Computer Architecture in Humanity's Space Ventures

And its impact on our everyday lives

Wojciech Krzos
ARCHITEKTURA KOMPUTERÓW

CONTENTS

1 INTRO

1.1 FOREWORD

Humanity's space exploration has had a significant impact on various areas of science and technology, including computer architecture. The development of space technology and exploration has pushed the boundaries of what is possible in computing, driving innovation and progress in this field. In this essay, it will be delved deeper into the impact of space exploration on computer architecture. Challenges that space technology has posed for computer designers and the ways in which space exploration has driven the development of new computing technologies will be discussed.

1.2 AIM OF PAPER

The aim of the paper is to be an introduction to the subject to all of those, who may be interested in it but are unsure of whether to go deeper into this rabbit hole. Furthermore, some case studies will be taken under consideration to find the factual impact of the advancements of computer architecture induced by us exploring the cosmos.

1.3 STRUCTURE OF THE PAPER

The paper firstly discusses the very beginnings of space exploration to establish the needed background for the reader. Then, it moves to the first space rockets, followed by the initial stages of modern space industry. The paper then discusses different hazards a space computer architecture faces to showcase the broadness of the subject. Then, it takes under investigation several case studies of both great achievements and failures of space industries all around the world. In the end, a conclusion summarizes the paper coming to the final judgment of the topic.

2 WHAT CAN BE EXPECTED OF COMPUTER ARCHITECTURE IN SPACE

2.1 FIRST STEPS

Since the dawn of our species, we had been fascinated by everything about our world – especially, the sky above us. Many theories were tailored as to what those small speckles of dust – the stars – in the night sky were. However, for the proper space exploration we should look no further than 1608, when Hans Lippershey – a Dutch eyeglass maker – had invented the first telescope, later used by Galileo Galilei in 1609, whom is often mistaken as the inventor (King 2011).

A quick jump to the World War II and one of Third Reich's greatest engineers – Wernher von Braun (Krzos 2022). In 1944 the first ever human-made object reached the space – an artificial boundary known as the Kármán line (Bright 2019). Although the technology was more sophisticated, the rocket was operated by on-board analogue systems and mechanical components. Due to its heavy reliance on gyroscopes, discussing computer architecture as we know it today becomes challenging.

It's important to note that the V-2 missile was developed and deployed in the 1940s, several decades before the advent of electronic digital computers. Computers as we know them today were still in their infancy during that time, and their miniaturization and integration into military systems occurred in subsequent years.

However, a new era was slowly crawling over the horizon – the information revolution – and with it, the gates of space exploration opened ever so slightly.

2.2 RELIABILITY AND RESILIENCE IN EXTREME ENVIRONMENTS

The importance of reliability and resilience in extreme environments cannot be overstated. In space exploration, a single failure in a computing system can result in catastrophic consequences, such as the loss of a spacecraft or satellite. Therefore, ensuring the reliability and resilience of space-based computing systems is crucial.

Radiation is one of the most significant challenges that space-based computing systems face. High-energy particles can cause soft errors, which can result in data corruption or system crashes. Radiation-hardened components are specifically designed to withstand these effects by using materials that are less susceptible to radiation-induced errors. These components are often used in critical systems that require high reliability, such as navigation and communication systems.

Extreme temperatures are another challenge that space-based computing systems face. Temperatures in space can range from hundreds of degrees Celsius to hundreds of degrees below zero. These temperature extremes can cause electronic components to fail or degrade over time. Therefore, designers of space-based computing systems have developed technologies that can operate in a wide range of temperatures, such as thermal management systems and heat-resistant materials.

In addition to radiation and temperature challenges, space-based computing systems also face other environmental factors such as vibration, shock, and electromagnetic interference. These factors can cause mechanical stress and electromagnetic interference that can damage electronic components. To address these challenges, designers have developed fault-tolerant architectures that can detect and correct errors in real-time. These architectures can also provide redundancy, allowing systems to continue operating even if a component fails.

The technologies developed for space-based computing systems have also been adopted in critical systems on Earth. For example, radiation-hardened components are used in military and aerospace applications to ensure reliable operation in harsh environments. Fault-tolerant architectures are used in medical applications, such as pacemakers, to ensure that critical systems continue operating even if a component fails.

