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Networked Control of Cooperating Distributed Pico-Satellites

Klaus Schilling

Julius-Maximilians-University Würzburg, 97074 Würzburg, Germany
(Tel: +49-931-318 6647; e-mail: schi@ informatik.uni-wuerzburg.de).

Abstract: In spacecraft engineering a paradigm shift is emerging with the tendency from traditional, single, large, and multifunctional satellites towards cooperating, distributed small spacecraft systems. In particular modern miniaturization techniques allow realization of satellites with continuously smaller masses, and thus enable cost-efficient implementation and launch of distributed multi-satellite systems. This raises challenges in control approaches at each individual spacecraft by required compensation of limitations and of increasing noise effects due to miniaturization of the satellite components. The higher noise susceptibility is to be counterbalanced by filtering and robust control approaches on-board. At the level of formation control, innovative orbit control approaches for multi-satellite networks based on relative position and attitude control of each satellite are to be developed. This contribution addresses related technology approaches, which have been tested with UWE-satellites in orbit, and reports about the obtained performance results.

1. INTRODUCTION

Similar to the evolution in Computing, where the traditional mainframe computers of the 70ies have been replaced by the internet connected laptops or smart phones, also in spacecraft system design the established multifunctional large spacecraft are expected to become in specific application areas complemented or substituted by networked small satellites. In this context control technologies play a key role in order to keep several cooperating spacecraft in a formation, suitable to perform joint observations in multi-satellite systems (Alfriend et al. 2010, Lyke 2012, Schilling et al. 2011, Sandau et al. 2012, D´Errico 2012, Schilling et al. 2012).

In the University Würzburg's Experimental satellites (UWE) program (Schilling 2006, Schilling et al. 2012), already two satellites at only 1 kg mass have been placed in orbit to demonstrate key components for formation flying, like communication on basis of Internet Protocols (UWE-1, launched 2005) (Barza et al. 2006), attitude determination (UWE-2, launched 2009) (Schmidt et al. 2009) and attitude control (UWE-3, launched 2013) (Bangert et al., 2014). Thus, necessary sensor inputs as well as related data exchange approaches had been established. As next step research emphasis was placed on actuators and related control functionalities, providing the main topics of this contribution. After its launch on 21.11.2013 UWE-3 successfully performed attitude control experiments, based on integrated magnetic torquers and one reaction wheel (Bangert et al. 2012, Bangert et al. 2014). At the end of 2014 UWE-4 it is planned to emphasize orbit control by an electric propulsion system on basis of vacuum arc thrusters (Kronhaus et al. 2013) in order to complete the necessary technology basis for pico-satellite formation flying.

The basis for formation control is based on combination of optimal control strategies for coordination of relative motion with a robust flow of information in the network of satellites and ground stations, implemented via delay tolerant networks and ad-hoc networks (Schilling / Schmidt 2012). Thus, crucial interdisciplinary control engineering challenges include distributed, embedded, mechatronic, and networked systems.

Distributed satellite networks will enable innovative approaches in areas like Earth observation, scientific exploration and telecommunications. In particular, significant application potential is foreseen for future satellite services in Earth and Space Weather observations based on multipoint measurements.

Fig. 1. Artist impression of UWE-3 in orbit

2. THE UWE PICO-SATELLITE PROGRAM

The impressive progress in miniaturization of electronic systems impacts also reduction of mass for individual spacecrafts. As extreme case, complete satellites are realized as so-called pico-satellites at a mass of only 1 kg. In order to enable pico-satellite formations at the University Würzburg's Experimental satellites (UWE) program (Schmidt / Schilling 2010) a technology roadmap was established. Here the technology objective is integration of all essential functionalities for sensors, control and data processing, as well as actuators at minimum mass. If possible we will try to realize a formation of satellites at the 1 kg mass level.

