Conceptual Design of the FAST-D Formation Flying Spacecraft

D. Maessen(1), J. Guo(1), E. Gill(1), B. Gunter(1), Q.P. Chu(2), G. Bakker(2), E. Laan(3), S. Moon(4), M. Kruijff(5), G.T. Zheng(6)

(1)Delft University of Technology, Department of Earth Observation and Space Systems, Kluyverweg 1, 2629 HS, Delft, the Netherlands
(2) Delft University of Technology, Department of Aerospace Design, Integration & Operations, Kluyverweg 1, 2629 HS, Delft, the Netherlands
(3) TNO Science & Industry, Stieltjesweg 1, 2600 AD, Delft, the Netherlands
(4) cosine Research B.V., Niels Bohrweg 11, 2333 CA, Leiden, the Netherlands
(5) Delta-Utec, Middelstegracht 89g, 2312 TT, Leiden, the Netherlands
(6) Tsinghua University, School of Aerospace, 100084, Beijing, China

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Abstract

The paper presents the latest results in the design of FAST-D, the Dutch micro-satellite for the Dutch–Chinese FAST (Formation for Atmospheric Science and Technology demonstration) formation flying mission. Over the course of the 2.5 year mission, the two satellites, FAST-D and FAST-T, will demonstrate various new technologies and perform observations of atmospheric aerosols and seasonal variations of height profiles in the cryosphere using spectropolarimeter and altimeter payloads on both spacecraft. A conceptual design for the Dutch spacecraft, FAST-D, is presented. Special focus is laid on the design of the attitude determination and control subsystem and on the space-based computing experiments to be performed on this spacecraft. Furthermore, new results in the development of the science payloads on FAST-D, the aerosol characterisation instrument SPEX (Spectropolarimeter for Planetary Exploration) and the altimeter SILAT (Stereo Imaging Laser Altimeter), are described. For SPEX, several design changes have been made to make the instrument more compatible with the FAST mission. For SILAT, an instrument re-design for Earth missions is presented, which results in considerable mass savings as compared to the earlier design.

1 Introduction

The FAST (Formation for Atmospheric Science and Technology demonstration) mission is a collaboration between Delft University of Technology in the Netherlands and Tsinghua University in Beijing, China. It is a formation flying mission consisting out of two micro-satellites: FAST-D (Delft) and FAST-T (Tsinghua). Mission objectives exist in the fields of technology, science, and education. Detailed information on the mission can be found in [1-4]. The following sections focus on the conceptual design of FAST-D that was developed during phase A of the project and on the progress made in the development of the two science payloads of FAST-D.

2 FAST-D Conceptual Design

The conceptual design of FAST-D is explored in the following subsections. First, the overall system design is briefly discussed, followed by a more in-depth treatment of the attitude determination and control subsystem (ADCS) and the planned space-based computing experiments to be performed on the spacecraft.

2.1 Overall system design

The current design for the 50 kg FAST-D, cf. Fig. 1, foresees in a 0.5 x 0.5 x 0.7 m^3 box-shaped structure with three body mounted solar panels and a secondary Li-ion battery for power supply during eclipse. The internal structure consists of multiple load carrying trays for easy spacecraft integration. A GNSS (Global Navigation Satellite System) receiver will function as absolute navigation sensor for onboard orbit determination, which will be enhanced through uploading of enhanced GNSS ephemerides from ground. Relative navigation with respect to FAST-T, required for autonomous formation flying, is achieved by exchanging GNSS data products between the two satellites using an S-band inter-satellite link. Communications with the ground stations will also be performed in S-band. FAST-D will be primarily nadir pointing and will utilize three axis attitude control. Formation and orbit control is achieved by means of a cold gas propulsion system capable of providing a total ΔV of 12 m/s.

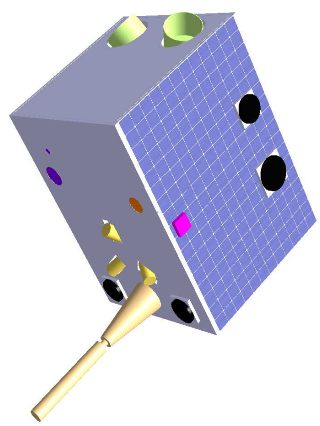

Fig. 1: FAST-D conceptual design

2.2 Attitude determination and control subsystem

Conventional attitude control of satellites has been based on classical techniques which, together with a conservative trend of thought, form bottlenecks for ADCS to achieve a higher performance rating, flexibility in mode switching, and fault tolerance. FAST, being an educational and technology demonstration mission, allows the application of innovative ADCS technologies aimed towards solving these bottlenecks. The FAST-D ACDS currently utilizes the following sensor types for attitude determination: Earth horizon sensor, fine sun sensor, autonomous star tracker, 3-axis magnetometer, and 3-axis rate sensor. Attitude control is achieved by means of four reaction wheels in a pyramid configuration maximizing control effectiveness, cf. Fig. 2, together with three magnetic coils for de-saturating the reaction wheels when necessary.

