Fault-tolerant satellite computing with modern semiconductors

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List of Selected Publications

[Fuchs1] C. M. Fuchs, P. Chou, X. Wen, N. M. Murillo, G. Furano, S. Holst, A. Tavoularis, S.-K. Lu, A. Plaat, and K. Marinis. **A Fault-Tolerant MPSoC For CubeSats**. In *IEEE International Symposium on Defect and Fault Tolerance in VLSI and Nanotechnology Systems*. IEEE, 2019.

[Fuchs2] C. M. Fuchs, N. M. Murillo, P. Chou, J.-J. Liou, Y.-M. Cheng, X. Wen, S. Holst, A. Tavoularis, G. Furano, G. Magistrati, K. Marinis, S.-K. Lu, and A. Plaat. **Fault Tolerant Nanosatellite Computing on a Budget**. In *AIAA/USU Conference on Small Satellites*. AIAA, 2019.

[Fuchs3] C. M. Fuchs, N. M. Murillo, A. Plaat, E. van der Kouwe, D. Harsono, and P. Wang. **Software-Defined Dependable Computing for Spacecraft**. In *IEEE Pacific Rim International Symposium on Dependable Computing*. IEEE, 2018.

[Fuchs4] R. Perea-Tamayo, Fuchs, C. M., E. Ergetu, and B.-X. Li. **Design and Evaluation of a Low-Cost CubeSat Communication Relay Constellation**. In *IEEE Microwave Theory and Techniques Society Latin America Microwave Conference*. IEEE, 2018.

[Fuchs5] C. M. Fuchs, Nadia M Murillo, A. Plaat, E. van der Kouwe, and P. Wang. **Towards Affordable Fault-Tolerant Nanosatellite Computing with Commodity Hardware**. In *IEEE Asian Test Symposium*. IEEE, 2018.

[Fuchs6] C. M. Fuchs, N. M. Murillo, A. Plaat, E. van der Kouwe, D. Harsono, and T. P. Stefanov. **Fault-Tolerant Nanosatellite Computing on a Budget**. In *Conference on Radiation and its Effects on Components and Systems*. IEEE, 2018.

[Fuchs7] C. M. Fuchs, N. M. Murillo, A. Plaat, E. van der Kouwe, and T. P. Stefanov. **Dynamic Fault Tolerance Through Resource Pooling**. In *NASA/ESA Conference on Adaptive Hardware and Systems*. IEEE, 2018.

[Fuchs8] C. M. Fuchs, T. P. Stefanov, N. M. Murillo, and A. Plaat. **Boosting Fault-Tolerance in High-Performance COTS-based Miniaturized Satellite Computers**. In *COSPAR Symposium*. ISC, 2017.

[Fuchs9] C. M. Fuchs, T. P. Stefanov, N. M. Murillo, and A. Plaat. **Bringing Fault-Tolerant Gigahertz-Computing to Space**. In *IEEE Asian Test Symposium*. IEEE, 2017.

[Fuchs10] C. M. Fuchs, N. Dafinger, M. Langer, and C. Trinitis. **Enhancing Nanosatellite Dependability Through Autonomous Chip-Level Debug Capabilities**. In *ESA/CNES 4S: Small Satellites, System & Services Symposium*. ESA Press, 2016.

[Fuchs11] C. M. Fuchs, N. Dafinger, M. Langer, and C. Trinitis. **Enhancing Nanosatellite Dependability Through Autonomous Chip-Level Debug Capabilities**. In *International Conference on Architecture of Computing Systems*. Springer, 2016.

[Fuchs12] C. M. Fuchs. **Dependable Computer Architectures and Software Concepts for Next-Generation Nanosatellites**. Master's thesis, Technical University Munich, 2015.

[Fuchs13] M. Langer, N. Appel, M. Dziura, Fuchs, C. M., P. Günzel, J. Gutsmiedl, M. Losekamm, D. Meßmann, T. Pöschl, and C. Trinitis. **MOVE-II - der zweite Nanosatellit der Technischen Universität München**. In *German Aerospace Congress*. Deutsche Gesellschaft für Luft-und Raumfahrt-Lilienthal-Oberth eV, 2015.

[Fuchs14] N. M. Murillo, S. Bruderer, E. F. van Dishoeck, C. Walsh, D. Harsono, S.-P. Lai, and Fuchs, C. M. **A low-mass protostar's disk-envelope interface: disk-shadowing evidence from ALMA DCO+ observations of VLA1623**. *Astronomy & Astrophysics*, 579, 2015.

[Fuchs15] C. M. Fuchs. **Enabling Dependable Data Storage for Miniaturized Satellites**. In *AIAA/USU Conference on Small Satellites*. AIAA, 2015.