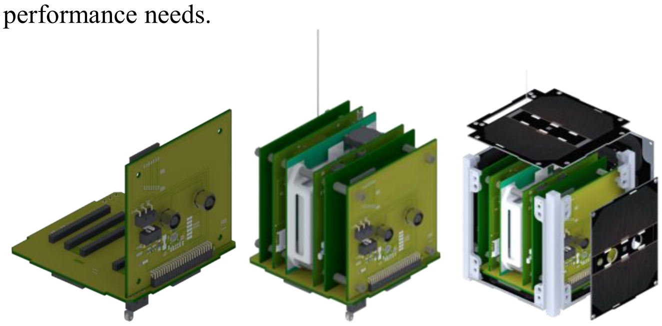
2.1 UWE-1 and -2

The first German pico-satellite UWE-1 (launched 2005 by a Russian Cosmos 3M) was developed in University Würzburg for communication experiments in order to optimize Internet Protocol (IP) parameters with respect to the encountered space environment (Schilling 2006). The scientific objective to provide an attitude determination capability with UWE-2 (launched 2009 by an Indian PSLV rocket) was addressed by a GPS, inertial MEMS-sensors, Sun sensors and magnetometers providing inputs to sensor data fusion on basis of a Kalman-filter (Schmidt et al. 2009).

2.2 The UWE-3 Satellite Design

The main scientific objective for UWE-3 was realisation of attitude control and of a modular spacecraft bus, which is suitable for future UWE multi-satellite missions due to its flexibility to adapt it to specific mission needs. This was specifically addressed by the UWE-3 satellite bus design emphasizing flexibility and modularity (Busch et al. 2012). Its outer structure layout is compliant with the classical CubeSat design specification of a 10 cm cube with four parallel rails at the edges (see Figure 2). The classical subsystems, like power, on-board data handling, communication, attitude determination and control, are placed each one on a dedicated PCB. A complementary inner structure is realized by titanium screws fixing the PCBs in the four corners at fixed positions and providing the only contact to the outer structure. Thus this design is in parallel also part of the thermal layout.

The UWE pico-satellite electrical system uses a backplane, eliminating all wiring. All subsystem PCBs are in contact to the backplane with standardized connectors (see Figure 2). It offers digital interfaces like SPI or I^2C, as well as power interfaces at different voltage levels. Several general purpose lines and dedicated signal lines for reset or debug support are provided by this bus. This backplane approach thus offers scalability and flexibility to replace subsystem boards to adapt to future technology advances and increasing performance needs.



(a) (b) (c)

Fig. 2. The UWE architecture is based on the backplane at the bottom, which accommodates all individual subsystem boards (as visible in configuration (b)). Outer structure rails in the edges and side panels complement the satellite (cf. (c))

The evaluation of the attitude control capabilities in orbit is based on an efficient combination of magnetic torquers mounted on the inner side of all side panels (see Figure 3) and one reaction wheel (see Figure 4) (Bangert et al. 2012, Bangert et al. 2014). Each side panel (accommodating the solar cells on the outer side) also hosts a sun sensor, and a single axis magnetometer (cf. Figure 3). The central on-board data processor, together with MEMS gyroscopes and magnetometers, is placed as a dedicated Attitude Determination and Control System module (ADCS) on one of the subsystems boards. The magnetic torquers thus control attitude relative to the Earth's magnetic field lines, covering two degrees of freedom. The remaining axis is controlled by one miniaturized reaction wheel, enabling rotation of the satellite around the axis oriented in direction of the magnetic field line. Thus by attitude control activities performed at appropriate timing, all desirable pointing directions can be achieved within one orbit revolution. The inputs are generated by an attitude determination system, based on sun sensors, gyros, and magnetometers, as tested in the UWE-2 mission (Schmidt et al. 2009). By an extended Kalman filter the misalignments in attitude are detected and then corrected by the described actuators.