In conclusion, the need for reliability and resilience in extreme environments has led to the development of new architectures and technologies that can withstand harsh conditions. These technologies have not only enabled space exploration but have also been adopted in critical systems on Earth. The ongoing development of new technologies will continue to push the boundaries of what is possible in extreme environments.

2.3 Real-time data processing

The need for high-performance computing systems in space exploration has been driven by the growing complexity and sophistication of space-based instruments and sensors. These instruments generate vast amounts of data that must be processed and analysed in real-time to support scientific research and other space-based activities. For example, in the field of astronomy, space-based telescopes generate large amounts of data that must be processed quickly and accurately to produce high-quality images and other scientific data.

To address these challenges, designers of space-based computing systems have developed new architectures and technologies that are optimized for high-performance computing. One of the key developments in this area has been the use of multi-core processors, which can perform multiple tasks simultaneously, allowing for faster and more efficient processing of data. High-speed interconnects are also essential for transferring data between different processing elements quickly and efficiently, reducing processing time and improving overall system performance.

In addition to multi-core processors and high-speed interconnects, specialized hardware accelerators have also been developed for space-based computing systems. These accelerators are designed to perform specific tasks, such as signal processing or image analysis, more efficiently than general-purpose processors. This can significantly improve overall system performance and reduce processing time.

The development of high-performance computing systems for space exploration has also had significant benefits for other areas of computing. For example, the technologies and architectures developed for space-based computing systems have been adopted in a wide range of other applications, such as scientific research, defence, and finance. The high-performance computing systems used in these applications can process vast amounts of data quickly and efficiently, enabling new insights and discoveries.

In conclusion, the need for high-performance computing systems in space exploration has driven the development of new architectures and technologies that are optimized for processing large amounts of data in real-time. These developments have not only enabled scientific research and other space-based activities but have also had significant benefits for other areas of computing. The ongoing development of new technologies will continue to push the boundaries of what is possible in high-performance computing, enabling new discoveries and innovations.

2.4 SOFTWARE

Space exploration has been a catalyst for the development of new software and programming models optimized for space-based computing. These models are designed to address the unique challenges of computing in space, such as the need for fault-tolerant systems that can detect and recover from errors in real-time. To ensure reliable and efficient data processing, new programming languages and models have been developed that support the processing of vast amounts of data in parallel.

Space exploration has also contributed significantly to the development of new computing applications and technologies. The development of space-based computing systems has led to the creation of new applications in fields such as remote sensing, weather forecasting, and global communications. For instance, satellites equipped with advanced imaging and sensing technologies have made it possible to track weather patterns and monitor natural disasters, which has significantly improved the accuracy of weather forecasts and increased our ability to respond to natural disasters.

In addition, space-based technologies have led to the creation of satellite-based navigation systems and high-bandwidth data networks that have revolutionized various aspects of our lives. GPS navigation systems have become ubiquitous in cars and smartphones, providing us with accurate and real-time location information. High-bandwidth data networks have made it possible to communicate with anyone anywhere in the world, facilitating the sharing of information and the growth of global commerce.

Moreover, space exploration has also had significant implications for the development of new computing hardware. The extreme conditions of space, such as high radiation levels and temperature fluctuations, have required the development of specialized hardware that can operate reliably in such harsh environments. This has led to the creation of new materials and manufacturing processes that have enabled the production of rugged and reliable hardware for use in space and other extreme environments.

In conclusion, space exploration has been a driving force behind the development of new computing applications, technologies, and hardware. The need to address the unique challenges of computing in space has led to the creation of new software and programming models optimized for space-based computing. These models have been applied to various fields such as remote sensing, weather forecasting, and global communications, leading to the development of new computing applications and technologies that have revolutionized many aspects of our lives. Additionally, the need to operate in harsh environments has led to the creation of new materials and manufacturing processes, enabling the production of rugged and reliable hardware for use in space and other extreme environments.

