STATUS OF THE FAST MISSION: MICRO-SATELLITE FORMATION FLYING FOR TECHNOLOGY, SCIENCE AND EDUCATION

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ABSTRACT

FAST (Formation for Atmospheric Science and Technology demonstration) is a cooperative Dutch-Chinese formation flying mission led by Delft University of Technology (TU Delft) in the Netherlands and Tsinghua University in China. It is expected to be the first international micro-satellite formation flying mission to achieve objectives in three distinct fields: technology demonstration, earth science and space education. In this paper the latest status of the FAST mission is presented. The mission scenario consisting of different formation flying stages is described, and the system design of both the space and the ground segments is introduced, with emphasis on Dutch contributions. Some key technical issues related to autonomous formation flying are also addressed.

INTRODUCTION

Space science missions consisting of multiple small platforms flying in formation are now often considered as a feasible and logical alternative to the traditional approach of using a large and complex monolithic spacecraft. Important arguments in favour of space missions with formation flying satellites are risk mitigation, flexibility, and reduced spacecraft complexity.

In May 2007, a Letter of Intent was signed between Tsinghua University, China, and Delft University of Technology, The Netherlands, to jointly define, develop and operate a space mission with Formation Flying (FF) micro-satellites in 2011. Thereafter, an investigation into the following four candidate missions was carried out, all involving formation flying:

- Atmospheric science mission,
- Interferometric Synthetic Aperture Radar (InSAR) mission,
- Earth mass balance mission,

A trade-off was performed, which clearly puts the atmospheric science mission ahead of others, mainly due to science output and mission feasibility.

During a joint workshop in December 2007, an initial payload selection and mission design was carried out. This culminated into a concept for the Formation for Atmospheric Science and Technology Demonstration (FAST) mission which consists of two satellites, FAST-D (to be developed in Delft) and FAST-T (to be developed in Beijing) [1]. From 2008 to 2009, parallel phase-A studies were carried out in Delft and Beijing.

In this paper the latest status of the FAST mission is presented. The rest of the paper is organized into three parts. The first part describes the mission scenario and definition, highlighting different formation flying phases and operational modes. The second part details the system design of both the space and the ground segments, with emphasis on Dutch contributions. In this part, information about the science payloads (a spectropolarimeter, an altimeter and a microwave radiometer) are provided. The up-to-date system/subsystem design of FAST-D is specified along with an introduction of FAST-T. The architecture of the ground segment is also described with a focus on scientific data processing and distribution. The third part deals with key technical issues related to autonomous...
formation flying. Design challenges related to inter-satellite link, distributed computing, and cooperative control are addressed. An agent-based framework is presented under the FAST system architecture, as a solution for these problems.

**THE FAST MISSION**

FAST, described in detail in [1, 2], is a mission for the synoptic evaluation of local, regional and global aerosol data and altitude profiles of the cryosphere with cooperating micro-satellites flying in formation, foreseen to launch at the end of 2011. The mission covers technology demonstrations, scientific observations, and education. This is reflected in its three equally important top level objectives:

1. Demonstrate Autonomous Formation Flying (AFF) using various communication architectures with distributed propulsion systems.
2. Characterize atmospheric aerosols, monitor the variation of height profiles in the cryosphere, and correlate these data for improved scientific return.
3. Teach cutting-edge technology, broaden the international view of students and boost skills through the exchange of students and staff.

The baseline orbit for the two satellites is a sun synchronous orbit at 650 km altitude with an ascending node time of ~10:00 hr.

The 2.5 year mission is divided into four phases, each with a distinctly different orbital geometry. The rationale for and the orbital geometry during these phases are treated in the following. Each satellite has been assigned a total velocity change (ΔV) budget of 12m/s. This includes a 100% contingency to allow for failure of the propulsion system on one of the satellites [3].

