SCHOOL OF PHYSICS,
ENGINEERING AND TECHNOLOGY

Autonomous Re-Configuration of Modular Spacecraft with Manipulator Arm

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CONTENTS

I. STATEMENT OF ETHICS

After consideration of the University's code of practice and principles for good ethical governance no ethical issues were identified in this project.

II. Introduction

A. Background and Context

Space systems have rapidly developed in recent years, with a global drive to increase commercial availability. Current commercial systems designed under the limitation of mass and launch costs, are traditionally highly customized whole systems which consequently have very limited or no maintenance and repair capabilities. The number of ageing satellites is rapidly increasing and upon reaching end of life, are discarded through atmospheric deconstruction methods if possible, or left in orbit contributing to space debris build-up.

Technology to circumvent these conditions is not currently available and as such, the HORIZON 2020 EU-funded MOdular Spacecraft Assembly and Reconfiguration (MOSAR) project was launched to develop novel technologies that would allow standardising satellites and components [1]. The modularisation and standardisation of space systems will benefit the European space industry by facilitating mass production of standard components and therefore decreasing assembly costs, reducing time between customer orders and commissioning in space, and allowing repair and upgrading of components directly in-orbit.

MOSAR primarily aims to produce on-orbit modular and reconfigurable satellites. At present the project has developed a demonstrator for re-configuring cubic modules to simulate the movement of modules through the use of a mobile robotic manipulator. Currently fixed instructions facilitating module mobility are sent to the manipulator from a software simulation on earth [2], this research project aims to further develop the capabilities of the system by developing an algorithm to automate the module reconfiguration process, facilitating self-repair and self-assembly. Following development, this technology has the potential to facilitate the automated assembly of space systems and platforms directly in space, expanding the limitations currently imposed on the space industry.

B. Review Objectives and Questions

This literature review aims to identify gaps and opportunities in current reconfiguration technologies and produce a plan to undertake the associated research over the following semester.

To guide this literature review, we will aim to answer the following research questions:

- What is the current state-of-the-art of modular spacecraft autonomy in the real-world?
- What are the challenges to improving automated reconfiguration in space?
- What research is being conducted into automated reconfiguration?
- What gaps and opportunities can be identified in current research?

III. Project Specification

This project intends to introduce the capability of autonomous modular assembly and reconfiguration of a spacecraft by implementing a planning program of simple algorithms that, given the initial state and final state of a modular craft as parameters, can produce a list of commands to send to a mobile manipulator to autonomously rearrange modules on a spacecraft or space platform in operation.

To accomplish the research goal, a reconfiguration planning program must be implemented in software. Which can then be evaluated and demonstrated in simulation if time permits. For measuring project success, the efficiency, error rate, robustness and potential for future advancement of the overall system will be considered.

Due to the strict guidelines required to acquire licensing for use in space, robustness will be an especially important measure of success as no matter the speed and efficiency of the program, if the manipulator arm ever receives instructions which jeopardise the system, spacecraft could be destroyed and in the worst-case scenario, lives lost. It is preferred for the planning program to return an error and be unable to provide a list of commands than to return commands which are not confirmed to be safe and accurate.

IV. Overview of Modular Spacecraft

Modular spacecraft are a design concept where the overall space system is composed of interchangeable modules / components, where each module is designed to serve a specific function such as propulsion, communication, power generation, or sensing. These modules are standardized allowing them to be easily connected to form a singular system, where modules can be moved or replaced to improve craft efficiency during operation and extend the overall lifetime of the system. Taking a modular approach to design offers several advantages over traditional designs such as flexibility, adaptability, and ease of maintenance.

Modules are equipped with standardised interfaces which define how modules physically and electronically interact, enabling modules with different purposes or made from different manufacturers to seamlessly integrate into the overall system architecture. The size and shape of modules can vary in different modular designs however standardisation principles allow these components to be integrated with other modules regardless. The size of the final space system architecture is only limited by the type and number of modules it is comprised of, providing scalability which enhances the spacecrafts versatility and cost-effectiveness, as the system can be tailored to meet specific needs of different missions without requiring a complete redesign.

V. State-of-the-art in Spacecraft Modularity and Autonomous Reconfiguration

The following section explores existing cases of spacecraft modularity and reconfiguration technologies currently or previously in operation. Due to the challenges related to developing automated reconfiguration systems for operation in space, there are no relevant existing cases of automated reconfiguration other than the International Space Station (ISS), however the use of modular design principles has been present in the space industry for development of spacecraft from as early as the 1980s with the development of the MMS.

