Louvain School of Management

A Systematic Literature Review Of Software For Mars Missions

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Master [60]: Management Science

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to Professor Jean Vanderdonckt for his guidance, invaluable insights, and continuous support throughout the entire duration of this thesis. Professor Vanderdonckt's expertise, encouragement, and commitment to excellence have been instrumental in shaping the trajectory of this thesis.

I am also profoundly grateful to my friends and family for their love, encouragement, and unwavering support. Their belief in me, endless patience, and understanding have been a constant source of strength and motivation throughout this journey.

To all those who have contributed in various ways, whether through discussions, feedback, or simply being there to lend an ear, thank you for being part of this endeavour. Your support has been invaluable and has enriched this thesis in ways beyond measure.

Abstract

This thesis presents a systematic literature review that examines essential software design principles for Mars missions, with a focus on modularity, fault tolerance, communication protocols, security measures, and the integration of artificial intelligence. A meticulous selection of 32 studies reveals the crucial role these principles play in ensuring the scalability, maintainability, and reliability of software systems in challenging space exploration environments. The research emphasizes the potential of machine learning and predictive analytics to enhance mission efficiency and safety, fostering increased autonomy in space operations. Moreover, this study discusses critical limitations, including selection and reporting biases, time and access constraints, and a concentration on certain mission phases, which may influence the generalizability of the findings. Despite the exhaustive approach, the limited sample size and the student's singular perspective highlight the need for a cautious interpretation of the results. The thesis advocates for continuous innovation and adaptation in software design to meet the evolving demands of Mars exploration, laying the groundwork for future research to expand upon these findings with broader methodologies and access to diverse resources.

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Chapter 1

Introduction

1.1 Context And Background Of Mars Missions Software

Since the dawn of the space age, humanity has been captivated by the allure of the Red Planet, Mars [1]. Mars is the fourth planet from the Sun and the second smallest planet in the solar system after Mercury [1]. Interestingly, Mars shares many similarities with Earth, such as polar ice caps, seasonal changes, and evidence of ancient rivers and lakes [2]. These similarities have raised the possibility of past or present life on Mars, making it a focal point for scientific exploration and potential colonization efforts [3]. Mars presents unique challenges and opportunities that can provide valuable insights into Earth's history and prospects for interplanetary exploration [4].

Over the decades, numerous missions have been launched by space agencies around the world with the ambitious goal of exploring and understanding Earth's neighbouring planet [5]. From the early days of simple flybys to sophisticated rovers traversing its surface, each mission has contributed to our growing knowledge of Mars and its potential for past or present habitability [5]. These missions require sophisticated software systems to control spacecraft, rovers, and various instruments [6]. To contribute to the advancement of software development for Mars exploration, it is crucial to conduct a systematic literature review to examine and analyze the existing software used for Mars missions [7].

A systematic literature review allows researchers to gather and analyze all relevant studies on a particular topic in a methodical and structured manner [8]. In the case of Mars missions, this approach can provide insights into the types of software being used, current trends in software development for Mars missions, and potential areas for improvement or further research. Moreover, a systematic literature review can help identify gaps in current knowledge and highlight areas where future research is needed [9]. This thesis aims to conduct a systematic literature review on the software used, currently in use, or planned to be used for Mars missions.

It is worth mentioning that a systematic literature review of software for Mars missions has not been previously conducted, making this study the first of its kind. The completion of this research will provide a comprehensive overview of the software landscape for Mars missions, allowing for better understanding and potential improvements in software development for future Mars missions.

1.2 Research Question

The purpose of this thesis is to conduct a systematic literature review of software currently in use, planned to be used or used for Mars missions in order to gain practical knowledge of best practices for Mars software development. Consequently, the research question for this systematic literature review is:

What are the key design principles that contribute to the successful implementation of applications/software in Mars mission environments?

Throughout this systematic literature review, we will explore and analyze the existing literature to address this research question and gain a comprehensive understanding of the software used for Mars missions.

1.3 Research Method

This section provides a brief overview of the research method used for this systematic literature review. The research method used in this systematic literature review is a meta-narrative approach, which includes the process of identifying, analyzing, and recognizing patterns and themes from various research results relevant to the topic [10]. All the different points mentioned here are going to be seen in more detail in the next chapters.

- Query: form a query to use in the literature databases to identify relevant studies on software used for Mars missions.
- Inclusion and exclusion criteria: determine which study is relevant to the systematic literature review on criteria related to the form and content of each paper.
- Study selection: using the inclusion and exclusion criteria to select studies that meet the research objectives and are relevant to the topic of software used for Mars missions.
- Data extraction: collecting information and data from the selected studies, which includes details about the software used in Mars missions, its functionalities, limitations, and impact.
- Classification schemes: organizing the extracted data into categories or classification schemes to facilitate analysis and comparison across studies.
- Analysis: analyze the collected data to identify patterns, themes, and trends related to

software used for Mars missions, as well as potential areas for improvement and future research.

- Synthesis: Synthesis of the findings from the analysis to provide a comprehensive overview of the software landscape for Mars missions, highlighting key findings and implications for future missions.

Chapter 2

Methodology

In conducting research for any academic endeavour, a robust and systematic search strategy is paramount to ensure the thoroughness, relevance, and reliability of findings [11]. This section delineates the methodological approach employed to identify pertinent literature, laying the foundation for the subsequent analysis and discussion within this thesis.

By articulating the rationale behind database selection and delineating the precise terms and syntax employed in the search process, this section aims to provide transparency and reproducibility in the research methodology.

2.1 Databases

In pursuit of a comprehensive understanding of the research landscape, an array of reputable scholarly databases was meticulously selected to facilitate the identification and retrieval of relevant literature. The chosen databases were deemed to offer a rich reservoir of peer-reviewed articles, conference proceedings, and scholarly publications pertinent to the research objectives [12].

The following databases were utilized:

1. **ACM Digital Library**: renowned for its extensive collection of research articles, conference proceedings, and technical literature spanning various subfields within computer science, the ACM Digital Library served as a primary repository for sourcing scholarly content [13].

2. **IEEE Xplore**: esteemed for its comprehensive coverage of electrical engineering, computer science, and related disciplines, IEEE Xplore provides access to peer-reviewed journals, conference proceedings, and standards publications [14].

3. **ScienceDirect**: leveraging the expansive repository of scientific and technical research hosted by Elsevier, ScienceDirect offered access to a diverse range of journals, articles,

and book chapters across numerous disciplines, including computer science [15].

4. **SpringerLink**: renowned for its extensive collection of scholarly publications, SpringerLink facilitated access to a wide array of peer-reviewed journals, books, conference proceedings, and reference works within the field of computer science [16].
5. **Google Scholar**: widely utilized for its comprehensive coverage of scholarly literature, Google Scholar served as a supplementary resource for identifying potentially relevant articles and publications beyond traditional academic databases [17].
6. **Elicit**: a specialized AI platform tailored to the needs of researchers, Elicit provided access to curated content, enabling targeted exploration of academic literature within specific domains of interest, further enriching the search process [18]
7. **Jenni AI**: an AI assistant for scientific literature research and scientific paper writing.

To ensure inclusivity and comprehensiveness, the initial search process involved retrieving the first 100 papers from each selected database. Subsequently, a rigorous screening process, guided by predefined inclusion and exclusion criteria, was undertaken to narrow down the initial pool of 600 papers to a refined selection of 32 papers. Details regarding the criteria utilized for this selection process will be expounded upon in a subsequent section, elucidating the rationale behind the final composition of the literature review.

2.2 Search Query

The search query used for this literature review encompassed a combination of keywords and Boolean operators to find the relevant literature on software for Mars missions. However, before arriving at the final query used for retrieving relevant literature, a series of iterative queries were tested and refined to optimize search results. These iterations were essential to identify the most effective combination of keywords, Boolean operators, and search strings that yielded the highest proportion of relevant results in the titles and abstracts of retrieved documents.

Formerly, these iterations included the following queries:

Q1= ”Mars” OR ”red planet” AND ”software” OR ”application” OR ”device” OR ”user interface”

For example purposes, the results of the first query are shown in figure 2.1, 2.2 and 2.3. The results are taken from the ACM digital library, SpringerLink library, and Google Scholar. As presented, this query aimed to encompass a broad range of relevant software topics, but as demonstrated in the figures, it resulted in articles primarily focused on user interfaces and software applications unrelated to Mars missions. The retrieved results included articles about generic user interfaces, space-related technologies, and applications that, while potentially relevant to broader space exploration, did not specifically address the context of Mars missions.

This highlights the difficulty in constructing search queries that balance breadth and specificity and underscores the necessity of refining search terms.


$ mars $: Mobile **application** relaunching speed-up through flash-aware page swapping
W Guo, K Chen, H Feng, Y Wu… - IEEE Transactions on …, 2015 - ieeexplore.ieee.org
… **MARS**, a prototype system implementing the **application** relaunching oriented redesign of Linux page swapping on Android. **MARS** … mechanism for **application** relaunching speedup. …
☆ Enregistrer 99 Citer Cité 27 fois Autres articles Les 4 versions

Finite-difference modeling of acoustic and gravity wave propagation in **Mars** atmosphere: **application** to infrasounds emitted by meteor impacts
RF Garcia, Q Brissaud, L Rolland, R Martin… - Space Science …, 2017 - Springer
The propagation of acoustic and gravity waves in planetary atmospheres is strongly dependent on both wind conditions and attenuation properties. This study presents a finite-…
☆ Enregistrer 99 Citer Cité 30 fois Autres articles Les 18 versions

[PDF] **MARS**, the MAGIC analysis and reconstruction **software**
R Zanin, E Carmona, J Sitarek, P Colin… - Proc. of the 33st …, 2013 - inspirehep.net
… included in the **MARS** (MAGIC Analysis and Reconstruction **Software**) package. **MARS** is a … The current **MARS** version 2.12.2 is designed to work with ROOT version 5.34 and it is …
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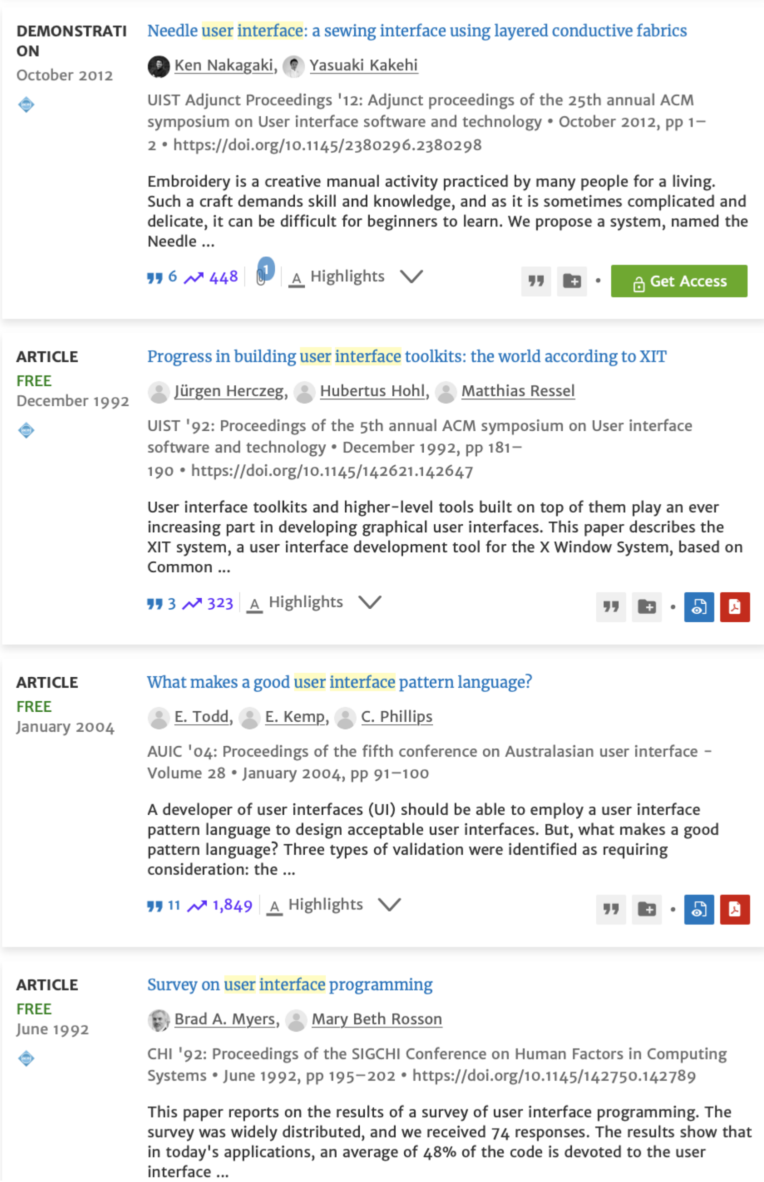
Origins of life: a comparison of theories and **application** to **Mars**
WL Davis, CP McKay - Origins of Life and Evolution of the Biosphere, 1996 - Springer
… life appeared on Earth we have evidence for liquid water present on the surface of **Mars**. … for autotrophs on Earth, is sufficient on **Mars** even though **Mars** is at a greater distant. The …
☆ Enregistrer 99 Citer Cité 109 fois Autres articles Les 8 versions

