Networked Distributed Pico-Satellite Systems for Earth Observation and Telecommunication Applications

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Abstract: A paradigm shift from single large, multifunctional satellites to cooperating groups of smaller satellites can be observed in Earth observation as well as in telecommunications. Another trend is to employ modern miniaturization techniques to realize satellites at continuously smaller masses, enabling a cost-efficient realization of systems composed of multiple satellites. Such distributed satellite systems carrying coordinated heterogeneous sensors rise challenges with respect to an efficient implementation of the flow of information and its storage, as well as for optimal control strategies regarding position and attitude. In Earth observation, the innovation potential by employing a distributed network of satellites is obvious in order to provide higher temporal resolution in observation data and to achieve higher availability. Especially in emergency, surveillance and observation tasks, such robust capabilities are important. In case of telecommunications, networks of small satellites in low Earth orbits can offer a cost-efficient approach for robust communication links at low bandwidth.

Keywords: spacecraft formations, spacecraft formations, small satellites, formation control, telecommunication, Earth observation, attitude determination.

1. INTRODUCTION

Distributed systems of small satellites offer interesting capabilities to complement traditional satellites. Thus in Earth observation multiple satellites can support an increase in temporal and spatial resolution. Observations of surface points from different viewing angles at long baseline distances provide the potential to derive 3-D-images by sensor data fusion approaches. In telecommunications, satellite systems in low Earth orbits offer telecommunication links at a minimum use of resources.

In addition, modern miniaturization technologies enable realization of electro-mechanical components at very small masses. Thus, satellites of few kilograms of mass can already provide interesting functionalities and services [Schilling/Brieß, 2008], [Twiggs 2002]. Combination of data from groups of small satellites enables provision of high performance results despite the limitations in resources of each individual small satellite. Technology challenges to implement such innovative distributed spacecraft system concepts relate to robust telecommunication and control capabilities, as will be addressed for formations in this paper.

2. DISTRIBUTED SATELLITE SYSTEMS

Networks of multiple satellites offer interesting benefits in applications with respect to

- higher temporal and spatial resolution in observation data,
- higher availability,
- graceful degradation in case of failures.

But distributed satellites also raise challenging control and coordination requirements regarding

- orbits at different altitudes,
- optimal control strategies for position and attitude of the specific system components,
- activities of heterogeneous sensors,
- flow of information and storage in the system.

Multiple coordinated satellites are described as

- ***Constellation***, when several satellites flying in similar orbits are organized in time and space to coordinate ground coverage, without on-board control of their relative positions. They are controlled separately from ground control stations.
- ***Formation***, if multiple satellites with closed-loop control on-board provide a coordinated motion control on basis of their relative positions to preserve the topology. It is the collective use of several spacecrafts

to perform the function of a single, large, virtual instrument.

- ***Swarm*** or ***Cluster,*** if a distributed system of similar spacecraft is cooperating to achieve a joint goal without fixed absolute or relative positions. Each member determines and controls relative positions to the other satellites.

Examples for typical spacecraft constellations are provided in different application fields, such as navigation (GPS, GLONASS, Galileo), telecommunication (TDRSS, Iridium, Globalstar, Orbcomm, Teledesic), remote sensing (Rapid Eye). With respect to formations ESA's planned DARWIN mission points synchronously five free flying telescopes towards one target point in order to achieve enough resolution to detect planets in remote solar systems (for further details see www.esa.int). Formations thus enable higher resolution imagery and interferometry.

2.1 Formation Flying Architectures

In order to perform complex tasks in a broad range of applications, groups of vehicles with varying dynamics are to be analyzed, such as groups of aircrafts, UAVs, submarines and land vehicles [Murphy/Pardalos, 2000]. In general three different architectural approaches are discussed:

- ***Virtual Structures***: the entire formation is treated as one single structure controlled by a centralized planner. The dynamics of the complete structure is translated into a desired motion for each vehicle, which has an individual tracking control.
- ***Behavioral strategies***: in this distributed control approach, following inspirations from nature (flock of birds, school of fish), several desired behaviors for each agent are specified. The control action of each agent is the weighted average of the controls for each behavior.
- ***Leader - follower***: vehicles are divided into leader(s) and followers, the followers track position and orientation of a designated reference point (leader) with a prescribed offset. It can be implemented as
  - *absolute control architecture*, where a central controller sends position and velocity commands to each vehicle regulating its own position, or as
  - *relative control architecture* sending absolute position and velocity commands of the leader, while the followers regulate their own position relative to the leader.

While there is a transparent group behavior, the leader is a particularly sensitive position.

