Pico-Satellites for Education and Research in Networked Space Systems

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IEEE Robotics and Automation Society (RAS) – Distinguished Lecturer Program
Egypt Chapter, New Cairo, October 11, 12
The University Würzburg
- was founded 1402
- was the place, where of Prof. Roentgen found the X-rays
- was the home of 14 Nobel prize winners
- is in the rankings among the top 10 German research unis
- hosts about 25 000 students in arts and sciences

Prof. Roentgen and his equipment

The Computer Science Institute
Space Exploration

Industry

Education

Research Areas at University Würzburg
Small Satellite Terminology

- Dramatic progress in miniaturisation technologies enables smaller satellites
- Advantages of small satellites: less expensive, more flexible, but limited capabilities

(>500 kg )  (100 – 500 kg)  (50 – 100 kg)  (1-50 kg)  (~1 kg)

Small satellites are complementary to classical satellites

Overview Very Small Satellites
Amount of launched Pico-Satellites

Overview Very Small Satellites
Pico-Satellites in Germany

Objectives

Telecommunication tests: Internet in Space

Technology demonstration AOCS: magnetometer, magnetic coils, sun sensors
Objectives

- Internet in Space
- advanced attitude determination

- national program “pico-satellites for education“ by DLR since 2007
- annual Pico-/Nano-Satellite national/European Workshop since 2007, alternating between Uni Würzburg and TU Berlin
- scientific perspective on very small satellite formation flying
- organisation of universities in national Pico-/Nano-Satellite Initiative

Educational Pico-Satellites in Germany
Ongoing and future activities for European educational pico-satellite activities

International network of ground stations for educational satellites endorsed by the International Space Education Board (ISEB), coordinated by ESA Educational Office

The VEGA Maiden flight carried 8 pico-satellites into orbit in February 2012, coordinated by ESA educational office

QB50: An European initiative started 2009 to build 50 CubeSats for
- in situ study of the temporal and spatial variations in the lower thermosphere at 90-300 km altitude,
- study of the re-entry process

Educational Pico-Satellites in Europe
Space Weather Applications for Characterization of the Upper Atmospheric Layers

Gamma ray emissions as potential reaction of anti-matter above lightning clouds detected (October 2010, FERMI)

Mapping of ionospheric plasma structures and of irregularities

Exploration of the lower thermosphere (90-330 km) by in-situ measurements using small satellites (QB50-project)
CubeSat Experiments

- E & M fields and waves
- Radio waves
  - VLF-UHF
  - microwave
- Plasma and particles
  - Electrostatic probes – mass & imaging spectrometers,
  - keV-MeV
- Photometers & imagers
  - near IR- UV
  - X & gamma rays

Payloads for Small Satellites
Plenary on Pico-Satellites at 60th International Astronautical Congress Daejeon (South Korea), 17.Oktober 2009
CubeSats

- A CubeSat is a cube-shaped spacecraft with side length of 10 cm and a mass of 1 kg.
- The structure is standardized for launcher adaptation.
- Students groups typically design in about 1 academic year the spacecraft.
- Interdisciplinary student teams have to analyse the orbit properties and related implications on different satellite subsystems, such as on board data handling, power, telecommunications, attitude determination and control, thermal control, structure.
- The complete satellite life cycle from feasibility analyses to design, implementation, launch, in orbit operations, data collection and interpretation is to be covered.
Standard P-Pod for 3 CubeSats

UWE-2 in the single launcher adapter of Astrofein

The standardized launcher adapter
Education on Building Satellites: first steps CanSats

Students learn to build from components powerful measurement systems

CanSat - in a can are to be placed sensors in order to characterize the atmosphere

CanSats for preparation to finally build satellites
**SpaceMaster** is supported by scholarships within the "ERASMUS MUNDUS"-Program of the EU for European elite-curricula. It is offered at University Würzburg in cooperation between Computer Science and Physics/Astronomy, and by the partner universities