The Mouse Action Recognition System (**MARS**) **software** pipeline for automated analysis of social behaviors in mice
C Segalin, J Williams, T Karigo, M Hui, M Zelikowsky… - Elife, 2021 - elifesciences.org
… **MARS**), a quartet of **software** … **software** is accompanied by three datasets aimed at characterizing inter- annotator variability for both pose and behavior annotation. Together, the …
☆ Enregistrer 99 Citer Cité 156 fois Autres articles Les 16 versions

Figure 2.1: Google Scholar search results for the first query


DEMONSTRATION
October 2012
Needle user interface: a sewing interface using layered conductive fabrics
Ken Nakagaki, Yasuaki Kakehi
UIST Adjunct Proceedings '12: Adjunct proceedings of the 25th annual ACM symposium on User interface software and technology • October 2012, pp 1–2 • https://doi.org/10.1145/2380296.2380298
Embroidery is a creative manual activity practiced by many people for a living. Such a craft demands skill and knowledge, and as it is sometimes complicated and delicate, it can be difficult for beginners to learn. We propose a system, named the Needle ...
6 448 1 Highlights
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ARTICLE
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December 1992
Progress in building user interface toolkits: the world according to XIT
Jürgen Herczeg, Hubertus Hohl, Matthias Ressel
UIST '92: Proceedings of the 5th annual ACM symposium on User interface software and technology • December 1992, pp 181–190 • https://doi.org/10.1145/142621.142647
User interface toolkits and higher-level tools built on top of them play an ever increasing part in developing graphical user interfaces. This paper describes the XIT system, a user interface development tool for the X Window System, based on Common ...
3 323 Highlights

ARTICLE
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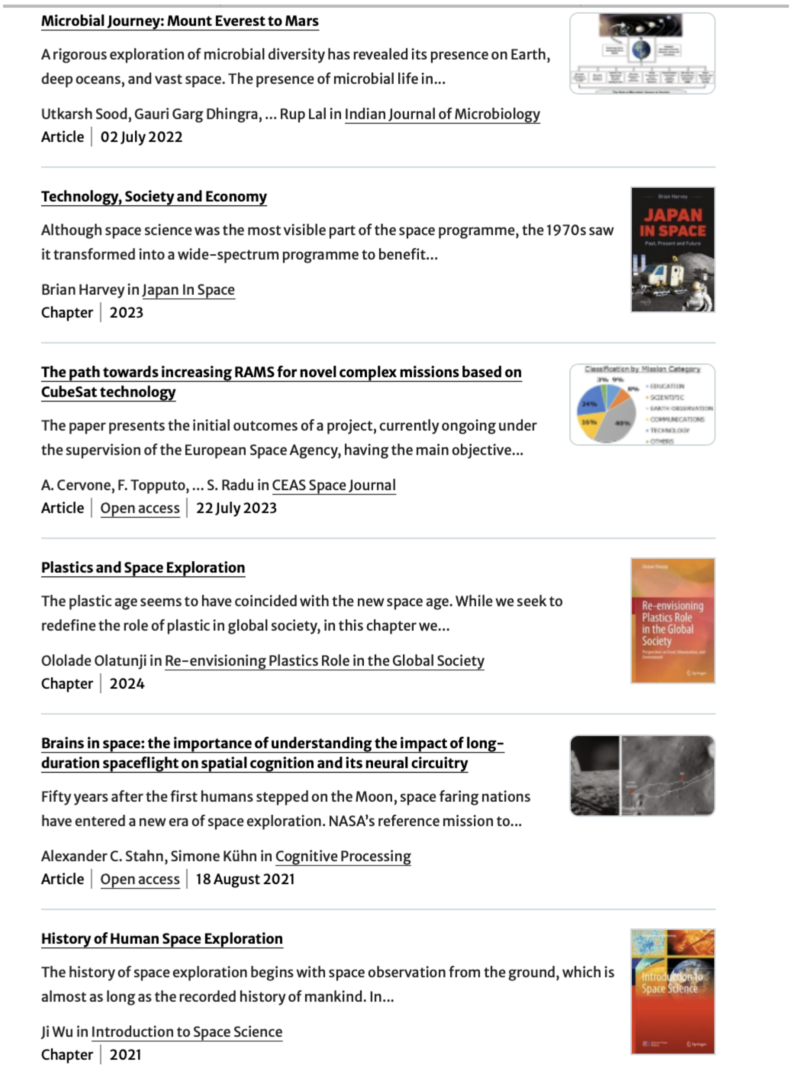
January 2004
What makes a good user interface pattern language?
E. Todd, E. Kemp, C. Phillips
AUIC '04: Proceedings of the fifth conference on Australasian user interface - Volume 28 • January 2004, pp 91–100
A developer of user interfaces (UI) should be able to employ a user interface pattern language to design acceptable user interfaces. But, what makes a good pattern language? Three types of validation were identified as requiring consideration: the ...
11 1,849 Highlights

ARTICLE
FREE
June 1992
Survey on user interface programming
Brad A. Myers, Mary Beth Rosson
CHI '92: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems • June 1992, pp 195–202 • https://doi.org/10.1145/142750.142789
This paper reports on the results of a survey of user interface programming. The survey was widely distributed, and we received 74 responses. The results show that in today's applications, an average of 48% of the code is devoted to the user interface ...

Figure 2.2: ACM search results for the first query



Microbial Journey: Mount Everest to Mars

A rigorous exploration of microbial diversity has revealed its presence on Earth, deep oceans, and vast space. The presence of microbial life in...

Utkarsh Sood, Gauri Garg Dhingra, ... Rup Lal in Indian Journal of Microbiology
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Although space science was the most visible part of the space programme, the 1970s saw it transformed into a wide-spectrum programme to benefit...

Brian Harvey in Japan In Space
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A. Cervone, F. Topputo, ... S. Radu in CEAS Space Journal
Article | Open access | 22 July 2023

Plastics and Space Exploration

The plastic age seems to have coincided with the new space age. While we seek to redefine the role of plastic in global society, in this chapter we...

Ololade Olatunji in Re-envisioning Plastics Role in the Global Society
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Brains in space: the importance of understanding the impact of long-duration spaceflight on spatial cognition and its neural circuitry

Fifty years after the first humans stepped on the Moon, space faring nations have entered a new era of space exploration. NASA's reference mission to...

Alexander C. Stahn, Simone Kühn in Cognitive Processing
Article | Open access | 18 August 2021

History of Human Space Exploration

The history of space exploration begins with space observation from the ground, which is almost as long as the recorded history of mankind. In...

Ji Wu in Introduction to Space Science
Chapter | 2021

Figure 2.3: SpringerLink search results for the first query

Q2= "Mars" or "red planet" AND "exploration technology" OR "space missions" OR "space technology"

Furthermore, similar to our previous experience, the second query resulted in articles addressing broader topics within computer science for space exploration or general computer science, rather than focusing specifically on software for Mars missions. While the intent was to capture a wide array of relevant technological advancements, the results predominantly included studies on space exploration technologies and missions in general, without the necessary specificity to Mars missions. Examples are shown in Figure 2.4 and Figure 2.5. They are retrieved from the ACM digital library and the IEEE Library. This reiterates the challenge of crafting precise search queries that effectively filter for the exact niche of software applications pertinent to Mars mission objectives, necessitating further refinement to enhance the relevance of our literature review findings.

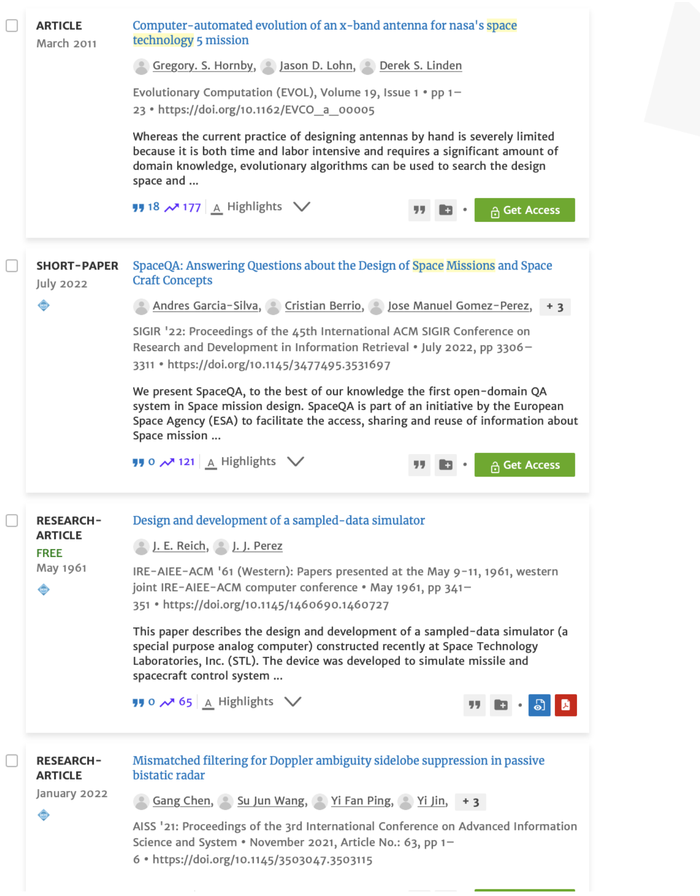


Figure 2.4: ACM search results for the second query

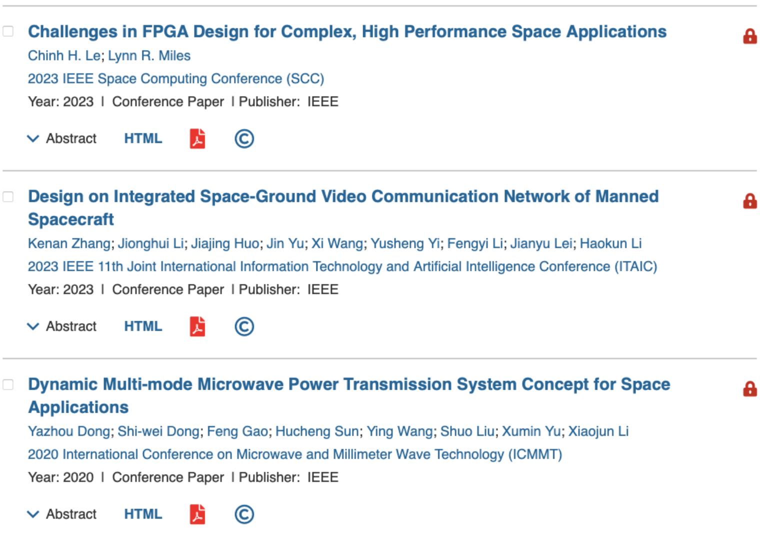
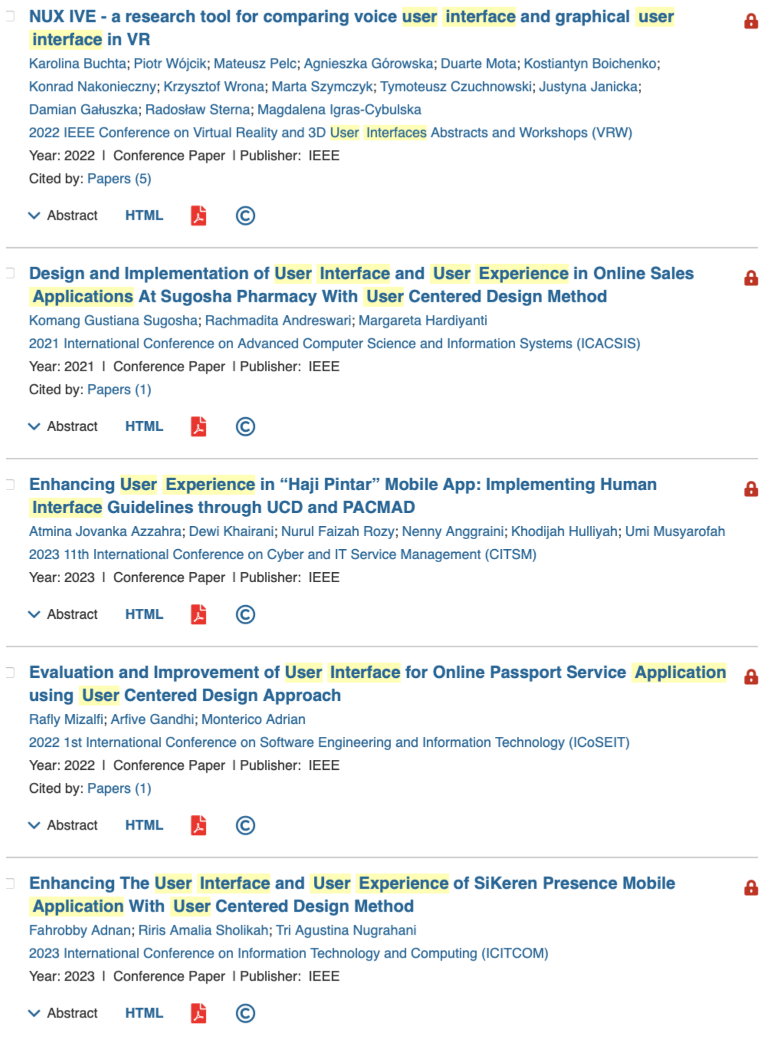


Figure 2.5: IEEE search results for the second query

Q3= ”Mars” AND ”Exploration” AND ”Software” OR ”Application” OR ”user interface” OR ”interaction” OR ”user experience”

Finally, the third query, Q3= ”Mars” AND ”Exploration” AND ”Software” OR ”Application”

OR ”user interface” OR ”interaction” OR ”user experience,” was utilized. As with the previous queries, the results did not align with our criteria. Instead, the search yielded articles centred around user interface applications and user experiences in various contexts, with no specific relevance to Mars missions. Some results are shown in Figure 2.6 and Figure 2.7.


