Dutch Micro Systems Technology for the Next Generation of Small Satellites

Gill, E.; Monna, G.L.E.; Scherpen, J.M.A.; Verhoeven, C.J.M.

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DUTCH MICRO SYSTEMS TECHNOLOGY FOR THE
NEXT GENERATION OF SMALL SATELLITES

E. Gill, G.L.E. Monna[+], J.M.A. Scherpen[‡], C.J.M. Verhoeven[*]

Chair of Space Systems Engineering (SSE), Faculty Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, e.k.a.gill@tudelft.n

[+]SystematIC design B.V., Motorenweg 5G, 2623 CR Delft, The Netherlands

[‡]Faculty of Mathematics and Natural Sciences (ITM), University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

[*]Chair of Electronics, Faculty Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands

ABSTRACT

Advanced microelectronics and Micro Systems Technology (MST) enable an increased functional performance of small satellites with decreased demands on mass, size and power. The research and development cluster MISAT stimulates the design and development of advanced small satellite platforms based on MST aiming at innovative space and terrestrial applications. Focus of research and development is on MST-based bus and payload components as well as on satellite architecture and distributed systems in space. MISAT is part of the Dutch MicroNed program which has established a microsystems infrastructure to fully exploit the MST knowledge chain involving public and industrial partners alike.

Rapid in-orbit demonstration of MST onboard satellites is an accompanying objective of the research cluster. To that end, the first satellite to demonstrate technologies developed within MISAT is the Delfi-C3 nano-satellite of the Delft University of Technology. The satellite will demonstrate, from 2008 onwards, operations of the next generation of Sun sensors, power subsystems and satellite architecture technology.

INTRODUCTION

The rapid advance of microelectronics and Micro Systems Technology (MST) is nowadays of major relevance in the application fields of automotive industry, medicine, communication and control as well as chemistry[1]. Gradually, MST is starting to penetrate also space systems[2] with the prospect to increase the functional performance of small satellites and to decrease demands on mass, size and power. This trend can significantly contribute to enhanced new space missions in the future involving complex distributed systems in space which may even revolutionize traditional concepts of space missions or spacecraft architectures.

However, the introduction of MST for space applications still holds a series of major threats.

Modeling tools for micro-systems are still in their development phase and micro-machining of devices poses severe challenges on processes and materials. Moreover, qualification of MST-based sensors or actuators for space applications is largely lacking due to the harsh mechanical, thermal and radiation conditions during launch and operations in the hostile environment of space.

MISAT is a research and development cluster to address these opportunities and threats. It is part of the Dutch MicroNed program funded by the Dutch government in the context of the "Besluit subsidies investeringen kennisinfrastructuur" (BSIK)[3]. The overall MISAT mission is the advancement and dissemination of MST and fundamental knowledge for space-oriented science and technology. In particular, the goals are to

- demonstrate the power of MST by executing forefront science leading to a next generation of micro-satellites,
- develop and deploy highly capable MST systems,
- coordinate, combine research efforts and encourage interaction to take advantage of the synergies amongst the partners.

In MISAT, four universities (TU Delft, University of Twente, TU Eindhoven, Rijksuniversiteit Groningen) and a number of industrial and research institutions cooperate to cover a broad area of physics and engineering subjects[4]. MISAT is structured into four work packages (spacecraft bus, payload, architecture and distributed systems) comprising a total of 22 research projects and involving some 18 PhDs.

SPACECRAFT BUS

The MST developments for the spacecraft bus within MISAT are primarily related to sensors for micro navigation, autonomous wireless sun sensors, re-configurable radio frequency front ends, and autonomous and distributed guidance and control.

The development of sensors for micro navigation is emphasizing accelerometers and

gyroscopes. The objective is to develop fully integrated and simplified packed sensor systems with read-out and self test using a minimum number of additional processing steps. While early accelerometers were fabricated using bulk micromachining and used mainly wet anisotropic etching, MST can provide almost comparable accuracy at much less mass. Also, advanced read-out techniques including piezo-resistive, capacitive, resonating and optical are considered while optical readout appears to be most suitable for devices operating in a high radiation environment.

