Multi-Robot Cooperation in Space: A Survey

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***Abstract*—This paper reviews the literature related to multi-robot research with a focus on space applications. It starts by examining definitions of, and some of the fields of research, in multi-robot systems. An overview of space applications with multiple robots and cooperating multiple robots is presented. The multi-robot cooperation techniques used in theoretical research as well as experiments are reviewed, and the applicability for space applications is investigated.**

***Keywords*-Cooperative systems, Satellite applications, Space Vehicle Control, Intelligent robots, Intelligent systems, Mobile robots**

I. INTRODUCTION

This survey will present multi-robot systems and especially how those systems incorporate cooperation. It includes a short discussion of taxonomy in multi-robot systems; a more thorough overview and background information can be found in [1], [2]. The main focus of this review are multi-robot systems and their applications in areas where cooperation and collaboration between robots is found. A special focus is placed on space applications.

Section II will give a short introduction to multi-robot systems, a definition of cooperation and an overview of the taxonomy used in the literature.

Section III focuses on literature describing multi-robot systems in (mainly planned) space applications. Examples of the few current applications of multiple spacecrafts working together will be listed.

Section IV gives a short round-up and conclusion.

II. MULTI-ROBOT COOPERATION

A. Introduction

Multi-robot systems have been of interest to researchers for a long time and the topic has become more and more interesting over recent years and an increasing amount of research is done today in the field of robot cooperation.

A good summary with good reasoning why to chose multi-robot systems over a single robot can be found in [3], the main reasons for choosing a multi-robot system over a single-robot are also presented in [1]–[4].

B. What is Cooperation?

The Oxford English Dictionary (ODE) defines *"to cooperate"* as *"to work together, act in conjunction (with another person or thing, to an end or purpose, or in a work)"*. In robotics cooperation is not very often explicitly defined and the few definitions tend to be very broad, some include communication, some progressive results (e.g. increasing performance). The few exceptions are listed in [2]. Cooperative and collaborative robotics started with the introduction of behaviour-based control into robotics. This paradigm is biologically inspired and encouraged researchers to find cooperating systems in nature, which then were used for multi-robot systems [5]. Cooperation is also a very long and much discussed research topic in political science and other human sciences, e.g. Axelrod & Hamilton in 1981 [6] published a work on the famous prisoner's dilemma.

Cooperating behaviours are a subset of collective behaviours, in which the cooperation can be manifold and usually is not clearly defined. Examples of cooperating in nature (e.g. bees and ants) show possibilities for "simple" robots to work together to solve a very complex task. The mechanism of 'cooperation' may be incorporated into the system in various ways, by dynamics, by design or by accident.

In general there exist two groups of cooperation:

Passive Cooperation: The robots do not use explicit communication, the cooperation appears only when the whole system is observed (sometimes named emergent cooperation or behaviour). One example are robots that sense each other only as obstacles and plan their way around these. The decision making and action planning is local only and not communicated to the other agents.

Active Cooperation: A communication link is used for cooperation, where agents may be actively coordinating their decision-making and actions. This does not necessarily mean radio or (wired) electronic communication, including also other sorts of communication and communication via the environment.

A special case of active cooperation is the case of **tight cooperation**, in which the robots need to coordinate in very detail the action they are going to perform, e.g. cooperative construction and transportation [3], [7], [8].

Though there has been a lot of theoretical research in this field, experimental and real world implementations have only recently started to emerge. There are various reasons for this, including communication costs and problems, unreliability and sensor noise in the real world [9].

Multi-robot systems have the potential to perform better than single robots in a variety of fields, but it has been seen that only clearly designed multi-robot systems achieve a good performance. More research is needed to make those systems use cooperation as ubiquitously as it appears in nature.

Relevant fields of research are: *Distributed Artificial Intelligence (DAI), multi-robot systems*, which in turn relies heavily on the research done in *Multi-Agent Systems (MAS)*, *high-level control* and *theoretical computer science*. Similarities to problems in those fields suggest that techniques and solutions found there can be applied in the area of multi-robot cooperation.

C. Taxonomy

There are various terms, most of them not clearly and uniquely defined, that describe multi-robot systems.

As defined by *Dudek et al.* [1], multi-robot systems can be classified with the following taxonomy:

Problem-based Classification: Depending on the task multi-robot systems might be a better choice than a single robot [1]. The groups are defined by *Tasks that*: *(a) require multiple agents*, *(b) are traditionally multi-agent*, *(c) are inherently single agent*, and *(d) may benefit from multiple agents*.

