Institution: University of Leicester		
Unit of Assessment: 11		
Title of case study: Solutions for robust electronic and computing systems on-board satellites		
Period when the underpinning research was undertaken: 2011–2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Tanya Vladimirova	**Role(s) (e.g. job title):** Professor of Electronic and Computer System Engineering	**Period(s) employed by submitting HEI:** 2011–Present
Period when the claimed impact occurred: August 2013–2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Digital technology research at the University of Leicester has provided novel solutions to mitigate in-flight damage to satellites in space by migrating tasks to non-damaged parts of the system, thus extending flight time. The impact of the research is three-fold. First, **economic impact** from significantly extending the flight time of satellite systems; second, through **understanding and awareness** by addressing a gap in the current space qualification process of the European Space Agency; third, through training and **knowledge transfer** to the space industry. The beneficiaries of the impact include international space agencies (e.g. UK, European and Pakistan) and the UK space industry.

2. Underpinning research

The University of Leicester (UoL) is at the forefront of advancing space systems and there has been ongoing research in the area of digital technology since Professor Tanya Vladimirova joined the University in 2011.

The cost of space flight and satellites is extremely high. Extending a satellite's flight time has huge economic impact by helping to spread the enormous costs across a greater time span. Operating conditions in space are harsh; there are several threats to the effective flight time of satellites and this is an on-going area of research and development. Vacuum force can damage exposed equipment and render it non-functional. Temperatures can vary greatly (-100 to +240°C) depending on orientation to the Sun. Meteorite impact can puncture outer skins and collide with delicate on-board equipment. Whilst such impacts are rare, the rising levels of manmade objects (space junk or debris) are increasing the chances of collisions. Finally, radiation damage is probably the most significant threat, especially to sensitive equipment (sensors, computers, guidance systems, etc.) and can render almost all instruments useless. The focus of this research has been to extend the flight time of satellites by addressing—and mitigating the effects of—some of these threats.

High-Performance Embedded Computing Systems

Current and future space missions demand highly reliable, high-performance embedded computing **[R1, R2]**. No solution has existed which efficiently meets both the requirements of reliability and high-performance computing **[R2]**. By working with Airbus Defence and Space, Toulouse (2011-2014), a novel, distributed fault-management system was proposed, together with a new approach to task-oriented, fault-tolerant, distributed computing (FTDC) **[R3, R4]**, for use on board spacecraft. The fault-management functionality and seamless adaptability of the distributed system is supported by a newly designed adaptive middleware for fault-tolerance (AMFT) block, which is external to the node-processing unit and operates in parallel with it. This is the first work that addresses fault management by migrating tasks to other healthy units in a distributed system.

Improving Reliability of Satellite Data Processing Systems
Increased processing capabilities are required for payload data processing on board spacecrafts. In a technology assessment, NASA scientists found that static random-access memory (SRAM)-based field-programmable gate arrays (FPGAs) are best suited for hardware acceleration of high-performance tasks. This is owing to their flexibility, parallel architecture, and embedded digital signal processing (DSP) blocks, compared to single-board computers and DSP processors. However, all modern SRAM-based FPGAs are prone to nondestructive radiation effects **[R5]** regardless of their grading (space, defence, or commercial). When dealing with such FPGAs in space applications, the common types of faults that must be mitigated are caused by single-event upsets (SEUs) that can change the state of a bistable element. SEUs are triggered by heavy ions and protons and result from ionization by a single energetic particle or the nuclear reaction products of an energetic proton. By working with the European Space Agency and Airbus Defence and Space, Stevenage (2012-2015), Vladimirova proposed a novel, distributed-failure detection method **[R6]** that applies fault detection, isolation, and recovery methods to multi-FPGA systems by shifting failure detection mechanisms to a higher intercommunication network level.

3. References to the research

[R1] M. Fayyaz, **T. Vladimirova**. “Fault-Tolerant Distributed Approach to Satellite On-Board Computer Design”, Proc. of 2014 IEEE Aerospace Conference, March 2014, Blue Sky, Montana, USA.

[R2] M. Fayyaz and **T. Vladimirova**, "Survey and Future Directions of Fault-Tolerant Distributed Computing on Board Spacecraft", Elsevier Advances in Space Research, Vol. 58, Issue 11, pp. 2352-2375, 2016.