An autonomous wireless sun sensor has been developed as part of MISAT (cf. Fig. 1). It uses a local solar panel to generate the power for autonomous operations. The sensor data is processed locally and the sun direction information is forwarded from the sensor to the onboard computer using wireless communication. Thus, the sensor requires no cables which is not only relevant for mass savings but also for improved flexibility and eased integration. Further technological challenges relate to the development of miniature digital sun sensors with a high accuracy potential, offering at the same time major advantages like low mass, low power consumption and high robustness for operations in the hostile space environment (e.g. resistance to cosmic rays, compatibility with a wide temperature range).

Communication plays a vital role for all spacecraft. Nowadays, a variety of radio front-end architectures exist and many parameters can, in principle, be varied in any of these architectures. However, typically only a few parameters of a fixed architecture can be varied at run-time. Therefore, current radio front-ends are mostly designed for worst-case scenarios resulting in high power consumption. A novel approach is investigated within MISAT which intends to overcome these problems by deciding on the architecture and all parameters at run-time. Recent advances in microelectronics enable the design of integrated radio-frequency (RF) circuits that contain the re-configurable hardware. The advantages of re-configurability are

- minimum power consumption,
- optimally matched architecture for given channel conditions,
- reconfigurable front-end for new applications.

The research involves both the RF-circuits and the control algorithms. A reconfigurable system may , however, reconfigure itself in an undesired state due to some system error. Therefore reliability will be investigated extensively in this project.
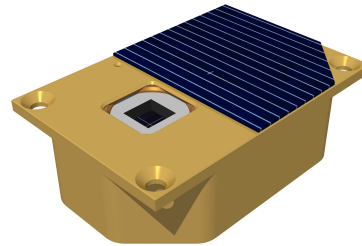

Fig. 1 Autonomous Sun Sensor (© TNO).

MST can also contribute to novel ways of docking between spacecraft using, e.g., micro-cilia. This approach is investigated in a project entitled "Adaptive neural control for micro-satellite precision docking based on MEMS actuator arrays with uncertain nonlinearities". The objective is to investigate the feasibility of a MEMS-based space precision docking system for micro-, nano- or pico-satellites. The application of micro-moment generation actuation devices using MEMS technologies in precision satellite docking has certain drawbacks, due to its high sensitivity to variations of environmental conditions, and their nonlinear and partly unpredictable properties. The objective is to develop an adaptive docking controller which can autonomously learn to compensate for, and correct the effects of these unknown mechanical imperfections of MEMS devices.

SPACECRAFT PAYLOAD

Within MISAT, various payload systems are developed with a clear focus on the minimization of volume and mass and on minimized and efficient use of satellite resources.

In this context, two projects are related to Global Positioning System (GPS) technology which is more and more applied in space for scientific purposes in addition to its traditional use for navigation. Examples of scientific GPS-based applications include signal reflectometry to characterize the ocean surface or ionospheric research. The project "Relative Navigation" applies concepts such as the space-borne differential Global Navigation Satellite System (GNSS) at triple frequencies to notably improve the identification of systematic measurement errors and degraded data points. These concepts are in turn applied to the development and implementation of GNSS-based relative navigation concepts. Specific topics addressed are the performance requirements on the GNSS receiver in relation to the required relative positioning accuracies, the strategies and the software algorithms for the processing of raw navigation data, and the simulation of the achievable relative position between two

spacecraft in a low-earth orbit at baselines between some ten to a few hundreds of km. This project provides input to the project "Re-configurable triple frequency GPS receiver", or "GPS receiver" in short. The latter project has a strong background in micro-electronics technology and intends to develop integrated circuits for GPS receivers which allow a flexible adaptation of their performance according to the specific temporary mission needs. Depending on these needs, a singe, dual of triple frequency mode can be turned on or off. Additionally, the receiver performance can be tuned depending on the user needs and the available satellite resources such as onboard power. In science mode, high accuracy and more power may be needed than during routine operations. Thus, a minimum demand on satellite resources is achieved while always keeping optimal performance. Advanced design techniques and commercially promising technologies will be used to realize this design taking into account the requirements for operations in space.