Size of the Collective: single robot (`SIZE-ALONE`), a *minimalist multi-robot system* (`SIZE-PAIR`), a *limited amount of multiple robots* (`SIZE-LIM`) and an *infinite* (very large compared to the problem) *amount of robots* (`SIZE-INF`) (used for huge wireless sensor networks or robot swarms).

Communication: *Interaction via environment* (no direct communication) (`COM-NONE`), *interaction via sensing* (local only) (`COM-NEAR`), *interaction via a communication link* (wide area) (`COM-INF`). A detailed description can be found in [2].

Reconfigurability: systems *without reconfiguration abilities* (`ARR-STATIC`), *coordinated rearrangement (e.g. change of formation)*, (`ARR-COOR`) and *dynamic arrangement* (`ARR-DYN`).

Composition: *homogeneous* (`CMP-HOM`) and *heterogeneous* (`CMP-HET`) systems. Another possibility are marsupial systems that have a homogenous group of small robots, that can be transported by a "mothership" [10], [11]; therefore `CMP-MAR` is introduced.

Control: *Centralized* (`CTL-CEN`), *decentralized* (`CTL-DEC`) and *hybrid* (`CTL-HYB`) architectures exist.

These classifications and terms described here will be used in the rest of this review when describing the other publications, the research and the projects presented.

III. SPACE APPLICATIONS

Using multiple, modular and reconfigurable robots has a few possible advantages in space, where the systems have very strict requirements. These advantages range from saving weight (used as multiple tools), compressed form (saving space) to increasing robustness (increasing redundancy). Being light-weight is important since the weight is directly proportional to the cost of launching and deploying the system into space, hence smaller size is better since this is usually limited by the rocket size. A very high level of robustness is important to ensure that the mission is (at least partly) successful.

Other useful features are (or can be) adaptability and self-(re)configurability and even self-repair [12] has been proposed. Because of these advantages a trend towards multiple robots and robot teams is seen in (space) research and in the plans of space agencies, such as NASA, ESA and JAXA.

In those visions and plans another reason to use multiple cooperating robots is presented, namely to build human outposts (habitats) on planetary surfaces and in space. This will be further discussed in Section III-A2.

Chicarro [13] proposed multiple light-weight rovers to explore Mars as a feasible alternative to single robot missions already in 1993. They were part of the MARSNET system, which also included a satellite constellation for communications with Earth. In 2003 *Yim et al.* [12] showed their PolyBot implementation of a modular reconfigurable robot system developed at the Palo Alto Research Center (PARC, in California) intended for space applications. The PolyBot experiments showed their adaptability by using various modes of motion (e.g. different gaits) to overcome obstacles.

In publications of multi-robot systems for space applications very often humans are included as members of the team, working closely together with the robots to complete the explorative tasks. Areas of interest in research regarding this are human robot interaction [14] and sliding autonomy [3], [15], [16].

A. Planned Missions and Visions

Several space missions, where multiple mobile robots play a central role, are currently proposed. The research and funding of those areas has increased in the last years, mainly due to the above mentioned exploration visions announced by various space agencies [17]–[19]. Some of these missions are presented here.

1) In-Orbit Operation and Satellite Formations: Many multi-satellite applications, especially in cooperation, are envisaged but very few are planned or even partly funded. The main focus in research is currently on optimizing formation flying (with respect to fuel usage) and on-orbit servicing, which might also help the development of in-orbit construction for larger structures.

In the field of simulation [20] proposed a trajectory/path planning technique based on dynamic networks, with simulation in 3D for use with satellites. These systems are only in the very early development stage and do not provide optimizations of, e.g. fuel consumption. For simulation and testing purposes the MIT has created a satellite testbed, the Free-Flying Robot Testbed (FFRT), to verify planning and control algorithms experimentally. It allows for a 2D simulation of micro-gravity satellite control using air-bearings [21].

On-Orbit Servicing (OOS): On-orbit servicing is an increasingly interesting field in space applications. Some tests of servicing systems have already been performed, but those spacecraft usually have only passive cooperation. No direct communication between the servicing and the to-be-serviced craft are used.