A. *Multi-mission Modular Spacecraft (MMS)*

The Multi-mission Modular Spacecraft (MMS) was designed and deployed by NASA in the 1980s and 1990s [4] with the intention of decreasing space mission costs. Intended to be recoverable/serviceable by the Space Shuttle Orbiter [5], It is one of the first cases of modular designs seen in the space industry and has paved the way for future innovations.

Fig. 1. Artist rendering of the TOPEX/Poseidon mission. Image from [3]

The MMS consisted of a small number of immobile modules, with the most basic deployed MMS containing only modules for altitude control, communications and data handling, and the power subsystems module [4].

The MMS flew only six missions through its lifetime which was vastly different from the thirty-one expected in the 1970s [4], it suffered limitation in the form of electronic technologies rather than mechanical restraints. NASA's first Standard Spacecraft Computer (NSSC-1) [6] was developed to prevent requiring an entire redesign of onboard computers for each mission, requiring only a software redesign, though this was still a heavy burden affecting the MMS's mission flexibility. While no longer in operation as of 2006 [7], the system did show cost-savings in the range of 55% to 65% [4]. "The idea of a modular system serving many purposes was the pioneer of the leading systems within the space technology ecosystem today as it has left a lasting legacy" [4]. In the wake of the MMS's legacy, new design techniques were developed such as the Modular, Adaptive, Reconfigurable Systems (MARS) system-level architecture [4] that has built the foundation for modern space systems.

B. Modular Common Spacecraft Bus (MCSB)

The MCSB is a fast-development, low-cost, general purpose spacecraft platform consisting of a series of 4-5 modules stacked on top of each other, each serving separate functionality [9]. According to NASA, “the spacecraft is roughly one tenth the price of a conventional unmanned mission and could be used to land on the Moon, orbit Earth, or rendezvous with near-Earth objects.” [10]
The MCSB system received the Popular Mechanics 2014 breakthrough Award for innovation in science and technology [11] and is proving to be at the forefront of existing modular space technologies, first deployed on the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission in 2013 [12].

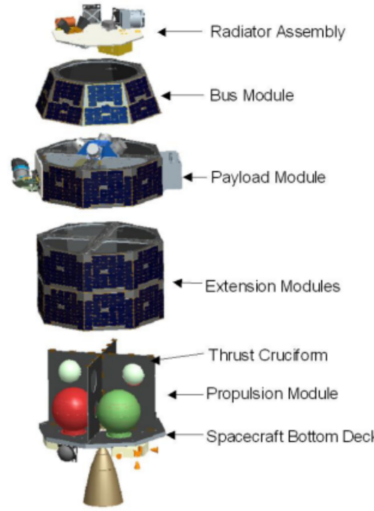

Fig. 2. LADEE Bus Modules from the MCSB Architecture. Image from [8]

The MCSB system is an example of modularity being used to streamline and reduce costs of the initial development process of the craft, being able to carry up to 50kg of scientific equipment inside its payload module [9], though the end product is still a whole system that has limited in-operation service capabilities and is not capable of being reconfigured to adapt to mission requirements in-orbit.

C. International Space Station

The International Space Station (ISS) seen in figure 3 is the largest space platform ever built, created with the purpose of performing micro-gravity and space environment experiments. First launched in 1998[14] and expanded through the integration of additional modules and serviced by human occupants up until its planned de-orbit in 2031 [15], it is a monument to advancements in the space industry.

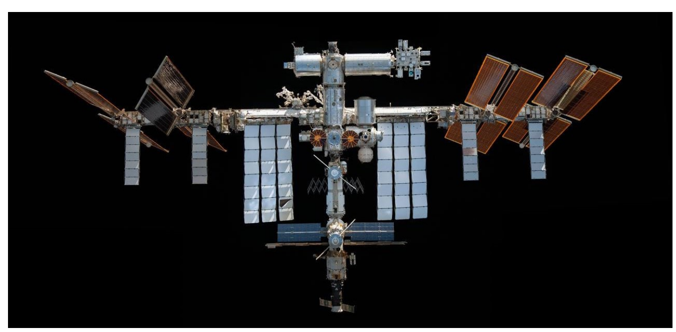

Fig. 3. The ISS pictured from the SpaceX Crew Dragon (Dec. 8, 2021). Image from [13]

The ISS is capable of reconfiguration using a robotic arm and automated docking with human oversight [16] unlike previous cases, though unsupervised automated reconfiguration is yet to be attempted due to the consequences of failure.