**Launch and Early Operations**

The Launch and Early Operations (LEOP) phase consists out of the launch, orbit insertion, detumbling, and checkout of the two satellites. The LEOP phase, during which the satellites will not fly in formation, will take approximately one month. In this time, the inter-satellite distance will increase to 60km, requiring a bang-bang formation initialization maneuver costing 0.2m/s to start the next mission phase.

**Technology Demonstration Mode**

During technology demonstration mode, c.f. Fig. 1, the two spacecraft will demonstrate the ability to autonomously maintain an along-track separation of 1±0.1km by means of autonomous formation flying (AFF) using propellant optimized distributed propulsion. This capability requires a propulsion system on each spacecraft as well as an inter-satellite communication link.

![Fig. 1](Fig. 1 Technology Demonstration Mode)

For solar maximum conditions, it will take the satellites slightly over one day to traverse the 200m control window of this mission phase. To maintain the desired formation geometry, taking into account differential drag only, a ΔV of 2mm/s is then required to bring the inter-satellite distance back to the other extreme of the control window.

Although the orbital geometry is not optimized for it, some first science observations will be performed during this phase of the mission. Due to the relatively small inter-satellite distance, this phase also lends itself well to perform distributed computing experiments between the two spacecraft and to perform cross-calibration between the instruments on the different spacecraft. The AFF demonstration will be performed for several weeks and will be followed by a transition to the required relative geometry for science mode.

**Science Mode**

In this mission mode, the along-track separation between the satellites will be 1225±5.7km, as shown in Fig. 2. Since natural drift of the formation will require approximately 100 days before this geometry is achieved, preference is given to a controlled maneuver requiring a total ΔV of 2m/s and taking a bit more than two days. For one year of formation maintenance, taking only differential drag into account, approximately 1.2m/s of ΔV is required and a maneuver needs to be executed every nine days.
The orbital geometry of this mission phase lends itself extremely well to perform synoptic and synergetic observations with the altimeters and especially the spectropolarimeters on both spacecraft. The orbital geometry combined with the nine Earth-looking Fields-Of-Views (FOVs) of the spectropolarimeter results in many simultaneous intersections of the spectropolarimeter FOVs and in several overlapping the spectropolarimeter FOVs at the Earth's surface. This allows retrieval of aerosol characteristics at specific altitudes at a single moment in time and it allows making more observations of geolocations from various angles during a single pass (especially near the equator), which is highly desired for aerosol characterization. The ±5.7km accuracy in the inter-satellite range is driven by the pixel size of the spectropolarimeter at 650km altitude, which is approximately 11.4km.

THE SYSTEM DESIGN

The system design of the FAST mission is explored in the following subsections. First, the overall system architecture is discussed, followed by the more in-depth descriptions of the payloads, the spacecraft buses, and the ground segment.

System Architecture

The architecture of the FAST system is schematically shown in Fig. 3. Like many other space systems, the FAST system consists of both space and ground segment. However, due to the feature of formation flying, the space segment is comprised of two spacecraft, i.e. FAST-D and FAST-T. During the procedure of formation flying, i.e. the scientific mode as well as the technology demonstration mode, the two spacecraft will communicate with each other either through a direct Inter-Satellite Link (ISL) or through ground stations. The distributed computing and other technologies will be implemented via the ISL. Details about the elements of this architecture, the ISL and other issues will be discussed in the remaining part of this paper.

In total three scientific payloads will be flown by the FAST mission: two Dutch payloads spectropolarimeter (on both FAST-D and FAST-T spacecraft) and Stereo Imaging Laser AlTimeter (SILAT, on FAST-D), and one Chinese payload Dual-Frequency Microwave RadioMeter (DFMRM, on FAST-T).

Scientific Payloads

Spectropolarimeter

Due to the capability of accurate full linear spectro-polarimetry without moving parts or liquid crystals, the spectropolarimeter is an ideal instrument for measuring and characterizing aerosols from space.