[R3] T. Vladimirova and M. Fayyaz, "Wireless Fault-Tolerant Distributed Architecture for Satellite Platform Computing" - Lecture Notes in Computer Science, 2012, Vol. 7425, pp. 428-436, G. Lee, D. Howard and D. Slezak (Eds.), Springer-Verlag Berlin Heidelberg.

[R4] T. Vladimirova and M. Fayyaz. “Fault-Tolerant Distributed Attitude and Orbit Control System for Space Applications”, Proc. of 12th NASA/ESA Conference on Adaptive Hardware and Systems (AHS-2018), August 2018, Edinburgh, UK (winner of the Hermann Oberth Best Paper award).

[R5] F. Siegle, **T. Vladimirova**, J. Ilstad and O. Emam, "Mitigation of Radiation Effects in SRAM-based FPGAs for Space Applications", ACM Computing Surveys Journal, Vol. 47, Issue 2, pp. 1-34, 2015.

[R6] F. Siegle, **T. Vladimirova**, J. Ilstad and O. Emam, "Availability Analysis for Satellite Data Processing Systems Based on SRAM FPGAs", IEEE Transactions on Aerospace and Electronic Systems, Vol. 52, Issue 3, pp. 977-989, 2016.

Grants and contracts

[G1] EU Project: 'ReVuS: Reducing Vulnerability of Space Systems', PI **T. Vladimirova**, FP7 Space Grant Coordinated by Airbus Defence and Space (EADS Astrium) in Toulouse, France, https://cordis.europa.eu/project/id/262156, partners include Fraunhofer, Germany and Astri Polska, Poland, Duration 1/3/11-30/1/14, Value [EUR1.97M] GBP1,800,000 (17-11-2020).

[G2] ESA / Airbus Defence and Space Grant: 'Failure-Detection, Fault-Isolation and Recovery Schemes for Reconfigurable Spaceborne FPGA-Based Systems'; PI **T. Vladimirova**, Duration 1/10/12-30/9/15, Value GBP132,000.

4. Details of the impact

Extending the Flight Time of Satellite Systems

Building, launching, and maintaining a satellite is very expensive. The cost of building a satellite can vary from USD200,000,000 to in excess of USD400,000,000. Launching a satellite can cost in the region of USD50,000,000 – 400,000,000, although a launch vehicle may be capable of carrying several satellites, thus spreading the cost. Finally, annual maintenance cost varies between USD400,000 to 1,500,000. Clearly, extending the functional life of a satellite spreads these huge costs over a greater time-period, helping to make them more cost-effective and economical.

Vladimirova's research into extending flight times of satellites was in collaboration with Airbus Defence and Space in Toulouse, France, within the EU FP7 project ReVuS (2011-2014), with economic impact through to 2020. Based on the innovative distributed fault-management system **[R3, R4]**, Airbus was provided with a novel architecture for computing systems for on board spacecraft applications, which offers both highly-reliable operation and high-performance data processing capability. This provides an **economic benefit** to the company as it allows the flight time of their space systems to be increased: *"The impact is in the form of increased understanding and awareness of intra-satellite fault-tolerant distributed computing as a new capability, providing a robust response of on-board computing systems to debris impact and extending spacecraft lifetime"* **[E1]**. The work received a commendation from Airbus: "*[T]he contribution of the University of Leicester was the most innovative outcome of the ReVuS project*" **[E1]**.

A further impact from the research was in terms of training and **knowledge transfer**. The National Space Agency of Pakistan (SUPARCO) has used the research to help develop their real space missions: *"The impact is in the form of increased understanding and awareness and addresses a gap in the current on board computer design enabling a high computational performance and a high reliability. Elements of the proposed methods have been successfully demonstrated in flight on board the recent Pakistan Technology Evaluation Satellite PakTES-1A, developed by SUPARCO, which was launched on the 9th July 2018"* **[E2]**.