A European consortium of space companies proposed the *HERMES OOS* system. It is planned to use fuel from damaged, overloaded satellites as well as their fail-safe fuel at EOL and store the fuel on-orbit and use it to service other satellites. The system would consist of 5 different satellites in various sizes and specialized to do various tasks [22]. [Classification: `SIZE-LIM, COM-NEAR, ARR-DYN, CMP-HET, CNT-DEC`]

JAXA is researching possible Hubble Space Telescope (HST) servicing missions based on their HII-Transfer Vehicle (HTV) spacecraft with added experience from the ETS-VII (see Section III-B1). The research concentrates on robotic service (capture/de-orbit). Future tests and operations are planned, e.g. the Smartsat-1 mission, which will test automatic docking and orbital re-configuration with small satellites.

The **SUMO** (*Spacecraft for the Universal Modification of Orbits*) sponsored by DARPA, was going to demonstrate machine vision, robotics, and autonomous control on board the satellite to accomplish an automatic rendezvous. A test with a prototype was done at the US Naval Center for Space Technology in 2005. [Classification: `SIZE-PAIR, COM-NONE, ARR-DYN, CMP-HET, CTL-CEN`]

TECSATS (*TEChnology SAtellite for demonstration and verification of Space systems*) was a joint project between EADS, Babakin Space Center and DLR started in 2003. It was planned to launch 2 satellites, where one (*chaser*) is equipped with a seven axis robot arm and a gripper system. The proejct stopped in 2006 but DLR started a very similar project **DEOS** (*Deutsche Orbitale Servicing Mission*) is currently awaiting Phase-A. DEOS focusses on Guidance and Navigation and the capturing mechanism for non-cooperative as well as cooperative client satellites. While attached it will performing orbital maneuvres which can be used for de-orbiting of old or damaged/non-functioning satellites. [Classification: `SIZE-PAIR, COM-NONE, ARR-DYN, CMP-HET, CTL-CEN`]

The main discussion right now seems to be whether a single platform servicing architecture or a fractioned servicing architecture will be the better choice. Most of the before-mentioned, planned missions are currently on hold, under review or in an unknown state.

A more thorough overview of the field of on-orbit servicing can be found in [23].

Satellite Formations: There are three types of satellite formations being used:

Cluster Formations: A few satellites put in a dense formation to allow the fusing of satellite sensor data. These arrangements are used for interferometric observations, for creating high-resolution maps of Earth or for finding distance stars and planets.

Trailing Formations: Two or more satellites follow each other in the same orbit with only small separation. The satellites are usually equipped with different sensors and scientific instruments. This formation is used for high-resolution images and more insight into climatic trends in the Earth's environment.

Constellation Formations: Multiple, similarly equipped, satellites are (usually evenly) dispersed in a pattern to provide a wide area coverage. These are usually used for global communication and positioning networks.

There are few satellites currently in orbit that are really cooperating, that means they use direct communication, arrange themselves to do tasks together or have some level of autonomously maintaining the formation. In academia there has been quite some research on optimization [24], [25], decentralized control algorithms [26] and autonomy [27], which increases the autonomy of the satellites and decrease the necessary control from the ground station and ground personnel. Examples of current cooperating satellites are listed in Section III-B.

The **TechSat21** mission was a try by the AFRL started in the late 1990s to test and show micro-satellite formations to enable unlimited (virtual) aperture sizes, easier system upgrade, and low cost mass production [27]. A flexible 3 satellite configuration, varying from 5km to just distances of metres, was planned. [Classification: `SIZE-LIM, COM-NONE, ARR-COOR, CMP-HOM, CTL-CEN`]

In 2003 the Space Vehicles Directorate of AFRL cancelled the project because of a technical problem and related cost overruns but research done for this project in the field of autonomous formation flying (and changing) might see reuse in other projects, e.g. *System F6*.

The **TanDEM-X** *(TerraSAR-X add-on for Digital Elevation Measurement)* mission is a mission designed by DLR planned to launch in the autumn of 2009. It will be the first bistatic SAR mission by adding the TanDEM-X satellite into a closely controlled formation with the TerraSAR-X satellite. The mission objective is to generate a very high-accuracy DEM[1]. [Classification: `SIZE-PAIR, COM-NONE, ARR-STATIC, CMP-HET, CTL-CEN`] New proposals to improve the accuracy and keep the costs low use multiple passive micro satellite flying behind the SAR satellite(s). One proposed formation is named ”Trinodal Pendulum”, with 3 satellites flying in orbit with distances between 250 and 500m [28]. Developed at DLR it is an evolution of the Interferometric CartWheel proposed by CNES scientists in 2000 [29].