2.2 Relative Motion in a Formation

When satellites are flying in a formation on almost similar orbits, it is of interest to derive the relative motion to each other with respect to one moving reference satellite, described by the Euler-Hill equations. With $\mathbf{r_1}$ and $\mathbf{r_2}$ being the vectors from Earth to the reference satellite and the second satellite, the relative distance between them is $\boldsymbol{\rho} = \mathbf{r_2} - \mathbf{r_1}$

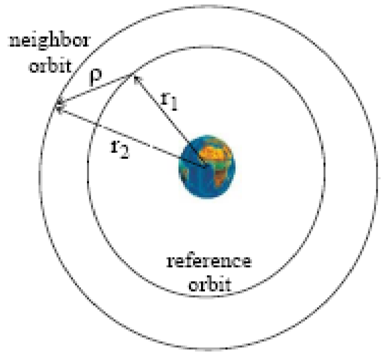


Fig. 1: Relative motion between satellites in neighboring orbits

The dynamics can then be derived from the equations of motion for the two satellites

$$\ddot{\mathbf{r}}_1 = -\mu\, \mathbf{r_1} / r_1^3 \quad , \quad \ddot{\mathbf{r}}_2 = -\mu\, \mathbf{r_2} / r_2^3 + \mathbf{f}$$

with driving force $\mathbf{f}$ (bold letters describe vectors, while standard letters represent the related length).

Using $\mathbf{r_2} = \mathbf{r_1} + \boldsymbol{\rho}$, for small $\boldsymbol{\rho}$ the relative acceleration of the relative distance results as

$$\ddot{\boldsymbol{\rho}} = (\mu / r_1^3)\ [-\boldsymbol{\rho} + 3\ (\mathbf{r_1}/r_1 \bullet \boldsymbol{\rho})\ \mathbf{r_1}/r_1 + \mathbf{f} + O(\mathbf{r^2})$$

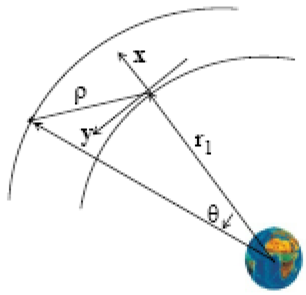


Fig. 2: The local xy-coordinate system in the orbit plane

For an almost circular orbit (with small eccentricity ε), with neglecting higher order terms (ε^2, ρ^2, products of ε and ρ) in the components of relative motion, there results for the representation of $\boldsymbol{\rho}$ in the LVLH coordinate frame (Local Vertical Local Horizontal) rotating with the reference satellite in its orbit (cf. Fig. 2) $\boldsymbol{\rho} = (x, y, z)^T$:

$$\ddot{x} - 2\, n\, \dot{y} - 3\, n^2\, x = f_x$$
$$\ddot{y} + 2\, n\, \dot{x} = f_y$$
$$\ddot{z} + n^2\, z = f_z$$

with $n = (\mu / r_1^3)^{1/2}$ being the angular velocity of the reference orbit (almost constant in near circular orbits) (for details see [Sidi, 2001]; [Vallado, 1997]). These equations are decoupled in the cross-track motion (with respect to z) and the in-track/radial motion (with respect to x, y), providing as solution for the free force in

- in-track/radial motion:

$$x' = -c_1 n \sin(n t + \alpha)$$
$$y' = -2 c_1 n \cos(n t + \alpha) - 3/2\, n c_2$$
$$x = c_1 \cos(n t + \alpha) + c_2$$
$$y = -2 c_1 \sin(n t + \alpha) - 3/2\, n c_2 t + c_3$$

with integration constants c_1, c_2, c_3 and α.

- cross-track motion, describing the change in orbit plane :

$$z = c \cos(n t + \beta)$$
$$z' = -c n \sin(n t + \beta)$$

with integration constants c, β.

Thus these approximate analytical solutions can be used for predicting the evolution of relative distances. The Euler-Hill approach provides also an elegant way to handle rendezvous and docking tasks in orbit.

3. SMALL SATELLITE TECHNOLOGIES

Modern miniaturization techniques enable realization of satellites at continuously smaller masses, leading in particular to decreased costs for a launch. Thus, fully functional satellites performing meaningful experiments have been realized at a mass of less than 1 kg. This provides opportunities to install within a reasonable cost frame formations of multiple satellites in orbit.

Table 1: Classification of satellites

satellite type	mass
classical satellite	larger 500 kg
mini-satellite	100 … 500 kg
mikro-satellite	20 … 100 kg
nano-satellite	1 … 20 kg
pico-satellite	ca. 1 kg

There is currently a significant increase of pico- and nano-satellite launches (cf. Fig. 3), mainly due to research and educational activities from universities [Schilling, 2006], [Twiggs, 2002].