- Luleå University of Technology, Sweden
- Cranfield University, United Kingdom
- Czech Technical University, Czech Republic
- Helsinki University of Technology, Finland
- Université Paul Sabatier Toulouse III, France

www.spacemaster.eu
spacemaster.uni-wuerzburg.de
University partners outside the EU:
- Stanford University, USA
- Utah State University, USA
- University of Tokyo, Japan
- University of Toronto, Canada
- Shanghai Jiao Tong University, China

Recent awards of Würzburg students:
- ZARM Award 2006
- First price in Student Contest at International Astronautical Conference 2006 Valencia
- Award of the British Interplanetary Society
- IABG-Award 2008 for Oliver Kurz
- Silver medal at Student Contest of International Astronautical Conference 2008 Glasgow

International students:
- ~25 from outside EU
- ~15 Europeans outside Germany
- ~10 German students

International Education
UWE X Formation Flying Mission

- Formation Control
- Higher Data Rates
- Ad-Hoc Networks
- Relative Navigation
- ...

2013 UWE-4
- Position Control

2013 UWE-3
- Attitude Control

2009 UWE-2
- Attitude- and Orbit Determination

2005 UWE-1
- Telecommunication

The UWE Pico-Satellites from Würzburg
Distributed satellite systems require coordination of

- orbits at different altitudes,
- optimal control strategies for position and attitude pointing of the specific system components,
- activities for heterogeneous sensors,
- flow of information and its storage.
UWE-1 Objectives

- Adaptation of parameters in internet protocols for the telecommunication link to delays and disturbances, typical for space environments
- Technology Development Tests
  - Demonstration of modern miniaturization techniques to implement of fully functional 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 international network of CubeSat ground stations via Internet

Objectives of UWE-1
UWE-1: University Würzburg’s Experimental Satellite with only 1 kg mass, launched on 27. 10. 2005, 8:52
UWE-1 Experiments

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.

The specific implementation of ISO/OSI reference model layers on-board of UWE-1. Here for comparison reasons several transport layer alternatives were realized.
The two system engineers (from Japan, Romania) during final integration

Integration into the adapter
31.5.2005

UWE-1 in spring 2005
The other passengers for ESA

SSETI – a 80 kg satellite built by 23 groups of European students

Xi-V from Japan

N-Cube 2 from Norway

Satellites sharing the launch on 27.10.2005
Pico-Satellites for Education and Research

Contributions to world wide networks of ground control stations

Network of Pico-Satellites
UWE-1 was the first German Pico-Satellite and is now on display as technology demonstrator at the Deutsche Museum (Munich)
UWE-2

Scientific objectives

- Precise attitude determination by using GPS, MEMS inertial sensors, magnetic field and sun sensors
- Continuation of telecommunication experiments related to IP in space

Successful launch: 23.9.2009 with Indian PSLV-launcher
The UWE-2 boards:
- Telecommunication (UHF / VHF)
- Energy storage and distribution
- Data processing (H8, μLinux)
- GPS receiver
Pico-Satellites for Education and Research

Functional block diagram of the UWE-2 attitude determination software, designed to provide the inputs for control actions in formation flying

UWE-2 Attitude Determination System
UWE-3 addresses attitude control
UWE-3 Bus Design

- Miniaturized flexible and modular structure
  - lighter, more space, easier manufacturing
  - modularity and flexibility accelerates development, integration, test, maintenance, replacements and extensions

- Decoupling of mechanical and electronics structure
  - Protect interior from thermal hazards
  - provide comfortable access to all subsystems in a functional configuration, even after integration
  - easy assembly and disassembly
Thermal Vacuum Tests

- Vacuum chamber
- Liquid nitrogen conducting pipes
- Cooled shroud
- Window
- EMI shielded electronics
- Lamps as sun simulation
- Aluminium stands for external operation
- Test satellite
- Satellite rack made of PTFE

UWE-3
UWE-4 in preparation, emphasis on orbit control

- Micro propulsion system (EU FP7 development)

Current preparation of UWE-3 and UWE-4 engineering and flight models

- Vacuum arc thruster propulsion system (Uni BW)

Pico-Satellit UWE-4
• Temporal and spatial coverage requirements

• Minimization of the amount of necessary satellites by selecting appropriate orbit constellations

• A frequently used class is the Walker Delta pattern for a continuous coverage of the Earth’s surface by a minimum number of spacecraft.
Mobile Ad-Hoc-Networks in Orbit

Telecommunications for swarms of satellites
Physical network structure and logical structure in a satellite based overlay network
What is measured?