VI. Challenges and Limitations of Automated Reconfiguration in Space

The lack of deployment of complex automated systems such as automated reconfiguration systems in space is not due to a lack of interest, but instead due to the difficulty of the technical challenges presented by such systems and the risk introduced to extremely expensive and often critical missions that cannot afford failure.

Space systems must be reliable and work in a wide range of conditions. The more complex a system is, the more likely it can go wrong, which makes the validation, verification, and deployment of such systems in the space industry a lengthy and expensive process. Challenges that autonomous space systems face include:

- **Communication latency –** delays in communications from systems make it impossible for human controllers to react to unexpected situations in real-time, meaning any autonomous system must be capable of performing completely without human intervention. Simply having an autonomous system that is allowed to operate under human observation such as a self-driving car does not meet the reliability requirements for space applications.
- **Safety Requirements** – Systems will often be hosting expensive scientific equipment while operating in harsh, unpredictable environments where various hazards are present such as extreme temperature differences, radiation, space debris, ice and lack of gravity.
- **Limited Power Sources –** autonomous systems require power which depending on a crafts power source is not always guaranteed. For example, a craft relying on solar power may lose power during eclipses or due to unexpected collisions. Autonomous systems must be capable of recovering from temporary power loses or have reliable backup power sources to prevent mission failure.
- **Isolation** – unlike on land, it is usually not possible for a craft to quickly receive help or be viewed by an external observer. An autonomous system must have the sensing capabilities to self-diagnose problems or detect anomalies and halt standard operation, otherwise the system could cause further damage to itself.

Overcoming these challenges requires a level of technology that has only become available in recent years leading to the undertaking of research projects such as this one. It can be expected to see the number of autonomous systems present in the space industry drastically increase over the next few decades as computational power and materials sciences continue to advance.

VII. Emerging Advancements in Reconfiguration Technologies

A. *MOSAR Outcomes*

Up till now the MOSAR project has produced several major outcomes:

- A standardised module framework making use of the HOTDOCK adapter.
- Design and fabrication of a walking manipulator arm.
- Related system architecture to control the arm remotely.
- Successful ground demonstration of the manipulator arms capabilities to move and connect modules.

At this stage, an in-orbit implementation of the MOSAR demonstrator would be capable of reconfiguration functionality, though requires reconfiguration instructions to be manually sent to the craft. Further work is required for automated functionality such as:

- Automatically find a desired module configuration for the craft to meet mission requirements.
- Automatically compute a set of manipulator instructions required to reconfigure the craft from one configuration to another.

The following review of literature will be focused on identifying the best method to perform the latter.

B. *Automated Reconfiguration*

Automatic planners, algorithms that find a solution for which sequence of operations must be accomplished to achieve a specified goal, have been an area of development attracting wide-spread interest since the earliest days of robotics. Currently there are many different types of automatic planning techniques available. They encompass a large set of algorithmic requirements which trend towards purely discrete or purely continuous search space characteristics. The development of "Hybrid" automated planning approaches with search space characteristics that are not purely discrete or continuous, especially Task and Motion Planning (TAMP) algorithms, represent an area of study of which solutions are considered the most computationally difficult in theory [17]. Consequently, the application of automated planning algorithms to robotic assembly of modular satellites is a very recent development in which little work has been published that implements automatic reconfiguration algorithms while fully considering the range of real-world physical restraints and limitations presented by usage of a mobile manipulator arm in a low-gravity environment.

Motion Planning is finding solutions to move a robot "from one configuration to another configuration without colliding with the objects in the world" [18]. It involves searching for paths within the robots reach which is a continuous configuration space limited by dimensions represented by the joints of

