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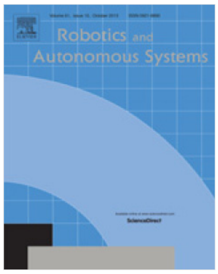

Perspectives for miniaturized, distributed, networked cooperating systems for space exploration

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Perspectives for Miniaturized, Distributed, Networked Cooperating Systems for Space Exploration

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Abstract. Space exploration raises challenging autonomy requirements due to significant signal propagation delays and data transmission interruptions in real-time critical situations. This is exacerbated by poorly known working environments and high noise levels. Currently a paradigm shift from traditional large multifunctional spacecraft towards networked formations of distributed small spacecraft is emerging. This places even more emphasis on related research topics for autonomous reactions, in particular

- real-time failure detection, identification and recovery on-board, as miniaturization increases susceptibility to noise effects,
- networked control of the multi-satellite system, requiring integration of attitude and orbit control with the communication in order to be tolerant to interruptions of the link,
- coordination inside the formation for guaranteeing continuous payload measurements, as well as safe operations guaranteeing collision avoidance.

The required increasing autonomous on-board control and coordination capabilities are outlined, as well as the cross-fertilization to mobile robots, despite different dynamic properties are underlying. Crucial key functionalities shared are relative navigation, robust data processing, electric miniature actuators, antenna pointing capabilities in order to achieve innovative cost-efficient, fault tolerant, distributed small satellite designs.

Key words: small satellite, formation, distributed system, robustness, FDIR, cooperative control.

1 Introduction

Spacecraft are just mobile robots operated at far distances in a very specific dynamic environment, mainly determined by gravity. Recent trends emphasizing in spacecraft engineering the field of vehicle formations and miniaturization might cross-fertilize the link to terrestrial robotics, where similar demands challenge autonomous reaction capabilities. In space applications autonomy is often unavoidable, as required real-time reactions to uncertain environments cannot be handled by a tele-operator due to the signal propagation delay related to the huge distances and due to noisy communication links.

As in most mobile systems also in spacecraft design miniaturization is crucial to increase efficiency. While in mobile robots energy constraints drive the decrease of mass, spacecraft launch costs are proportional to mass. Thus spacecraft design is currently revolutionized by miniaturization. The accompanying disadvantages, like higher susceptibility to noise, are to be compensated by software providing capabilities to autonomously detect and correct deviations.

During the last 10 years mainly Universities pioneered technologies for very small satellites (cf. [31], [22], [25], [26], [4]). Thus the first pico-satellites were only launched since 2003, but in the two years 2013/14 already more than 200 pico-and nano-satellites have been placed in orbit. Nowadays pico-satellites (at a mass of about 1 kg) and nano-satellites (at a mass of about 10 kg) are entering first commercial applications [33], [18] in fields like

- Earth observation: with a volume of 30 cm x 10 cm x 10 cm a constellation of satellites provides a high temporal resolution Earth surface coverage at an image resolution of 5 m [12], [8],
- Telecommunication: several consortia plan a worldwide network of several hundred small satellites in order to provide Internet access everywhere (http://spectrum.ieee.org/tech-talk/aerospace/satellites/spacex-raises-1-billion-from-google-fidelity-for-satellite-internet-project),
- Space weather observations: NSF and NASA initiated a very successful program for CubeSats, for measurements in different electromagnetic bands [19],
- technology testing, in order to test software and operational procedures ESA initiated realization of OPS-SAT, a 3 kg CubeSat [9].

Fig. 1: The pico-satellite UWE-3 providing a fully functional spacecraft at 1 kg mass.

Miniaturization of electronic components increases in the harsh space radiation environment the sensitivity for noise effects. This challenges the software functions in order to compensate and correct occurring defects at the level of each single spacecraft. Nevertheless the small satellite concepts exhibit full potential when inherent limitations are overcome by combining them to decentralized cooperating spacecraft systems. This requires innovative adaptations of networked control approaches to the specifics of the space environment. As there are more frequent launch opportunities for small satellites, faster reaction on lessons learned from previous mission accelerate technology innovation cycles significantly.