NUX IVE - a research tool for comparing voice user interface and graphical user interface in VR
Karolina Buchta; Piotr Wójcik; Mateusz Pelc; Agnieszka Górowska; Duarte Mota; Kostiantyn Boichenko; Konrad Nakonieczny; Krzysztof Wrona; Marta Szymczyk; Tymoteusz Czuchnowski; Justyna Janicka; Damian Gałuszka; Radosław Sterna; Magdalena Igras-Cybulska
2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)
Year: 2022 | Conference Paper | Publisher: IEEE
Cited by: Papers (5)
Abstract HTML

Design and Implementation of User Interface and User Experience in Online Sales Applications At Sugosha Pharmacy With User Centered Design Method
Komang Gustiana Sugosha; Rachmadita Andreswari; Margareta Hardiyanti
2021 International Conference on Advanced Computer Science and Information Systems (ICACSIS)
Year: 2021 | Conference Paper | Publisher: IEEE
Cited by: Papers (1)
Abstract HTML

Enhancing User Experience in “Haji Pintar” Mobile App: Implementing Human Interface Guidelines through UCD and PACMAD
Atmina Jovanka Azzahra; Dewi Khairani; Nurul Faizah Rozy; Nenny Anggraini; Khodijah Hulliyah; Umi Musyarofah
2023 11th International Conference on Cyber and IT Service Management (CITSM)
Year: 2023 | Conference Paper | Publisher: IEEE
Abstract HTML

Evaluation and Improvement of User Interface for Online Passport Service Application using User Centered Design Approach
Rafly Mizalfi; Arfive Gandhi; Monterico Adrian
2022 1st International Conference on Software Engineering and Information Technology (ICoSEIT)
Year: 2022 | Conference Paper | Publisher: IEEE
Cited by: Papers (1)
Abstract HTML

Enhancing The User Interface and User Experience of SiKeren Presence Mobile Application With User Centered Design Method
Fahrobby Adnan; Riris Amalia Sholikah; Tri Agustina Nugrahani
2023 International Conference on Information Technology and Computing (ICITCOM)
Year: 2023 | Conference Paper | Publisher: IEEE
Abstract HTML

Figure 2.6: IEEE search results for the third query

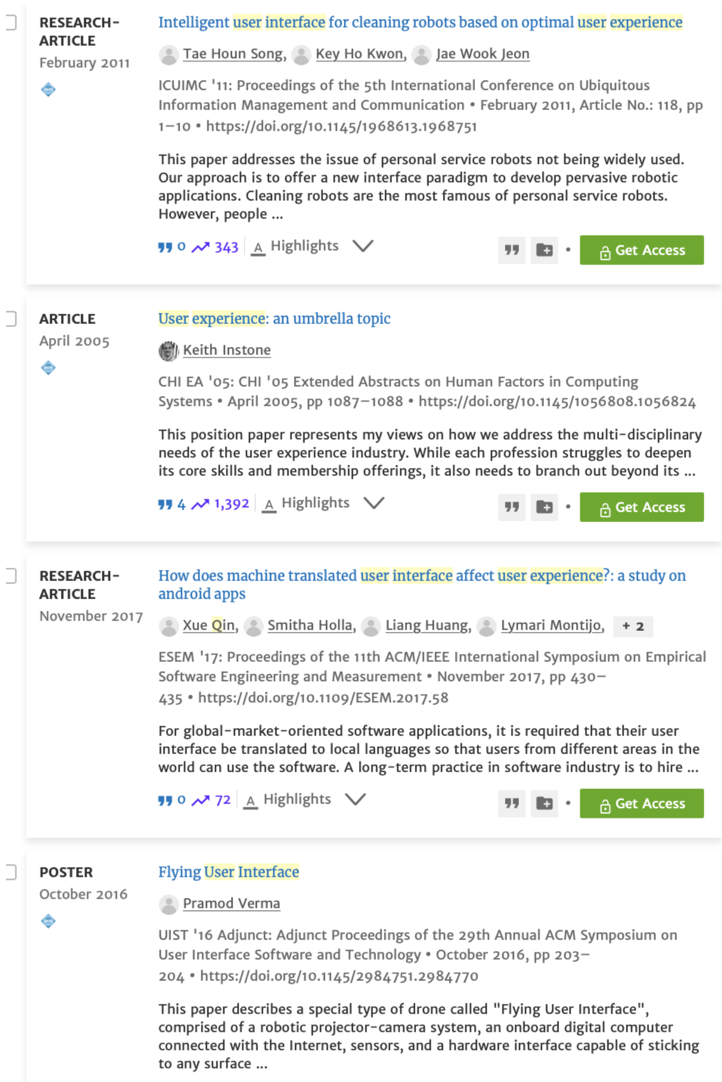
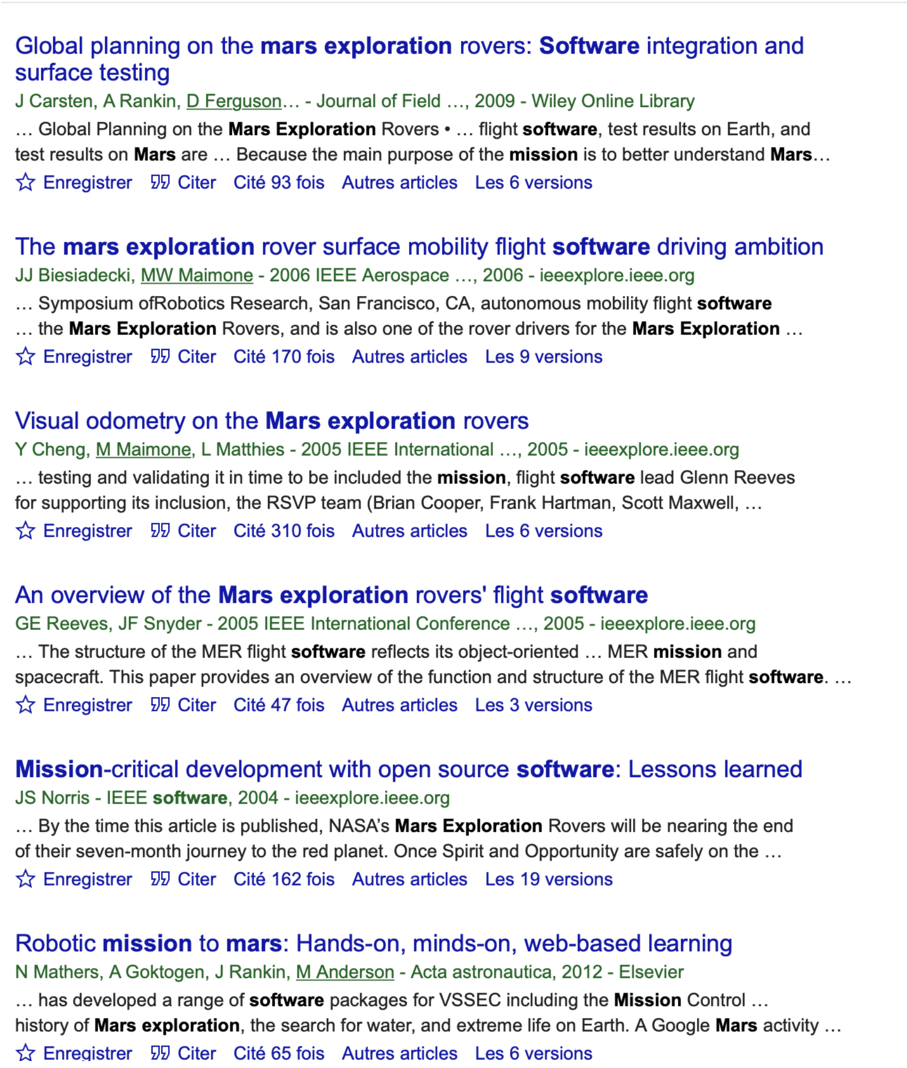


Figure 2.7: ACM search results for the third query

Although none of these iterations were satisfactory in yielding a comprehensive set of relevant articles, they were essential to building up the right search query. Consequently, a final search query was formulated as follows:

Chosen Query = ”Mars” AND ”Mission” OR ”Exploration” AND ”Software” OR ”Application” AND ”Interactive”

This query was the most satisfying one. The ratio of relevancy was greater compared to others. The results are shown in Figures 2.8, 2.9 and 2.10.



Global planning on the mars exploration rovers: Software integration and surface testing
J Carsten, A Rankin, D Ferguson… - Journal of Field …, 2009 - Wiley Online Library
… Global Planning on the **Mars Exploration** Rovers • … flight **software**, test results on Earth, and test results on **Mars** are … Because the main purpose of the **mission** is to better understand **Mars**…
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The mars exploration rover surface mobility flight software driving ambition
JJ Biesiadecki, MW Maimone - 2006 IEEE Aerospace …, 2006 - ieeexplore.ieee.org
… Symposium ofRobotics Research, San Francisco, CA, autonomous mobility flight **software** … the **Mars Exploration** Rovers, and is also one of the rover drivers for the **Mars Exploration** …
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Visual odometry on the Mars exploration rovers
Y Cheng, M Maimone, L Matthies - 2005 IEEE International …, 2005 - ieeexplore.ieee.org
… testing and validating it in time to be included the **mission**, flight **software** lead Glenn Reeves for supporting its inclusion, the RSVP team (Brian Cooper, Frank Hartman, Scott Maxwell, …
Enregistrer Citer Cité 310 fois Autres articles Les 6 versions

An overview of the Mars exploration rovers' flight software
GE Reeves, JF Snyder - 2005 IEEE International Conference …, 2005 - ieeexplore.ieee.org
… The structure of the MER flight **software** reflects its object-oriented … MER **mission** and spacecraft. This paper provides an overview of the function and structure of the MER flight **software**. …
Enregistrer Citer Cité 47 fois Autres articles Les 3 versions

Mission-critical development with open source software: Lessons learned
JS Norris - IEEE **software**, 2004 - ieeexplore.ieee.org
… By the time this article is published, NASA's **Mars Exploration** Rovers will be nearing the end of their seven-month journey to the red planet. Once Spirit and Opportunity are safely on the …
Enregistrer Citer Cité 162 fois Autres articles Les 19 versions

