satellites*, Logan, UT, Aug. 2006.

[77] M. B. Quadrelli, R. Hodges, V. Vilnrotter, S. Bandyopadhyay *et al.*, "Distributed swarm antenna arrays for deep space applications," in *IEEE Aerospace Conference*, Big Sky, MT, 2019.

[78] Jet Propulsion Laboratory, California Institute of Technology. Mars Cube One (MarCO). URL: https://www.jpl.nasa.gov/cubesat/missions/marco.php [cited 2020-02-10].

[79] Space. Confirmed: Voyager 1 in Interstellar Space. URL: https://www.space.com/26462-voyager-1-interstellar-space-confirmed.html [cited 2020-02-10].

[80] Breakthrough Initiative. Breakthrough Starshot. URL: https://breakthroughinitiatives.org/initiative/3 [cited 2020-02-10].

[81] ——. Breakthrough Starshot Challenges. URL: http://breakthroughinitiatives.org/challenges/3 [cited 2020-02-10].

[82] N. E. Leonard, D. A. Paley, F. Lekien, R. Sepulchre, D. M. Fratantoni, and R. E. Davis, "Collective motion, sensor networks, and ocean sampling," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 48–74, Jan 2007.

[83] I. Maza, K. Kondak, M. Bernard, and A. Ollero, "Multi-uav cooperation and control for load transportation and deployment," in *Selected papers from the 2nd International Symposium on UAVs, Reno, Nevada, USA June 8–10, 2009*. Springer, 2009, pp. 417–449.

[84] J. Werfel, K. Petersen, and R. Nagpal, "Designing collective behavior in a termite-inspired robot construction team," *Science*, vol. 343, no. 6172, pp. 754–758, 2014.

[85] D. Tardioli, D. Sicignano, L. Riazuelo, A. Romeo, J. L. Villarroel, and L. Montano, "Robot teams for intervention in confined and structured environments," *J. Field Robotics*, vol. 33, no. 6, pp. 765–801, 2016.

[86] J. L. Baxter, E. K. Burke, J. M. Garibaldi, and M. Norman, *Multi-Robot Search and Rescue: A Potential Field Based Approach*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007, pp. 9–16. [Online]. Available: https://doi.org/10.1007/978-3-540-73424-6_2

[87] T. Takahashi, S. Tadokoro, M. Ohta, and N. Ito, "Agent based approach in disaster rescue simulation - from test-bed of multiagent system to practical application," in *RoboCup 2001: Robot Soccer World Cup V*, A. Birk, S. Coradeschi, and S. Tadokoro, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2002, pp. 102–111.

[88] H. L. Akin, N. Ito, A. Jacoff, A. Kleiner, J. Pellenz, and A. Visser, "RoboCup rescue robot and simulation leagues," *AI Magazine*, vol. 34, no. 1, p. 78, dec 2012.

[89] H. Kitano, S. Tadokoro, I. Noda, H. Matsubara, T. Takahashi, A. Shinjou, and S. Shimada, "Robocup rescue: search and rescue in large-scale disasters as a domain for autonomous agents research," in *IEEE SMC'99 Conference Proceedings. 1999 IEEE International Conference on Systems, Man, and Cybernetics (Cat. No.99CH37028)*, vol. 6, Oct 1999, pp. 739–743 vol.6.

[90] J. S. Jennings, G. Whelan, and W. F. Evans, "Cooperative search and rescue with a team

of mobile robots," in *1997 8th International Conference on Advanced Robotics. Proceedings. ICAR'97*, July 1997, pp. 193–200.

[91] M. Yong, M. Koes, K. Sycara, M. Lewis, I. R. Nourbakhsh, and S. Burion, "Human-robot teaming for search and rescue," *IEEE Pervasive Computing*, vol. 4, pp. 72–78, 01 2005. [Online]. Available: doi.ieeecomputersociety.org/10.1109/MPRV.2005.13

[92] H. Kitano, "Robocup rescue: A grand challenge for multi-agent systems," in *Multi-Agent Systems, International Conference on(ICMAS)*, vol. 00, 07 2000, p. 0005. [Online]. Available: doi.ieeecomputersociety.org/10.1109/ICMAS.2000.858425

[93] E. Olson, J. Strom, R. Morton, A. Richardson, P. Ranganathan, R. Goeddel, M. Bulic, J. Crossman, and B. Marinier, "Progress toward multi-robot reconnaissance and the MAGIC 2010 competition," *Journal of Field Robotics*, vol. 29, no. 5, pp. 762–792, jun 2012.

[94] J. Butzke, K. Daniilidis, A. Kushleyev, D. D. Lee, M. Likhachev, C. Phillips, and M. Phillips, "The university of pennsylvania magic 2010 multi-robot unmanned vehicle system," *Journal of Field Robotics*, vol. 29, no. 5, pp. 745–761, 2012. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21437

[95] A. Lacaze, K. Murphy, M. Del Giorno, and K. Corley, "Reconnaissance and autonomy for small robots (rasr) team: Magic 2010 challenge," *Journal of Field Robotics*, vol. 29, no. 5, pp. 729–744, 2012. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21428

[96] M. T. Wolf, A. Rahmani, J.-P. de la Croix, G. Woodward, J. Vander Hook, D. Brown, S. Schaffer, C. Lim, P. Bailey, S. Tepsuporn, M. Pomerantz, V. Nguyen, C. Sorice, and M. Sandoval, "CARACaS multi-agent maritime autonomy for unmanned surface vehicles in the Swarm II harbor patrol demonstration," in *Proceedings of the SPIE Defense + Security*, April 2017.

[97] K. Spieser, K. Treleaven, R. Zhang, E. Frazzoli, D. Morton, and M. Pavone, "Toward a systematic approach to the design and evaluation of automated mobility-on-demand systems: A case study in singapore," in *Road Vehicle Automation*. Springer International Publishing, 2014, pp. 229–245.

[98] A. Stoica, E. Chow, L. Alkalai, A. Aubrey, L. Bergman, R. Doyle, T. Estlin, A. Rahmani, C. Ruoff, R. Some, and D. Wiberg, "Jpl vision 2030 - autonomous transportation study," Jet Propulsion Laboratory - California Institute of Technology, Tech. Rep., 2015.

[99] K. Short and D. V. Buren, "Printable spacecraft - flexilbe electronic platforms for nasa missions," Nasa Innovative Advanced Concepts Phase II Report, Tech. Rep., 2014.

[100] T. Huntsberger, P. Pirjanian, A. Trebi-Ollennu, H. D. Nayar, H. Aghazarian, A. J. Ganino, M. Garrett, S. S. Joshi, and P. S. Schenker, "CAMPOUT: a control architecture for tightly coupled coordination of multirobot systems for planetary surface exploration," *IEEE Trans. Systems, Man, and Cybernetics: Part A (Systems and Humans)*, vol. 33, no. 5, pp. 550–559, Sept 2003.

[101] E. Mankin. (2011) Nasa funds usc lunar project. Available at https://news.usc.edu/28841/nasa-funds-usc-lunar-project/. USC News.

[102] C. D. Edwards, "Relay communications for mars exploration," *International Journal of Satellite Communications and Networking*, vol. 25, no. 2, pp. 111–145, 2007.