The **MetNet** project of the Finnish Meteorological Institute was started in 2000 and intends to land multiple probes on Mars to analyze the Martian atmosphere. The idea presented is more of a widespread sensor network and no actuators are used. The sensors on the surface are planned to communicate with the satellite in orbit which relays the data back to Earth. The precursor mission with the MetNet Lander (MNL) is planned to be launched in 2009 or 2011 [30]. [Classification: `SIZE-LIM, COM-NEAR, ARR-STATIC, CMP-MAR, CTL-CEN`]

The *Laser Interferometer Space Antenna* (**LISA**) mission, a joint ESA-NASA mission, will use 3 identical spacecrafts flying in a very large and widely dispersed formation, with 5 million kilometres separation between each other. This is the biggest formation to be flown yet. The main mission objective is to detect and observe gravitational waves from astronomical sources such as massive black holes and galactic binaries. One spacecraft is the dedicated master spacecraft and the only one contacting and sending date to Earth. The other crafts send their data to the ‘master spacecraft’ via a laser link. [Classification: `SIZE-LIM, COM-INF, ARR-STATIC, CMP-HOM, CTL-CEN`]

LISA Pathfinder (planned for launch in 2010) is, as the name indicates, mission to pave the way for the LISA mission developed by ESA. It is though a single spacecraft hence no cooperation is planned.

The DARPA **System F6** *(Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft)* project is currently in its early Preliminary Design Review (PDR) (contract with Boeing, Lockheed Martin) stage and planned for a launch in 2012. A few papers have been presented but more on the reasoning behind this project not much yet on how they will implement it. In 2008 they

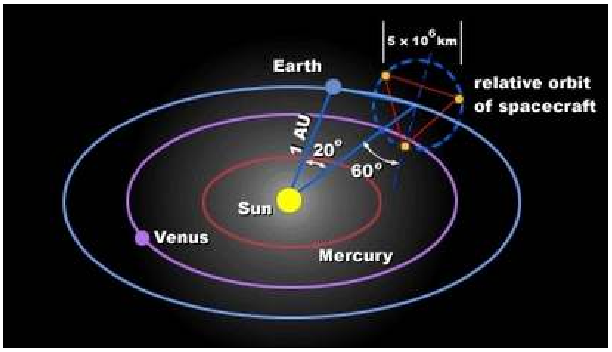

Figure 2. The LISA spacecraft formation in orbit around the Sun. The spacecraft trail behind Earth about 20 degrees (50 million km). *Courtesy: ESA*

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[1] Digital Elevation Map

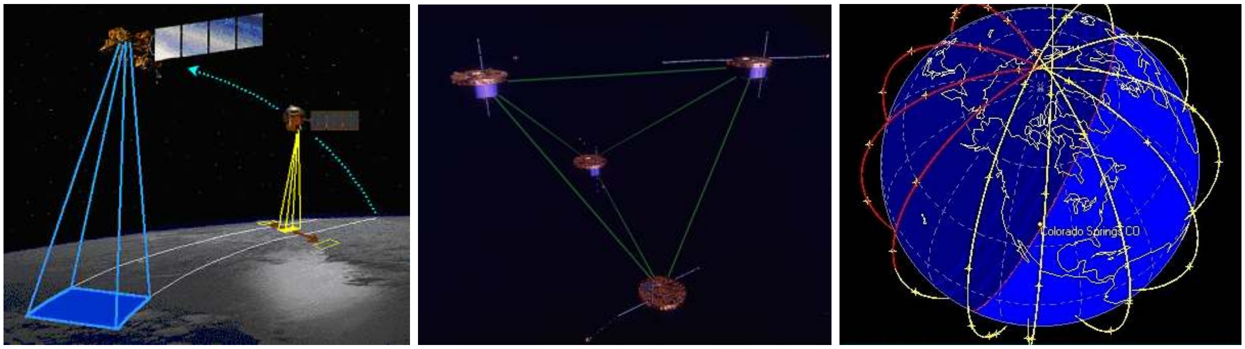

Figure 1. The 3 types of formations: (a) trailing formation, (b) cluster and (c) constellation formation

announced that BOEING, Lockheed Martin, Northrop Grumman, and Orbital Sciences were contracted for further development of the idea. [Classification: `SIZE-LIM, COM-NEAR, ARR-DYN, CMP-HET, CTL-HYB`]

The idea of fractioned spacecraft was proposed by Molette in 1984. He claimed that the advantages would outweigh the higher mass and costs. A more recent presentation by BOEING comes to the same conclusion [31].