An integrated attitude determination system combines the rate and vector sensor data in an Extended Kalman Filter (EKF) to obtain highly accurate attitude and rate estimates for the entire mission duration, cf. Fig. 3. Furthermore, the ADCS system utilizes a double-loop Nonlinear Dynamic Inversion (NDI) technique, cf. Fig. 4. This allows flexible control of a nonlinear system in different flying modes, separating spacecraft dynamics from its kinematics, and providing high pointing accuracy in a dynamic environment. A reconfigurable control allocation system is utilized to optimally assign angular momentum profiles to each reaction wheel, accounting for over- and under-actuated situations maintaining control effectiveness during potential actuator failure modes.

The combination of these techniques provides various advantages to the ADCS design: The double-loop NDI technique avoids strong nonlinear feedback which causes unnecessary actuator saturations. Furthermore, it provides flexibility for multiple operational modes by separating rate and angular control. The reconfigurable control allocation contributes to the overall ADCS robustness.

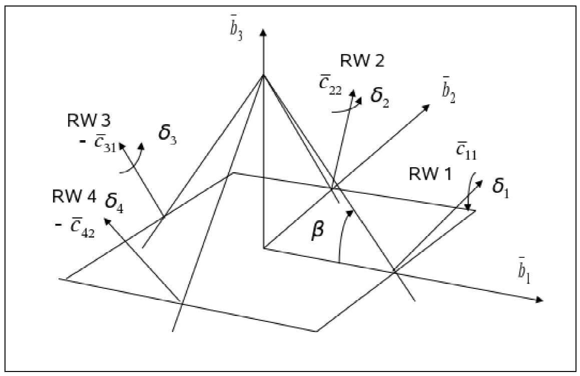

Fig. 2: Four reaction wheels in a pyramid configuration [5]

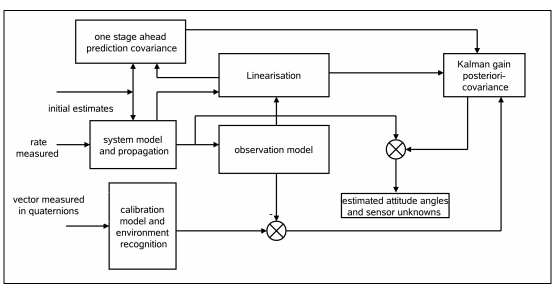

Fig. 3: Sensor integration structure with EKF

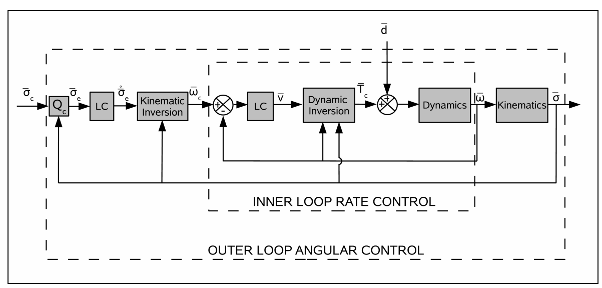

Fig. 4: Double loop NDI nonlinear attitude control

2.3 Space-based computing

The space-based computing experiments for the FAST mission are split into two components: on-board and distributed computing. On-board computing includes those computations that are done on a single satellite; however, this can also include parallel processing methods if the on-board processor has multiple cores. The primary goal of the on-board experiments is to reduce the amount of data that needs to be downloaded by conducting some degree of data processing in flight. For example, this could include the pre-processing of data generated from one of the on-board instruments, such as the SPEX instrument, cf. subsection 3.1, or a GNSS receiver. This pre-processing has the potential to dramatically reduce the amount of data that needs to be transferred to the ground stations, without sacrificing the quality of the final science products. The primary concerns with such an experiment are the processor speed, and consequent power usage. Fortunately, advances in computer hardware for commercial mobile devices have produced low-power processors that may be well suited for small satellite systems. For example, though not space-certified, products such as the Intel Atom* processor are small (13 x 14 mm) and powerful (2 GHz) with relatively low power requirements (< 2.5 W).