Packet loss (sliding window according to software timeout)

Round trip times of commands

Terrestrial MaNet-telecommunication for swarms
Intersatellite communications: Protocols

- Network protocols affect the quality of data transfer
- IEEE 802 standards can be adapted for ISLs
- standards differ according to range, frequency and data rates

<table>
<thead>
<tr>
<th>Name</th>
<th>Reichweite</th>
<th>Reichw. erweiterbar?</th>
<th>Frequenz</th>
<th>Datenrate</th>
<th>Modulation</th>
<th>Ad-Hoc-Fähigkeit</th>
<th>Weltalltauglich</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11..</td>
<td>0.1 - 10 km</td>
<td>ja</td>
<td>2,4 / 5 GHz</td>
<td>&lt; 54 Mbit/s</td>
<td>OFDM</td>
<td>ja</td>
<td>ja</td>
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<tr>
<td>802.11a</td>
<td>&lt; 120 m</td>
<td>N/A</td>
<td>5.2 - 5.8 GHz</td>
<td>&lt; 54 Mbit/s</td>
<td>SOFDMA</td>
<td>ja</td>
<td>ja</td>
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<tr>
<td>802.15...</td>
<td>&lt;100 m</td>
<td>N/A</td>
<td>868/915 MHz/2,45 GHz</td>
<td>&lt; 54 Mbps</td>
<td></td>
<td>nein</td>
<td></td>
</tr>
<tr>
<td>802.16..</td>
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<td>0.7 - 66 GHz</td>
<td>&lt; 100 Mbit/s</td>
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<td>ja</td>
</tr>
<tr>
<td>802.16e</td>
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<td>N/A</td>
<td>1,25-20 GHz</td>
<td>5 - 10 Mbps</td>
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<td>ja</td>
<td>ja</td>
</tr>
<tr>
<td>AX.25</td>
<td>&lt;100m</td>
<td>N/A</td>
<td>N/A</td>
<td>2.4/9.6 kbps</td>
<td></td>
<td>nein</td>
<td>ja</td>
</tr>
<tr>
<td>CCSDS Proximity 1</td>
<td>&lt; 70 km</td>
<td>ja</td>
<td>~400 MHz/~26 GHz</td>
<td>2kbps - 2Mbps</td>
<td></td>
<td></td>
<td>ja</td>
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</tbody>
</table>
Orbit Drift Analysis for the September 2009 Launch of UWE-2, BeeSat, ITUSat1, Swisscube

Relative distances after one year

<table>
<thead>
<tr>
<th>Satellite pair</th>
<th>Relative Distance (km)</th>
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<tbody>
<tr>
<td>ITUpSat1 ↔ SwissCube</td>
<td>21.623</td>
</tr>
<tr>
<td>SwissCube ↔ UWE-2</td>
<td>35.095</td>
</tr>
<tr>
<td>UWE-2 ↔ ITUpSat1</td>
<td>56.714</td>
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Comparison of Ranging Technologies

<table>
<thead>
<tr>
<th></th>
<th>cost</th>
<th>weight &amp; power</th>
<th>range</th>
<th>reliability</th>
<th>accuracy</th>
<th>flexibility</th>
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</thead>
<tbody>
<tr>
<td>NORAD-RADAR + TLE</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>laser technologies</td>
<td>- -</td>
<td>- -</td>
<td>+</td>
<td>o</td>
<td>++</td>
<td>-</td>
</tr>
<tr>
<td>binocular cameras</td>
<td>+</td>
<td>+</td>
<td>- -</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>3D time-of-flight cameras</td>
<td>0</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>++</td>
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<td>GNSS</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
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</tr>
<tr>
<td>radio based ranging</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>O</td>
<td>++</td>
</tr>
</tbody>
</table>

++ : very good / o: indifferent / - -: very bad
Near range dynamics test facility based on two robotic manipulators to simulate a relative motion, picturing a satellite (on left arm) by a PMD camera (right arm).
Rendez-vous and docking for in-orbit servicing