2.5 Artificial Intelligence

The use of AI and ML technologies in space exploration has significantly advanced our understanding of the universe and enabled us to conduct missions that would otherwise be impossible. With the ever-increasing amount of data being generated by space-based instruments and sensors, AI and ML have become essential tools for processing, analysing, and interpreting this data. They enable us to extract meaningful insights and patterns from vast amounts of information, providing us with a deeper understanding of the universe and its mysteries.

One example of the use of AI and ML in space exploration is the development of autonomous spacecraft and robotic explorers. These spacecraft and robots are designed to operate in remote and hazardous environments, such as the surface of Mars or the depths of outer space, where human intervention is impossible or impractical. AI and ML technologies are used to enable these spacecraft and robots to make decisions and take actions autonomously, based on their environment and the data they collect.

AI and ML are also being used to develop predictive models for space weather forecasting. Space weather refers to the environmental conditions in space, including solar flares, coronal mass ejections, and other phenomena that can affect space-based infrastructure and technology. By using AI and ML algorithms to analyse historical data and predict future space weather events, we can better prepare for and mitigate the impact of these events on our space-based assets.

Furthermore, AI and ML are being used to develop advanced simulations of space-based systems and environments. These simulations enable us to test and validate new technologies and systems before they are deployed in space. They also enable us to explore and model different scenarios and potential outcomes, providing us with valuable insights and information for mission planning and execution.

In conclusion, space exploration has played a significant role in the development and advancement of AI and ML technologies. These technologies have become essential tools for processing and analysing the vast amounts of data generated by space-based instruments and sensors, enabling us to gain a deeper understanding of the universe. They are also being used to develop autonomous spacecraft and robotic explorers, predictive models for space weather forecasting, and advanced simulations of space-based systems and environments. With the continued development and application of AI and ML technologies, we can expect to see further advances in space exploration and our understanding of the universe.

3 CASE STUDIES

3.1 HOW TO LOSE $370 MILLION IN 40 SECONDS

On June 4, 1996, the inaugural flight of the Ariane 5 rocket (Flight 501) ended in failure. Approximately 40 seconds after liftoff, the rocket veered off course and self-destructed due to a software error in the rocket's guidance system. The failure was traced back to a conversion of a 64-bit floating-point value to a 16-bit signed integer (look line 12 of Figure 1), causing an exception and subsequent loss of guidance and control. This led to a system diagnostic error and simultaneous control transfer to a backup computer, resulting in uncontrolled motor movement beyond permissible limits and catastrophic consequences (Prakash 2023). The explosion resulted in the loss of the rocket and its payloads, which included four Cluster satellites (Dowson 1997).

```
1  L_M_BV_32 := TBD.T_ENTIER_32S ((1.0/C_M_LSB_BV) * G_M_INFO_DERIVE(T_ALG.E_BV));
2
3  if L_M_BV_32 > 32767 then
4      P_M_DERIVE(T_ALG.E_BV) := 16#7FFF#;
5  elsif L_M_BV_32 < -32768 then
6      P_M_DERIVE(T_ALG.E_BV) := 16#8000#;
7  else
8      P_M_DERIVE(T_ALG.E_BV) := UC_16S_EN_16NS(TDB.T_ENTIER_16S(L_M_BV_32));
9  end if;
10
11 P_M_DERIVE(T_ALG.E_BH) :=
12   UC_16S_EN_16NS (TDB.T_ENTIER_16S ((1.0/C_M_LSB_BH) * G_M_INFO_DERIVE(T_ALG.E_BH)));
```

Figure 1: Ariane 5 software snippet responsible for the critical error

The failure was then under heavy investigation and set back the European Space Agency's plans by a significant amount of both money and time. The software used by the engineers from previous Ariane 4 rockets was unsuited for the new rocket of drastically different parameters: from its mean thrust all the way to Δv parameters (Dowson 1997).

This incident emphasizes the need for meticulous software design, robust error handling, and rigorous testing procedures to ensure the integrity and safety of complex systems. It serves as a crucial lesson for the aerospace industry, driving the adoption of enhanced practices to fortify the reliability and security of future rocket missions.