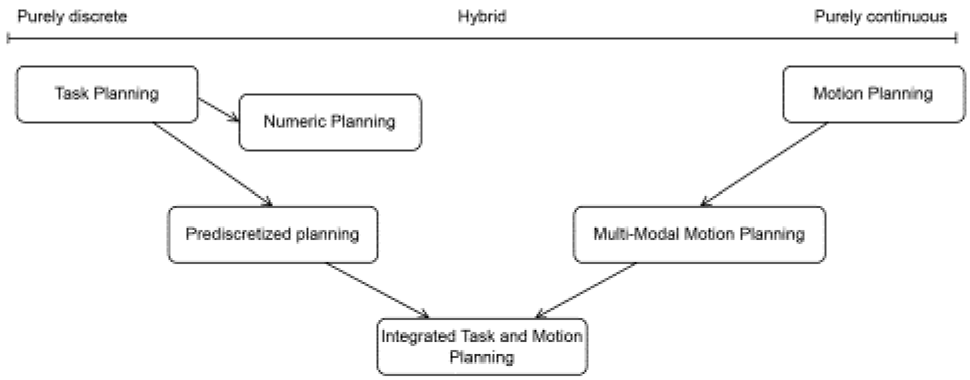

Fig. 4. Taxonomy of automated planning approaches based on their search spaces' characteristics. Image from [18]

the robot. These collision-free paths are important for robot motion but do not by themselves allow the robot to interact with the world. Further planning must be implemented to allow manipulation of objects through manipulation planning (known as Multi-Modal Motion Planning).

Due to the increased complexity of the problem presented by manipulation planning, the problem is best broken down into a hybrid discrete-continuous search problem of "selecting a finite sequence of discrete action types (e.g. which objects to pick and place), continuous action parameters (such as object poses to place and grasps), and continuous motion paths" [18].

While Motion and Manipulation planning are seen as problems mainly within the robotics field, planning within large discrete domains such as in problems presented by task planning has been more deeply researched within the artificial intelligence (AI) community [19]. Task planning (also known as Action planning) referring to deducing a composition of symbolic actions to achieve a high-level goal (e.g. computing a sequence of actions required to stack boxes in a specified order). The discrete nature of the problem makes it particularly suitable for many machine learning techniques which have particularly advanced in recent years.

Current research in task and motion planning (TAMP) primarily aims to combine the robotics solutions for manipulation planning under physical constraints with the usually unrestricted AI approach to task planning. With the goal of deriving automated planning systems capable of reasoning symbolically with discrete "high-level" robotic action sets while geometrically taking into account continuous "low-level" robotic motion planning and restrictions. To date, several papers have developed algorithms for similar TAMP problems to the scenario of modular satellite reconfiguration that unfortunately are not compatible due to the method of module mobility, but act as a proof of concept that a solution is possible [20]–[22].

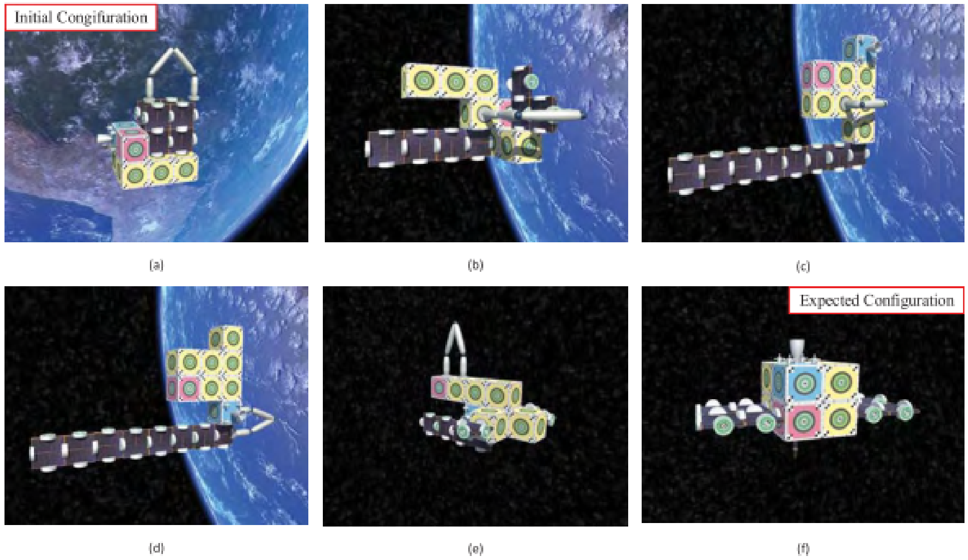

Fig. 5. Melt-Grow algorithm simulation results. Image from [25]

The 2010 Intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly (IBOSS) project [23] by DLR provided many advances in the area of satellite modularization with the development of standardised building blocks and interfaces [24]. Simple task planning techniques were implemented using Hierarchical task network (HTN) planning to produce high-level mobile arm instruction sets to then be verified through inverse kinematic checks and motion planning. This implementation solved the discrete and continuous planning problems separately, which simplified the problem however does not allow the separate systems to properly integrate. The system was not capable of efficiently solving more difficult tasks of identifying were solutions where not feasible.