New challenges for rendez-vous and docking to non-cooperative objects in order to place non-operable satellites to graveyard orbit

Example mission DEOS

Example mission Smart-Olev

Formation Flying Geometry: Rendez-vous & Docking
Earth observation with small satellites

- Several satellites enable improved temporal and spatial coverage
- Interactive attitude pointing enables more extended observation of interesting areas
Science: Interactive Earth observation (Frankfurt airport)
Formation flying: improved 3-dimensional spatial and temporal resolution

Future Pico-Satellite Research Topics: Swarms
Innovative Launch Concepts for Pico-Satellites

Approach 1: EM-Launch to Space

- Advantages
  - high exit velocity
  - moderate acceleration levels

- Restrictions
  - high electrical power needs
  - huge R&D efforts still needed
  - high static infrastructure demands

Approach 2: Gun-Launch to Space

- Advantages
  - most technologies are available
  - mobile capabilities

- Restrictions
  - limited exit velocity
Gun launches of small satellites

Alternative launcher principles: light gas guns
Conclusions

Paradigm shift from traditional large spacecrafts with multiple payloads to decentralized, distributed small satellite offering challenges for research and education, but also great opportunities for cooperation.

Research perspective

Networked satellite systems offer efficient approaches

- for exploiting parallel activities for faster mission completion
- for cooperatively solving complex tasks
- for higher fault tolerance and robustness of the overall system
- for scalability: according to application needs satellites can be added
- for high spatial and temporal resolution of observation data

- Appropriate interdisciplinary integration of control, graph theory, path planning, communication, localization and tracking
- Combinations of satellite systems, composed of few large and many small satellites will provide the required data quality, as well as flexibility and robustness.

Conclusions for Distributed Space Systems
Conclusions for Educational Aspects

Small Satellites relate to

- Exciting areas to attract students to science and engineering
- A huge global need for Aerospace engineers (20 000 engineers just for retirement replacements for next 10 years in Germany alone)
- Feasible implementation durations compliant to study plans (about 1 year)
- Excellent field to practice system design approaches
- Huge demand for innovative technology development
- Efficient approach for innovative technology testing in space by frequent small satellite in-orbit demonstration
- Attractive area for University / Industry cooperation
- Good field for national and international university cooperation

Essential to establish a continuous, sustainable satellite program to attract students, to establish international university and industry cooperation.

Further information: http://www7.informatik.uni-wuerzburg.de
Offers for cooperations

- In the IEEE lecture program (we are grateful for the travel grant for this lecture)
- Intensive classes on small spacecraft design (Turin, Samara, Barcelona, Monastir, Sfax, Istanbul, Dos Campos, Stanford University, University of Ohio, …)
- Emphasis on formations in Earth observation and telecommunications
- Networked ground stations
- Cooperation in small satellite design
- Networked distributed satellite projects (QB 50, HUMSAT, …)
- Pico- and Nano-Satellite conference (alternating in Berlin and in Würzburg, already 7 conferences, > 100 participants)

Contact: schi@informatik.uni-wuerzburg.de
19th IFAC Symposium on Automatic Control in Aerospace

September 2-6, 2013
Würzburg, Germany
www7.informatik.uni-wuerzburg.de/aca2013

International Federation of Automatic Control

Schedule

- Submission of draft papers: January 31, 2013
- Notification of acceptance: April 30, 2013
- Submission of full paper: May 31, 2013
- Symposium: September 2-6, 2013

Keynote Address

The space pioneers Prof. Dr. Eveline Gottzein (formerly EADS/Astrium) and Wolfgang Wimmer (formerly ESOC) will report first hand from the exciting starting phase of European Space activities and about the foundation of the IFAC TC on Aerospace.

Conference Location

The IFAC symposium will be held at the Informatics building, Turing-Hörsaal, located at Hubland campus of University of Würzburg and can be quickly be reached by public transport from the city center.
Thanks to the complete team

Further Information: www.telematik-zentrum.de
www7.informatik.uni-wuerzburg.de