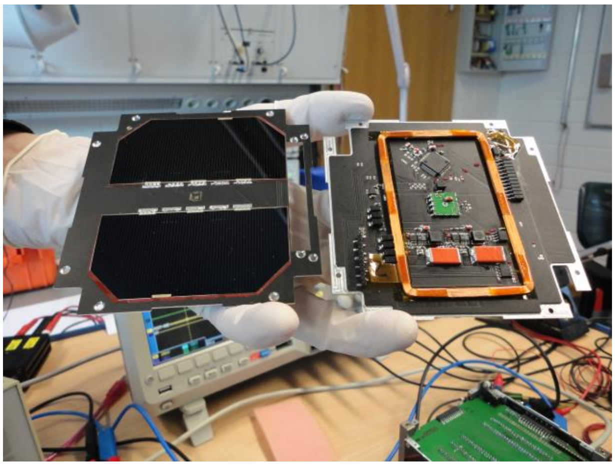


Fig. 3. Integrated magnetic torquers on the backside of the panel with the solar arrays.

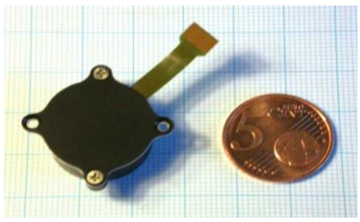


Fig. 4. The UWE-3 very small reaction wheel

The performance of this approach has been extensively tested on ground by dedicated equipment. Here the small satellite mass enables a very efficient approach for simulations of most in orbit scenarios. To test the performance of the actuators (six magnetic torquers and the reaction wheel), UWE-3 is placed in a ball floating on an air cushion (Fig. 5). Magnetic field forces are generated and can be varied by the two external magnetic coils. For attitude determination tests a miniature turntable with one degree of freedom was used in combination with a sun simulator (Fig. 6). This way the attitude determination and control functionalities were intensively tested.

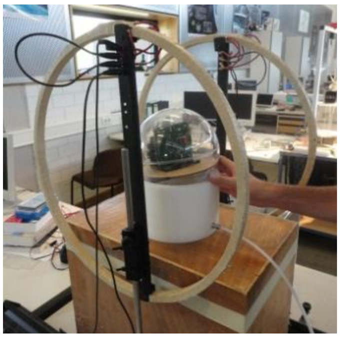


Fig. 5. Attitude control tests of the magnetic torquers, to characterize in interaction with external magnetic coils the performance.
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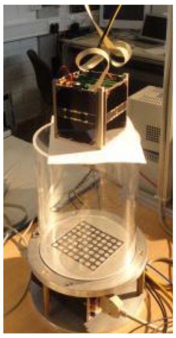

Fig. 6. Turntable to test along one axis the attitude determination properties.

2.3 The UWE-4 Mission

Technology development in electrical propulsion systems, in particular on micro-arc thrusters (Kronhaus et al. 2013), provides orbit control capabilities and is planned to be demonstrated in orbit end of 2014 by UWE-4. This satellite inherits most components from UWE-3, taking advantage of its modular design. In addition, it will include orbit control capabilities provided by an electrical propulsion system. Orbit disturbances on the different formation members cause drift effects, which need to be corrected to keep the satellites together. Assessment of required correcting forces has been derived from drift observations of UWE-2 and its 3 passive CubeSat companions. Micro-arc thrusters (see Figure 7) comply with demanded forces, as well as with limited power and mass budgets of a pico-satellite. The cathode material is used as propellant to generate a plasma plume ejected by a velocity of up to 10^4 m/s. This propulsion system will be integrated in each of the four rails of the outer structure, which provides also the feeding material. By coordinated activation of the different thruster heads a momentum can be generated to provide in addition to orbit control also attitude control functionality.