One example that highlights the potential benefit of conducting on-board computing involves the SPEX payload. This instrument samples a spectrum from approximately 400-800 nm at 1 nm intervals, resulting in roughly 400 data points that are then convoluted by the instrument electronics into a sinusoidal function. The instrument has nine fields of view (FOVs), with each FOV measuring a spectrum across a 7° x 1° swath, sampled into 8 separate pixels. Data is collected in two sets for each swath, at a rate of 0.5 Hz, resulting in 72 total data sets (400 points each) per second. Using the standard processing approach, the data points collected are transmitted to the ground for post-processing, which primarily consists of fitting a sinusoidal or high-order polynomial (i.e., 5^{th} order) curve through the data using standard least squares. The raw SPEX data has 10-bit precision, meaning that 49 minutes of SPEX data collection (assuming a 50% duty factor for SPEX) generates approximately 106 megabytes (MB) of data. If the least squares operation is performed in space, then the transmitted data will only consist of the estimated curve parameters, which for a 5^{th} order polynomial (i.e., 6 parameters) will be on the order of 5.1 MB (assuming conversion to single precision numbers). This translates into a 95% reduction in the total transmitted data. Furthermore, while a standard space-certified processor (e.g., the LEON3FT**, operating at 4 MFLOPS (floating-point operations per second)) does not have the speed to keep pace with the processing demands, a processor such as the Intel Atom or similar, operating at ~3 GFLOPS, is able to manage well. The fact that the processor is not fault-tolerant can potentially be addressed through the application of software (i.e., algorithmic) fault-tolerance [6]. This approach requires ~10% overhead, but verifies that the calculations are correct, while significantly reducing the cost and performance loss incurred by utilizing space-ready hardware components.

The distributed computing experiments planned will be a first among small satellite formations. As such, the inter-satellite communication will be an integral part of the process. Multiple communication lines will potentially be utilized throughout the mission lifetime, including ground-based relays, direct inter-satellite links, and possibly through commercial satellite phone networks [2]. Different links will be utilized at different stages of the mission, since the separation distance of the two satellites will change [4]. Ideally, the use of the various communication links will be selected automatically depending on which link offers the highest bandwidth at a given time. All these features require an uncommon and highly flexible communications subsystem design. The primary goal of the distributed computing experiment on FAST will be to exercise the process and identify performance boundaries. Once established, future experiments with this approach could involve topics which make use of large, dense linear systems that are well suited for distributed computing, such as real-time high accuracy orbit determination or real-time gravity field determination.

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* www.intel.com

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3 Science Payloads

For FAST-D, the opportunity exists to fly two advanced Dutch science payloads: SPEX (Spectropolarimeter for Planetary Exploration) and SILAT (Stereo Imaging Laser Altimeter). Although these instruments are ultimately intended for planetary science missions, some minor adjustments allow them to be used as Earth observation payloads on a micro-satellite. Since the FAST mission is not totally geared towards scientific observations and since the science payloads are not tailored explicitly for Earth use, the FAST mission cannot compete with 'big' science missions in terms of science output, but it can certainly provide supplementary science data. The next two subsections will discuss the science payloads of FAST-D.

3.1 SPEX

The shoebox-sized SPEX instrument, cf. Fig. 5, is under development by a consortium of Dutch companies and knowledge institutes. SPEX is capable of accurate full linear spectropolarimetry without moving parts or liquid crystals, making it an ideal instrument to measure and characterize aerosols from space. Being developed using a stepwise approach, its use on the FAST mission presents an intermediate step towards its ultimate goal: to act as payload on a future Mars observation satellite to study Martian dust and clouds.

The SPEX version to be used for the FAST mission is known as the SPEX breadboard (BB). SPEX BB is a modified version of SPEX, which is tailored for Martian use and discussed extensively in [7]. An important modification of SPEX BB compared to SPEX is the change from seven planet-looking FOVs and two limb-looking FOVs to nine planet-looking FOVs. Reason for this change is that SPEX BB will focus on characterizing aerosols, leading to a preference for planet-looking FOVs over limb-looking FOVs. The SPEX BB FOVs measure 7° x 1°, resulting in a spatial resolution of 11.4 km from a 650 km high orbit, and have angles of ±56°, ±42°, ±28°, ±14°, and 0° with respect to nadir.