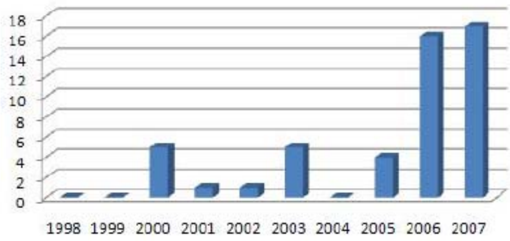


Fig. 3: Amount of launched pico-satellites worldwide.

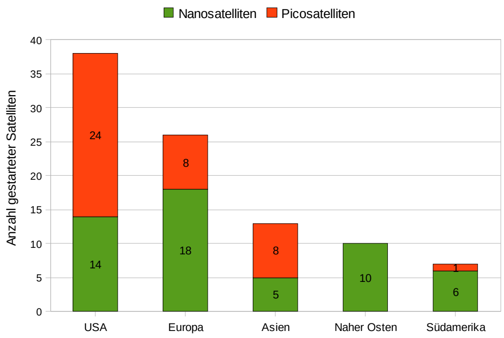
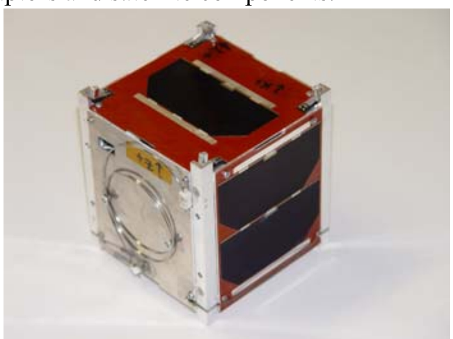


Fig. 4: Geographical distribution of launched pico- and nano-satellite missions in the period 1990 – 2008

In particular the standardization within the CubeSat framework towards satellites with the shape of a cube with side length of 10 cm and a mass below 1 kg promoted significant international university cooperation [Twiggs, 2002]. This supports sharing of joint launcher adaptors and satellite components.



3.1 The UWE pico satellites

A specific example of such very small satellites for scientific experiments is provided by the UWE (***U***niversity ***W***ürzburg's ***E***xperimental satellites) program initiated in 2003 on basis of the CubeSat-standard.

Fig. 5: The pico-satellite UWE-2 designed for experiments related to telecommunication and attitude determination.

The objective of the UWE-program is step-by-step development of the technologies needed for formation flying with extremely small satellites of a mass below 1 kg. The first satellite UWE-1 (***U***niversity ***W***ürzburg's

Experimental Satellite) was launched in 2005 with a focus on

- adaptation of parameters in internet protocols for the telecommunication link to delays and disturbances, typical for space environments.
- technology developments related to
  - demonstration of modern miniaturization techniques to implement a satellite at a mass below 1 kg,
  - use of micro-Linux as on-board operating system,
  - test of highly efficient, triple-junction GaAs solar cells, manufactured in Europe, in space environment,
  - integration of the ground control station into a inter-national network of CubeSat ground stations via Internet.

The mission of UWE-1 was successfully accomplished begin of 2006, demonstrating the capabilities of pico-satellites for space science. The second satellite of the UWE series was built in 2007 with final integration finished in spring 2008. The launch with an Indian PSLV-rocket was delayed and is now planned for summer 2009. UWE-2 is based on the same satellite platform to continue IP telecommunication experiments and a new sensor suite for attitude determination supporting data fusion in a postprocessing step for a distributed satellite system. The newly developed Attitude Determination System (ADS) was optimized with respect to minimal power consumption, size and mass to fit within the 1 kg requirement. Currently UWE-3 is implemented and includes additional attitude control components to coordinate the field-of-view in the formation.

3.2 Technical description of the UWE pico-satellites

The following subsections describe selected electrical, mechanical and software subsystems of the UWE satellites.

On-Board Data Handling

The OBDH subsystem is built around a 16 bit H8S 2674 microprocessor. This combines very low power consumption with good performance. Under normal condition, the complete OBDH system requires typically less than 300 mW, which is one significant benefit of this architecture. This provides a good basis for additional payloads like the GPS system integrated in UWE-2.
Several interfaces connect the main processor to the various on–board components. A connection to the power bus supplies the board with energy, a control bus to the power board offers the possibility to implement in software an efficient power management based on sensor information, one I2C interface is used to read data from the on–board sensors, and an RS232 interface to the transceiver is used to send and receive data from the ground station. An on–board real–time clock counter offers the possibility to set the current time on the satellite via commands from ground. Different hardware protection schemes including power consumption limitation, watchdog supervised operation and multiple triggering possibilities for the antenna deployment mechanism were realized.