Robotic mission to mars: Hands-on, minds-on, web-based learning
N Mathers, A Goktogen, J Rankin, M Anderson - Acta astronautica, 2012 - Elsevier
… has developed a range of **software** packages for VSSEC including the **Mission** Control … history of **Mars exploration**, the search for water, and extreme life on Earth. A Google **Mars** activity …
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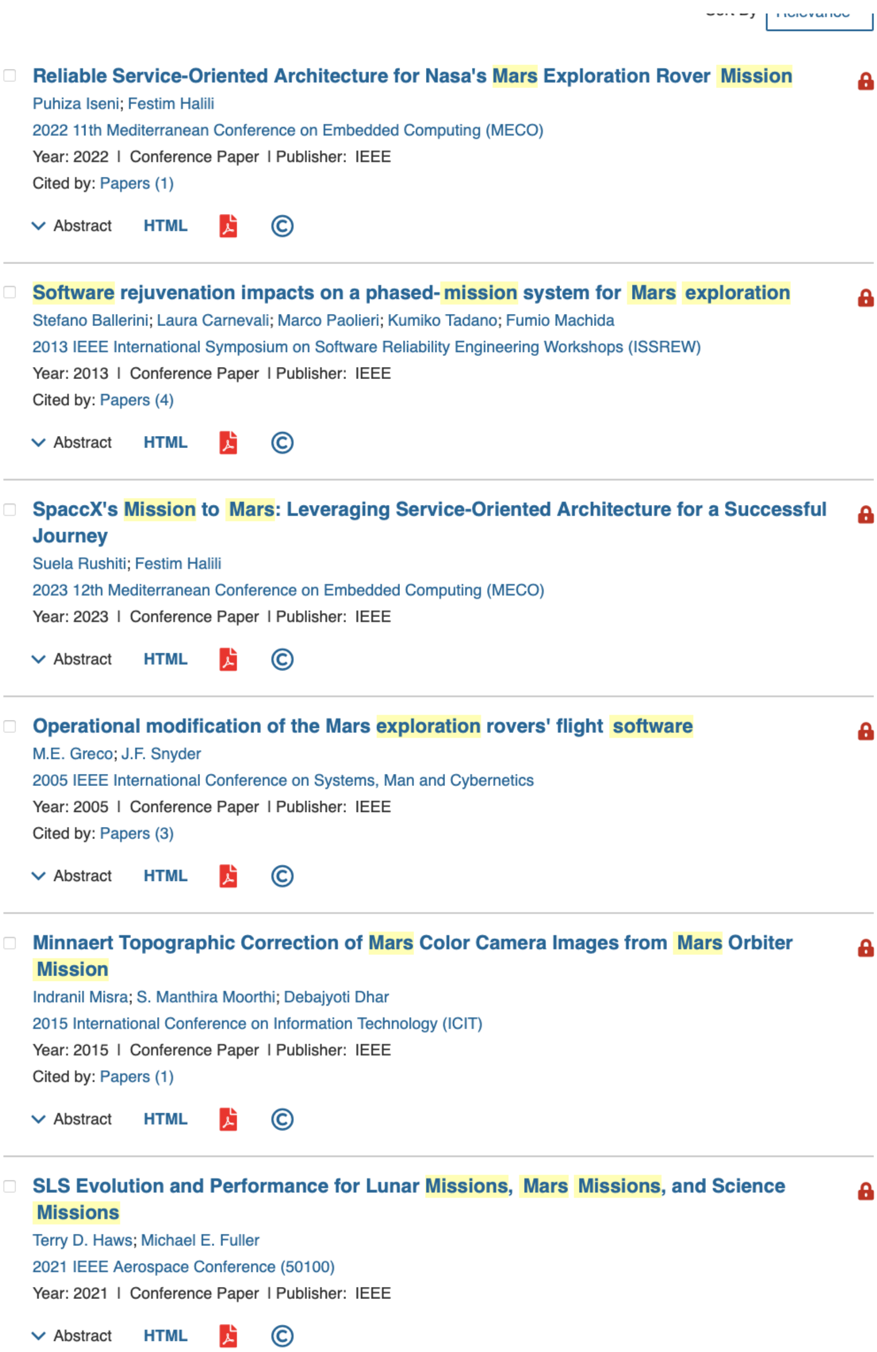
Figure 2.8: Google Scholar results for the chosen query



Reliable Service-Oriented Architecture for Nasa's Mars Exploration Rover Mission
Puhiza Iseni; Festim Halili
2022 11th Mediterranean Conference on Embedded Computing (MECO)
Year: 2022 | Conference Paper | Publisher: IEEE
Cited by: Papers (1)
Abstract HTML

Software rejuvenation impacts on a phased-mission system for Mars exploration
Stefano Ballerini; Laura Carnevali; Marco Paolieri; Kumiko Tadano; Fumio Machida
2013 IEEE International Symposium on Software Reliability Engineering Workshops (ISSREW)
Year: 2013 | Conference Paper | Publisher: IEEE
Cited by: Papers (4)
Abstract HTML

SpaccX's Mission to Mars: Leveraging Service-Oriented Architecture for a Successful Journey
Suela Rushiti; Festim Halili
2023 12th Mediterranean Conference on Embedded Computing (MECO)
Year: 2023 | Conference Paper | Publisher: IEEE
Abstract HTML

Operational modification of the Mars exploration rovers' flight software
M.E. Greco; J.F. Snyder
2005 IEEE International Conference on Systems, Man and Cybernetics
Year: 2005 | Conference Paper | Publisher: IEEE
Cited by: Papers (3)
Abstract HTML

Minnaert Topographic Correction of Mars Color Camera Images from Mars Orbiter Mission
Indranil Misra; S. Manthira Moorthi; Debajyoti Dhar
2015 International Conference on Information Technology (ICIT)
Year: 2015 | Conference Paper | Publisher: IEEE
Cited by: Papers (1)
Abstract HTML

SLS Evolution and Performance for Lunar Missions, Mars Missions, and Science Missions
Terry D. Haws; Michael E. Fuller
2021 IEEE Aerospace Conference (50100)
Year: 2021 | Conference Paper | Publisher: IEEE
Abstract HTML

Figure 2.9: IEEE results for the chosen query

Emirates Mars Mission Characterization of Mars Atmosphere Dynamics and Processes

The Emirates Mars Mission (EMM) – Hope Probe – was developed to understand Mars atmospheric circulation, dynamics, and processes through...

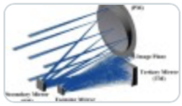
Hessa Almatroushi, Hoor AlMazmi, ... Roland M. B. Young in Space Science Reviews
Article | Open access | 07 December 2021

Towards an extension of equivalent system mass for human exploration missions on Mars

NASA mission systems proposals are often compared using an equivalent system mass (ESM) framework, wherein all elements of a technology to deliver an...

Davian Ho, Georgios Makrygiorgos, ... Aaron J. Berliner in npj Microgravity
Article | Open access | 02 August 2022

High Resolution Imaging Camera (HiRIC) on China's First Mars Exploration Tianwen-1 Mission



The High-Resolution Imaging Camera (HiRIC) is one major payload of China's first Mars exploration mission, and its main objective is to obtain the...

Qingyu Meng, Dong Wang, ... Jihong Dong in Space Science Reviews
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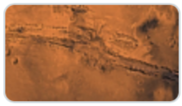
Evaluation of aerial vehicle configurations for high-range Mars missions



As part of an envisioned autonomous swarm exploration mission in Valles Marineris on Mars a design investigation of a high-range scout UAV is...

Victor Zappek, Markus Rinker, ... Manfred Hajek in CEAS Space Journal
Article | Open access | 03 January 2023

Mission Overview and Scientific Contributions from the Mars Science Laboratory Curiosity Rover After Eight Years of Surface Operations

NASA's Mars Science Laboratory mission, with its Curiosity rover, has been exploring Gale crater (5.4° S, 137.8° E) since 2012 with the goal of...

Ashwin R. Vasavada in Space Science Reviews
Article | Open access | 05 April 2022

Figure 2.10: Springer Link results for the chosen query

2.3 Inclusion And Exclusion Criteria

We distinguish criteria related to form and content:

Form

Inclusion: all English-language publications that have undergone a competitive, peer-review process with full text available. This encompasses short and full research papers published in peer-reviewed journals, as well as technical reports, and works presented at conferences, symposia, or workshops.

Exclusion: all sources that did not undergo a competitive peer-review process or are not purely research contributions. This includes books, PhD and master theses, patent descriptions, standards and recommendations, book or thesis summaries, white papers, invited talks, demo papers, tutorial papers, poster publications, posters, editorials, prefaces, articles or columns in non-peer-reviewed magazines, newsletters, encyclopedia entries, and blog posts. Additionally, sources where the full text is not published, such as abstracts, extended abstracts, and presentations, are excluded.

Content

Inclusion: all publications conforming with the previous criteria, and satisfy at least one of the following two conditions:

1.a It tackles one or several research topics directly relevant to the development of software or applications for Mars missions.

1.b The abstract or the introduction explicitly mentions a software or application that was deployed, has been deployed, or is planned to be deployed for Mars missions.

1.c The abstract or the introduction explicitly uses computer-related terms as intended synonyms for a software/hardware or application (e.g. Middleware, user interface, user experience, real-time program, dynamic front-end, etc.) that was deployed, has been deployed or planned to be deployed for Mars missions.

Furthermore, the following mandatory conditions must be met:

2. It can be deduced from the abstract or the introduction that the research is explicitly performed within the context of any software/hardware for a computer-based system intended to be used for Mars missions.

2.4 Data Extraction And Synthesis

In this study, a meticulous and systematic approach was undertaken to extract relevant data from the extensive pool of scholarly literature retrieved from various databases. The methodology employed can be delineated into several distinct stages:

1. **Content Analysis of Abstracts**: the initial phase involved a thorough examination of the abstracts of 600 papers obtained from reputable scholarly databases such as ACM Digital Library, IEEE Xplore, ScienceDirect, SpringerLink, Google Scholar, and Elicit. This content analysis focused on identifying key themes, concepts, methodologies, and findings elucidated within the abstracts.
2. **Initial Screening and Pre-selection**: based on the content analysis of abstracts, an initial screening was conducted to pre-select 112 papers that demonstrated alignment with the research objectives. This screening process aimed to identify papers that appeared to address themes or topics of interest as indicated by the information gleaned from their abstracts.

3. **Further Investigation and In-depth Reading**: the pre-selected papers underwent further investigation through in-depth reading and comprehensive evaluation. Each paper was scrutinized to assess its relevance, depth of analysis, and contribution to the research inquiry. This phase involved a detailed examination of the full-text articles to ascertain the suitability of each paper for inclusion in the study.

4. **Final Selection**: following the thorough screening process, a final selection of 32 papers was made based on their demonstrated alignment with the research objectives and the robustness of their content. These papers were deemed to offer the most valuable insights and evidence pertinent to the study's objectives, thereby forming the foundational basis for the subsequent literature review and analysis.

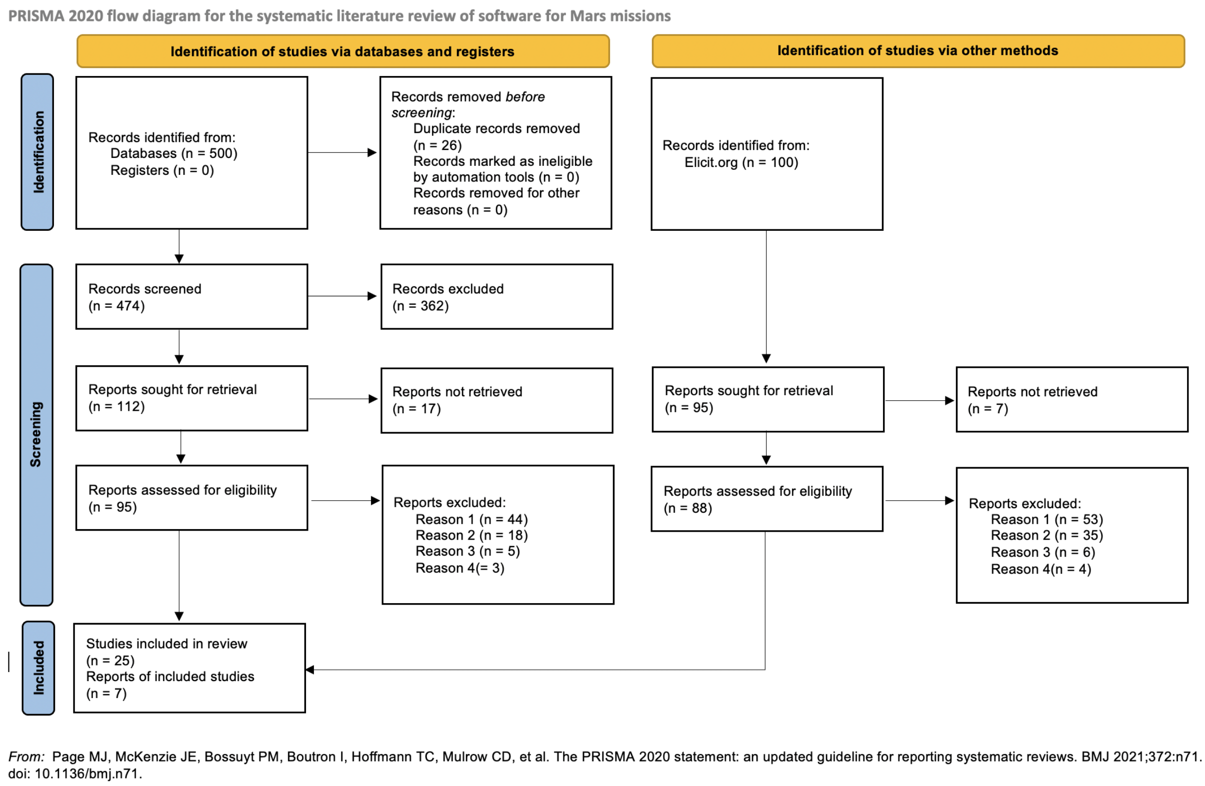


Figure 2.11: PRISMA Diagram

2.5 AI Tools: usefulness and limitations

2.5.1 Elicit

Elicit employs semantic similarity to find papers related to the research question, even when they don't use the exact keywords. For instance, when the question ”What are the software or applications we use for Mars missions?” was queried, Elicit retrieved papers that mentioned synonymous terms like ”red planet” instead of ”Mars.” This semantic approach ensured a comprehensive capture of relevant literature. Additionally, Elicit's ability to provide abstracts and generate custom summaries of the studies was a huge gain of time as it allowed for a quick inclusion criteria evaluation of the articles. An example of the articles suggested by Elicit can be seen in Figure 2.12

Despite its advanced semantic similarity capabilities, which helped identify relevant papers even when they did not use exact keywords, Elicit is based on early-stage language models that have inherent limitations[19]. These models, around since only 2019, are not explicitly trained to be faithful to a body of text by default. Consequently, Elicit sometimes produced summaries that missed the nuances of the papers or misunderstood specific details, a phenomenon known as ”hallucination”[19]. For example, it occasionally misinterpreted numerical data or the context of certain findings, leading to inaccuracies[19]. Additionally, as an early-stage tool, Elicit's content is around 80-90 per cent accurate, but not entirely reliable[19]. Some of the papers lacked clear information, reflecting the tool's limitation in discerning the quality of underlying research[19]. Elicit cannot yet evaluate the trustworthiness of papers effectively, except by using imperfect heuristics like citation count and journal reputation. This can result in summarizing findings from studies with questionable methodologies on par with well-conducted research[19]. Moreover, Elicit's current focus on empirical research in social sciences and bio-medicine means it may not perform as well in other domains, including software for Mars missions, which can limit its overall usefulness in my specific area of study[19].