As can be seen from the projects and further papers, these multi-satellite systems are getting more autonomous and self-configuring, in the sense that these satellites can be launched by multiple launchers and different systems. After launch they are able to find their way into a given formation [32] by themselves. ESA's ACT[2] is also actively investigating swarms of pico-satellites for autonomous formations [33]. These will allow for future satellite swarms to stay in formation autonomously and also to change their formations to best fit the mission objectives.

Space Structures Assembly: JAXA plans to use robots to build space structures (in orbit and on the moon) with the need for automatic rendezvous maneuvres, as well as construction of a space-based solar power system over the next 20 to 30 years.

[7] present a control algorithm for tight cooperation between two robots to transport a beam in space. It presents ways to reduce the vibrations and reduce the fuel consumption of the robots.

The *Skyworker* proposal by [34] is an assembly, inspection and maintenance robot designed for space operations (`SIZE-ALONE`). It is designed as an attached manipulator with the ability to "walk" on the structure it is building. The paper referenced presents research into the mechanical subsystem as well as power and control issues.

Space-based Solar Power (**SBSP**) or *Space Solar Power Satellites* (**SSPS**) are actively researched in JAXA as well as NASA, but not widely supported within those agencies. JAXA has already tested a "legged" in-orbit construction manipulator in their laboratories on the ground and a schedule for a 1GW SSPS was proposed in 2003. The schedule planned to have small SSPS in operation by 2015 and the final satellite, constructed fully in space, by 2020 [35].

2) Surface & Planetary Exploration: The Mars Exploration Rovers (**MER**) are already in operation and although they do not cooperate [36] they show the future direction of (robotic) space exploration: rovers with more autonomy and bigger systems (i.e. multiple rovers). This section tries to shed a light on planned missions over the next decade and further visions of space exploration.

The above mentioned possibilities for robots to be part of precursor missions for human space exploration are one of the main drivers in multi-robot (space) research. Since humans are more vulnerable to space conditions (e.g. radiation) and missions are planned to take longer than the current Space Shuttle missions, most of the proposed human space exploration missions for the next 2 decades include some form of human shelter (e.g. Mars or Lunar bases). Robotic teams are needed to investigate and prepare the landing site for the astronauts to follow [18], [37], [38].

ESA is planning to use multi-robot teams in space exploration and included them in their visionary outlook for R&D over the next decade [18]. One of the three main mission and research tracks from this outlook will be robotic agents, esp. working in hostile and dangerous areas and acting in place of humans to perform assembly, maintenance and production tasks. They are esp. trying to support the research and the possible applications of reconfigurable robot teams [18]:

> The aim is the development of heterogeneous, reconfigurable robots [...] to enhance the horizon of future mission regarding application areas, duration, and operational distance.

These tasks are planned to be tele-operated or in some cases performed semi-autonomously.

Examples: Proposed topics for robotic space exploration include the mining of moons and asteroids, the construction of habitats, the detection of valuable resources (e.g. water or oxygen) and astronaut support during manned missions. A good overview can be found in [39], though there is no focus on multi-robot system. Rovers that are currently developed with a focus on space applications and use on Lunar or Mars surface are listed here.

The *Robot Work Crew* (**RWC**) at NASA's Jet Propulsion Laboratory (JPL) was a project simulating the construction of planetary habitats by tightly coordinated robots [37]. A new robot architecture named "CAMPOUT" was introduced and is still being improved and extended. It utilizes the behaviour-based approach in robotics and should allow for distributed control, sensing and communications. The RWC consisted of two robots that together should complete a task used for "building" a structure. It showed transportation of a beam in various combinations. Another project

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[2] The European Space Agency's *Advanced Concepts Team*

at JPL called **RCC** intends to follow-up the research done with the RWC. It does also use the CAMPOUT architecture [38]. [Classification: `SIZE-PAIR, COM-INF, ARR-COOR, CMP-HET, CTL-DEC`]

Developed at NASA's JPL the **LEMUR** (Limbed Excursion Mechanical Utility Robots) (`SIZE-ALONE`) robots are designed to be easily reconfigurable and are intended for space applications. Lemur 1 was designed for help with in-orbit construction, the current Lemur II can traverse very diverse terrains. They are though only single robots so far, no cooperation abilities have been added. The idea is though to have multiple Lemur robots work together with a bigger "spider" robot (see Figure 3) and help in construction and maintenance of satellites in space. [Classification: `SIZE-LIM, ARR-DYN, COM-NEAR, CMP-MAR, CTL-CEN`] In connection with Northrop Grumman designs for a a next-generation Lemur (AWIMIR) for satellite inspection are created. [40]

More research is done in the fields of exploration, cooperative mapping (SLAM) and improving the robots' abilities to do coordinated "field research".