Alternatively, another approach was taken here [25] through the implementation of the melt-grow algorithm [26]. The physical restraints of the robot were not including in the reconfiguration planning stage of the system, effectively reducing the problem to task planning. This reduces complexity though can only be achieved due to the behaviour of the melt-grow algorithm, which deconstructs (melts) the initial module configuration into chains of modules defined as the intermediate configuration, seen in configuration d in figure 5, before then reconstructing (growing) the modules into the expected configuration. The system then does not need to consider whether a move is possible for the mobile arm through manipulation planning as due to the algorithms inclusion of an intermediate state between the melting and growing operations, the algorithm essentially reconstructs the satellite instead of modifying the current state, all required moves are possible for the mobile manipulator and simply require motion planning. While proven to work, this method is shown to be highly inefficient for the

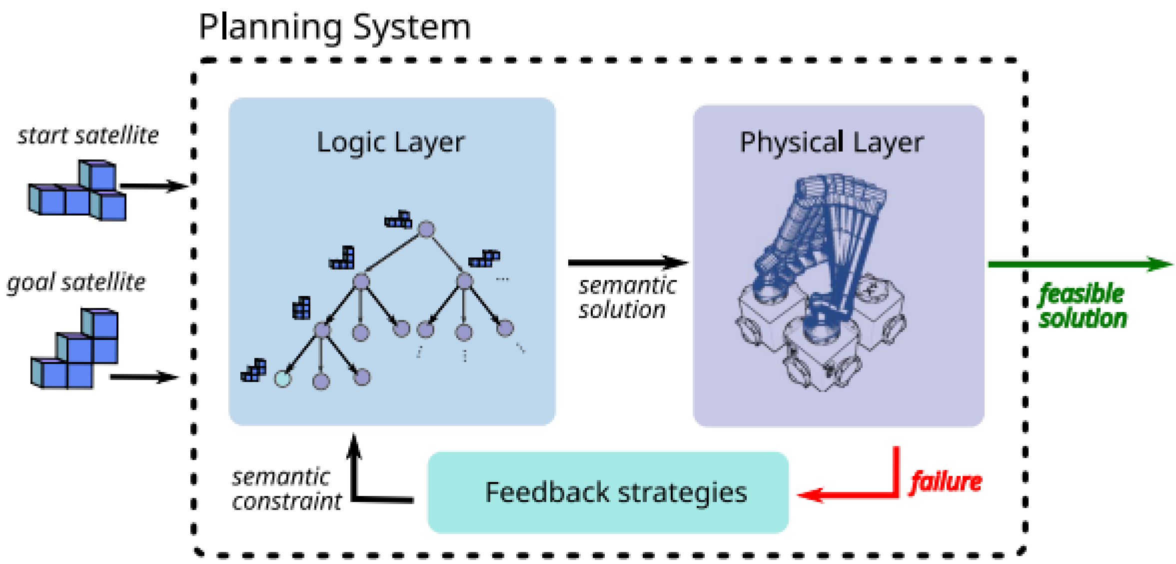

Fig. 6. "Architecture of the autonomous robot planning system. The system receives as inputs the start and goal satellite configurations, and iterates between the logic and physical layer until a solution is found." Image and text from [27]

mobile manipulator, especially as the number of modules increases in the system. Though, the paper [25] suggests this could be offset by the inclusion of additional manipulators which would consequently increase construction and operational costs.

More recent research has taken inspiration from these previous works to propose a comprehensive Task and Motion Planning (TAMP) problem solver [27] to intrinsically include the robot constraints into the system. The system, seen in figure 6, includes a logic layer, a physical layer, and a feedback system. Where the logic layer acts as a task planner finding a semantic solution by considering the solution as a sequence of states, with module movements defining the transition between states. A graph is developed to represent the possible states where nodes are system states and edges represent module movements which are verified by the physical layer which provides manipulation planning results through the feedback system. Using this graph the shortest and hence most efficient set of operations to reconfigure the system into the desired state can be identified. The removal of the intermediate configuration present in the melt-grow algorithm improves the efficiency of the solution set of operations, especially as the number of modules in the system increases, requiring less movement from the mobile manipulator.