2.5.2 Jenni AI

Jenni AI, also, played a crucial role in both expanding the literature base and enhancing the writing quality of this thesis. Unlike Elicit, Jenni AI facilitated the discovery of papers through an interactive writing process, where I could write about the topic and request citations that aligned closely with the content. This feature was particularly useful for integrating relevant literature seamlessly into the thesis. Moreover, the AI suggestion tool for text generation provided by Jenni AI, though sometimes generic, offered valuable inspiration and helped refine the writing. This dual functionality of finding relevant literature and enhancing text quality significantly contributed to the thoroughness and coherence of this systematic literature review.

In terms of limitations, the AI text generator, though helpful for finding inspiration, often produced sentences that lacked clear meaning or thorough explanations. This limitation necessitated additional revisions and refinements to ensure the generated text met academic standards and alignment with the research topic. Similar to Elicit, Jenni AI is based on large language models that, while refined for research purposes, can still experience hallucinations, leading to occasional inaccuracies or misleading information in the generated content.

Additionally, the citation tool, despite being a valuable feature, did not always provide relevant papers and sometimes offered repetitive results. This required cross-checking and verifying the citations to ensure their relevance and uniqueness to the research topic.

Paper	Abstract summary	Main findings
MARS NAVIGATOR: an interactive, multimedia exploration of the red planet R. Wolff +1 *COMG* 1991 4 citations **DOI**	The knowledge gained from the Mars Navigator can be applied to other multimedia projects.	The main findings of the paper are the design and display of the Mars Navigator as a public space exhibit and its use of various multimedia technologies to create an engaging and educational interactive experience. The paper also discusses how the knowledge gained from this project can be applied to other multimedia projects.
Visualizing Mars Using Virtual Reality: A State of the Art Mapping Technique Used on Mars Pathfinder C. Stoker +3 1999 6 citations	Virtual reality can be a powerful cartographic tool.	Virtual Reality provides an intuitive way to archive and retrieve information. Virtual Reality allows for interactive measurements within the model, making operations easier and less time-consuming.
Using virtual reality for science mission planning: A Mars Pathfinder case Jacqueline H. Kim +2 1994 5 citations	The perspective from the lander camera will enable scientists to plan activities more accurately and completely.	The main findings of the paper are the development of a new software strategy integrating virtual reality technology, successful completion of design and testing phases, and the potential for more accurate and complete planning of activities on Mars.
Entertainment virtual reality system for simulation of spaceflights over the surface of the planet Mars Ricardo Olanda +4 *Virtual Reality Software and Technology* 2006 12 citations **DOI**	Virtual reality tools have been developed specifically for entertainment purposes.	The main findings are: - Virtual Reality technologies have enabled scientific exploration of the Universe, including Mars. - Mars has been a focal point for research projects using Virtual Reality technologies. - The paper introduces MarsVR as an entertainment research project for educating people about the topography and orography of Mars from the perspective of popular science.
Methods for user-based reduction of model complexity for virtual planetary exploration L. Hitchner +1 *Electronic imaging* 1993 47 citations **DOI**	The level of detail of a feature should relate to its importance to the application task.	The study presents methods for visualizing large planetary terrains in an interactive, immersive virtual environment system using a head-mounted display, introduces three level of detail (LOD) criteria for terrain visualization, and utilizes analysis functions for each criterion to compute normalized scale factors. Parameters for each criterion can be interactively or automatically set to meet performance criteria.
Photo-realistic Terrain Modeling and Visualization for Mars Exploration Rover Science Operations L. Edwards +4 *IEEE International Conference on Systems, Man and Cybernetics* 2005 30 citations **DOI**	The on-site support team for the software systems during the primary MER mission responded to unanticipated opportunities to generate 3D terrain models during the primary MER mission.	The paper emphasizes the success and importance of employing a complex "system of systems" in modern planetary exploration, the flexibility and adaptability of Viz in supporting NASA's evolving robotic planetary exploration program, and the critical need to incorporate and utilize system elements that can quickly and easily change to meet unforeseen needs in order to maximize the return from these missions.

Figure 2.12: An example of Elicit's research results

In Figure 2.13 the citation search window pops up after initiating a citation search by clicking on the cite button in the menu bar at the bottom of the page.

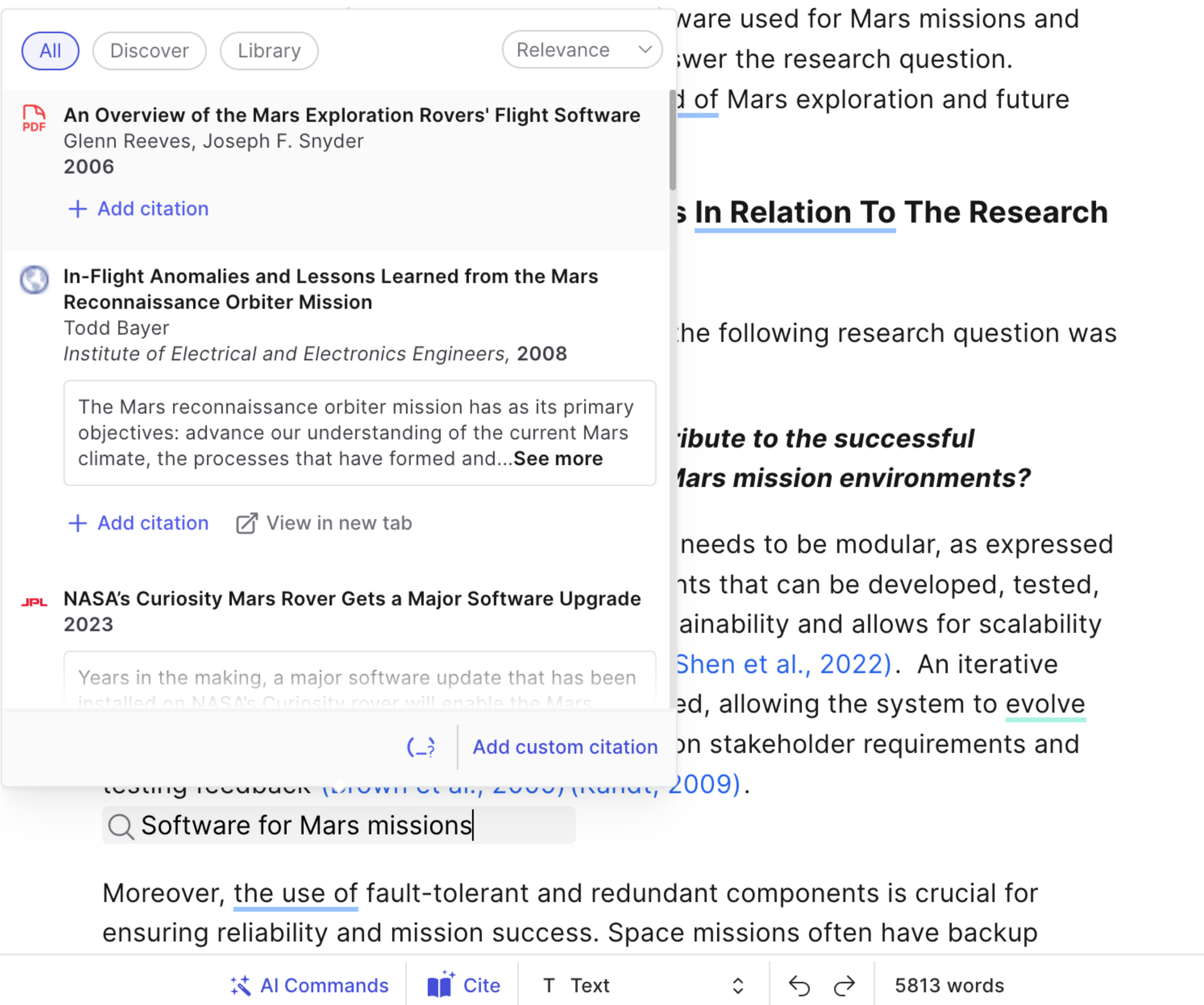


Figure 2.13: An example of the citation tool in Jenni AI

Chapter 3

Classification Schemes

3.1 Presentation Of The Classification Schemes

Missions on Mars have different goals and objectives. Flybys, Orbiters, Atmospheric, Landers, Penetrators, Rovers, Observatories, and Communications Navigation spacecraft, all serve a different purpose and require different software systems for their operations [20]. Moreover, non-spacecraft software are also massively utilized in Mars Missions to support data analysis, simulation, and communication tasks [21]. These software also matter for the overall success and efficiency of Mars missions [22]. In this literature review, rather than analyzing software for a specific mission, we focused on drawing generalities from the literature. To achieve this, seven classification schemes that are highly relevant for software development in the case of Mars missions were considered [23] [24] [25] [26] [27] [28]. These classification schemes included:

1) Architecture Type: the architecture type refers to the overall design and structure of the software system used in Mars missions.

- Monolithic: systems with a single, integrated structure.
- Modular: systems composed of independent modules that can be combined or replaced.
- Distributed: systems with components spread across multiple physical locations.
- Cloud-based: systems utilizing remote servers for processing and storage.

2) Communication Protocol: the communication protocol refers to the method or set of rules used for exchanging information between different components or systems in Mars missions [29].

- Point-to-point: direct communication between specific components.
- Broadcast: communication sent to multiple recipients simultaneously.
- Mesh: interconnected network where each node can communicate with every other node.

- Store-and-forward: data is collected, stored, and forwarded to its destination when appropriate.

3) Redundancy Level: redundancy is the intentional duplication of critical components or functions of a system with the goal of increasing the reliability of the system

- Single point of failure: systems with critical components prone to failure.
- Redundant components: systems with duplicate components to ensure reliability.
- Fault-tolerant: systems designed to continue operating despite component failures.
- Fail-safe: systems designed to enter a safe state in case of failure.

4) Data Processing Approach:

- Batch processing: processing data in groups at scheduled intervals.
- Real-time processing: processing data immediately as it becomes available.
- Stream processing: continuous processing of data as it flows through the system.
- Edge processing: processing data locally near its source rather than sending it to a central server.

5) Security Measures:

- Encryption: data is encoded to prevent unauthorized access.
- Authentication: verification of the identity of users or systems.
- Access control: limiting access to certain resources based on predefined rules.
- Intrusion detection/prevention: monitoring and preventing unauthorized access or malicious activity.

6) Mission Phase:

- Pre-launch: software used in mission planning, simulation, and design.
- Transit: software used during spacecraft transit from Earth to Mars.
- Entry, Descent, and Landing (EDL): software for the critical phase of landing on Mars.
- Surface Operations: software for rover control, data collection, and analysis on the Martian surface.
- Return or Extended Operations: software for sample return missions or extended surface operations.

7) Software Development and Validation:

- Verification and Validation: processes for ensuring software correctness and reliability.
- Simulation and Testing: techniques for simulating mission scenarios and testing software

performance.

- Iterative Development: approaches to agile software development and incremental improvement.