Cliff Descending Robots: [41], presenting the *AXEL* robot, [Classification: `SIZE-LIM, COM-INF, ARR-COOR, CMP-MAR, CTL-CEN`] as well as other projects show that there is an increased need (from a science point-of-view) to provide the rovers with a higher mobility on rough terrains in future space applications. *Mumm et al.* [42] presented a system of 3 robots for these situations. It uses 2 anchor robots to lower a third robot (attached by tethers), called a 'rapeller', down a cliff by cooperative action. The robots communicated via RF transceivers so that each robot has a complete knowledge of the system's state. The anchors are aware of their positions and can control the tether. A behaviour-based approach is used to allow the team to work together.

Some effort has been put into the development of architectures that are optimized for space applications and include behavioural and cooperation patterns. They should also be easy to extend and open to develop them further. NASA has developed a multi-agent system based on the Brahms programming language [43], it was tested during field campaigns at the Mars Desert Research Station (MDRS) run by the Mars Society in Utah, U.S.A. JPL is using the before mentioned CAMPOUT architecture for various space and rover-based systems.

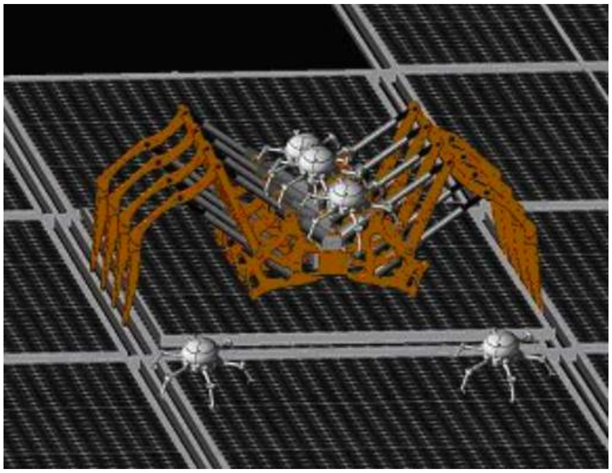

Figure 3. A marsupial, lemur robots with a Spider robot, system to inspect a solar array. *Stroupe et.al.*

The rovers of the future are only envisaged, but so far no multi-robot missions with cooperation are funded either by NASA (the next rover missions are *Mars Science Laboratory* (2011) and a Mars sample return mission), ESA (trying to fly the *ExoMars* mission after various delays) or JAXA. This was also visible at the ASTRA 2008 conference at ESTEC where no multi-robot cooperation talks or papers were presented.

B. Implemented Space Applications

This section focuses on literature describing multi-robot systems that have already been implemented in space missions. Examples of the few current applications of multiple spacecraft working together will be listed.

1) Automatic Rendezvous and Docking: The automatic docking and rendezvous of spacecraft has been shown by a few space agencies. The first successful mission was by the Soviet space programme in 1967. The satellite Kosmos-188 (`SIZE-ALONE`) achieved the world's first automatic docking with the artificial Earth satellite Kosmos-186. A historical and technical overview of rendezvous systems can be found in [44].

For the development of an autonomous transfer vehicles for the International Space Station (ISS), JAXA (then called NASDA) demonstrated in 1997 the autonomous docking with its ETS-VII satellite. It used GPS and laser guidance to successfully dock two satellites autonomously. [Classification: `SIZE-PAIR, COM-INF, ARR-COOR, CMP-HET, CTL-CEN`]

NASA did try the same with their DART satellites in 2005, but the control used too much fuel and the docking was not successful. DARPA's **Orbital Express** mission demonstrated during its operation (March to July 2007) the on-orbit servicing between the two satellites ASTRO and NextSAT. It included rendezvous, capture, propellant transfer and repair [45]. [Classification: `SIZE-PAIR, COM-INF, ARR-COOR, CMP-HET, CTL-DEC`]

ESA's *Automatic Transfer Vehicle* (**ATV**) successfully docked with the ISS in April 2008 (`SIZE-ALONE`). The mission named "Jules Verne" was the first of five planned ATV dockings at the ISS. The ATV provides resupplies and orbit-lifting capabilities for the ISS. After a multi-month stay at the ISS it will detach and de-orbit before burning up during atmospheric reentry. The ATVs use GPS and a star tracker to automatically rendezvous with the Zvedzda module of the Space Station. At a distance of 249 m, the ATV uses videometer and telegoniometer data for final approach and docking maneuvres [46].