On-Board Software

An important feature of the UWE approach is the provision of a fully-functional micro-Linux (μCLinux) operating system running on the main CPU. This offers significant advantages: Linux software has good portability, it is widely available, and standard programs and libraries are already available at a well tested stage. Further software modules for mission-critical sensor data processing, house keeping, fault handling, communication as well as data flow control have been implemented and tested. An efficient battery management strategy has also been implemented in software, based on sensor inputs, in order to increase the lifetime of the batteries.

Attitude Determination and Stabilization

The UWE satellites are passively stabilized by using small permanent magnets on-board to align to the Earth magnetic field lines. The UWE-2 mission uses an elaborate sensor system based on six pairs of Sun sensors on each side of the cube, one magnetometer and three gyros.

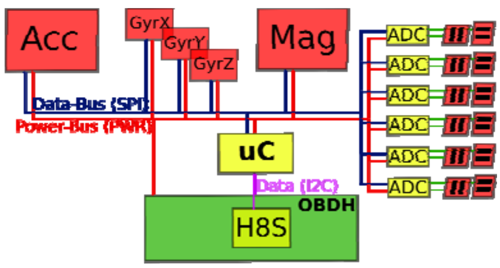


Fig. 6: The data flow between the distributed sensors and the OBDH

A combination these measurements with models of the orbit and the environment provides the inputs to an extended Kalman filter to perform sensor data fusion for robust determination of position and attitude [Schmidt, et al., 2008].

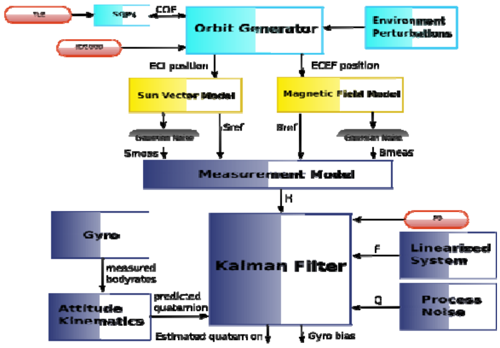


Fig. 7: The sensor data fusion scheme for attitude determination on basis of an extended Kalman filter as employed for UWE-2.

Communication subsystem

A modified off–the–shelf transceiver is used to communicate with the ground station in the UHF radio-amateur band. The radio transmits with a power of about 1W through an end–fed half–wave antenna. AX.25 is used as low level communication protocol. All AX.25 parameters can be modified via command from ground in order to achieve better communication performance. The transmission rate and modulation can also be modified by command, to either 9600 baud FSK or 1200 baud AFSK-modulated signal. Default safe values are stored on–board the satellite and can be loaded in case a failure is detected.

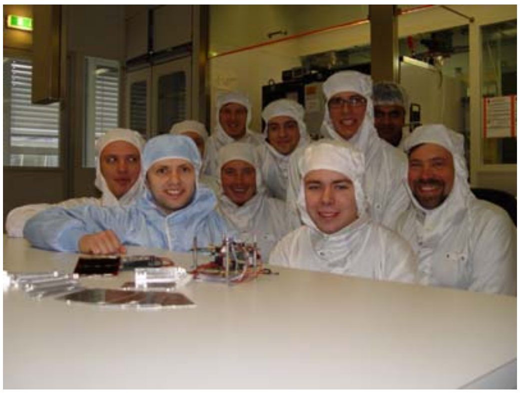


Figure 8: UWE Team in clean room at satellite integration.

The ground station in Würzburg

As necessary resource for communication with the satellite a ground station was set up 2004, which also served on experiments related to ground station networks. It supports communication in the VHF and UHF amateur frequency bands (2m and 70cm). The antenna tower (cf. Fig. 9) is mounted on top of the computer science building; it consists of an antenna tower with elevator for antenna rotor and Yagi antennas. The control hardware is composed of COTS components (ICOM transceiver, Yaesu rotor controller). The ground station hardware is connected to several desktop PCs, responsible for satellite tracking, command sending and data management.

Fig. 9: Ground station antenna mounted on top of the Computer Science Department

Coordinated activities of several ground stations in network improve satellite operations significantly. The University of Würzburg cooperates with different institutions worldwide to increase contact periods to the satellite and to integrate received data from different ground stations into a consistent project data base.
Redundant tracking with more than one ground station uses overlapping contact windows to correct measurements received from the satellite to most reliable data sets.