3.2 Results from the Literature Review

Architecture type

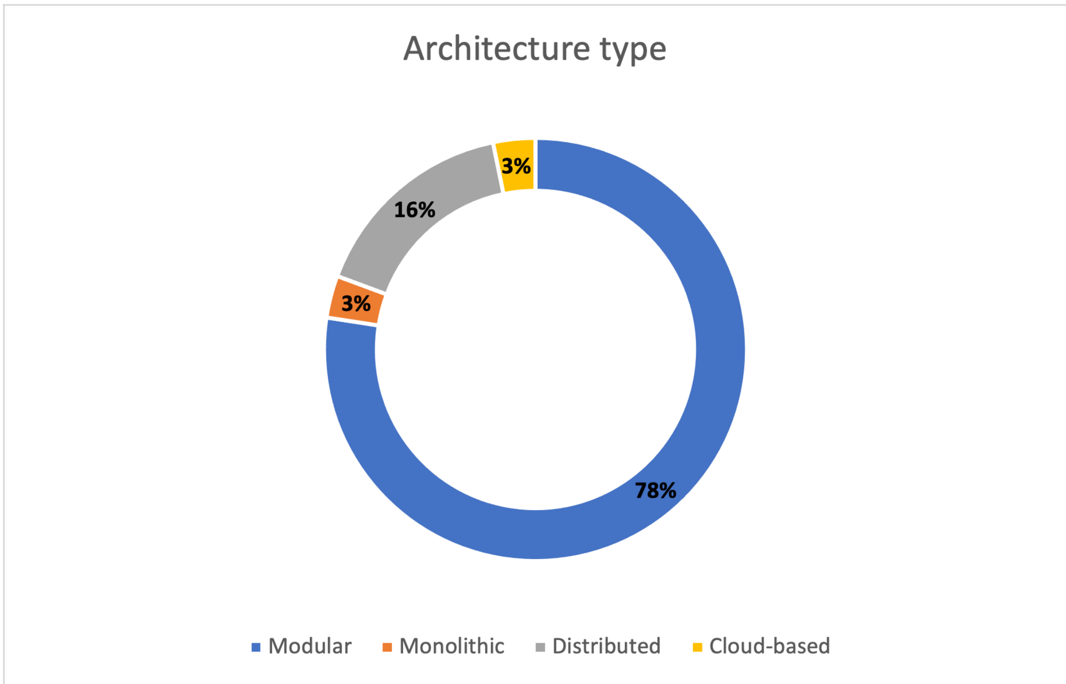


Figure 3.1: Architecture Type

Based on the literature review, the most commonly used architecture types for software in Mars missions are modular architectures.

Modular architectures have become the cornerstone of software systems utilized in Mars missions and space exploration endeavours, primarily due to their multifaceted advantages [30].

These systems offer unparalleled flexibility, allowing for swift adaptation to evolving mission requirements [31]. By virtue of their reconfigurability, modular designs enable spacecraft to efficiently fulfil diverse roles over extended durations, ensuring optimal resource utilization [32]. Moreover, the scalability inherent in modular architectures permits seamless adjustments to mission complexities without necessitating comprehensive system overhauls [33]. This approach significantly streamlines integration and testing processes, as individual modules can be developed and validated independently before integration into the larger system [33] [34] [32]. Beyond operational benefits, modular systems boast economic advantages, reducing costs associated with design, manufacturing, and testing through mass-produced modules [33]. Furthermore, the ease of upgrades and maintenance afforded by modular architectures ensures that spacecraft remain at the forefront of technological innovation without substantial redesign efforts [33] [32]. Ultimately, the resilience of modular systems to component failures, coupled with their capacity for graceful degradation, underscores their indispensability in the demanding and unpredictable environment of space exploration [31] [35] [33] [34] [32].

Redundancy Level

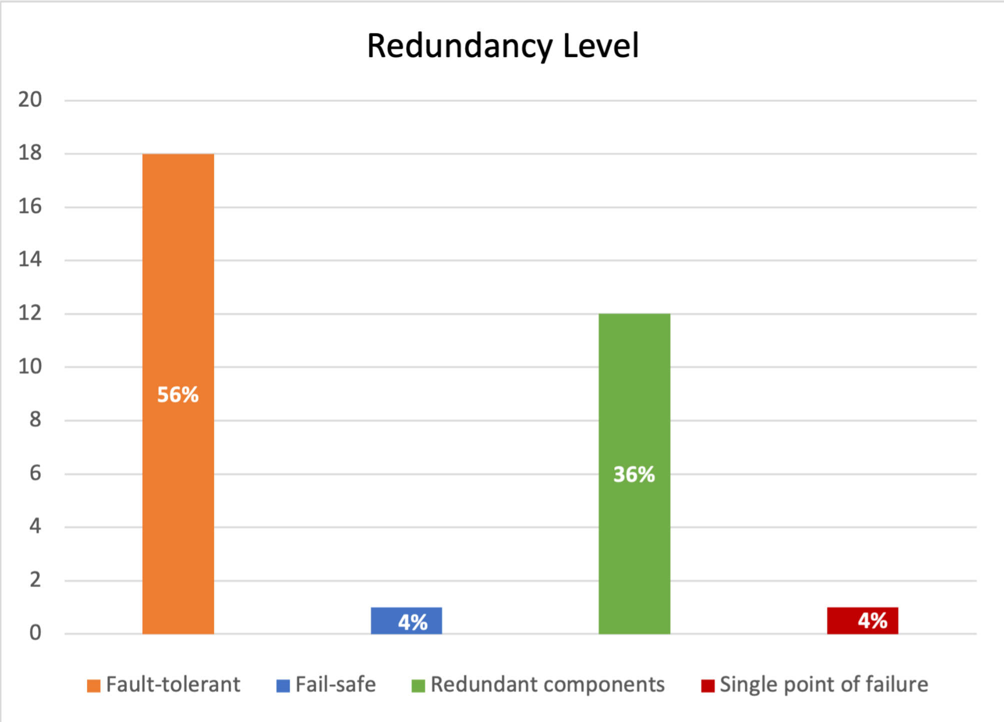


Figure 3.2: Redundancy Level

Any good software is comprised of a redundancy infrastructure to ensure smooth and continuous operation, and software used in Mars missions is no exception [36]. The literature review revealed that software used in Mars missions typically includes redundant components or incorporates fault-tolerant mechanisms. These redundancy measures are implemented to increase mission success rates and ensure the reliability of critical systems [37] [38].

More importantly, these measures are justified by the challenging space environment, where risks like single-event upsets and communication delays pose constant threats to mission success [39] [40] [41] [42]. The need for fault tolerance and redundant components is accentuated by the unique constraints of space, including limitations on power, space, and weight, which restrict the use of redundancy and diversity [40] [39] [41] [42].

For instance, the Mars Science Laboratory's flight software, renowned for its nearly flawless performance, owes its success to robust redundancy and fault tolerance mechanisms [43]. Similarly, the Mars Reconnaissance Orbiter (MRO) exemplifies the necessity for fault-tolerant systems in orbiters [44] [45] [46]. The NASA Jet Propulsion Laboratory, an important information hub for space missions, elucidates the MRO's architecture, which incorporates extensive redundancy and semi-autonomous fault-tolerant software to address time-critical failures, ensuring mission continuity despite communication delays with Earth [42]. Moreover, the reliability requirements extend to rovers like the Curiosity rover, which relies on fault-tolerant systems to navigate and conduct scientific experiments on the Martian surface [47] [48] [49].

Software Development And Validation

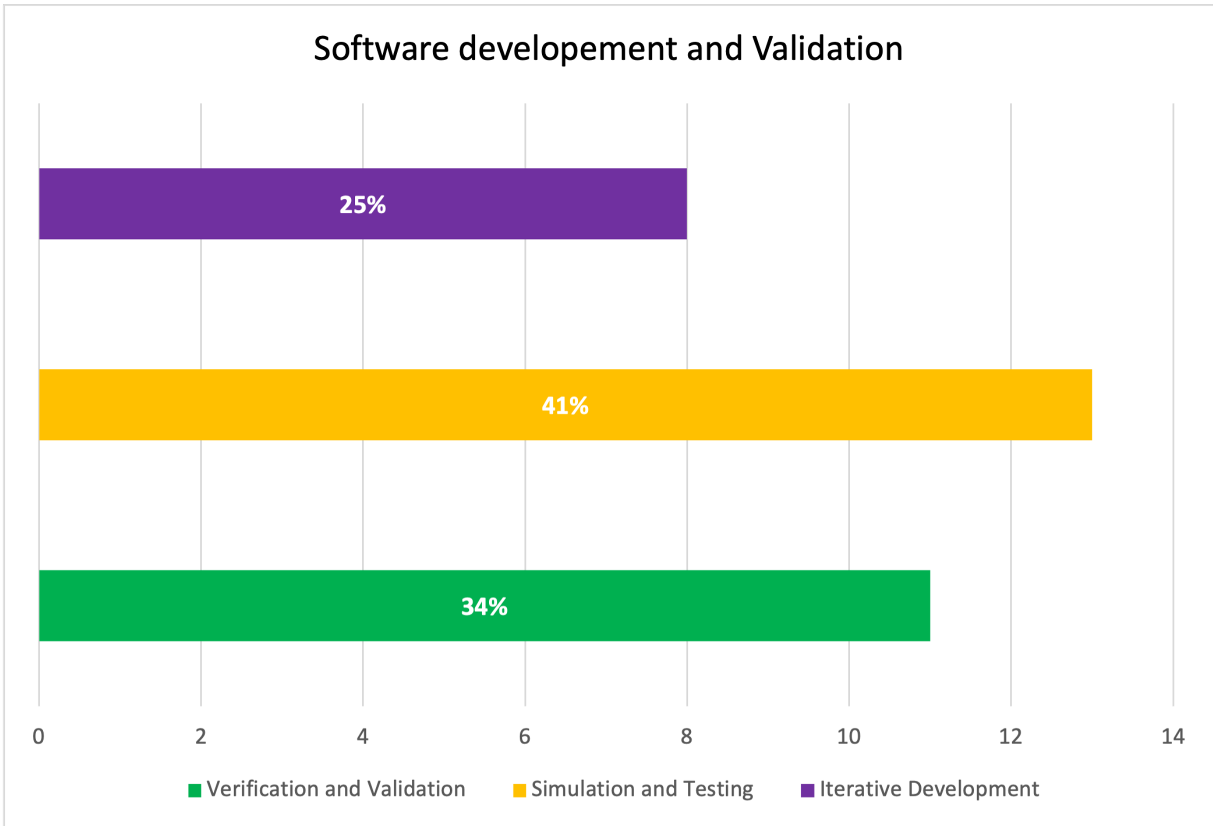


Figure 3.3: Software Development And Validation

Software development and validation processes are essential in spacecraft software engineering to ensure that the software operates correctly and safely under all nominal and off-nominal conditions [50]. In the context of Mars missions, the software must be able to handle complex interactions with the hardware, as well as unexpected environmental factors. [51]

The data collected through the systematic literature review shows that the majority of software for Mars missions undergo rigorous simulation and testing processes as well as verification and validation processes [52] [50] [53]. Moreover, some studies also mention the use of iterative development [54] [55] [56]

For instance, the importance of Verification Validation can be demonstrated through the development and testing of the Mars Science Laboratory Curiosity Rover. The Verification Validation process for this mission involved an incremental test program that verified individual functions and then validated system capabilities in mission-like scenarios to ensure complex behavioural interactions could be trusted [53].

3.3 Cross-Classification Schemes And Results

Crossing classification schemes together allows for a more comprehensive understanding of the software used in Mars missions. More importantly, it helps identify common patterns and trends in software development and usage across different mission types.

For this systematic literature review of software for Mars missions, Two cross-classification schemes were built:

- Data Processing Approach and Mission Phase: combining these two schemes is pragmatic as the data processing approach is typically aligned with the phase of the mission [57] [58]. By understanding how different data processing approaches perform across various mission phases, researchers can identify optimal strategies to efficiently operate software throughout the mission lifecycle, ensuring high-quality data collection and reliable decision-making in the harsh and dynamic Martian environment [57] [58].
- Communications Protocol and Security Measure: understanding how different communication protocols interact with security measures allows for the identification of optimal strategies to protect sensitive information, mitigate cyber threats, and maintain communication resilience in the challenging Martian environment [59] [60].

Additionally, these cross-classification schemes made sense in terms of relevancy and applicability to Mars missions [61] [25] [62] [63] [43] [64] [49] [44] [65]

Data Processing Approach And Mission Phase

The data processing approach and mission phase cross-classification scheme aims to understand how different data processing approaches are applied in different phases of a Mars mission.

From Figure 3.4, it can be observed that approximately 60 per cent of the literature mentioned real-time processing as the data processing approach during surface operations (31.3 per cent) and Entry, Descent, and Landing (28.1 per cent) phases.

There are several reasons why real-time processing is widely used during surface operations and Entry, Descent, and Landing (EDL). First of all, the distance between Mars and Earth which varies from about 54.6 kilometres to 401 kilometres depending on their relative positions in their orbits leads to significant communication delays [30] [66] [43]. Therefore, real-time processing is essential for immediate decision-making and response during critical phases of a Mars mission without waiting for commands from Earth [63] [67].