[Fuchs16] C. M. Fuchs, C. Trinitis, N. Appel, and M. Langer. **A fault-tolerant radiation-robust mass storage concept for highly scaled flash memory**. In *Data Systems In Aerospace*. Eurospace, 2015.

[Fuchs17] M. Langer, C. Olthoff, J. Harder, Fuchs, C. M., M. Dziura, A. Hoehn, and U. Walter. **Results and lessons learned from the CubeSat mission First-MOVE**. In *Symposium on Small Satellites for Earth Observation*. IAA, 2015.

[Fuchs18] C. M. Fuchs, M. Langer, and C. Trinitis. **FTRFS: A fault-tolerant radiation-robust filesystem for space use**. In *International Conference on Architecture of Computing Systems*. Springer, 2015.

[Fuchs19] C. M. Fuchs. **The evolution of avionics networks from ARINC429 to AFDX**. In *Innovative Internet Technologies, Mobile Communications, and Aerospace Networks*, volume 65, 2012.

[Fuchs20] M. Brunner, Fuchs, C. M., and S. Todt. **Integrated Honeypot Based Malware Collection and Analysis**. In P. Schoo, M. Zeilinger, and E. Herrmann, editors, *Advances in IT Early Warning*. Fraunhofer IRB Verlag, Germany, 2013.

Curriculum Vitae

I was born on May 22nd 1984 as first child of a computer engineer and a teacher in Linz, Austria. I remember my early childhood full of adventures out in nature, exploring forests, climbing mountains, mobile-home trips all across Western Europe, and mysterious castles and fortresses. As Austria was a nonaligned country during the Cold War, we also undertook frequent trips across the border to the Eastern Block during the 1980s. During these good times, I for the first time witnessed physics simulations running on my dad's computer, which fascinated me and made me curious about how computers can do such a thing.

In primary school, I spent countless hours reading science books, drawing spacecraft and rockets, and later constructing ship-, aircraft- and spacecraft models from plastic and wood. And I passionately watched science fiction TV-series and movies, especially Star Trek, appreciating the values of curiosity, exploration, collaboration, and peaceful cooperation it conveyed.

In middle school, I discovered that the repetitive, memorization-based teaching style used in Austrian schools was not conductive for me. However, I did very well in science, history, and geography, enjoying lengthy discussions beyond what was taught in class with my teachers. With these teachers, I enjoyed doing advanced physics- and chemistry lab experiments, and learned a lot about the time periods on which my history teachers were specialized.

I finally came into the possession of a my first hand-me-down computer in 1994, which enabled me to ... do difficult calculations! I certainly conducted those, but mostly experimented, learned how computers work, traded software with neighbors, and I played computer games. At that time, one of my mother's students became my first mentor, passing on some of his computer-science knowledge. I began to spend countless after-class hours in my middle school's computer lab, exploring "The Internet", a newfangled curiosity that had just recently arrived in mid-1990's Austria. I witnessed the beginning of the Dot-com era, and became an avid user of Internet Relay Chat (IRC) networks and various Bulletin Board Systems (BBS). In 1997, I gained access to "The Internet" also at home. Subsequently, I got in touch with a group of people in my region to organize LAN parties, share knowledge, modify computer hardware and software, build special purpose servers, and experiment with new technology.

By the time my school career came to an end, I had achieved an advanced level of understanding of computer architecture, operating systems, and network security. I began to read scientific papers, and surrounded myself with people working in the tech industry, academia, and the open source community, but pursuing academic studies was impossible. Subsequently, I briefly worked on a google-maps like web service,

and in 2002 began doing consulting as a freelancer next to working as consultant for a computer company, formally completing apprenticeship in computer engineering as well.

The tech sector evolved rapidly during the 2000's, and so did my consulting job. Supporting corporate clients, governmental organizations, and hospitals on computer and network security, failure analysis, and technical advise, I became department leader in 2005. In retrospect, it was a busy and exciting time, and I learned on the job how important good systems engineering and management can be.

In 2007, I joined Ars Electronica as computer and network security expert. Industrial R&D took up more and more of my time, as I gradually replaced the aging corporate servers and network architecture with a modern failure- and fault-tolerant one. I helped organize large-scale events for tens of thousands of participants. In this truly international and interdisciplinary environment I worked with artists on realizing experimental "cyberarts" showcases, for who hard limitations of technology were just minor obstacles that had to be overcome for the sake of art, science, and public outreach. Working there showed me that interdisciplinary collaborations between scientists, engineers, and artists can achieve much. Many Ars Electronica members actually were scientists, and in part this motivated me to finally pursue academic studies.