The Japanese *H-II Transfer Vehicle* (**HTV**) is currently planned to dock with the ISS in 2009 (`SIZE-ALONE`). Like the European ATV it is used as a resupply vessel for the ISS but it will not automatically dock. The *Canadarm2* attached to the ISS will grab the HTV during approach and then manually dock it to the station. Unlike the Progress or ATV, the HTV is designed to carry pressurized cargo but is only planned to be berthed at the ISS for 30 days.

2) Formation Flying: Examples of previous and current formation flying satellite systems include the following:

The **NMP/EO-1** *(New Millennium Program - Earth Observation 1)* mission was launched on November 21, 2000 as a technology mission designed to fly in a trailing formation (60 seconds (450 kilometres) behind) with NASA's Landsat-7.It autonomously maintains the separation within 2 seconds. This is done by a controller capable of autonomously planning, executing and calibrating satellite orbit maneuvres developed at NASA's Goddard Space Flight Center (GSFC). It allows for paired-scene comparisons with the images from Landsat-7. [Classification: `SIZE-PAIR, COM-NONE, ARR-STATIC, CMP-HET, CTL-DEC`]

The EFF (enhanced formation flying) algorithm uses GPS data and on-board attitude sensors together with onboard predictions of where the satellites will be to calculate and command the actual firing of the thrusters. The autonomous formation flying technologies developed for EO-1 will enable the control of a large number of satellites by a minimum of ground support personnel for future missions. A group of satellites with the ability to detect errors and cooperatively agree on the appropriate maneuvre to maintain the desired positions and orientations is envisioned.

The *Earth Observing Sensorweb* project developed uses the EO-1 satellite to obtain high resolution coverage of areas of interest. This system autonomously checks databases of alerts on volcanoes (MODVOLC) that are parsed from low resolution cameras on board of various satellites. Such alerts are then parsed and a change of the EO-1 orbit is requested automatically to allow for additional data. In short, it reviews data from *"low resolution, high coverage sensors to trigger observations by high resolution instruments"* [47]. The ground control of EO-1 has a fail-safe and usually checks the automatic requests for validity. [Classification: `SIZE-LIM, COM-NONE, ARR-DYN, CMP-HET, CTL-CEN`]

The *Cluster* mission, launched in the summer of 2000, is a mission by ESA to study the effects of the solar wind around Earth in three dimensions. The mission, which was already designed in the early 90s but the first four Cluster spacecraft were destroyed during launch in 1996, was the first space project that built craft in true series production. The four identical spacecraft, using a cluster formation (Figure 1(b)), started operation in February 2001 and will run until December 2009. Using identical instruments simultaneously, three-dimensional and time-varying phenomena in the magnetosphere can be studied. The satellites used their own on-board propulsion systems to reach the final operational orbit (between 19 000 and 119 000 kilometres). [Classification: `SIZE-LIM, COM-NONE, ARR-DYN, CMP-HOM, CTL-CEN`]

A similar mission is the planned ESA mission *SWARM*. It is currently in the planning stage and will consist of 3 satellites, two flying parallel and one in a higher orbit. The main mission objective is to measure the geomagnetic field in 3D. The simultaneous measurements allow for higher accuracy but no active cooperation is used. [Classification: `SIZE-LIM, COM-NONE, ARR-STATIC, CMP-HOM, CTL-CEN`]

In March 2008, NASA launched two identical satellites named *TWINS*, in two high eccentricity (Molniya) orbits. The instruments are basically the same as the IMAGE satellite, but the use of 2 allows for a 3D image generation of the Earth's magnetosphere. The mission duration is planned to be 2 years, with fixed orbits [48]. [Classification: `SIZE-PAIR, COM-NONE, ARR-STATIC, CMP-HOM, CTL-CEN`]

The *Afternoon* (or **"A-Train"**) *satellite formation* consists of seven satellites flying in formation [49]. [Classification: `SIZE-LIM, COM-NONE, ARR-STA, CMP-HET, CTL-CET`] Currently five of the satellites are in orbit, two additional satellites, OCO and Glory, will join the constellation in 2009.