In the context of space exploration autonomous reaction capabilities are referred as:
Definition Spacecraft Autonomy
Autonomy is the capability of a vehicle

- to meet mission performance requirements for a specified period of time without external support,
- to optimise the mission product during this period within given constraints.

The "period of time" referenced here is typically correlated to unavoidable significant signal propagation delays in the contact with tele-operators in the ground control station on Earth, which can account for interplanetary missions to several minutes or hours. Mission products are usually the scientific instruments measurements characterizing the target environment. In particular lunar or planetary exploration missions offered challenging tasks and solutions in this context [23], [24].

In this contribution the following hypotheses and research directions in autonomous reaction capabilities related to distributed systems are anticipated:

- Spacecraft design will be driven by miniaturization
  advantages: launch cost reduction, faster deployment
  autonomy challenges: fault detection, identification and recovery in high noise radiation environments based mainly on software
- Traditional spacecraft architectures will be complemented by cooperating, distributed, networked, small multi-satellite systems
  advantages: sensor networks in orbit, higher spatial and temporal resolution in observations, graceful degradation in case of failures, cooperative observations, cost efficient approach, higher measurement quality by data fusion
  autonomy challenges: cooperation in of multi-satellite systems, coordinated attitude and orbit control, fusion of navigation data
- Relative navigation for safe collision avoidance in near range operations is possible
  advantages: near range formation flying for observations, space debris removal
  autonomy challenges: relative navigation, critical operations need to continue without ground control contact

These three problem areas, the current state-of-the-art, and related technology approaches for future improvements are discussed in the subsequent chapters.

2 Problem Scenarios and Technology Approaches

Here crucial fields for emerging new autonomous reaction demands in space are addressed related to fault detection, identification and recovery software, to coordinated networked distributed multi-satellite systems and to rendezvous & docking to passive objects.

2.1 Fault Detection, Identification and Recovery (FDIR) for Pico-Satellites

The hostile space environment requires appropriate preventions in order to guarantee a reasonable lifetime for satellites. Miniaturization usually increases related problems. Here an innovative FDIR-software based approach is presented.

2.1.1 The FDIR Scenario

The space environment is characterized by significant radiation noise effects, (such as single event upsets (SEU) and latching), having impact on reliable performance of the electronics (e.g. microprocessors, storage devices, communication system). In the UWE-3 mission in an altitude of 600 km every month such radiation events requiring a system restart is encountered. The traditional approach is to employ radiation-hard electronics based on stronger silicon layers. Thus this older technology is behind the state of the art in terrestrial electronics and less efficient. In addition metallic shielding as protection against radiation is applied. Both approaches reduce the probability for failures from radiation; nevertheless, noise effects cannot be completely avoided, but imply the negative effects of mass increases and reduced performance.

Here as alternative approach is proposed the employment of redundant low-power commercial-of-the-shelf chips, monitored by advanced software for fast detection and correction of failures. As modern chips are very power-efficient, hot redundant systems can even be realized within the limited power resources of small satellites.

2.1.2 In-Orbit FDIR Experiences by UWE-3

The ***U***niversity ***W***ürzburg's ***E***xperimental satellite UWE-3 realizes at 1 kg of mass all functionalities of a complete satellite (cf. Fig.1). It is based on an innovative modular and flexible electronic design approach by a backplane (BP) for all power and data lines, avoiding a traditional harness and wires to connect the subsystems (cf. Fig 2). The electrical design features a dual-redundant low power onboard computer (OBDH) [6], a redundant and scalable distributed electrical power system (POWER), a fully redundant UHF communication system (COMM) and an attitude determination and control system (ADCS) being capable of operating continuously on the small-scale pico-satellite [3], [5].