3.2 MARS GLOBAL SURVEYOR'S PREMATURE END

The Mars Global Surveyor (MGS) spacecraft lost contact in November 2006 due to a memory load command error that corrupted positioning parameters. This led to overheating of a battery and depleted spacecraft power (JPL 2007). An independent review board outlined 10 recommendations to improve operational procedures, address spacecraft design weaknesses, and mitigate risks associated with late-implemented changes.

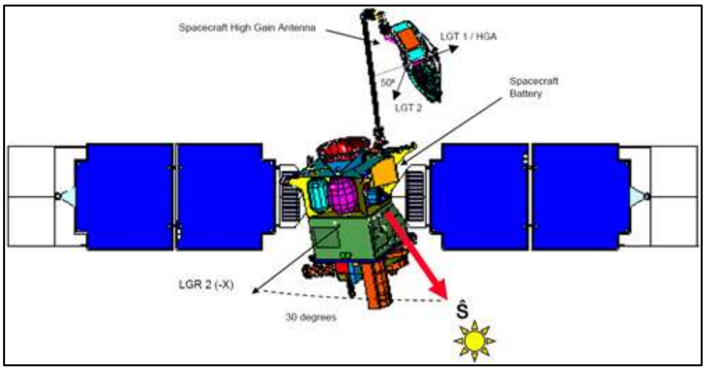

Figure 2: MGS in Sun-Stuck-Gimbal control state (JPL 2007)

During a routine contact, alarms indicated a solar array drive malfunction on the MGS spacecraft, triggering a switch to the redundant drive controller. However, subsequent attempts to establish communication failed. The mission loss resulted from a memory load command error sent months earlier, corrupting parameters and causing two separate faults.

The first fault led to a solar array being driven against its hard stop, activating Contingency Mode. This mode alternated between two control states, favouring battery charging even at the risk of thermal limits. The exposed battery overheated, depleting both batteries as the power management software reduced the charge rate (Minkel 2007).

The second fault caused the High Gain Antenna to point away from Earth, disrupting downlink communications and preventing ground controllers from addressing the thermal and power situation. After several Mars orbits, the batteries became fully discharged, resulting in the loss of attitude control and subsystem functionality (JPL 2007).

JPL points out 3 key lessons learned in the incident (2007):

1. Operational Procedures and Processes: Inadequate procedures contributed to error detection failures.
2. Spacecraft Design Weaknesses: Fault protection systems and thermal safety measures were insufficient.
3. Lifetime Management Considerations: Budget reductions and personnel turnover increased risks.

Some recommendations were made by engineers later analysing this occurrence:

1. Operational Procedures and Processes: Set appropriate alarm limits, conduct thorough reviews, prioritize predefined commands, implement robust configuration management, and establish quick data acquisition procedures.
2. Spacecraft Design Weaknesses: Improve fault detection and capture key data autonomously.
3. Lifetime Management Considerations: Perform independent reviews, update operational processes, and assess fault protection parameters regularly.

The premature end of the Mars Global Surveyor (MGS) spacecraft in November 2006 due to a memory load command error highlighted the importance of operational procedures, spacecraft design, and lifetime management considerations. The corruption of positioning parameters led to overheating of a battery and depleted spacecraft power. Inadequate fault protection systems, insufficient thermal safety measures, and communication disruptions exacerbated the situation. Lessons learned include the need for improved operational procedures, such as setting appropriate alarm limits, conducting thorough reviews, and prioritizing predefined commands. Addressing spacecraft design weaknesses involves enhancing fault detection capabilities and capturing key data autonomously. Regular independent reviews, updates to operational processes, and ongoing assessment of fault protection parameters are crucial for effective lifetime management, ensuring the safety and success of future space missions.

3.3 The everlasting partnership: NASA and IBM

NASA and IBM have a long-standing partnership in the field of space exploration and technology development. The two organizations have collaborated on numerous projects over the years, with a focus on advancing space-based computing and data analytics (Goldstein 2016).

Figure 3: First IBM 7094 (Goldstein 2016)

One notable project that NASA and IBM have collaborated on is the development of the NASA Earth Exchange (NEX), a platform that enables researchers to access and analyse large amounts of environmental data from space-based sensors and instruments. IBM provided the computing infrastructure and data management tools for the platform, while NASA provided the data and scientific expertise. The platform has been used for a variety of research applications, including climate modelling, ecosystem analysis, and natural resource management (Yip 2021).