The experiments demonstrate that even with a small amount of ground stations a significant increase of contact time can be achieved.

4. COMMUNICATION IN DISTRIBUTED SATELLITE SYSTEMS

The communication and tele-operation infrastructure provides a key element in establishing distributed satellite systems: flying information related to the status of each satellite in the formation is to be exchanged and observation data are to be transferred. The amount of data to be exchanged increases with the size of the satellite swarm. Thus efficient implementation of data pre-processing procedures, as well as intersatellite links and links to ground stations are to be analyzed. Here adaptations of terrestrial technologies for mobile distributed systems to the space environment are of particular interest.

4.1 IP infrastructure for spacecraft communications

In distributed applications on Earth the internet protocols TCP/IP became the established standard and attracts significant development efforts for further improvements. To benefit from these terrestrial activities, transfer of these technologies to the space environment is investigated; in particular adaptations to significant delays and to higher noise levels are to be analyzed. First experiments related to IP in space were performed 1999 by NASA during the UoSat-12 mission. One of the first missions, totally operated only over the TCP/IP protocol stack, was the CHIPsat mission launched in 2003 from NASA and the Space Science Laboratory in Berkley.

In 2005 the pico-satellite UWE-1 (University Würzburg's Experimental satellite) was launched with the main scientific objective to optimize Internet Protocol parameters in adaptation to the measured space environment [Schilling, 2006]. UWE-1 carried the on-board data handling system μ-Linux, implemented on a microcontroller. Thus advantage could be taken from integrated, appropriate IP-stack for related telecommunication experiments. The advantages of IP and its higher layer protocols (e.g. TCP, UDP) are the world wide usage, resulting in a fully tested reliable protocol stack and a broad spectrum of available applications using the IP interface. UWE-1 communication was based on a commercial transceiver, normally used by radio amateurs for data transmission via packet radio. The main experiments were related to cross layer optimizations between AX.25 and higher protocol layers (i.e. IP) and to application layer protocols like HTTP and TFTP.

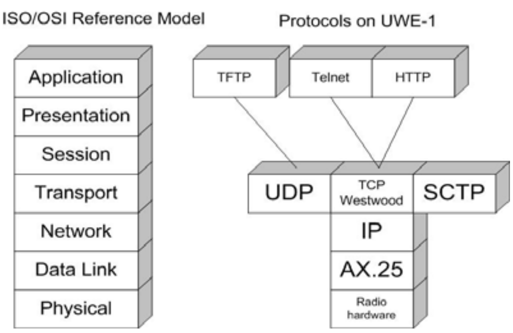


Fig. 10: the specific implementation of ISO/OSI reference model layers on-board of UWE-1. Here for comparison reasons several transport layer alternatives were realized.

A major disadvantage of the TCP/IP protocol stack is the performance problem of the TCP protocol in space conditions. As the TCP protocol was intended for usage in the terrestrial internet, a congestion avoidance algorithm decreases the transmission rate, if congestion occurs. This behavior is an essential feature of TCP in the terrestrial internet, when the network is overloaded by traffic. A congestion situation in the terrestrial internet is indicated by the loss of data packets. In a satellite communication the situation is totally different, loss of packets are normally caused by transmission errors, nevertheless TCP reacts in this situation with decreasing the transmission rate. Therefore it is important to choose very carefully the communication protocols. An alternative is the usage of UDP instead of TCP, a connectionless transport protocol. In this case the application layer has to provide mechanisms to guarantee the correct reception of data packets. Another possibility is to use a TCP extension protocol, which overcomes typical problems of TCP.

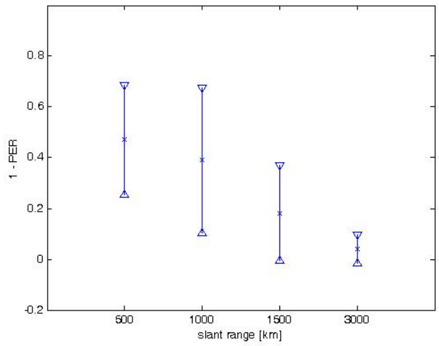


Fig. 11: packet error rate (PER) determination for the AX.25 radio link

The results of the UWE-1 experiments displayed, that it is possible to use IP on a CubeSat for communication, but different optimizations are necessary to enable a reasonable telecommunication between satellite and ground stations. Especially the high Packet Error Rate (PER) observed on the communication link with UWE-1 has influence on the performance of the AX.25 protocol. The measured PER values are presented in figure 19. The values are expressed in terms of confidence intervals, the variance of these intervals reveal the necessity to improve the combination between AX.25 and IP with additional redundancy for the communication link. Further redundancy for the telecommunication can be generated by hardware or software algorithms to solve the problems of high error rates.