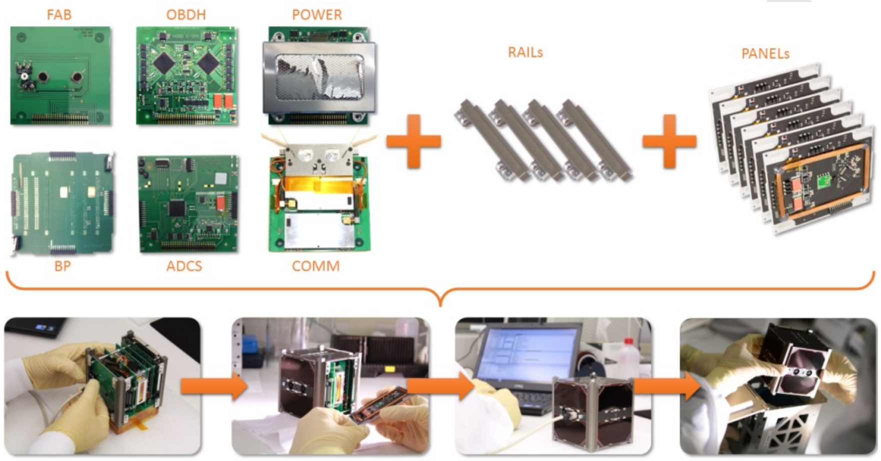

Fig. 2: Integration of subsystems and satellite components taking advantage of flexible modular design architecture

The OBDH core module plays a central role in the design of the UWE satellite bus as it is the only subsystem, which is continuously operating as a dedicated housekeeping module. Thus, the design is optimized with respect to robustness and energy efficiency. A dynamically priority adapted master-slave configuration is employed. It enables the instantaneous master module to maintain and re-program the slave via its embedded emulation module. Thus, the core module implements mutual flash protection and recovery capabilities in order to increase robustness against radiation deterioration. The utilized commercial-of-the-shelf (COTS) low-power consumption technologies are here very susceptible. With less than 10 mW nominal power consumption, here a most efficient redundant on-board computer design for pico-satellites [6] is provided.

Fig. 3: UWE-3 on-board data handling system with two redundant low-power consumption microcontroller units

The on-board computer is designed to be redundant and fail-safe by design. This is achieved by its mirrored hardware architecture. The micro-controllers are redundant, but also all the peripheries such as watchdogs, switches, flash memory devices and the micro-controllers' memory sections are built in a redundant configuration. The redundancy concept is completed by the interconnection of the two microcontrollers, which enables access even to an inactive micro-controller, independent from the state of its programmed software. Thus, the slave can always be accessed and controlled, but also completely reprogrammed, for memory recovery or secure software updates.

The advanced Fault Detection., Identification and Recovery (FDIR) software, implemented on both microprocessors and the watchdogs, has enabled continuous in-orbit operations for UWE-3 without any interruption since orbit insertion in November 2013 (at the time of writing for more than 2 years). It has been able to correct all encountered radiation effects (single event upsets as well as latches were detected). Related experiments are continuing and so far no performance degradations are visible.

Thus, the increased FDIR capabilities for autonomous corrections support usage of miniature commercial electronics in space, despite increased susceptibility to radiation. Related cost reduction and inclusion of high performance equipment will promote satellite technology evolution. Combination of these software FDIR approaches with traditional radiation hard technologies and shielding approaches offers perspectives for a broad spectrum of applications requiring highest reliability well beyond spacecrafts.

The UWE-3 electrical system design is complemented by a distributed power system implementation to assure that its performance scales with different satellite configurations and mission scenarios, while providing a high level of robustness. The redundant communication system of UWE-3 integrates two commercial UHF transceivers on a single subsystem board. Additionally, the board accommodates two independent monopole antennas. The UWE-3 attitude determination and control system uses magnetometers, sun-sensors, and gyroscopes for attitude determination [3]. The system controls the satellites attitude in all 3 axes using six independent magnetic torquers and a commercial single-axis miniaturized reaction wheel, intended for fast slew maneuvers.