Another area of collaboration between NASA and IBM is in the development of AI and ML technologies for space exploration. IBM's Watson AI platform has been used to develop advanced algorithms and models for analysing space-based data and supporting autonomous spacecraft operations. NASA has also worked with IBM to develop AI-based predictive models for space weather forecasting, which can help to mitigate the impact of solar storms and other space weather events on space-based infrastructure and technology (Blumenfeld 2023).

In addition to these projects, NASA and IBM have also collaborated on the development of new materials and manufacturing processes for space-based hardware. For example, IBM has developed a new process for manufacturing silicon-based semiconductors that can withstand the extreme conditions of space, such as high radiation levels and temperature fluctuations.

This technology has been used in the development of NASA's Juno spacecraft, which is currently in orbit around Jupiter (IBM Newsroom 2021).

NASA and IBM have also worked together on the development of quantum computing technologies for space-based applications. Quantum computing has the potential to revolutionize space-based computing and data analytics, enabling us to process and analyse vast amounts of data at speeds that are currently impossible with traditional computing systems. IBM has developed several quantum computing systems, and NASA has collaborated with the company to explore the potential applications of these systems in space exploration (Nikkei 2019).

In conclusion, the collaboration between NASA and IBM has been instrumental in advancing space-based computing and data analytics, as well as the development of new materials and manufacturing processes for space-based hardware. The two organizations have also worked together to develop AI and ML technologies for space exploration, as well as explore the potential of quantum computing for space-based applications. With their shared expertise and resources, NASA and IBM will continue to push the boundaries of space exploration and technology development (The Apollo Missions 2012).

4 CLOSURE

4.1 SUMMARY

The impact of humanity's space exploration on computer architecture has been significant, driving innovation and progress in this field. The challenges posed by space-based computing have led to the development of new architectures, technologies, and programming models that are now used in a wide range of computing applications. The development of space-based computing systems has also led to the creation of new applications and technologies that are transforming the way we live and work on Earth. As humanity continues to explore space and push the boundaries of what is possible in computing, we can expect to see further advances in this field that will benefit us all.

4.2 CONCLUSIONS

Space exploration has greatly impacted computer architecture, fostering innovation and technological advancements. Challenges in space, such as radiation and extreme temperatures, have driven the development of resilient computing systems and components, benefiting both space missions and critical systems on Earth.

The need for high-performance computing in space has led to optimized architectures and technologies for real-time data processing. Multi-core processors, high-speed interconnects, and specialized hardware accelerators have revolutionized data processing capabilities, benefiting scientific research and various computing applications.

Space exploration has also spurred the development of software and programming models tailored for space-based computing. AI and ML technologies have played a crucial role in processing vast amounts of data generated by space-based instruments and sensors. They have enabled autonomous spacecraft, predictive space weather models, and advanced simulations of space-based systems.

In conclusion, space exploration has been a catalyst for advancements in computer architecture. Challenges in extreme environments have driven the development of resilient systems, while the need for high-performance computing and real-time data processing has pushed the boundaries of what is possible. Optimized software and the integration of AI and ML technologies have further enhanced our capabilities in space exploration, expanding our understanding of the universe.

4.3 FURTHER EXTENSIONS

It is believed that future papers on this topic could be extend about the following points:

- Space-oriented computer architecture of other highly influential states, namely: Union of Soviet Socialist Republics, People’s Republic of China, Republic of India, Japan.
- The impact of big companies on the development of space-oriented computer architecture (mainly the 2020’). Namely: SpaceX, Blue Origin, Boeing, and Northrop.
- Space-oriented computer architecture of the present times, especially years 2010 – 2023.

4.4 EVALUATION

Some aspects of the paper were found to be significantly positive to be pointed out for future works:

- It is thought that the inclusion of different countries, companies, missions, and time frames improved the diversity of the topic in the paper. This shed a light on this subject across different fields of study.
- The structure of the paper, with the assumptions made in 1.2 Aim of paper, is thought to be beneficial for the reader and creates a rigid structure of the work. For future papers it is advised to firstly introduce the theory and overall background of the subject, and only then move to the case studies.