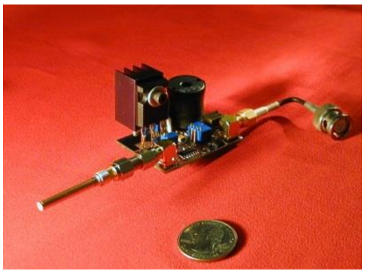

Fig. 7. UWE-4 vacuum arc thruster propulsion system

Laboratory tests have already started in order to test the performance of vacuum arc thrusters, and have provided promising results within the limited mass/power resources of a pico-satellite.
When these four missions are successfully completed, all essential technologies are in place to realize a formation, defined as a multi-satellite system with closed-loop control on-board in order to preserve topology as well as to keep relative distances and orientations according to plan.

3. ON-BORD DATA HANDLING AND CONTROL

The Onboard Data Handling (OBDH) is based on two hot redundant ultra-low power microcontrollers in master-slave configuration, which is dynamically supervised by a separate watchdog arbitration unit. The OBDH module is operating continuously. It consists of two redundant ultra-low power microcontrollers MSP430 16 Bit RISC mixed signal and of 256kB Program flash memory, as well as 16kB RAM, running at 16 MHz with a nominal power consumption of 15 mW. The external redundant watchdogs are based on toggle redundant microcontrollers (TWU). The OBDH includes latch-up protection, backup power control and housekeeping sensors for temperature, bus voltage monitors with alarm circuits, as well as precise temperature compensated real-time clock and redundant mass storage of two 32 Mbit Flash and an optional SD-Card. Cross connections like DMA support high speed communication. The active controller (master) can access the other one (slave) via its embedded emulation module (EEM) using the JTAG interface. This offers full control of the remote hardware, independent of the current state of the programmed software. Thus, it can be accessed and controlled or even completely reprogrammed for memory recovery or secure software updates after launch.

Fig.8. The Onboard Data Handling board with the two microcontrollers in hot redundancy

Testing hardware and software recovery mechanisms was realized by using Software Implemented Fault Injection (SWIFI) techniques. In order to enable SWIFI analysis of the OBDH a fault injector service was implemented in software. With the help of the memory map information, specified regions like RAM, TEXT, or even individual modules, functions or variables can be exposed to systematic fault injections. The script further monitors the core module, logging events like reset, system hangs, TWU toggle resets, PCU power cycles, etc. during the test execution. This way a highly reliable on board control system is realized, supervising and coordinating all subsystems.

4. UWE-3 IN-ORBIT TEST RESULTS

On 21.11.2013 a Dnepr-rocket launched from Yasni (Russia) delivered 32 satellites in a sun-synchronous orbit in about 700 km altitude, including UWE-3. All systems and commercial-of-the-shelf components on-board are now, 4 months later, still at good health and performing very well.

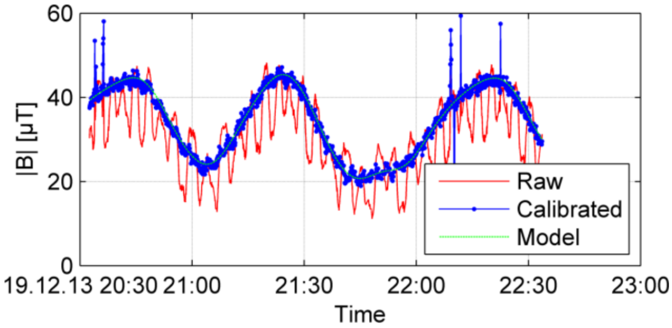

Fig. 9: Magnetic field determination: in red the measurement raw data, in blue after calibration

For attitude determination with the magnetometers the power flows inside the satellite generate significant noise effects in addition to sensor noise, model deviations and calibration inaccuracies. Therefore attitude and sun sensor raw data are processed in ECI coordinates and a filter comparing these with a magnetic field model (such as IGRF-11) is carried out. Until today 52.000 magnetic field measurements have been recorded, serving as basis for the post-processing step.

Initially, after separation from the upper stage, the satellite was spinning at a rate of 23 deg/s about a random axis. The detumbling manoeuvre was an interesting test case to demonstrate the capabilities of the attitude control by the magnetic torquers. Using a B-Dot controller the satellite was decelerated from its initial spin rate of 16.5 deg/s to about 1 deg/s within 7 minutes (cf. Fig. 10). .