The candidate for the spectropolarimeter is Spectropolarimeter for Planetary Exploration (SPEX), which is under development by a Dutch consortium consisting of companies and knowledge institutes [4]. Since SPEX is ultimately intended for Mars missions, a special version, i.e. SPEX-FAST, should be specifically designed for the FAST mission. An important modification of SPEX-FAST compared to SPEX-Mars would be the change from seven planet-looking FOVs and two limb-looking FOVs to nine planet-looking FOVs. Reason for this change is that SPEX-FAST will focus on characterizing aerosols, leading to a preference for planet-looking FOVs over limb-looking FOVs.

SILAT

SILAT, as shown in Fig. 4, is a highly integrated payload that is composed of three separate instruments; the Single Photon-Counting Laser AlTimeter (LAT), the High Resolution Camera (HRC) and the Stereoscopic Camera (SCAM) [5]. A structural re-design of the instrument has been made for the FAST mission, which results in considerable mass savings as compared to the
earlier design for a mission to Jupiter’s moon Europa.

Fig. 4 SILAT Integrated Payload Suite.

SILAT features custom fasteners for the optical components. These fasteners allow the optical components to be adjusted on the scale of micrometers. They are made from SiC, keeping in line with the SILAT design philosophy.

Another facet of SILAT is that it employs passive elements as much as possible. While the LAT is an obvious exception, SILAT contains no moving parts, and all cooling devices are passive; only cold fingers and radiators are used. This increases the reliability of the payload suite, which is essential for space missions.

A breadboard prototype of the LAT has recently been completed by cosine Research. The breadboard can be made mobile and is ready for outdoor testing. Successful indoor tests have already been performed, and the completed breadboard will be demonstrated in autumn 2009. This breadboard is capable of controlling a pulse emitted from a prototype microchip laser, detecting said pulse and then sorting and analyzing the resulting data to form a distance profile.

With the LAT, SiC frame and FPGA-based data processing algorithms have already been tested and developed, SILAT is expected to move towards an engineering model very shortly, and to a flight model after completion of the Single Point Diamond Turned (SPDT) mirror development project, which is due to be completed at the end of the 3rd quarter of 2010.

**DFMRM**

DFMRM is an instrument for measuring the global luminosity/temperature data at K-band (23.8GHz) and Ku-band (37GHz). After data processing, the physical parameters related to water present in both liquid and vapor forms in clouds can be obtained. These parameters then can be used to construct more accurate precipitation prediction models, and also to aid the in-depth analysis of the effect of aerosols on precipitation.

Currently, DFMRM is under development by General Establishment of Space Science and Application, Chinese Academy of Sciences (GESSA/CAS). The designed DFMRM is a box of the size 330x270x200mm$^3$, has the mass of no more than 15kg and the average power of less than 20W (peak power <25W). There are two observation channels on DFMRM: the primary one is nadir-oriented, and the secondary one points to cold space (off sunlight) for calibration purposes.

**FAST-D Spacecraft**

FAST-D is a 50kg micro-satellite currently under development by Dutch academia and industries [6]. As shown in Fig. 5, FAST-D has a 0.5mX0.5mX0.7m box-shaped structure with three body mounted solar panels on the zenith surface and the two along-track surfaces, respectively. The internal structure consists of multiple trays, which are used both for easy integration and for load carrying. On the nadir surface, the payload detector heads and a high-gain S-band data-downloading antenna are accommodated, as well as low-gain Telemetry & Tele-Command (TTC) antennas. The optical heads of the star tracker are installed on the surface that is parallel to the orbit plane.

Fig. 5 FAST-D Spacecraft.

FAST-D will be a synthesis and showcase of Dutch achievements on space-related Micro-Systems Technology (MST). Most of the components onboard are developed under development by Dutch universities or industries, and some of them have been demonstrated in space. For instance, the wireless sun sensor developed by TNO has been flown on the Delfi-C3 nano-satellite [7]. From this aspect, FAST-D will not only be a platform for MST demonstration, but also to some extent a System-of-MicroSystems (SoMS).

In the following sub-subsections, the subsystems of FAST-D will be briefly introduced.