After obtaining university qualification through evening school, I began to study at the University of Applied Science Upper Austria, Hagenberg, for my Bachelors degree, which felt like holidays compared to evening school. As part of a research project in the curriculum, I began to work at the Fraunhofer Institute for Secure Information Technology (SIT) and Applied and Integrated Security (AISEC) in Germany. I continued my research there for several years on industrial-scale malware analysis, reverse engineering, and classification. Upon receiving my Bachelor's degree in Austria, I moved back to Germany and pursued a Master's degree at the Technical University Munich (TUM). Between 2010 and 2012, I and my colleagues at AISEC established a fully automated malware collection, analysis, and classification environment, exploiting virtualization and machine learning. Several research papers and a book chapter were published on this research.

I began to work for the GNU project and therefore moved on from AISEC, and then had the opportunity to conduct a research project with and for Airbus (EADS at that time). In this project, I conducted research on Airbus' then newly standardized fault-tolerant avionics network technology ARINC664/AFDX, and provided feedback on potential future improvements. This project exposed me to avionics for the first time, and I became interested in their spaceflight applications. I learned about a student-run CubeSat project ongoing at the Institute for Astronautics of Prof. Ulrich Walter (DLR/STS-55). Hence, I left the open source project I was professionally involved in at that time, and began to work on the FirstMOVE satellite.

After launching FirstMOVE into space in late 2013, we conducted on-orbit operations and solar cell validation for Airbus Space & Defense for two months. Then we lost our ability to control the satellite. The next half year, we conducted a truly rigorous post-mortem analysis for the funding agency DLR, the German space agency, which many considered complete overkill, but for us was incredibly valuable. We reviewed and analyzed all available documentation generated throughout the years, checked all hardware designs used in FirstMOVE, including historical ones and alternations made to them. We spent many hours conducting face-to-face and remote interviews with

current and prior project members, most of who had at that time begun to work in the industry and were dispersed all across the globe. This analysis indicated that the on-board computer was the cause for FirstMOVE's failure, and a lack of suitable diagnostics functionality prevented recovery of the spacecraft. We published a redacted version of these results and lessons-learned.

By the end of the post-mortem, a group of students had formed to begin working on a successor satellite – MOVE-II. I took on the supervisor role of the on-board computing team, which initially included all computerized subsystems, including also COM, and payload data handling. As one of the main designers, I began to develop a fault-tolerant system architecture for this satellite, just to discover that there exists no suitable technology to enable it. This astonished me and my colleagues, and I sought advice from the European Space Agency's technical directorate (ESA TEC-EDD), looking for clues to solutions that, I assumed, surely had to exist. It became clear that there was simply no technology which could enable robust and reliable on-board computer consisting of CubeSat-style hardware, and no suitable protective concepts, or ready made solutions existed. On the positive side, I henceforth was in contact with the right people at ESA, who initially gave me many requirements to work with. This kickstarted my on-board computer fault tolerance research, the results of which are described in this PhD thesis.

I have been pursuing research on satellite computer architecture and fault tolerance ever since we began working on MOVE-II. And together with my colleagues in Munich, Nadia, and her colleagues in astronomy in Leiden, we published several research papers and journal articles in the different fields my research is connected to. During some of these conferences, my contacts at ESA encouraged me to expand my research and offered support in pursuing research grants. In 2015, my research on fault-tolerance and computer architecture had outgrown the MOVE satellite program, and I established ties and made preparations for proposing for funding. At the end of 2015, my first proposal was awarded funding through the Networking and Partnership Program of the European Space Agency.

My Master's thesis essentially was a summary of my work within the MOVE-II satellite project at that time, and the main challenge was to compress 3 published scientific papers and two additional research projects reports into a single Master's thesis. For this work, I was awarded the first prize of the ZARM Award for Young Scientists, as well as monetary grant from the Center of Applied Space Technology and Microgravity in Bremen, Germany. I also presented my results at the Conference on Small Satellites of the American Institute of Aeronautics and Astronautics organized at Utah State University (AIAA/USU SmallSat), where I participated in the Frank J. Redd Student Competition of the AIAA and won the second prize. SmallSat truly has been a remarkable and inspiring experience every since I attended it the first time back then.

In early 2016, I moved to The Netherlands, into close proximity to ESTEC, ESA's technical research center and satellite testing facility. My PhD research began in July 2016 at Leiden University, and in November of the same year I received another ESA/NPI grant for my research. While deepening my research, I also sought to expand the scope of my research through collaboration. Together with a group of researchers from Singapore, Peru and Ethiopia through the Committee on Space Research (COSPAR), we developed an ultra-low cost satellite relay constellation. We won the COSPAR Small Satellite Design Competition in 2017 with this concept, and

published a paper on it. In the second half of my PhD I had the privilege of giving talks and lectures at institutions in East Asia, the Americas, and in Europe. Finally, I spent a good part of 2019 as guest researcher at National Tsing Hua University, in Taiwan. Most of my successful and productive collaborations today are international.

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