While SPEX will be a fully space-qualified instrument, SPEX BB will be as much space qualified as possible to reduce development time and costs. Pragmatically, this means that it is foreseen to use space qualified optics, a space qualified detector and a housing that can withstand the launch environment of the Ariane 5 launcher. This specifically does not include space qualification of the polarisation optics and space qualified read-out electronics.

3.2 SILAT

SILAT, cf. Fig. 6, is a miniaturized, integrated instruments suite consisting of a high resolution camera (HRC), a stereo imaging camera (SCAM) and a photon counting laser altimeter (LAT). The instrument is treated in detail in [8]. 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. The drivers for the mass changes are changes in the thermal and harmful radiation constraints due to the shift in operational orbit from Europa to Earth. The main changes to the structure are the replacement of Densimet, a high density tungsten alloy used for radiation shielding of the SILAT electronics in the high radiation environment of Europa, by aluminium and the reduction in thickness of other structural components made out of aluminium. This leads to a reduction in mass of ~1.5 kg. Due to this mass reduction, the thickness of the SiC baseplates of SILAT can also be reduced, resulting in an additional mass saving of ~1 kg, leading to a total mass reduction from the initial 7.8 kg for the Europa design to 5.2 kg for FAST. Other reductions will be investigated as the FAST project moves forward into the detailed design phase.

Performance evaluations conducted for the FAST mission indicate that the optical elements of SILAT as designed for Europa will perform well in an Earth environment. Therefore, no modifications to the optical elements of SILAT are required for the FAST mission.

A prototype of the complete LAT is currently being developed at cosine Research. As of writing, all of the components in the prototype have been completed; these are the micro-chip laser, the detector array, readout electronics and the controlling firmware. These components are being integrated at tested at the moment, with prototype performance results expected by the end of May, 2009.

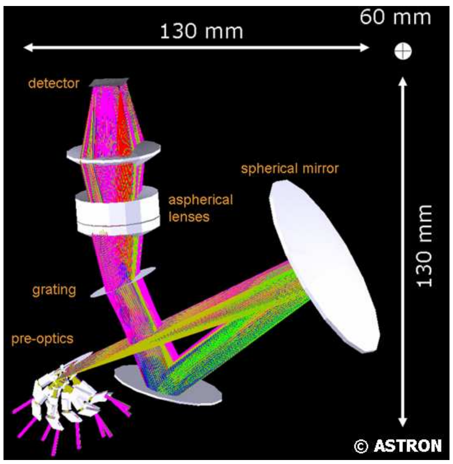

Fig. 5: SPEX optics

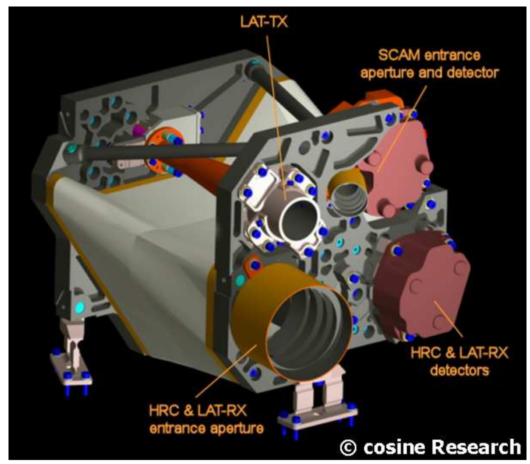

Fig. 6: SILAT

4 Conclusions

The conceptual design of FAST-D has been presented, with special emphasis paid to the novel attitude control system and the impact of the space based computing experiment on the FAST-D system design. Furthermore, the two science payloads on FAST-D have been treated in detail, highlighting changes in their design for the FAST mission.

The 50 kg FAST-D spacecraft differs from most other micro-satellites in that it is capable of formation flying with another spacecraft, namely FAST-T, by means of exchanging GNSS data products for relative navigation and through a cold gas propulsion system for formation and orbit control. The ADCS of FAST-D will make use of a double loop nonlinear dynamic inversion technique for the attitude control, which has never before been implemented on a spacecraft. FAST-D will also serve as test platform for several space-based computing demonstrations such as onboard processing of scientific data and distributed computing between two satellites. Lastly, the scientific payloads of FAST-D, both designed for inter-planetary missions, are specially modified for this mission to increase science output and limit their impact on the overall spacecraft design.

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