The paper notes "the goal of this work was not to set a baseline for planning problems in terms of absolute times, but to demonstrate the usefulness of integrating feedback from the physical layer on the logic layer." [27], suggesting that there is an opportunity for further research into the components of the planning system and the related feedback strategies to prepare the system for space applications.

VIII. Gaps and Opportunities

Modular reconfiguration defines a subclass of the generic planning problems usually addressed by TAMP. Although research has previously demonstrated effective systems that can handle both symbolic and geometric reasoning, their application to robotic assembly and in particular robotic re-assembly is currently limited. There is additionally a distinct lack of discriminating modular blocks by type in existing algorithms which could potentially be easily implemented without a substantial hit to system performance.

The system proposed in figure [27] is promising due to the robustness of solutions and flexibility of the logic layer, however, there lacks the extensive performance testing required to recognise weaknesses and future improvements, identifying why this system could not be used in real-world application currently.

IX. Research Approach

The approach to this research project will be to replicate the system proposed in [27] to meet the project specification using an implementation that can display the system results in simulation. Then the system will be subjected to a range of performance tests to evaluate how modifications to feedback strategies affect overall performance and identify what roadblocks exist preventing space application in its current state.

As there is not enough time to build two completely different systems and compare them, the project takes an identifiably robust system and searches for improvements and failure points in the functionality.

X. Research Schedule

The schedule the project will follow can be seen in figure 7. Task descriptions can be seen below:

1.0 **User Interface**

- 1.1 **State graph creator** – Create a program that can be used to input modular state configurations and represent the state configuration appropriately in software.
- 1.2 **State viewer (user interface)** – Implement a user interface that can display, and allow the manipulation of, a state configuration to allow human input.
- 1.3 **Simulation display** – A simulation displaying the movement of the mobile manipulator as it reconfigures the craft from one state to another. This task will be highly time dependent as it pushes the boundary of the project scope.

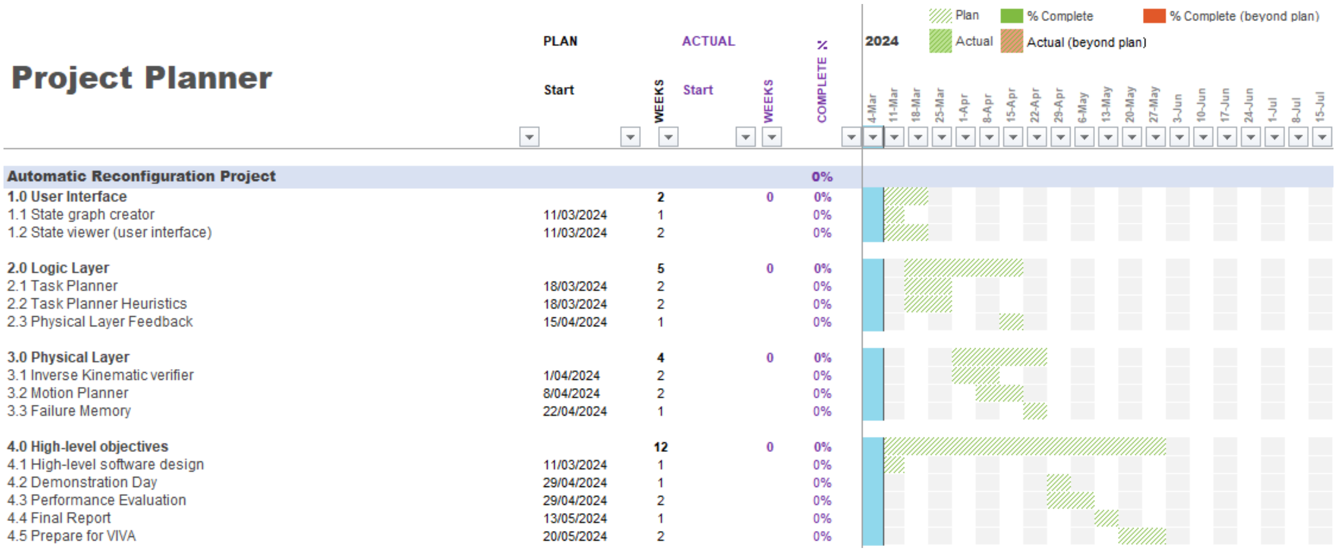

Fig. 7. A Project Planner displaying the overall project schedule

2.0 **Logic Layer**

2.1 **Task Planner** – Create a decision tree planner to compute basic semantic solutions.