4.2 Ground station networks for satellite swarms

The intensive activities in development of small satellites initiated the establishment of

many ground stations in academia all over the world. Due to the limited bandwidth of small satellites, it is here especially desirable to increase the contact periods by using multiple interconnected ground stations for data transmission. Thus, a consistent homogeneous telecommunication framework for space and ground segment based on Internet Protocols promises interesting capacities for teleoperation of these small satellites.
Current activities to implement such ground station networks are the "Global Education Network for Satellite Operation (GENSO)", the "Ground Station Network (GSN)" of the Japanese UNISEC group and the "Mercury Ground Station Network" initiated by Stanford University.

The UWE-1 ground station (c.f. Fig.12) was set up on the University Würzburg campus with capabilities to communicate with satellites in the 2m and 70 cm frequency bands.

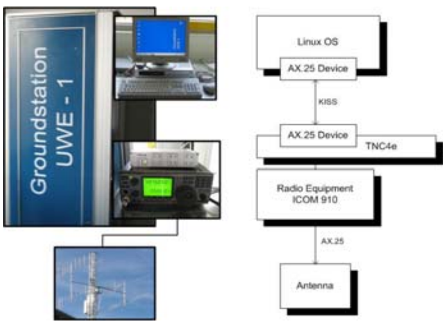


Fig. 12: Realization of the UWE ground station

A critical point for ground station networks are cross layer dependencies between IP and lower protocol layers, like AX.25 as in case of UWE-1. It is only relevant when a direct connection between the satellite and the remote controller over IP is used. The AX.25 protocol is a data link layer protocol designed for amateur radio networks. The AX.25 protocol can be operated in a connection oriented (virtual circuit) mode or in a connection less (datagram) mode. Connection oriented communication is already provided by transport layer protocols like TCP thus conflicts with this second acknowledgement system could arise, if insufficient coordination with higher layers is established. Thus, the parameterization of the Medium Access Control (MAC) is to be implemented, for avoiding collisions between sending stations by delaying of sending attempts.

4.3 Mobile Ad-Hoc Networks in Space

Establishment of robust network communications attracts significant research efforts in terrestrial applications. A mobile ad-hoc networks (MANet) combines several stations to a self-organizing telecommunication network with integrated initialisation and reconfiguration capabilities, in particular in case of deffects or of changes in the topology. Therefore in formations of satellites, exhibiting high dynamics and link interruptions, a reconfiguration of the communication path via several members of the space and ground segment promise significant increses in robustness. Related routing methods are therefore to be analyzed.

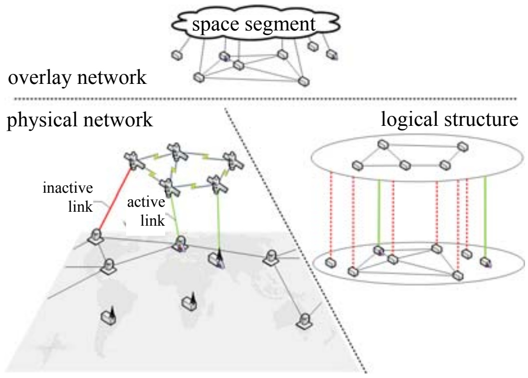


Fig. 13: Schematic of an overlay Network approaches for an integrated space and ground segment taking into account the available physical network structure and the abstracted logical structure

At the University Würzburg a MANet demonstrator and test facility based on WLAN (IEEE 802.11) has been installed, consisting of a system of several mobile robots and fixed stations as nodes (cf. Figure 14).

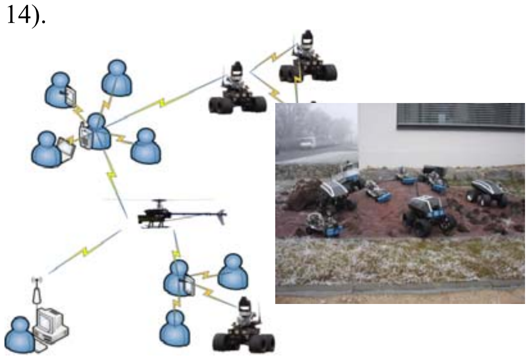


Fig. 14: Network of mobile systems with heterogeneous dynamics

In this test facility experiments to prepare future MANet applications in space have been performed with respect to re-routing performance. Typical ad-hoc routing protocols developed for mobile systems were compared in teleoperation scenarios for mobile robots, including:

- Reactive protocols, such as “Ad-Hoc On-demand Distance Vector (AODV)” or “Dynamic Source Routing (DSR)”,
- Proactive protocols, such as “Optimized Link State Routing (OLSR)”,
- Hybrid protocols, such as “Better approach to mobile ad-hoc networking (BATMAN)”.