Recent design approaches on fractionated spacecraft address functionalities distributed on several networked heterogeneous satellite modules, possibly even spread across different spacecraft in a formation [13]. In particular in data processing distributed computing and storage concepts are envisaged. Of particular interest would be a capability to guarantee mission-critical functionalities despite defects or degradations by sharing autonomously in real-time resources from the different satellites. It is expected that this way even a higher degree of robustness and flexibility could be achieved.

While the limited reliability and short lifetime was one of the major critics to spacecraft miniaturization, nowadays the achieved progress in combined hardware redundancy and FDIR-software approaches overcame these earlier deficits, and offer still potential for further improvements.

2.2 Towards Distributed Satellite Systems from Multifunctional Traditional Spacecraft

Terrestrial data processing encountered in the last 30 years a dramatic evolution from large mainframe computers towards the internet connected laptops of today. In mobile robotics multi-agents systems [8] these trends evolved, too, increasing related demands for autonomy in the coordination. In a similar way, there emerges currently a paradigm shift from traditional multi-functional large satellites towards distributed networked satellite systems [1], [21], [28]. These new concepts offer interesting application potential in Earth observation [7] and in telecommunications [27]. Thus innovative capabilities for multi-point measurements are enabled by a significant baseline distance between the instrumentation placed on the cooperating multiple satellites [1], [7], [27].

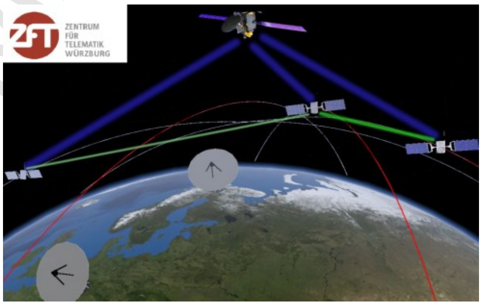

Fig. 4: Typical Network of cooperating multiple satellites and ground stations

2.2.1 The Distributed Networked Satellite Scenario

There are many multi-satellite *constellations* in orbit, where each satellite is individually controlled from ground. In case of a *formation*, the autonomous closed-loop control on-board has to preserve topology in the group and to control relative distances. So far only very few formations, limited to only two satellites and therefore addressing only a one-dimensional problem, had been realized (GRACE, PRISMA [20], TANDEM-X [14]). In formations, relative position and attitude are to be acquired before the control loop in-orbit can be closed for keeping the topology autonomously [28]. Here innovative electrical propulsion systems seem to provide breakthroughs as related pico-satellite actuators. Such autonomous real-time adaptation capabilities in-orbit will enable innovative approaches in areas like Earth observations based on multipoint measurements, scientific explorations or telecommunications. Advantages of multi-satellite missions for Earth remote sensing include a higher spatial and temporal resolution of observation data, as well as graceful degradation in case of failures

Miniaturization of traditional propulsion systems reaches efficiency limits for small satellites. Currently most promising are electrical propulsion systems as actuators for compensation of slow perturbations in the formation keeping of pico-satellites. Charged particles are accelerated in a magnetic field and ejected at high velocities. Nevertheless, due to the small propellant mass, the resulting limited impulse requires long thrust activities to achieve significant impact. In case of pico-satellite the satellite / propellant mass fraction is more favorable and thus is a promising candidate for orbit and attitude control [15]. In particular the drift in relative position resulting from perturbations needs to be corrected in a formation in order to keep the different satellites in the contact range.

By such propulsion systems also at the end of live the satellite should be injected into an appropriate graveyard orbit in order to satisfy the 25 years lifetime limitations for satellites. In case of anomalies autonomously such space debris avoidance strategies should be initiated.