Some negative aspects of the paper were found, which should be addressed in future investigations:

- Although the diverse case studies positively influence the paper, it is thought the case studies should have also included states of cultures other than the western culture. As mentioned above in 4.3 Further extensions. For now, the paper may seem biased and unappreciable of other state's influence on the subject.
- It is believed the Ariane 5 case study could have been further extended with appropriate documentation. However, this may prove itself to be challenging for future investigations due to lack of publicly accessible documentation on the topic.
- Furthermore, it is suggested that future investigations should increase the overall number of case studies. Although the existing case studies provide valuable insights, a larger sample size would enhance the generalizability and robustness of the findings. Increasing the number of case studies would allow for a more extensive exploration of the subject and help identify additional patterns or trends that may not have been captured with the current set of cases.

5 Bibliography

1. Blumenfeld J. NASA and IBM Collaborate to Apply AI to Earth Science Data. Earthdata. 2023 Feb 1 [accessed 2023 Jun 13]. https://www.earthdata.nasa.gov/news/nasa-ibm-ai-collaboration

2. Bright M, Sarosh C. Earth from space: epic stories of the natural world. 2019.

3. Dowson M. The Ariane 5 software failure. ACM SIGSOFT Software Engineering Notes. 1997;22(2):84. doi:10.1145/251880.251992

4. IBM Unveils World's First 2 Nanometer Chip Technology, Opening a New Frontier for Semiconductors. IBM Newsroom. 2021 May 6 [accessed 2023 Jun 26]. https://newsroom.ibm.com/2021-05-06-IBM-Unveils-Worlds-First-2-Nanometer-Chip-Technology,-Opening-a-New-Frontier-for-Semiconductors

5. IBM100 - The Apollo Missions. 2012 Mar 7 [accessed 2023 Mar 12]. http://www-03.ibm.com/ibm/history/ibm100/us/en/icons/apollo/

6. JPL. Mars Global Surveyor (MGS) Spacecraft Loss of Contact. 2007 Sep 3 [accessed 2023 Jun 26]. https://llis.nasa.gov/lesson/1805

7. King HC. The History of the Telescope. Mineola, N.Y: Dover Publications; 2011.

8. Krzos W. If we conclude that there is some knowledge we should not pursue on ethical grounds, how can we determine the boundaries of acceptable investigation within an area of knowledge? Discussed with reference to two areas of knowledge. [Unpublished]. 2022 May:9.

9. Minkel JR. Human Error Caused Mars Global Surveyor Failure. Scientific American. 2007 Apr 13 [accessed 2023 Jun 5]. https://www.scientificamerican.com/article/human-error-caused-mars-g/

10. Nikkei. NTT taps NASA to take on Google and IBM in quantum computing. Nikkei Asia. 2019 Nov 14 [accessed 2023 Jun 26]. https://asia.nikkei.com/Business/Technology/NTT-taps-NASA-to-take-on-Google-and-IBM-in-quantum-computing

11. Prakash A. A Floating Point Error That Caused A Damage Worth Half A Billion. It's FOSS. 2012 Oct 6 [accessed 2023 Jun 1]. https://itsfoss.com/a-floating-point-error-that-caused-a-damage-worth-half-a-billion/

12. Stallings W. Computer Organization and Architecture. 10th edition. Boston: Pearson; 2015.

13. Yip W. NASA Earth Exchange | NASA. 2021 Nov 30 [accessed 2023 May 24]. https://www.nasa.gov/nex/

14. Goldstein P. How the IBM 7094 Gave NASA and the Air Force Computing Superiority in the 1960s. Technology Solutions That Drive Government. 2016 Oct 11 [accessed 2023 Jun 28]. https://fedtechmagazine.com/article/2016/10/how-ibm-7094-gave-nasa-and-air-force-computing-superiority-1960s

15. Stallings W. Computer Organization and Architecture. 10th edition. Boston: Pearson; 2015.