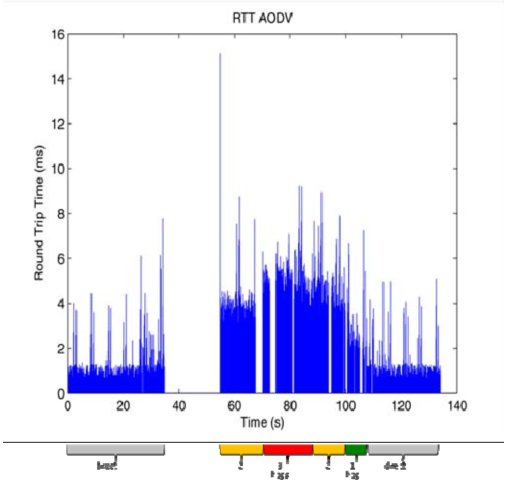


Fig. 15: Typical round trip time behaviors for a changing transmission topology, displaying in particular the significant transmission interrupts due to route reestablishment

A software system has been developed to record during test runs the crucial data about neighbors, route requests, potential routers, link costs and hop counts. Thus resulting characteristics of the packet stream like packet loss rates, time needed for route reestablishment, packet inter-arrival time, network topology and bandwidth can be evaluated. Files from the different nodes are to be synchronized (with respect to time or to events). Typically default parameter settings need to be adapted to the specific scenario to exhibit reasonable performance.

The performance measurements turned out to be very sensitive to noise effects, thus a careful setup is necessary to generate comparable results. In preparation of establishing MANets in space also adaptation procedures of protocols to the specifics of the encountered space environment are to be investigated.

Table 2: Performance comparison for test runs with tuned parameter settings in the protocols

Protocol	Packet Loss	min. Time for Rerouting	max. Time for Rerouting
OLSR	32.6%	5.0 s	< 21.6 s
DSR	28.8%	2.0 s	< 40.4 s
BATMAN	16.0%	0.8 s	< 26.2 s

5. EARTH OBSERVATION ANALYSES

Constellations of LEO-satellites are introduced to benefit from the shorter distance to the Earth’s surface, in particular from shorter signal propagation periods, lower energy intensity and power needs for data transmission and instrumentation. On the other side the high relative velocities relative to the surface imply short contact periods to ground stations or short observation periods of specific surface areas. Therefore several satellites in appropriate complementary orbits are placed to increase coverage. When placing the satellites in similar orbits (with respect to altitude, eccentricity, and inclination) perturbations affect all satellites in a similar way and station keeping manoeuvres to keep the satellite topology can be limited with positive implications for the satellites’ lifetimes. A frequently used class is the Walker Delta pattern constellation [Walker, 1984], with the objective of provision of a continuous coverage of the Earth’s surface by a minimum number of spacecraft. Despite this being a frequent aim, for different objectives alternative constellation patterns might be more appropriate. Typical non-Walker constellations address planes perpendicular to each other (by example a combination of a polar plane with an equatorial plane). For a Walker constellation with inclination i, total number of satellites t, number of equally spaced orbit planes p with t/p equally spaced satellites in each plane, and the relative phase difference between satellites in adjacent planes f ($0 \leq f \leq p-1$, measured in the direction of motion from the ascending node to the closest satellite in units of 360°/t), the standard notation for a constellation is presented in the following form:

$$i: t/p/f$$

The Gallileo navigation satellites are by example placed as a 56°: 27/3/1 constellation, having 27 satellites in orbit, inserted in 3 orbit planes separated by $\Delta\Omega$ =

120° . Each of the 3 orbit planes with an inclination i = 56° hosts 9 satellites at angular distances of 40°. The phase shift between adjacent orbits is $f \bullet 40°/3 = 1 \bullet 13⅓° = 13⅓°$.

Let $s = t/p$ satellites be equally spaced at an angular distance $\Delta\nu = 360°/s$ in a orbit plane. If in comparison to $\Delta\nu$ the maximum Earth central angle λ_{max} is

- $\Delta\nu < 2\ \lambda_{max}$, there is an area of continuous coverage, often called *street of coverage* (cf. Figure 16) with an angular range of λ_{street} on both sides of the ground track,
- $\Delta\nu > 2\ \lambda_{max}$, the coverage will be interrupted along the swath.