Further impact through knowledge transfer has benefited the space company, STAR-Dundee in Scotland, an aerospace engineering company focused on spacecraft on-board data-handling and processing technology, delivering a comprehensive range of test and development equipment, chip designs, and IP cores to the world's space agencies and international aerospace industry. STAR's Chief Technology Officer stated: *"Examples of significant contributions* [from working with UoL] *are: a novel distributed fault-tolerance management scheme based on a new approach to task oriented fault-tolerant distributed computing (FTDC) on board spacecraft, a new adaptive middleware design supporting task migration in case of a failure that is external to the processing unit, a novel scalable* *and efficient Multiprocessor System-on-a- Chip (MPSoC) based FTDC hardware platform, which was fully demonstrated though a near-realistic prototype of an FTDC Attitude and Orbit Control System (AOCS) computer for use on board satellites*" **[E3]**.

Thus, this significant work has achieved both national and international reach. The work has been prototyped in the context of educational pico- and nano-satellites, such as CubeSats. A CubeSat (U-class spacecraft), a type of miniaturized satellite for space research that is made up of multiples of 10cm × 10cm × 11.35cm cubic units, have a mass of no more than 1.33 kilograms (2.9lb) per unit, and often use commercial off-the-shelf (COTS) components for their electronics and structure.

Addressing a Gap in the Current Space Qualification Process

The novel research at UoL, reported in **[R5, R6]**, has provided the European Space Agency, along with Airbus Defence and Space in Stevenage, UK (2012-2015), with initial design and implementation of technology aimed at improving fault diagnostics and recovery schemes for instrument data processing systems (payloads) on board satellites. The research at UoL has led to a new SEU mitigation technique for use in space-borne static random-access memory field-programmable gate arrays (SRAM FPGAs). The impact is in the form of **increased understanding and awareness** and **addresses a gap in the current space qualification process of the European Space Agency [E4, E5]**: *"The novel solutions developed as a result of the project address real needs of fault tolerant data processing on board spacecraft and have undoubtedly influenced design practices within ESA"* **[E5]**. Whilst the specific research was aimed directly at space/satellite applications, as an indication of the future potential impact, this diagnostic approach is also applicable to mission-critical applications in the automobile and nuclear industries.

A further impact from the research into testing and validating systems incorporating SRAM-based FPGAs was in terms of knowledge transfer into the payload division of **the European Space Research and Technology Centre** (ESTEC) in Noordwijk, the Netherlands, which is the largest ESA site. ESTEC is the incubator of the European space effort, where most ESA projects are born and where they are guided through the various phases of development. Additionally, ESA were so interested in the work that they sponsored a proton irradiation test campaign worth EUR10,000 (10-2020), which was carried out at the Paul Scherrer Institute in Villigen, Switzerland, to validate the proposed fault detection, isolation and recovery technique (FDIR) **[E5]**.

There has also been knowledge transfer between UoL and Airbus Defence and Space in Stevenage, UK, **[E4]** and Cobham Gaisler in Gotenburg Sweden **[E6]**, who specialise in providing IP cores and supporting development tools for embedded processors based on the SPARC architecture, and are a recognised provider of digital hardware solutions for both commercial and aerospace applications. As a direct result of the ESA/Airbus Defence and Space project **[G2]**, Cobham Gaisler employed Dr Felix Siegle, a member of the UoL team, who gained transferable knowledge that enabled him to become "*a valuable member of the team"* who *"made a significant lasting contribution to our activities. For example, Dr Felix Siegle contributed substantially to the SpaceWire and SpaceFibre projects*" **[E6]**.

5. Sources to corroborate the impact

[E1] Testimonial, Head of Security, Defence and EU Space R&D, Airbus Defence and Space, 19 November 2020.

[E2] Testimonial, General Manager DH (Software DEV), National Space Agency of Pakistan (SUPARCO), Lahore, Pakistan, 29 May 2019.
[E3] Testimonial, Chief Technology Officer, STAR-Dundee Ltd., 12th September 2020.
[E4] E-mail testimonial, Head of Digital Systems Design, Communications Processors, Airbus Defence and Space, Stevenage, UK, 30 September 2015.
[E5] Testimonial, **European Space Research and Technology Centre** (ESA), Noordwijk, 4 June 2019.
[E6] Testimonial, General Manager, Cobham Gaisler AB, Goteborg, Sweden, 26 October 2019.