**AOCS**

The Attitude and Orbit Control Subsystem (AOCS) plays a key role for the FAST-D spacecraft. Due to the requirements from the payloads, FAST-D’s AOCS shall be able to provide attitude information with at least 30 arcseconds accuracy around the various body axes using fine attitude sensors, and shall allow the control of attitude with a minimum pointing accuracy of 300 arcseconds.
The attitude determination is achieved with the use of two redundant 3-axis magnetometers and two micro sun sensors for coarse information. For precise determination two miniaturized CMOS star trackers and a 3-axis gyro are used. The attitude control is performed with reaction wheels and using magnetoquers for momentum dumping and coarse control. The four micro reaction wheels are mounted in a pyramid configuration maximizing control effectiveness, and the three magnetoquers are mounted in an XYZ configuration.

A double-loop Nonlinear Dynamic Inversion (NDI) technique will be adopted, which allows flexible control of a nonlinear system in different flying modes [6]. The double-loop NDI technique avoids strong nonlinear feedback which causes unnecessary actuator saturations, and provides flexibility for multiple operational modes by separating rate and angular control.

A Global Navigation Satellite System (GNSS) receiver will function as absolute navigation sensor for onboard orbit determination. It is further enhanced through uploading precise GNSS ephemerides from ground. The relative position and attitude information will be obtained by exchanging navigation and attitude data via inter-satellite communication. Orbit control will be implemented by means of a cold gas thruster, which will be introduced later in this section.

**Power**

FAST-D uses three body mounted solar panels as the primary power supply, and two Li-ion battery packages as the secondary power supply. Each solar panel is populated with triple-junction GaAs cells which have a minimum average efficiency of 26.8%. The preliminary sizing calculations for the solar panels are shown in Tab. 1, which indicates that the power subsystem is able to provide at least an orbit average power of 45W at Begin-Of-Life (BOL), 50% more than required.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Required</th>
<th>Provided</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit average power</td>
<td>30.0W</td>
<td>45.0W</td>
</tr>
<tr>
<td>Power during daylight</td>
<td>41.7W</td>
<td>62.5W</td>
</tr>
<tr>
<td>Power at BOL</td>
<td>44.7W</td>
<td>66.6W</td>
</tr>
<tr>
<td>Plus 10% Margin</td>
<td>49.2W</td>
<td>73.3W</td>
</tr>
<tr>
<td>Solar panel area (normal to sun, with degradation factor and orbit seasonal offset)</td>
<td>0.2m² (worst case, fixed panel)</td>
<td>0.3m² (worst case, fixed panel)</td>
</tr>
</tbody>
</table>

**CDHS**

The philosophy behind the Command and Data Handling Subsystem (CDHS) is to develop a highly integrated avionics kernel that manages all the survival functions of the spacecraft. Considering about the difficulties such as redundancy and mixed Digital Current/Analogue Current (DC/AC), a relatively simplified architecture of this avionics kernel, schematically shown in Fig. 6, is proposed for FAST-D. This architecture consists of computers, data storage, data buses, and the relevant software.

![Fig. 6 FAST-D CDHS Schematics.](image-url)

There are two ARM processors in the kernel, one for housekeeping and data processing, and the other for AOCS and formation flying. They are also hot redundant for each other in case of failure. The payload data are stored in a radiation tolerant solid state memory with the capability of 8GB. The data buses are composed of a high speed bus for payload data transfer and a low speed bus for command/control. The onboard software performs three primary functions: system boot, housekeeping, and AOCS/FF processing.

**Communication**

The communication subsystem, also called Radio Frequency (RF) subsystem, is in charge of the signal reception and transmission of FAST-D. It operates at S-band due to the payload data download requirement.