The width of the *street of coverage* λ_{street} can be calculated from

$$\cos \lambda_{street} = \cos \lambda_{max} / \cos (\Delta\nu/2)$$

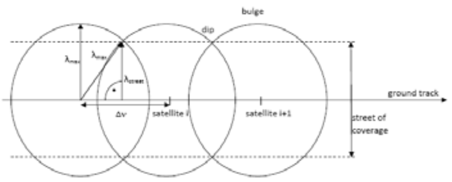


Fig. 16: topology of satellites in the same orbit plane

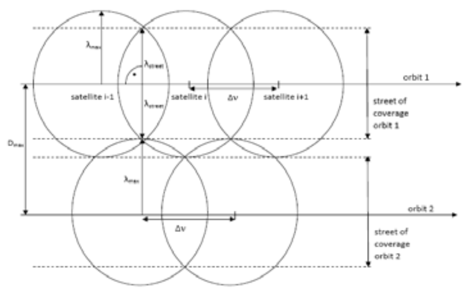


Fig. 17: suitable coordination patterns to be achieved for two adjacent orbits, moving in the same direction, by the choice of $f = \Delta\nu/2$ a

Adjacent orbits planes can now suitably be coordinated such that the bulges of the one orbit plane fill in to the dips of the other plane (cf. Figure 17). So for guaranteeing a continuous coverage the maximum distance between adjacent orbit planes D_{max} can be selected as

$$D_{max} = \lambda_{street} + \lambda_{max}$$

This effect just applies if the satellites are synchronized with similar velocity vectors. It should just illustrate that combinations of the different orbit parameters complicate optimisation for analysing coverage in distributed multi-satellite systems. Procedures for the replacement of defect satellites in a constellation need to be considered at deployment. Very often also soft parameters, like the flexibility with respect to growth potential for the satellite constellation are crucial.

For coordinated observations by swarms of small satellites, challenging technical research problems are to be solved. A necessary requirement is the ability of the satellites to maintain the formation. Thus the position and attitude relative to each other is to be determined with appropriate accuracy, before control actions correct towards the target position in the formation. All satellites of the swarm have to be equipped with suitable sensors and actuators to perform such maneuvers. Especially for pico- and nano-satellites there is still a need for small, low weight sensors and actuators. Within current technology it is by example not possible to integrate a star tracker at pico-satellit level, nevertheless an high accuracy attitude determination is desired. Recent activities in the field of sensor development demonstrate implementation of extremely small components by MEMS technology.

The UWE-2 satellite employs a GPS system for position determination and subsequent orbit determination. The companion pico-satellite BEESAT from TU Berlin carries a 3-axis attitude control system by three reaction wheels [cf. Schilling, Brieß, 2008]. The University of Toronto will demonstrate by the CanX-2 satellite at nano-satellite level actuators for formation control by using thrusters and 3-axis-stabilized attitude control. The motivation for this mission is the test of enabling technology for formation flying. In the next step the Can-X4 and Can-X5 satellites are planned for an autonomous formation flight. Thus, future missions will perform complex formation maneuvers with pico- and nano-satellites, but there is still significant research necessary in order to establish appropriate attitude control and formation control systems for satellites in the pico- and nano-satellite class.

6. CONCLUSIONS

The paradigm shift from large spacecrafts incorporating multiple payload capabilities to decentralized, distributed small satellite systems raises interesting research topics. Particular advantages in the context of Earth observation and surveillance are higher fault tolerance and robustness of the overall system. Such systems are scalable in a sense that according to application needs additional satellites can be added in order to increase resolution and coverage. The current progress in gun launches (with railguns or light gas guns) to orbit promise interesting quick future reaction capabilities for very small satellites (with a mass of some kg). Nevertheless high resolution data and high bandwidth links can only be provided by traditional large satellites. Thus combinations of coordinated satellite systems composed of few large and many small satellites might complement each other in order to provide the required data quality as well as flexibility and robustness.

Swarms of small satellites offer in particular for Earth observation applications interesting innovative approaches. Satellites in Low Earth Orbit (LEO) enable high spatial resolution on ground and offer interesting potential for applications like disaster monitoring. Due to the low orbit, these satellites exhibit a high relative velocity to reference points on ground, resulting in short observation and communication contact periods in the target areas. One approach to that problem is a higher temporal resolution by satellite constellations with several satellites in the same orbit. The achievable temporal and spatial resolution of such a formation opens new application areas in bio-monitoring and surveillance.

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