Two other projects concern the development of micro cooling systems for an application in micro-satellites. Miniaturized sensors that need cooling, e.g. low-noise amplifiers, super-conducting circuitry, or infrared detectors, can only be successfully applied in micro-satellites when the cooling system is also miniaturized and compatible with the satellite resources. The project "Micro Cooler" focuses on thermal subsystems and micro cooling for micro-satellites and high-frequency oscillating flow to meet these demands. The applicability of micro machining techniques is explored in the realization of cooler components with the long-term target of "on-chip" active cooling of micro-devices. The absorption-based coolers focus on a design without moving parts except for a few check valves and a circulating working fluid. As a result, they show a minimum of vibrations and, in addition, they have a potentially long lifetime. Scaling to small dimensions makes the cooler very attractive for cooling of vibration-sensitive detectors in micro-satellites.

To achieve on-chip cooling, a versatile interconnect between the micro cooler and the micro system is required. To investigate this, the project "Fluidic interconnects" tries to develop a micro fluidic interconnection technology that mimics the electronic printed circuit board in ease of use, reliability, and versatility, and can accommodate active components as well as coupling to other micro fluidic units and macroscopic equipment. Bond micromachining seems to be ideally suited to perform this task. It is a two-wafer process in which a fluidic channel is formed at the interface of two bonded wafers. Trenches and through-wafer holes are etched in one of the wafers and bonded with another

wafer to seal the trench. This technology is also considered and tested for micro propulsion applications.

The project "Micro Accelerometer" focuses on the development of micro-machined sensors that can replace the bulky accelerometers or gradiometers that are presently used in space application and that cannot be accommodated in small satellites. Floating test masses are considered using electrostatic force feedback. Advanced electronics is developed for sensor readout.

The project "Facility sharing" provides access to space-related facilities for prototyping and technological support. An example is the Delft Aerospace Rocket Test Stand (DARTS) cf. Fig. 2. The project is closely related to activities described under the header IN-ORBIT DEMONSTRATION below.

SATELLITE ARCHITECTURE

MST has a direct and strong impact on the spacecraft bus and its payload. It triggers, at the same time, novel approaches to satellite architectures which can provide at least the same level of improvement as for the bus and payload. Areas of improvement are mass and power savings, flexibility in integration and operation as well as robustness and enhanced functionality.

Despite a continuous miniaturization of spacecraft components, the physical architecture of space systems is still characterized by interfaces which remain of almost constant size, mass and energy use. The project on "System Architecture" concentrates on a radically different approach intended to lead to the miniaturization or even complete elimination of conventional data interfaces. The objective is to provide a fault tolerant and reliable wireless data handling system for spacecraft. To this end, a wireless sensor and actuator network tailored to a micro-satellite sample application will be established as a software model as well as a breadboard. Challenges in research are real-time communication and power management, signal-interference and fading, as well as distributed task management[5].

A paradigm change from conventional spacecraft architectures to wireless intra-spacecraft communication necessitates ubiquitous power generation at signal transmitters and receivers. A challenging innovative approach for decentralized power generation and distribution is based upon power scavenging and RF data transfer. Within the project entitled "Reduction of size, mass, power", focus is given to power scavenging.

Scavengers are power generators that recycle energy available in the ambient. This characteristic makes them particularly suited as power sources in autonomous sensor networks. For space applications, optical scavenging using on-system solar cells is the most conventional method. Thermo-electric energy scavenging has been demonstrated for use in sensor nodes with a power consumption in the range of a few milli-Watts.

The project "Software System Architecture" explores intra- and inter-system simulation using mobile ad hoc networks (MANET). Here, the cooperation of multiple cross-layers must be guaranteed based on specific scheduling mechanisms. Furthermore, routing protocols applicable to micro-satellites are developed since current internet protocol (IP) layer and Media Access Control (MAC) layer protocols are not suitable for micro satellite network due to their high consumption of system resources. Developments are validated using simulators such as the Network Simulator 2 (ns-2) demonstrating that multiple cross layer designs achieve their own goals under the scheduling framework.