As shown in Fig. 7, the subsystem consists of two parts. One part is the Satellite-Ground Communication Module, which is composed of two hot redundant command receivers, one low power transmitter, one high power transmitter, and associated antennas. The low power transmitter is primarily used for telemetry, and the high power one is primarily for payload data downlink. However, for redundancy on the transmit chain, these two transmitters both can be used as the backup of the other one. The two command receivers share two patch antennas, which are mounted on the nadir and the zenith surfaces of the satellite, respectively. The low power transmitter feeds another two patch antennas. The high power transmitter is connected with a helical antenna.
Another part is the Inter-Satellite Communication Module, which is composed of a transceiver and two patch antennas. During FF, the satellites will exchange information, such as position and attitude, between each other through this link. As payload data are not intended to be exchanged, only low power transceiver and low-gain antennas are utilized.

**Propulsion**

Due to the requirements of a piggy-back launch, FAST-D should avoid the utilization of hazardous components, such as high energy propellant, high pressure vessels, etc. Meanwhile, the relatively large ΔV requirements and the volume limitation on the spacecraft also prevent FAST-D from utilizing conventional chemical propulsion techniques. Alternatively, a cold gas generator is used on FAST-D to replace the cold gas tank.

The cold gas generator, developed by TNO and Bradford Engineering, consists of a solid block of chemical material inside a casing [8]. Once ignited, this solid material will decompose into the required gas that leaves the gas generator at ambient temperature. The major advantage of the cold gas generator over the gas tank is that it stores the propellant in solid state. Hence, no large volume, high-pressure tank and associated valves are needed; no risks for leakage; and the mass and volume of the complete propulsion subsystem are both optimized.

Currently nitrogen and oxygen generators are available. For FAST-D the nitrogen generator has been selected, because of its relatively high gas output efficiency (each kg of solid propellant can output 260 liters of gas with the pressure range of 0.1-15 MPa) and its availability for space applications through its imminent space qualification on ESA’s PROBA-2 satellite.

**Structure & Thermal**

The structure of FAST-D is to be manufactured from conventional aluminum alloy including the use of honeycomb panels. The primary structure consists of the following elements:

- Separation system
- Separation panel
- Avionics stack
- Payload panel
- Top panel
- Side honeycomb panels:
  - 3 Solar panels
  - Nadir panel

The overall spacecraft is designed to ensure a balanced thermal environment in all operating, eclipse and safe modes. Due to the utilization of the cold gas generator, the local heating for the propellant tank is not necessary anymore. Therefore, thermal control is achieved primarily by simple passive approaches. For instance, on external surfaces a mixture of first surface tape and second surface tape is utilized, and plain black carbon radiating surfaces are used to control heat flow by balancing absorption and emissive characteristics. Another example is internal equipment whose radiating properties are controlled by applying appropriate surface finishes.

**FAST-T Spacecraft**

FAST-T is a small satellite currently under development at Tsinghua University. As shown in Fig. 9, FAST-T is a 750mm×750mm×730mm cube with two deploy-fix solar panels, and the total mass is less than 130kg.
The primary attitude mode of FAST-T is 3-axis stabilized nadir pointing with the control accuracy better than 0.1° (3σ) and stability better than 0.01°/s (3σ). In case of any critical fault, the satellite will automatically enter into the safe mode, and then the opposite side of Y axis will point to the Sun with the accuracy of better than 5° and the stability better than 0.05°/s (3σ).

Ground Segment

According to the architecture in Fig. 3, the ground segment of FAST consists of two ground stations, one Mission Control Center (MCC), and one Science Data Center (SDC).

In order to increase the window for satellite-ground access, two geographically distributed ground stations are planned: one in Delft, and one in Beijing. Both ground stations are equipped with 3m paraboloid antennas and have identical functions: sending commands, receiving telemetry and payload data, and acting as backup route for ISL.

All ground operation decisions are made in a single MCC and then sent to the ground station for generating control commands, and all data received by ground stations are also initially analyzed in the MCC. The telemetry data will be further processed here, and the payload data will be sent to the SDC.

The development of the ground segment is currently ongoing in both Dutch and Chinese sides. The locations of the MCC and the SDC are to be determined shortly.