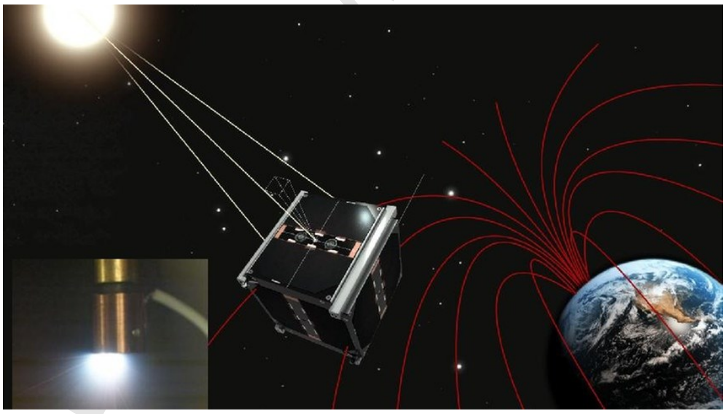

Fig. 5: The planned in-orbit demonstration of attitude and orbit control by UWE-4 based on an electric propulsion system (lower left corner during laboratory tests). Sun sensors and magnetometers are used for attitude determination, as well as magnetorquers and reaction wheels for attitude control.

A requirement for joint observations of surface areas and subsequent sensor data fusion are attitude control capabilities to coordinate pointing of the instrumentation towards same surface points. The related basis is provided by an infrastructure of attitude determination sensors, networked control activities and time synchronization between the different partner satellites. At the level of a single pico-satellite suitable attitude control capabilities have already been demonstrated in orbit by example by UWE-3 [3]. The next objective is to realize by networked control self-organizing, cooperating sensor networks for joint measurement activities in orbit.

A key ingredient for future distributed space missions is a high degree of autonomy. While in traditional space missions the communication is mainly treated as a point-to-point link between space vehicle and a ground station, the topology of future missions will be a network structure [29]. To operate such a sophisticated system with high dynamics, integrating the space and the ground segment, autonomous functions are vital. This will simplify operations of a large number of space vehicles compared to current individual spacecraft operations from ground control centers in a satellite constellation. Assisting functions for spacecraft operators will autonomously configure the space and ground network in order to set up the appropriate communication links.

2.2.2 Preparations of Demonstration Missions for Distributed Networked Small Satellite Systems

Multi-satellite constellations are already frequently used in a broad spectrum of applications, like telecommunications (including Iridium, Globalstar, TDRSS, Orbcom, Starsys), Earth observation (including Rapid Eye, Sentinel, Dove, SAR-Lupe, Disaster Monitoring Constellation), space exploration (including Cluster, Swarm) and navigation (including GPS, Glonass, Galileo, BeiDou, IRNSS, QZSS). Here there is so far no control via inter-satellite links installed for in-orbit coordination. With respect to a constellation composed of small satellites, the QB50-mission is in implementation stage, planned to deploy about 50 spacecraft in low Earth orbit in order to observe by a joint payload the upper Ionosphere (https://www.qb50.eu/). These satellites are not actively coordinated, but by providing a position and time reference it is intended to correlate post-factum the obtained data.

Coordinated activities by four pico-satellites in order to allow a three-dimensional configuration will be performed in the "NetSat" mission [28]. Here a distributed, cooperating satellite system will be realized, for demonstrating autonomous formation control to optimize observation periods. The energy-efficient realization of such multi-satelllite orbits is well investigated in orbital mechanics [11], [2], [1]. In typical low Earth orbits at about 600 km altitude the contact coverage to one ground station can only be expected up to 15% of the orbit period, but often orbits without any contact will occur. In constellations, therefore the effects of perturbations will only be corrected from ground control after extended delays. In case of formations, the cooperating spacecraft detect perturbations and exchange information in order to correct them in real-time. Thus accumulation of deviations is avoided and the quality of observations is not degraded for longer periods. Related ongoing technology research concerns relative attitude and position determination within the formation, based on data exchange directly between the satellites and data fusion of inputs, while on the actuator side model reference based adaptive control for the attitude and orbit control based on reaction wheels, magnetic torquers and electric propulsion are investigated. Key aspects of autonomous, networked satellite control concern reliable data exchange between the satellites by mobile delay tolerant networks (DTNs) and ad-hoc networks

(MaNets) to adapt to changing communication topologies and interruptions [29]. Supervisory control technics [30] are analyzed for ground control interaction with autonomous reactions on-board.