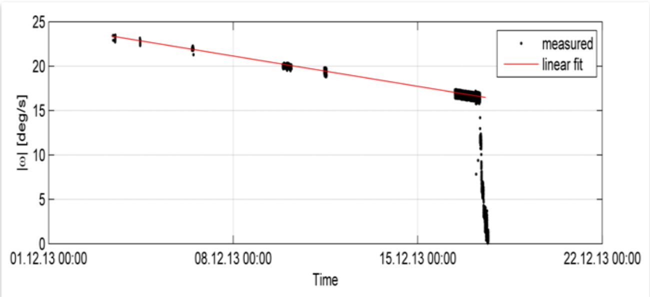

Fig. 10: Detumbling manoeuvre displaying the satellite's spin rate

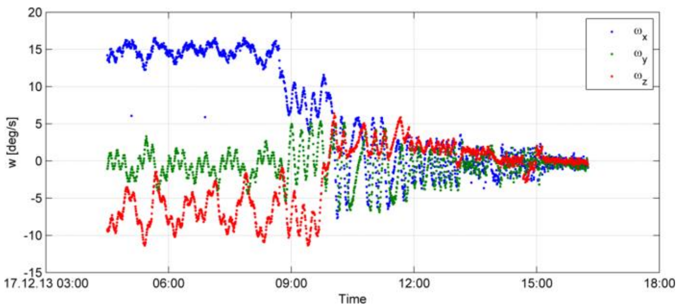

Fig.11: Rotation rates in x-, y- and z-axis during the detumbling manoeuvre

As the satellite generates control torques in all three axes during one orbit, a balanced decrease in all axes resulted.(cf. Fig 11).

5. COMPLEMENTARY TECHNOLOGY STUDIES

On-going studies address complementary technologies needed to establish a distributed networked satellite system of four satellites in NetSat. This includes the inter-satellite data exchange needed for cooperating multi-satellite systems (Schilling / Schmidt 2012). The system of four satellites will be employed for experiments to test autonomous adaptations of link protocols to take into account interruptions and changing topologies in this high dynamical environment. Communications concepts for the integrated satellite and ground station network are evaluated (Schmidt / Schilling 2012). Approaches include Internet Protocols (IP), delay tolerant networks (DTNs) and mobile ad-hoc networks (MANets) adapted to the specific space environment conditions (e.g. high noise levels, link interruptions, interferences, radiation, inaccuracies in pointing).
Relative navigation between the satellites in the formation is another key innovation field. Alternative sensors for measurements of relative distances and orientations between the satellites are analysed and compared in preparatory tests with mobile robots on ground. Sensor data fusion is practised with the measurements from different observers to generate a consistent and robust overall estimate of relative position and pointing direction of each satellite. This way application scenarios for satellite formations in Earth or Space Weather observation are to be prepared.

6. CONCLUSIONS

In the UWE pico-satellite program the key technologies to realize distributed networked multi-satellite systems are addressed. So far, UWE-1 to -3 tested in orbit communication, attitude determination and control, as well as the crucial miniaturisation and software technologies to enable appropriate functionalities at the limited power and mass budgets of a pico-satellite in the 1 kg range. Thus sequentially the critical functionalities for the long-term objective of formation flying are integrated and tested in orbit. UWE-3 demonstrated in-orbit the performance of the actuator design based on six magnetic torquers and one miniature reaction wheel. In addition, a modular, flexible satellite bus concept provides the hardware basis for future missions. End of 2014 UWE-4 will test a micro arc thruster electric propulsion system, finalizing in-orbit demonstration of all crucial components to maintain a robust pico-satellite formation despite perturbations. This will be tested in-orbit by the "NetSat"-mission composed of four pico-satellites. Thus, the technology basis will be ready for innovative multi-point data acquisition with significant application potential in future Earth and scientific observation missions.

Acknowledgments

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