KEY TECHNICAL CHALLENGES

The FAST mission will demonstrate FF technology; and will also generate increased science data return through FF. From this point, FF is the core of the whole mission, and many technical challenges are related to it. In this section, three key technical questions are to be discussed: 1) How do the two satellites exchange information? 2) How do they process the received information? And 3) how do they utilize the processed information?

Inter-Satellite Information Exchange

The most important issue for a successful FF mission is acquiring state information from other satellites in the formation. Usually, this could be done through direct ISL (RF or optical based). For the FAST mission, however, a mixed strategy for inter-satellite information exchange is proposed.

In the technology demonstration mode, the distance between the two satellites is only 1km, and each satellite is in the other one’s line of sight. Therefore, a direct ISL is utilized as the nominal communication route. To avoid technical complexity, an RF based ISL is chosen, which can achieve a relatively high data rate due to the low free space loss. Therefore it will be beneficial not only to exchange state information, but also to the distributed processing of data. This direct ISL in principle also allows for relative ranging between the satellites using the same signal.

In the science mode, the along-track separation between the satellites will be around 1225km, which implies that the two satellites are still in each other’s line of sight and the direct RF ISL is still available. However, a lower data rate is expected as the free space loss is much higher.

Except the direct link, a ground-in-the-loop communication route is used as backup [9]. For this type of communication, there are two options as shown in Fig. 10: 1) One satellite transmits data to one ground station, then this ground station transmits the data to the second satellite when it flies over; 2) One satellite transmits data to one ground station, then through internet the data are transferred to the other ground station, which is responsible for transmitting the data to the second satellite. In the FAST mission, these two options are mixed adopted subject to the shortest delay time.

Fig. 9 FAST-T Spacecraft.

Fig. 10 Ground-in-the-Loop Communication Routes.
Onboard Information Processing

Utilizing onboard information processing has a number of advantages for small satellites. The most important one is to provide near real-time results while avoiding the costs and limitations involved with sending the data down to Earth to be processed.

In order to avoid the primary disadvantage associated with onboard processing, i.e. the errors inherent in the onboard processing cannot be undone for previously computed results, the FAST mission adopts a conservative strategy: The scientific data will be processed onboard and, meanwhile, also stored in the large volume solid state memory. A substantial part of the onboard-processed data will then be validated with the original data in the ground station.

Considering about the technology readiness, the data processing will be primarily implemented in each satellite’s own onboard computer. The items for onboard processing include data compression and image processing. For example, the volume of data to be collected by SILAT could be dramatically reduced (i.e. to <1% of the original amount), if the images captured by HRC and SCAM can be identified and the useless images can be deleted onboard.

Besides the conventional “local” computing, also space-based distributed computing technique will be demonstrated by the FAST mission to explore the possibility of fully utilizing the computing powers of FF small satellites for onboard processing. The concept of space-based distributed computing will utilize the processors on each satellite as a true distributed computer. For the FAST mission this indicates a space-based computer with (at least) two geographically distributed processors.

The types of problems under consideration for such a distributed computing network are typically large, dense linear algebra problems. This is because these operations can be processed using blocked algorithms, which are well suited for distributed and, possibly, heterogeneous systems. An important experiment will be the real-time orbit determination of the FAST formation, because the size of this problem could be very large (i.e. thousands of parameters using thousands of observations) and beyond the capability of a single processor [9].

Distributed Utilization of Information

Through inter-satellite communication and onboard “local” or distributed processing, parts of the data received by the two satellites are shared, and each satellite has acquired the other’s state such as precise position and attitude. This information will be used to implement different tasks related to FF. Within the FAST mission, two of these tasks are given priority: the propellant optimized distributed propulsion, and the cooperative control.

Propellant optimized distributed propulsion

Without formation maintenance, the two satellites in the FAST formation will quickly drift apart due to differential air drag and differential semi-major axis. Since it is vital that the two satellites remain at a specified distance (for technology demonstration mode is 1±0.1km, and for science mode is 1225±7.5km) with respect to each other, the inter-satellite distance needs to be periodically adjusted using the propulsion subsystem. As each of the two satellites in the formation is equipped with a propulsion system, there is the possibility to implement propellant optimized distributed propulsion. This means that by having the direct ISL, the two satellites could autonomously make decisions that when and which satellite should fire the thruster(s), and therefore to minimize the propellant consumption. The two propulsion systems also provide redundancy: even if one does not function, the other one still can perform formation maintenance manoeuvres.