The A-Train formation is designed to provide near simultaneous observations and continues study of aerosol distribution, cloud layering, temperature, relative humidity, distribution of green-house gases and radiative fluxes.

Its formation is maintained in orbit with a separation of only 15 minutes between the leading and trailing spacecraft with **CloudSat** and **CALIPSO** separated by only 10 to 15 seconds. This formation is crucial for studying clouds, which often have lifetimes of less than 15 minutes. The satellites match the World Reference System 2 (WRS-2) reference grid, a system developed to facilitate regular sampling patterns by remote sensors during the Landsat programme. The constellation has a nominal orbital altitude of 705 km and an inclination of 98 degrees. The seven satellites are: **OCO** (to be launched in 2009, NASA), **AQUA** (launched 2002, NASA), **CloudSat** (launched 2006, NASA), **CALIPSO** (launched 2006, NASA/CNES), **PARASOL** (launched 2004, CNES), **GLORY** (to be launched in 2009, NASA), and **AURA** (launched 2004, NASA).

The **Iridium** *satellite constellation* (see Figure 1(c)) uses 66 satellites to allow for world-wide phone coverage. The satellites do not actively cooperate but have a communication link between each other to route voice transmissions.

The **NAVSTAR** (GPS) satellite constellation has been developed by the US Department of Defense and went fully operational in 1993 (there was restricted use available before, the first satellite was launched in 1978). It uses between 24 and 32 satellites that sent precise micro-wave signals with a time-stamp. The receiver can detect its position via triangulation.

The Soviet (now Russian) counterpart of the GPS system is called **GLONASS**. Early development started in the late 70s, the system only went fully operational in 1995. Due to economic woes, however, the system became quite unstable. Recently Russia announced to reactivate and update the GLONASS system. The system uses 21 active and 3 spare satellites which send radio signals.

The **Galileo** satellite constellation is currently being built by the EU and ESA. It will use 30 spacecraft and is planned to be operational by 2013.

Constellation formations as those mentioned above are usually not flying autonomously and are controlled from the ground [Classification: `SIZE-INF, COM-NONE, ARR-STATIC, CMP-HOM, CTL-CEN`], therefore they are not considered autonomously cooperating robots.

3) Rovers: As mentioned before no missions with cooperating rovers are currently in operation or have been thoroughly planned. The closest to this is the current *Mars Exploration Rovers* (**MER**) mission, which put two identical rovers on Mars in 2003. These are though positioned on quite far apart so no communication or coordination is possible. The software of the MER does include some behaviour based control which allows for a more autonomous exploration [36], [50] and the possibility to add cooperative

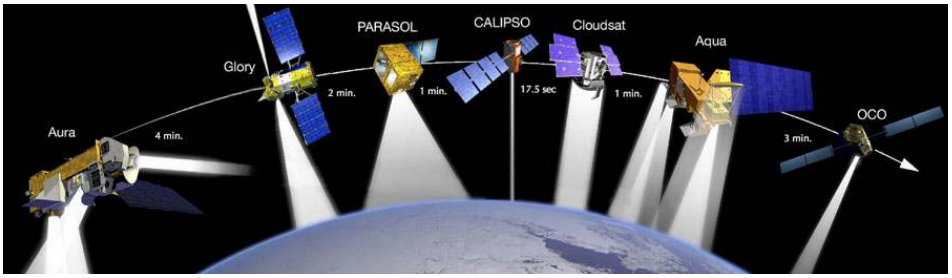

Figure 4. The 7 satellites of the A-train formation *Courtesy: NASA JPL*

behaviours into future rover software.

IV. CONCLUSION

A variety of space applications with various sorts of cooperation has been listed. There are some of those systems currently in development but especially on the rover (planetary exploration) side no missions are worked on. These space born applications bring better data, e.g. allowing better climate predication, a direct use for terrestrial applications is not seen, because of their specialized application areas.

In the case of planetary rovers a lot of systems developed are not primarily targeted at space applications and even those can be used in terrestrial applications, like resource mining, surveillance, demining of war zones and also home electronics (e.g. lawn-mower robots).

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