2.2 **Task Planner Heuristics** – Add heuristics to the task planner to increase efficiency.

2.3 **Physical Layer Feedback** – Join the logic and physical layer together through feedback to create a control loop to produce verified solutions.

3.0 **Physical Layer**

3.1 **Inverse Kinematic Verifier** – Create a function that takes a module movement as an argument, and uses inverse kinematics to verify whether the movement is feasible for the manipulator.

3.2 **Motion Planner** – Produce a motion planner for the mobile manipulator so arm movement can later be displayed in simulation.

3.3 **Failure Memory** – Implement a machine learning algorithm that is trained from simulated movements, to create a failure predictor. The probability of failure produced by the algorithm can then be used for task planning optimisation.

4.0 **High-level Objectives**

4.1 **High-level software design** – Basic high-level software design to follow during the project.

4.2 **Demonstration Day** – Demonstration of the project to supervisors and industry professionals.

4.3 **Performance Evaluation** – Conduct performance testing on the algorithm under various conditions and with modified feedback strategies.

4.4 **Final Report** – Assemble collected information into a final report.

4.5 **Prepare for VIVA** – Prepare a 15 minute presentation for final project presentation and VIVA.

A. Risk Register

ID	Risk Description	Impact	Risk Probability	Mitigation of Risk
1	Missing or corrupted documents	High	Medium	Documents are backed up to a GitHub repository
2	Ambitions for project are too great for the project time limit	High	High	Setting appropriate scope expectations from the beginning of the project
3	Illness or work unavailability	High	Medium	Record illness and provide proper explanation for missing work in final report. Decrease scope to provide meaningful results
4	Losing test results	Medium	Medium	Produce lab reports to document progress

XI. Conclusion

This literature review has highlighted the newest advances within a small subset of planning algorithms relevant to automated reconfiguration of modular satellites. The implementation of modular reconfiguration systems to space applications is a relatively new field, and this research project intends to show how interconnected systems handling symbolic and geometric reasoning in tandem can appropriately find solutions and identify where they are not feasible. Additionally, this research intends to identify the shortcomings of existing theoretical systems and provide areas for future research and development.

XII. References

[1] MOSAR, "About the project - mosar," 2020, Accessed 12-12-2023. [Online]. Available: https://www.h2020-mosar.eu/about/.

[2] MOSAR, "Detailed design document," 2020, Accessed 13-12-2023. [Online]. Available: https://www.h2020-mosar.eu/wp-content/uploads/2021/08/MOSAR-WP3-D3.6-SA_1.2.0-Detailed-Design-Document.pdf.

[3] J. P. Laboratory, "Topex/poseidon fact sheet," Accessed 03-02-2024. [Online]. Available: https://sealevel.jpl.nasa.gov/missions/topex-poseidon/summary/.

[4] J. Esper, "Modular, adaptive, reconfigurable systems: Technology for sustainable, reliable, effective, and affordable space exploration," 2005. [Online]. Available: https://api.semanticscholar.org/CorpusID:2408860.

[5] R. O. Bartlett, "Nasa standard multimission modular spacecraft for future space exploration," in *Proceedings of the Goddard Memorial Symposium, Washington, DC, United State, March 8–10, 1978*, ser. AAS PAPER 78-043, NASA, Goddard Space Flight Center Greenbelt, Md., United States, 1978.

[6] C. E. Trevathan, T. D. Taylor, R. G. Hartenstein, A. C. Merwarth, and W. N. Stewart, "Development and application of nasa's first standard spacecraft computer," *Commun. ACM*, vol. 27, no. 9, 902–913, 1984, ISSN: 0001-0782. DOI: 10.1145/358234.358252. [Online]. Available: https://doi.org/10.1145/358234.358252.

[7] E Hupp and E Moreaux, "Nasa's topex/poseidon oceanography mission ends," *Press Release*, pp. 06–001, 2006.

[8] B. Hine, S. Spremo, M. Turner, and R. Caffrey, "The lunar atmosphere and dust environment explorer mission," in *2010 IEEE Aerospace Conference*, 2010, pp. 1–9. DOI: 10.1109/AERO.2010.5446989.

[9] S. Tietz, J. H. Bell, and B. Hine, "Multi-mission suitability of the nasa ames modular common bus," in *AIAA and Utah State University 23rd Annual Conference*, 2009.

[10] W. M. NASA, "Common spacecraft bus for lunar explorer missions," 2008, Accessed 10-02-2024. [Online]. Available: https://lunarscience.arc.nasa.gov/articles/common-spacecraft-bus-for-lunar-explorer-missions/.