Research on innovative aerospace material is concentrated within the MISAT project on "Damage-tolerant aluminum alloys". The objective is to conceive, manufacture, characterize and test a shape memory alloy (SMA) particulate reinforced aluminum matrix composite to achieve strongly improved properties (mainly mechanical) as compared to the aluminum matrix. The scientific approach covers an integral study on the mechanics, kinematics, dynamics and thermodynamics of martensitic transformation. The composite material will be tested for improved strength, fatigue resistance, and damping behavior. Hot extrusion has been proven as a suitable method for producing shape memory alloy reinforced aluminum composite.

"Smart power" is the second project under the work package Satellite Architecture which deals with power systems. The current focus is on the analysis of various methods for maximum power point tracking (MPPT) for micro-satellite applications. Taking the avoidance of single point failures as a major design driver, the architecture of the power system has recently been changed from a centralized into a distributed power system.

DISTRIBUTED SYSTEMS

This work package is primarily focused on the research and development of distributed sensor and actuator microsystems including the development of novel formation flying
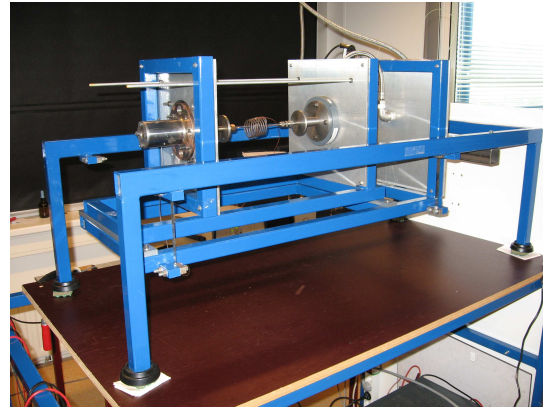

Fig. 2 Delft Aerospace Rocket Test Stand (DARTS).

algorithms. One of the significant challenges to successful formation flight of micro-satellites is the formation keeping, i.e. the control of the motion of individual spacecraft to maintain the overall formation. This includes both stabilization of a given formation as well as configuration or reconfiguration of the formation. Effective micro sensors and micro actuators in combination with distributed decentralized control strategies have to be developed in order to minimize fuel consumption during formation flight. Additionally, distributed sensor and actuator micro systems aim at improving e.g., earth observations, weather forecasting, and planetary research through the use of micro systems. In particular, the work package researches and develops MEMS based sensor technology, micro propulsion units, MST-based formation flying control algorithms and modeling and control algorithms of flexible and inflatable smart structures for a micro satellite.

The developments in the work package are divided into four topics. Firstly, the autonomous formation flying guidance and control for multiple satellite constellations project focuses on

- developing planning algorithms for clusters of several to many satellites

- developing autonomous guidance and control laws applicable to low impulse bit electric propulsion

- developing distributed estimation algorithms for relative navigation systems of multiple satellites clusters.

The project's major subject is sequential decision making under uncertainty (stochastic control). The objective is to select a decision making rule (feedback policy) that optimizes a certain performance criterion. Reinforcement learning and interval analysis are applied tools to solve this optimization problem for an improved behavior of formation flying.

Secondly, the project "Multi-sensor" focuses on the development of different sensing
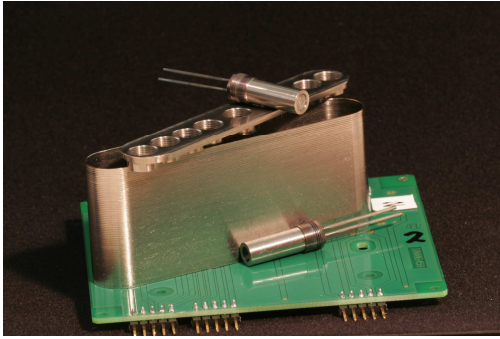
Fig. 3 Plenum, plate, gas generators and electrical interface before assembly – © H.J. Siemer (TNO).

Fig. 4 Exploded view of the Delfi-C^3 three-unit CubeSat of the Delft University of Technology.

measurements onboard of a micro satellite, being distance sensing (e.g. for formation flying), gravity and magnetic field sensing. Distance sensing involves the position determination of the various micro-satellites of the constellation with respect to each other and the sensing concerning a reference point. While the sensing techniques are already rather well developed, improvements in miniaturization are studied and being realized. Within magnetic field sensing, focus is on optically pumped magnetometers and technologies employing nonlinear magneto-optical rotation (NMOR) for miniaturized sensors.