Cooperative control

As mentioned early in last sub-subsection, FAST will perform propellant optimized distributed propulsion, which requires the cooperation of the propulsion subsystems on both satellites because the firing decisions are not intended to be made only based on one satellite’s state. Furthermore, the two satellites will observe overlapped areas on the Earth, which indicates that the AOCS of the two satellites need to work cooperatively to perform relative attitude maintenance and reference attitude tracking. The common feature of these problems is: No only the position and the attitude, but also the behavior of each satellite shall be coordinated and controlled. To solve these problems, cooperative control technology will be investigated and demonstrated by the FAST mission.

Cooperative control is a technology that allows a team (with at least two members) to cooperatively decide where to go, how to behave, and so on. It is not a fairly new term as it has already been studied in the context of a cluster of mobile robots or Unmanned Aerial Vehicles (UAVs), or even for deep space missions [9]. However this technology has not been demonstrated or tested on orbit so far. In general, there are three approaches for cooperative control: centralized, decentralized, or
distributed. Considering about technology readiness, mission need (only two satellites in the formation) and many other factors, the first two approaches are expected to be further studied and, eventually, demonstrated through the FAST mission.

Multi-Agent based Framework

To implement the proposed activities, including propellant optimized distributed propulsion and cooperative control, an agent-based framework (see Fig. 11) is preliminarily designed under the FAST system architecture (c.f. Fig. 3) [11]. The reasons for choosing a Multi-Agent System (MAS) are not only from the research aspect, but also due to the following facts:

1. Autonomy – both satellites are required to behave at least partially autonomous;
2. Local views – neither satellite has a full global view of the system, although both of them have some knowledge of each other;
3. Decentralization – due to the limited ground station coverage, there is no one centralized controller for the system during most of the flight time;
4. Flexibility – although so far the FAST mission only has two satellites, it actually has an open-system architecture, i.e. more satellites can join the formation later.

As shown in Fig. 11, the framework has agents at two levels: spacecraft level (e.g. FAST-D Agent) and function level (e.g. FF Agent). Spacecraft-level agents are in charge of sending/receiving information, local activity planning, command implementation, coordination of local agents, etc. Each function-level agent has several skills. For example, the FF Agent is able to plan the motion of the satellite, estimate current formation parameters, and produce formation control commands. Function-level agents can communicate with other local function-level agents and determine local behaviors.

The design of the MAS-based framework is still ongoing and further details are to be provided in future publications.

CONCLUSIONS

Up-to-date information on the Dutch-Chinese FAST mission has been presented. The mission scenario has been described, which consists of LEOP, technology demonstration and science observation phases. The orbital geometries of the different mission phases are also discussed. The system design of both the space and the ground segments is introduced. The latest information about the Dutch contributions, i.e. the spectropolarimeter, SILAT and the FAST-D spacecraft, are provided. Key technical challenges related to autonomous formation flying, such as ISL, distributed computing and cooperative control, are addressed with an agent-based framework.

The FAST mission has the potential to validate innovative technologies, such as MEMS-based sensors and actuators, and miniaturized RF components. It’s also suitable for demonstrating autonomous formation flying using low cost spacecraft. By having inter-satellite communication, distributed computing can be implemented on the two FAST satellites, which can greatly impact the design of future satellite missions by enabling space-based data processing to reduce downlink bandwidth and allowing the use of off-the-shelf hardware that is more capable and less expensive than current space hardware. Furthermore, an agent-based cooperative control architecture is foreseen. This architecture allows the greatest flexibility in an open system and, therefore, is promising for future large scale formation flying missions. FAST will be the first formation flying mission to validate this technology on orbit.

REFERENCES

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