Moreover, the Martian surface and atmosphere are unpredictable and can present dynamic and

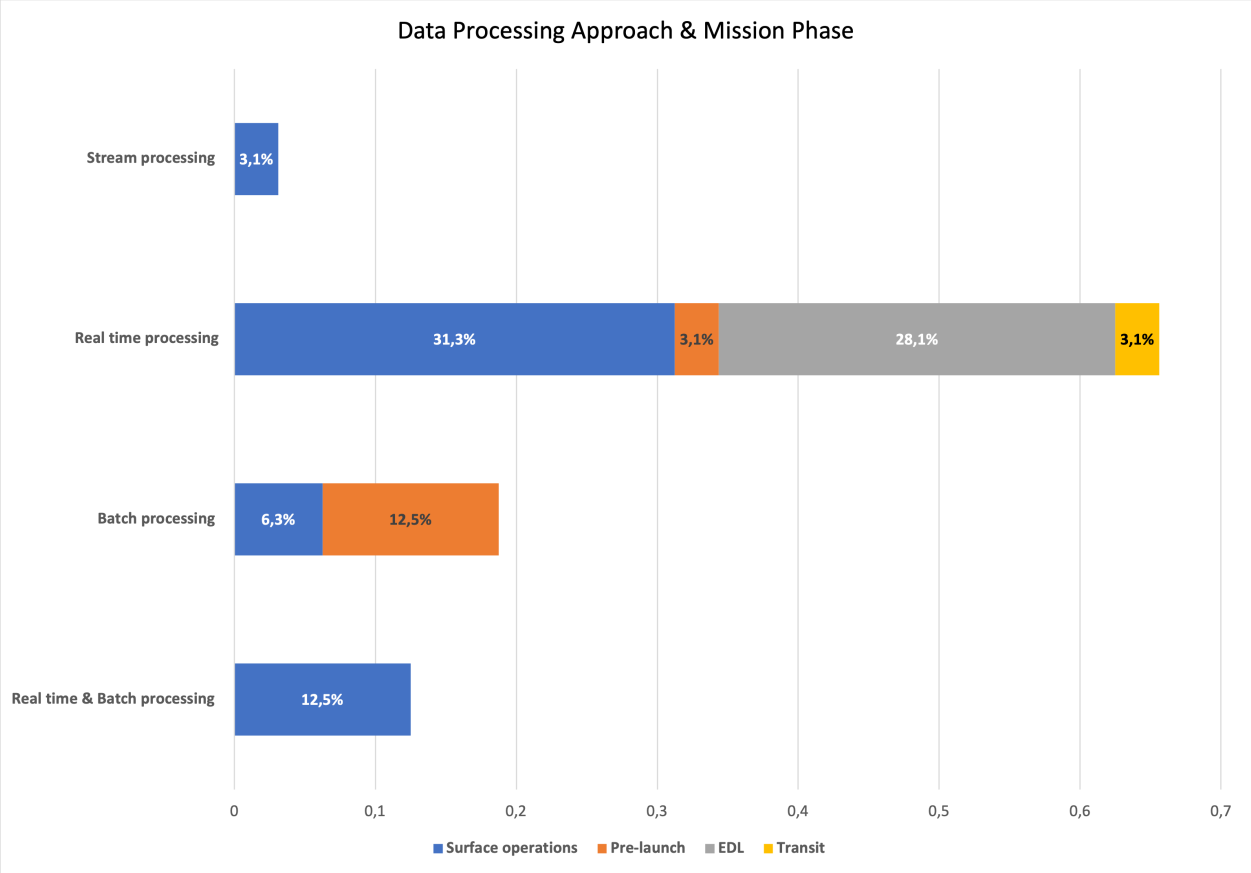


Figure 3.4: Data Processing Approach And Mission Phase

hazardous conditions for landing and surface operations [44] [25] [64]. Real-time processing allows the spacecraft to react quickly to changes in its environment, such as adjusting its trajectory during EDL to avoid obstacles or landing safely in a different location than originally planned [64] [68].

Additionally, real-time processing provides redundancy and reliability by allowing the spacecraft to continue operating even if communication with Earth is temporarily lost or disrupted [69] [70] [71]. This capability is essential for ensuring mission success and maximizing scientific return, especially during critical phases such as EDL [68] [64] [67].

Continuing with the analysis, it can be observed that a smaller percentage (around 20 per cent) of the literature mentioned batch processing as the data processing approach during surface operations (6.3 per cent) and Pre-launch phase (12.5 per cent). The use of batch processing during surface operations and pre-launch phases is attributed to the need for processing large volumes of data offline, such as scientific analyses [72] [73]. This type of processing is not time-critical, allowing for more comprehensive analysis and optimization of resource usage. Moreover, batch processing can also be beneficial for tasks that require extensive computations and data analysis, such as generating high-resolution maps or conducting complex simulations [74] [65] [62].

Furthermore, the rest of the data reveals that a combination of real-time processing and batch processing (12.5 per cent) is often utilized in surface operations. Typically, this combination in surface operations is used for analyzing the data collected through the rovers' missions (batch) and providing real-time updates and control for mission-critical activities (real-time) [49] [75] [68].

Finally, a small proportion of the literature (3.1 per cent) also revealed the use of stream processing as a data processing approach solely during surface operations. Stream processing is essential during surface operations because it enables the continuous and real-time analysis of data streaming in from sensors and instruments [48] [44].

Communication Protocol And Security Measure

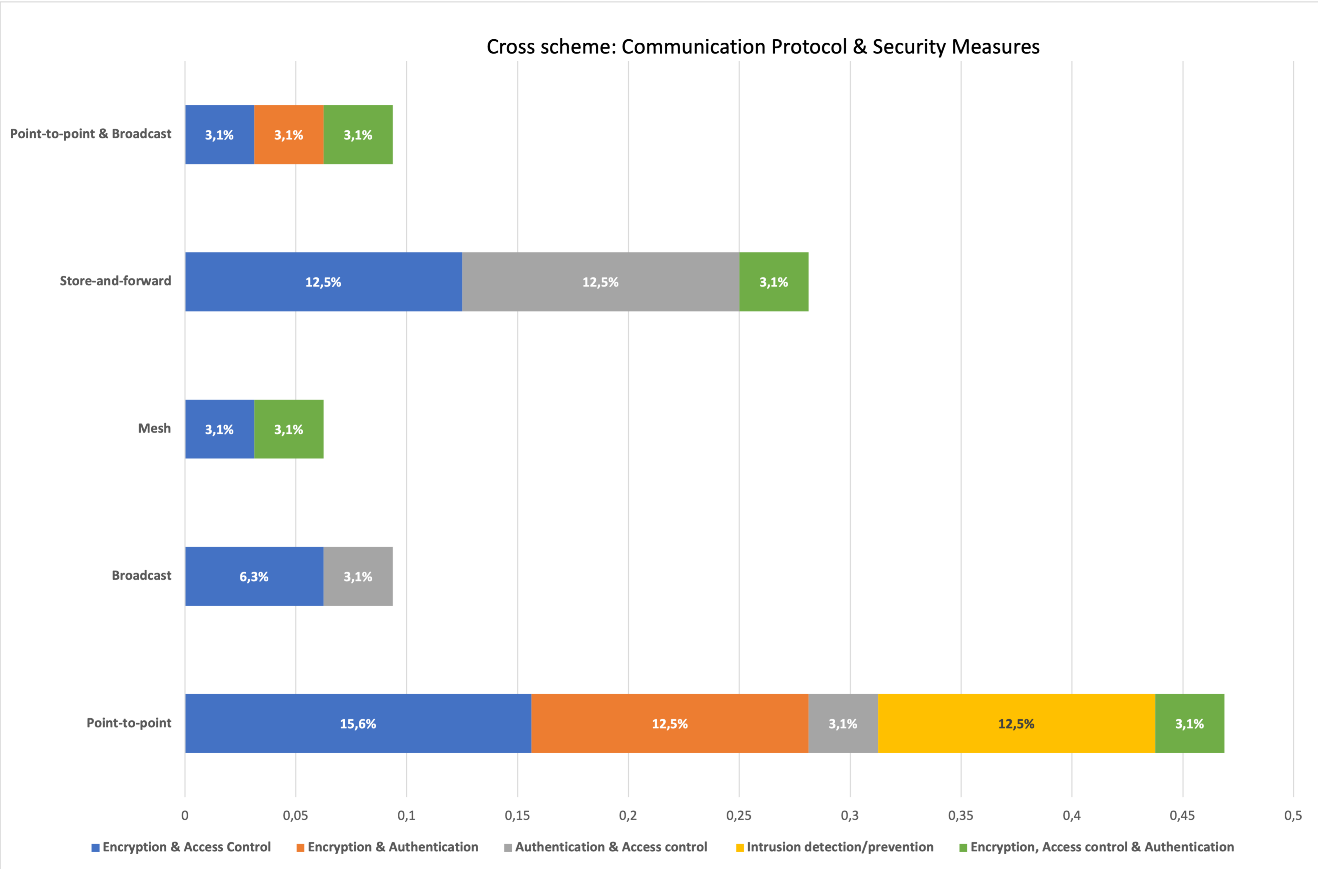


Figure 3.5: Communication Protocol And Security Measure

The communication protocol and security measure cross-classification scheme aims to identify the different communication protocols that are used with the different security measures in the context of Mars missions.

As in the previous cross-classification scheme, a stacked bar chart was used to analyze the frequency of communication protocols and security measures mentioned in the literature. The data are rendered in Figure 3.5.

The results of the analysis show that point-to-point communication protocols are the most commonly mentioned communication protocol in the context of Mars missions with a frequency of nearly 46 per cent, in combination with security measures such as encryption access control (15.6 per cent), encryption authentication (12.5 per cent), intrusion detection/prevention (12.5 per cent), and both authentication access control (3.1 per cent) and encryption, access control authentication (3.1 per cent).

Point-to-point communication protocols are often favoured in Mars missions for several reasons. First of all, reliability is paramount in space missions. Point-to-point communication protocols establish a direct connection between two communicating nodes, reducing the likelihood of interference or data loss compared to broadcast or multi-node protocols [76] [77]. This reliability is crucial when transmitting critical commands, telemetry data, and scientific findings over vast distances [78] [77]. Additionally, point-to-point communication protocols are often more efficient in terms of bandwidth usage and power consumption compared to broadcast or multicast protocols [79] [80]. In space missions where resources like bandwidth and power are limited, efficiency is key to maximizing the effectiveness of communication systems [44].

Even though the most common security measure combined with point-to-point protocols found in the literature review is encryption and access control, other security measures are also mentioned. The reason why one would choose encryption and access control as a security measure or any other method mentioned lies in the level of protection required to secure the transmission of sensitive data, the decision-making of humans, or the nature of the mission [81] [59] [82].

The second most used communication protocol found in the literature review is store-and-forward with approximately 28 per cent frequency, in combination with security measures such as encryption access control (12.5 per cent), authentication access control (12.5 per cent) and encryption, access control authentication (3.1 per cent).

The use of store-and-forward communication protocols in Mars missions is prevalent for several reasons. Mars missions often face challenges with intermittent connectivity due to factors such as planetary rotations, terrain obstructions, and limited visibility to Earth-based communication antennas [83] [46]. Store-and-forward protocols allow spacecraft, landers, and rovers to store data locally and transmit it when a communication link becomes available [84] [77]. This helps overcome interruptions in communication and ensures that important data is eventually delivered to Earth. Moreover, by storing data locally before transmission, store-and-forward protocols provide redundancy in the communication system. [85] [86] [77] Even if a transmission fails or is incomplete, the data can be retransmitted from the local storage, reducing the risk of data loss.

Similar to the point-to-point communication protocol, store-and-forward protocols often come with security measures such as encryption and access control. However, the reason why a developing team would choose other security measures as we can see in the stacked bar chart (just name the figure number) depends on the specific requirements and constraints of the mission, as well as the level of protection needed for the transmitted data [87] [88] [77].

To finish the analysis, I shall mention the other types of communication protocols found in the literature review though in smaller proportions: mesh, broadcast, and a combination of point-to-point and broadcast. These communication protocols also used security measures such as encryption access control, encryption authentication, authentication access control, or a combination of encryption, authentication, and access control.

Chapter 4

Conclusion

4.1 Discussion

In this section, key findings regarding the software used for Mars missions and their implications are discussed in order to answer the research question. Moreover, the broader implications for the field of Mars exploration and future missions are also considered.

4.1.1 Interpretation Of The Data Analysis In Relation To The Research Question

In the research question section of this work, the following research question was posed:

What are the key design principles that contribute to the successful implementation of applications/software in Mars mission environments?

To begin with, the software architecture often needs to be modular, as expressed in Figure 1, allowing for independent components that can be developed, tested, and deployed separately. This enhances maintainability and allows for scalability as mission requirements evolve [33] [35]. An iterative approach to software development is suggested, allowing the system to evolve through repeated cycles of refinement based on stakeholder requirements and testing feedback [89] [90].

Moreover, the use of fault-tolerant and redundant components is crucial for ensuring reliability and mission success. Space missions often have backup systems in place to ensure continuous operations in the event of a component failure [41] [42]. In terms of security, encryption and access control are fundamental security measures that are integrated into the software to protect against unauthorized access and ensure the integrity of mission data [43].

Furthermore, point-to-point communication protocols are emphasized for their reliability in establishing direct connections between nodes, which is critical when transmitting essential commands and data over vast distances [77]. The implementation of store-and-forward protocols helps manage intermittent connectivity issues. Data can be stored locally and transmitted when communication with Earth or other spacecraft is available, accommodating long signal delays due to the vast distance between Mars and Earth [83] [91] [63]. In terms of data handling, real-time processing and batch processing are both necessary for Mars missions, as real-time processing allows for immediate control and reactions, while batch processing enables less time-critical data analysis [69] [73].