Thirdly, micro-propulsion developments are of vital importance for MISAT. Micro thrusters can be applied for attitude and orbit control and to enable formation flying. Two types of micro-thrusters are being considered

- Cold gas thrusters, possibly in combination with resistojet
- Monopropellant thrusters using catalytic decomposition (e.g. hydrogen peroxide or hydrazinium nitroformate (HNF) or ammonium dinitramide (ADN) based monopropellants).

The micro propulsion developments are done by three closely collaborating project teams at TNO, University of Twente, and Delft University of Technology. A newly designed micro-propulsion system using cool gas generators is currently being fabricated[6] with a minimum impulse bit of 5 mNs working at a thrust level of 100 mN (cf. Fig. 3). The technological developments are MEMS based.

Finally, modeling for control of distributed systems is studied by two project teams at Delft University of Technology and University of Groningen. Inflatable structures for micro-satellites are being investigated taking advantage of current state of the art membrane material with distributed piezo actuation which makes distributed control feasible. Two new control methodologies are being developed for shape control of inflatable space mirrors by means of an array of micro sensors/actuators. The key research topic is the control
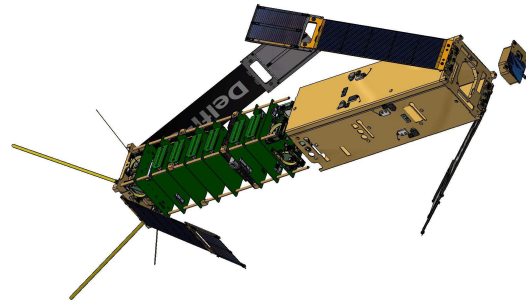
performance and robustness that can be achieved by distributed control methodologies as compared to a centralized controller. A model-based controller has been designed to investigate robustness with respect to failures in individual sensors, actuators, and modeling errors.

<u>IN-ORBIT DEMONSTRATION</u>

MISAT aims, in addition of being a research and development cluster, at a rapid in-orbit demonstration of developed technologies. In this context, the development of the Delfi-C^3 satellite (cf. Fig. 4) was a very important achievement.

Delfi-C^3, a nano-satellite with a mass of 3 kg, is the first Dutch university satellite and has been developed by students and staff of the faculties of Aerospace Engineering and Electrical Engineering, Mathematics and Computer Science of the Delft University of Technology. It will act as a technology test-bed for three payloads: Thin Film Solar Cells (TSFC), an Autonomous Wireless Sun Sensor (AWSS), and a radio-amateur, nano-satellite-based Ultra-High Frequency (UHF)/Very-High Frequency (VHF) linear transponder. The satellite has been delivered in August 2007 to the launch broker and is awaiting, at the time of writing, its launch onboard a Polar Satellite Launch Vehicle (PSLV) from India.

Delfi-C^3 benefits from MISAT especially through the projects "Micro Sun Sensor", "RF frontend", "Facility sharing", "System Architecture" and "Smart Power". With this satellite, an attractive way to test newly developed space technology has become available. It provides also valuable input for the projects on the exact constraints that a micro-satellite sets on various systems. Delfi-C3 is considered as first nano-satellite in a series of Delfi nano- and micro-satellites[7] which will employ ever increasing contributions from MISAT for small satellite pre-qualification. While the successor of Delfi-C^3 will be a single satellite, the mid-term objective is a full-fledged formation flying mission making use of small micro-satellites.

SUMMARY AND CONCLUSIONS

MISAT is a unique research and development cluster for innovative MST-based space technology. Research and development are performed in more than 20 projects centered around four major areas of spacecraft bus and payload, as well as spacecraft architecture and distributed systems. Key achievements have been made up to now in the fields of spacecraft autonomy, flexibility and mass and power savings.

A rapid technology pre-qualification has been achieved with the development of the Delfi-C^3 nano-satellite which will continue through a series of future satellites including a formation flying mission for advanced technology demonstration and novel scientific applications.

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