[11] R. H. Dwayne Brown, "Nasa lunar mission wins 2014 popular mechanics breakthrough award," 2014, Accessed 10-02-2024. [Online]. Available: https://www.nasa.gov/news-release/nasa-lunar-mission-wins-2014-popular-mechanics-breakthrough-award/.

[12] M. V. D'Ortenzio, J. L. Bresina, A. R. Crocker, *et al.*, "Operating ladee: Mission architecture, challenges, anomalies, and successes," in *2015 IEEE Aerospace Conference*, 2015, pp. 1–23. DOI: 10.1109/AERO.2015.7118961.

[13] NASA, *The station pictured from the spacex crew dragon jsc2021e064215_alt*, 2021. [Online]. Available: https://images.nasa.gov/details-jsc2021e064215_alt.

[14] S. K. Shaevich, "Results of five-years exploitation of the first iss element-fgb" zarya" module," in *54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law*, 2003, T–1.

[15] E. Mahoney, "Nasa provides updated international space station transition plan," Accessed 12-12-2023, NASA, 2022. [Online]. Available: https://www.nasa.gov/humans-in-space/nasa-provides-updated-international-space-station-transition-plan/.

[16] M. A. Post and J. Austin, "Knowledge-based self-reconfiguration and self-aware demonstration for modular satellite assembly," in *10th International Workshop on Satellite Constellations & Formation Flying 2019*, York, 2019.

[17] A. Deshpande, L. P. Kaelbling, and T. Lozano-Pérez, "Decidability of semi-holonomic prehensile task and motion planning," in *Algorithmic Foundations of Robotics XII: Proceedings of the Twelfth Workshop on the Algorithmic Foundations of Robotics*, K. Goldberg, P. Abbeel, K. Bekris, and L. Miller, Eds. Cham: Springer International Publishing, 2020, pp. 544–559, ISBN: 978-3-030-43089-4. DOI: 10.1007/978-3-030-43089-4_35. [Online]. Available: https://doi.org/10.1007/978-3-030-43089-4_35.

[18] Y. Huang, *Algorithmic planning for robotic assembly of building structures*, 2023.

[19] M. Ghallab, D. Nau, and P. Traverso, *Automated Planning: theory and practice*. Elsevier, 2004.

[20] S. Vassilvitskii, M. Yim, and J. Suh, "A complete, local and parallel reconfiguration algorithm for cube style modular robots," in *Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292)*, vol. 1, 2002, 117–122 vol.1. DOI: 10.1109/ROBOT.2002.1013348.

[21] D. Saldaña, B. Gabrich, M. Whitzer, *et al.*, "A decentralized algorithm for assembling structures with modular robots," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 2736–2743. DOI: 10.1109/IROS.2017.8206101.

[22] J. Paulos, N. Eckenstein, T. Tosun, *et al.*, "Automated self-assembly of large maritime structures by a team of robotic boats," *IEEE Transactions on Automation Science and Engineering*, vol. 12, no. 3, pp. 958–968, 2015. DOI: 10.1109/TASE.2015.2416678.

[23] iBOSS, "Iboss background," 2023, Accessed 25-02-2024. [Online]. Available: https://www.iboss.space/background/.

[24] M. Kortmann, T. Schervan, H. Schmidt, S. Ruehl, J. Weise, and J. Kreisel, "Building block-based "iboss" approach: Fully modular systems with standard interface to enhance future satellites," Sep. 2015.

[25] Y. Zhang, W. Wang, J. Sun, H. Chang, and P. Huang, "A self-reconfiguration planning strategy for cellular satellites," *IEEE Access*, vol. 7, pp. 4516–4528, 2019. DOI: 10.1109/ACCESS.2018.2888588.

[26] D. Rus and M. Vona, "Self-reconfiguration planning with compressible unit modules," in *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No.99CH36288C)*, vol. 4, 1999, 2513–2520 vol.4. DOI: 10.1109/ROBOT.1999.773975.

[27] I. Rodríguez, A. S. Bauer, K. Nottensteiner, D. Leidner, G. Grunwald, and M. A. Roa, "Autonomous robot planning system for in-space assembly of reconfigurable structures," in *2021 IEEE Aerospace Conference (50100)*, 2021, pp. 1–17. DOI: 10.1109/AERO50100.2021.9438257.