Lastly, verification and validation are integral to the software development and validation process, ensuring that every aspect of the software's functionality and reliability meets the mission's stringent demands [50] [53] [54].

4.1.2 Implications For Future Mars Explorations

The systematic literature review has demonstrated key software design principles and technological considerations that bear significant implications for the future of Mars explorations. While some of these findings reinforce aspects discussed in the interpretation of the data analysis, they also offer novel insights and directions for future missions.

One critical insight from the analysis is the indispensable need for modular software architecture [92]. By enabling independent development and testing of system components, modularity paves the way for scalable and maintainable systems that can adapt to evolving mission demands [35]. This architectural approach should be embraced as a standard in developing software for long-duration space missions, ensuring flexibility and resilience in the face of dynamic mission requirements [93].

In addition to modularity, fault tolerance emerges as another crucial design principle highlighted by our review. The longevity of missions to Mars necessitates systems that can autonomously identify and overcome failures to maintain mission integrity [41]. As future explorations push the boundaries of human presence in space, investment in fault-tolerant computing technologies becomes imperative [42].

Furthermore, our review underscores the effectiveness of point-to-point and store-and-forward communication protocols in interplanetary data transmission. These protocols, coupled with robust security measures like encryption and access control, have proven reliable for transmitting critical commands and data over vast distances [43] [90]. Future missions should continue to refine these protocols and integrate advanced security measures to mitigate the risks posed by evolving cyber threats [94].

Moreover, as technology advances, the integration of artificial intelligence stands to revolutionize Mars exploration [95] [96]. Autonomous software capable of identifying scientifically interesting features or navigating challenging terrain without human intervention could significantly enhance the efficiency and safety of future missions [95] [96]. Building on past successes like the Mars Exploration Rovers, the integration of AI technologies holds promise for increasing the scientific return and autonomy of planetary exploration [95] [96].

Finally, the growing role of software in decision-making processes for Mars missions points toward a future where adaptive and learning algorithms play a critical role [97] [98]. Machine learning and predictive analytics can optimize missions in real-time, enhancing scientific discovery and ensuring crew safety [99]. By evolving software systems to become more intelligent and self-reliant, future missions can tackle complex tasks with minimal human intervention, pushing the boundaries of exploration further than ever before [99] [97].

4.2 Limitations

4.2.1 Internal Validity

This research, while comprehensive, encountered several limitations that could potentially affect the internal validity of the systematic literature review. More importantly, the internal validity of this systematic literature review may be compromised by selection and reporting biases inherent in the reviewed studies. Not all relevant studies may have been accessible, potentially resulting in the omission of key literature. The search strategy, inclusion criteria, and data extraction processes could have introduced selection bias, limiting the breadth of the findings presented. Positive or significant results might be disproportionately published, overshadowing null or negative findings, which could skew the representation of software effectiveness and reliability.

4.2.2 External Validity

The external validity of this review is limited due to the concentration of studies on specific mission phases, such as surface operations and Entry, Descent, and Landing (EDL) instruments. Each Mars mission may have distinct goals, environments, and constraints, which can make it challenging to apply conclusions from studies focused on one type of mission to others. This narrow focus may limit the generalizability of the findings to other phases of Mars missions.

Moreover, the external validity of this review is further constrained by the inherent complexity and specificity of Mars missions. The unique and highly specialized requirements of each mission make it difficult to generalize findings across different missions or to emulate the conditions accurately in the reviewed studies.

Additionally, rapid technological advancements present another challenge to external validity. Software and systems used in past missions may differ significantly from those planned for future missions, affecting the applicability of historical findings to current or upcoming missions.

Finally, many studies included in this review are based on simulations or controlled environments, which may not fully capture the complexities and unpredictability of actual Mars mission conditions. This limitation can affect the relevance and applicability of the findings to real-world scenarios.

4.2.3 Construct Validity

Construct validity in this systematic literature review may be affected by individual cognitive biases and the student's lack of domain expertise. These factors could influence the accuracy, interpretation and measurement of the data extracted from the reviewed studies.

4.2.4 Ecological Validity

Ecological validity is constrained by the limited accessibility to the software systems discussed in the reviewed literature. The inability to directly examine or test these highly protected and complex systems restricts the applicability of the findings to real-world Mars mission scenarios.

Moreover, Studies conducted in simulated environments on Earth may not fully capture the challenges and conditions of actual Mars missions. The sensory inputs, physical objects, and tasks experienced in these studies might not reflect the complexities of real missions. Differences in how software is used during actual missions versus controlled study conditions can affect the applicability of the findings.

4.3 Short and Medium-To-Long Term Perspectives

4.3.1 Short Term Perspective

Addressing the limitations of this work in the short term involves immediate and practical measures to enhance the robustness, applicability, and reliability of software for Mars missions. Several key strategies can be implemented within a relatively short time frame, focusing on overcoming current constraints and paving the way for more effective future research and development.

One of the primary limitations identified in this review is the reliance on simulations or controlled environments that may not fully capture the complexities and unpredictability of actual Mars mission conditions. To address this, the development of more sophisticated simulation environments is essential. These environments should incorporate advanced modelling of Mars' terrain, atmospheric conditions, and potential anomalies that might be encountered during missions. By doing so, the simulation results will better reflect real-world scenarios, thereby improving the reliability and relevance of the findings.

Moreover, the review highlighted the need for a broader methodology that includes Grey's literature. In the short term, expanding the scope of literature searches to encompass a wider array of sources will provide a more comprehensive understanding of the software landscape for Mars missions. This approach will help identify more diverse and potentially overlooked research, thereby mitigating selection and reporting biases.

Furthermore, strengthening partnerships between industry, academia, and space agencies can accelerate the development and testing of mission-critical software. Collaborative efforts should focus on sharing knowledge, resources, and best practices to enhance the quality and applicability of software solutions. These partnerships can also facilitate access to proprietary data and systems that are otherwise restricted, improving the ecological validity of the research.

Finally, while the potential of AI to improve mission efficiency and safety has been acknowledged, there is a need for more incremental and systematic integration of AI technologies into mission software[100] In the short term, this can be achieved by implementing AI modules that handle specific tasks such as anomaly detection, data analysis, and autonomous navigation in controlled test environments. These initial implementations will provide valuable insights.

4.3.2 Medium-To-Long Term Perspective

In the middle to long term, the integration of advanced artificial intelligence (AI) and machine learning (ML) systems will be pivotal in overcoming the current limitations of software for Mars missions[101][102]. As missions become more complex and autonomous, AI can enhance decision-making processes, enabling spacecraft to operate independently in unforeseen circumstances. Future AI systems should be capable of autonomously navigating the Martian terrain, identifying scientific points of interest, and making real-time decisions without waiting for instructions from Earth will be crucial[103]. This level of autonomy will significantly reduce the communication delay impact and increase the efficiency of scientific operations[102].

Moreover, the implementation of AI-driven predictive maintenance will preemptively identify potential system failures and perform necessary repairs autonomously. This approach will minimize downtime and extend the operational lifespan of mission-critical hardware[102].

Furthermore, the incorporation of AI and ML which can process vast amounts of data generated by Mars missions more efficiently than traditional methods will help tremendously improve the overall quality and speed of scientific discoveries [104][105]. These technologies can identify patterns and anomalies in data that might be overlooked by human analysts.

On the other side of the coin, energy efficiency and sustainability will also play a crucial role in future Mars endeavors[106][107]. Future software should aim to optimize energy consumption through energy-efficient algorithms and processes. Additionally, implementing software solutions that support sustainable resource management, including the recycling and efficient use of onboard resources, will be essential for the sustainability of long-term missions[106][107].

4.3.3 Biology-based Technology To Enhance Mars missions

To increase our knowledge of Mars, sending humans to the planet will eventually become paramount. Integrating biology-based technologies into software for Mars missions offers innovative solutions to several challenges, significantly enhancing the safety, efficiency, and well-being of astronauts [108]. These technologies, discussed in the Report of the Workshop on Biology-based Technology to Enhance Human Well-being and Function in Extended Space Exploration[108], provide essential insights into improving mission outcomes.

One significant challenge is the design and functionality of space suits. Current suits often compromise comfort and dexterity, which is particularly problematic in high-pressure environments. Integrating bio-mechanical data into space suit software can enhance their design[108]. For instance, sensors that monitor the astronaut's movements and physiological conditions can provide data to software that adjusts the suit's settings[108]. Algorithms can dynamically modify wrist angles and other joints to maintain optimal ergonomics, reducing fatigue and improving dexterity[108]. Additionally, software can monitor vital signs such as heart rate and body temperature, adjusting the suit's environment to maintain optimal conditions for the astronaut[108].

Managing advanced life support systems that incorporate biological elements is another area where software is crucial. Software can control bioreactors and other systems that recycle air, water, and waste, continuously monitoring efficiency and optimizing resource recovery[108]. Additionally, software managing plant growth systems for food production can adjust lighting, water, and nutrient delivery based on real-time data, ensuring optimal conditions for plant health and productivity. These systems are essential for creating a sustainable environment for astronauts on long-duration missions.

Software applications can also enhance habitat functionality and sustainability on Mars by integrating biology-based solutions[108]. Continuous monitoring of habitat structures made from bio-inspired materials by software can detect wear, potential breaches, and microbial contamination[108].

In conclusion, integrating biology-based technologies into software for Mars missions addresses many challenges of space exploration. By enhancing space suit functionality, managing regenerative life support systems, and optimizing habitat environments, software systems leveraging biological insights can significantly improve the safety, efficiency, and overall success of Mars missions. This approach not only addresses current limitations but also facilitates innovative and sustainable solutions for future missions.

4.4 Conclusion

This thesis has explored the critical software design principles and technological considerations that will play a pivotal role in the advancement of Mars explorations. Through a systematic literature review, this research has highlighted the indispensability of modular software architectures, emphasizing its value in creating scalable and maintainable systems capable of adapting to the evolving demands of long-duration space missions. Moreover, the importance of fault tolerance has been underscored as integral to the longevity and integrity of missions, particularly as they venture further into space.

The findings also demonstrate the role of communication protocols and security measures in ensuring reliable transference of mission-critical commands and data. Additionally, This thesis also acknowledges that artificial intelligence could greatly improve Mars missions' efficiency and safety. The predictive powers of machine learning and analytics promise to optimize missions in real time, empowering software systems to become more intelligent and self-reliant.

However, it is important to address the numerous limitations that were encountered in the conduct of this research. The selection and availability of sources, the potential for selection and reporting biases, and challenges in the generalizability of the results are among the chief limitations that temper the reach and applicability of the findings presented. These constraints highlight the need for cautious interpretation of the research conclusions and their practical implications.

Future research is called upon to embrace a broader methodology, one that includes the latest studies and Grey literature to bolster the robustness of systematic reviews in the field. The swift pace of technological advancement accentuates the necessity for the persistent reassessment of established software paradigms, encouraging ongoing innovation and adaptation in the design of Mars mission software.

In conclusion, this thesis has offered a critical examination of the factors influencing software design for Mars missions, shedding light on the path forward. As missions become more autonomous and the quest for scientific discovery expands, our software must evolve in synchrony, ensuring the success and safety of interplanetary exploration. The insights provided here serve as a guiding beacon for future endeavours.

This systematic literature review examines the critical software design principles required for Mars missions, focusing on modularity, fault tolerance, communication protocols, security measures, and the integration of artificial intelligence. By analyzing 32 studies, the research underscores the importance of these principles in ensuring the scalability, maintainability, and reliability of software systems in the harsh environment of space exploration. The review highlights the potential of machine learning and predictive analytics to improve mission efficiency and safety, advocating for increased autonomy in space operations. However, the study also acknowledges significant limitations, such as selection and reporting biases, time constraints, and a focus on specific mission phases, which may affect the generalizability of the findings. Despite these limitations, the research emphasizes the need for continuous innovation and adaptation in software design to meet the evolving challenges of Mars exploration, laying a foundation for future research with broader methodologies and diverse resources.

Cette revue systématique de la littérature porte sur les logiciels utilisés pour les missions sur la planète Mars. Elle met l'accent sur la modularité des systèmes, la tolérance aux pannes, les protocoles de communication, les mesures de sécurité et l'intégration de l'intelligence artificielle. Une analyse de 32 études souligne l'importance de ces principes pour assurer le développement, la maintenance et la fiabilité des systèmes logiciels dans l'environnement difficile de l'exploration spatiale. De plus, cette analyse met en évidence le potentiel de l'apprentissage automatique et de l'analyse prédictive pour améliorer l'efficacité et la sécurité des missions, préconisant une autonomie accrue des opérations spatiales. Cependant, des limites significatives telles que les biais de sélection et de rapport, les contraintes de temps et une concentration sur certaines phases de mission peuvent affecter la généralisation des résultats. Malgré ces limites, l'analyse souligne la nécessité d'une innovation et d'une adaptation continues dans la conception de logiciels avec des méthodologies plus larges et des ressources diversifiées afin de répondre aux défis de l'exploration de Mars.

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