Very interesting control aspects are raised, when heterogeneous spacecrafts cooperate, e.g. high performance, energy-demanding large spacecraft acting as emitters in combination with many distributed small space vehicles forming a detector network for the reflected signals from the Earth's surface. An interesting example is provided by large radar satellites acting as emitters, which are escorted by small satellites just carrying detectors for the backscatter. In the traditional way detectors are only placed on the emitter spacecraft and thus only the signals reflected from the surface back into the emitter direction will be measured, while the signals scattered into other directions are lost. When a distributed detector network placed on small accompanying satellites is in place, due to the increased detection by the wide area covered, an unprecedented improvement in resolution can be achieved.

2.3 Relative Navigation in Formations and in Rendezvous & Docking

So far relative distance and orientation measurements played no significant role in traditional satellite design. Only when inter-satellite links, or approaches and landings to planetary bodies (planets, moons, asteroids, comets) were addressed, specific solutions based on the infrastructure of large satellites were implemented. Currently the challenges relate to upcoming new application scenarios, such as formations, in-orbit servicing and space debris removal, in combination with miniaturization for efficiency purposes.

2.3.1 Application Scenarios

In case of a formation, where the spacecraft exchange relative position data and the orbit control loop is closed in space, much closer distances can be realized than in constellations. The only flown formations TANDEM-X [14], PRISMA [20], and GRACE are all missions composed of just two spacecraft, thus so far only one dimensional distance variations have been studied in orbit.

In the example of TANDEM-X [14], Synthetic Aperture Radar data are collected from two coordinated spacecraft flying in a distance as close as 200 m. On basis of continuously updated relative position measurements by GPS, the distances are adapted by the orbit control system, enabling safe operations at such near range. In case of PRISMA [20] the distances were varied down to 10 m based on GPS data [17].

In-orbit servicing missions to exchange degraded or broken components are supported by a modular spacecraft design with related standardized interfaces [16]. In order to allow maintenance by a servicing satellite, rendezvous & docking maneuvers and good access to the different satellite's building blocks need to be included already in the early satellite design phases. Future near vicinity operations are particularly supported by placing markers on the spacecraft for future safe approach maneuvers. The rendezvous & docking task is realized as formation flying with decreasing relative distance decreasing towards 0. In particular near vicinity operations demand autonomous real-time reactions to relative distance and orientation sensor data.

Similar approach strategies are also applied in space debris removal scenarios in Earth orbit, where a servicer satellite has to establish a fixed link with the passive target object (e.g. a dead satellite or a natural space object fragments) in order to move it in the next step safely to a graveyard orbit. Operations in the near vicinity of the target are very risky, as collisions with appendages (e.g. solar arrays, antennas) can easily occur, when the dynamics of the target object is not completely known. In this most challenging scenario, the target characterization must be completely based on the servicer's sensor system. Due to the orbit dynamics inevitable ground station contact interruptions and -even when the satellite is in the field of view- signal propagation delays require autonomous reaction capabilities in order to guarantee collision avoidance. Such space debris removal missions did not yet move beyond preparatory stage and still need to be demonstrated in orbit.

2.3.2 The Near Range Operations Test Scenarios

Typical sensor systems for collision avoidance in case of passive target objects include vision based sensors (like lidar, time-of-flight 3D cameras, stereovision cameras), often including active illumination units, and radar. All these approaches also contribute to relative navigation in cooperative scenarios (as in formations), where the exchange of information between the agents is possible. Sensors use external reference systems to derive relative distance from absolute values as in case of GPS receivers, and relative orientation as in case of star sensors, sun sensors and magnetometers. Those are complemented by radiofrequency transceivers for range detection and inertial sensor for increments in orientation.

Crucial for obtaining high reliability and accuracy information for position and attitude is the on-board software for sensor data fusion and interpretation of obtained data from measurements by these different sensor types. By combining those inputs from the various satellites, ambiguities and deviations can be further reduced. Software challenges relate to models to process these data in real-time for predictions in order to apply adaptive control algorithms to derive autonomous reactions.

In preparation of the national German mission DEOS for space debris removal, several simulator environments have been realized in Europe to evaluate crucial technologies for the critical near range operations. By using two robot arms (cf. Fig. 6) the dynamics, causing the change of relative attitude and position, between servicer and target object can be simulated. Thus the performance of sensors as well as the autonomous reaction capabilities, in particular the collision avoidance algorithms can be analyzed and tested. Crucial is the characterization of the target body dynamics for safe near vicinity operations. Sensor candidates tested in this context include LIDAR, stereovision cameras, radar and 3-D time of flight cameras [32]. In particular autonomous real-time reactions capabilities on debris threats are investigated.

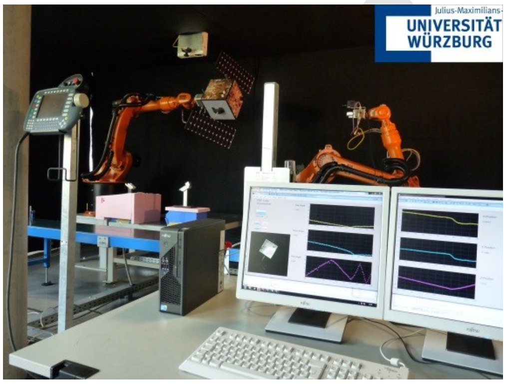

Fig. 6: Simulation of dynamics in rendezvous & docking by robots with a passive satellite (mounted at left side) to determine position and attitude from servicer sensors (mounted at right side).

3 Conclusions

Recent technology progress for very small satellites promotes a paradigm change in spacecraft design, encouraging innovative distributed networked system approaches, promising cost-efficient and robust alternatives to traditional mission design. In particular in-orbit demonstration of reliable miniaturized satellites by autonomous FDIR software on board, as well as attitude and orbit control capabilities provide the basis for the next step of self-organizing formations of small satellites. These emerging distributed satellite systems raise challenging demands for autonomous reaction capabilities based on relative navigation and networked control. Formations in near range - as extreme rendezvous & docking operations - impose high risks for collisions, and thus demand preventive autonomous real-time reactions in direct response to three-dimensional environment characterization and predictions of the target object dynamics. Thus networked distributed small satellite systems offer the potential as disruptive technology in spacecraft design and accelerate innovation cycles already today. Nevertheless, challenging problem areas in multi-satellite systems related to relative navigation and networked control/self-organisation are still to be solved, and offer good potential for cross-fertilization from mobile robotics. The achieved progress already opens interesting perspectives in application areas like Earth observation, space weather and telecommunication due to advantages of better spatial and temporal resolution, as well as increased robustness.

4 Acknowledgements

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Prof. Dr. Schilling had in space industry responsibility in interplanetary satellites (such as HUYGENS to the Saturnian moon Titan and ROSETTA for exploration of comets) before he was appointed professor and chair for Robotics and Telematics at University Würzburg. In parallel he is president of the research company „Center for Telematics“. His team built the first German pico-satellite UWE-1, launched 2005 to optimize Internet in space. He published more than 300 papers and received several awards, including the Walter-Reis-Award for Robotic Innovations 2008 (for research in mobile robotics) and 2012 (for medical robotics), as well as an Advanced Grant of the European Research Council for research on control of networked distributed satellite systems. He is member of the International Academy of Astronautics and was appointed as Consulting Professor at Stanford University 2002-2006.

In international professional societies he served in IEEE as chairman of „TC on Networked Robotics“ and in the International Federation on Automatic Control (IFAC) as coordinating chair for the area “Computers & Control” after having been TC chair for „Telematics: Control via Communication Networks“ and for “Aerospace”.

Highlights

- Challenging autonomy requirements are raised by small satellites sharing similar functionalities with mobile robotics despite different dynamics
- Distributed cooperating small satellites offer promising innovation and application potential in telecommunication and Earth observation applications
- Innovative small satellite techniques are based on software to compensate miniaturization deficits, especially in on-board data handling, and in attitude and orbit control