SCHOOL OF PHYSICS,
ENGINEERING AND TECHNOLOGY

Autonomous Re-Configuration of Modular Spacecraft with Manipulator Arm

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Abstract

WRITE ABSTRACT HERE

Acknowledgements

I would like to give a big thank you to my project supervisor, Dr Mark Post, for providing guidance and feedback throughout the project; Along with giving me the freedom to explore and develop what interested me most. My exceptional peers at university that always pushed me to a higher standard throughout my time at university; And my family for making my time at university to further develop myself possible and providing endless support.

Contents

II. 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.

III. Introduction

This section builds, and expands, on material previously included in the project Initial Report (see Appendix D - Initial Report)

A. Background and Context

In recent years, there has been rapid development in space systems driven by a global push for increased commercial accessibility. Current commercial systems are designed with a focus on minimizing mass and launch costs, resulting in highly customized configurations that often lack robust maintenance and repair capabilities. Consequently, the population of ageing satellites is expanding, and upon reaching the end of their operational life, they are either deliberately de-orbited using atmospheric deconstruction methods or left in orbit, contributing to the accumulation of space debris.

At present, there is little available technology to overcome these conditions. The HORIZON 2020 EU-funded MOdular Spacecraft Assembly and Reconfiguration (MOSAR) project [1] was therefore initiated to develop innovative technologies aimed at standardising satellites and components. Modularising and standardising space systems will benefit the European space industry by enabling mass production of standardised components, reducing assembly costs, shortening the time between customer orders and deployment in space, and facilitating direct in-orbit repair and component upgrades, thereby extending the lifetime of space systems.

MOSAR's primary objective is to create modular and reconfigurable satellites that can be assembled and adjusted in orbit. The project has developed a demonstrator for reconfiguring cubic modules using a mobile robotic manipulator to simulate module movement. Currently, the manipulator receives fixed instructions for module mobility from software simulations on Earth [2]. This research aims to enhance the system by developing an algorithm to automate module reconfiguration, enabling self-repair and self-assembly. Once implemented, this technology could automate space system assembly and platform construction in space, overcoming current limitations in the space industry.

B. Project Objectives and Specification

This project intends to enable autonomous assembly and reconfiguration of modular space systems by implementing a reconfiguration planning program made up of simple algorithms. This program, given the initial state and final state of a modular system, will generate a list of commands to be sent to a mobile manipulator to autonomously rearrange modules on a spacecraft or space platform. The planning program must account for physical constraints imposed by the mobile manipulator present on the modular system; therefore, this project will strive to explore methods of incorporating physical constraints into the planning process.

To achieve the research goal, the primary objective is to implement a functional planning program capable of autonomous module reconfiguration, which will be demonstrated through software simulation. If time allows, an additional goal is to physically demonstrate the planning program by integrating it with the available manipulator arm in the lab to reconfigure real modules.

To achieve the research objectives, the following sub-objectives have been identified:

1) Develop a reconfiguration planning program that generates module movement instructions for a mobile manipulator based on initial and final state configurations.
2) Enhance the reconfiguration planning program to integrate physical constraints imposed by the mobile manipulator.
3) Implement a display function to create reconfiguration slideshows or videos, allowing users to visualise the modular systems reconfiguration process.
4) Conduct systematic testing of the system with various inputs to analyse system performance during solution generation.
5) Demonstrate the system by integrating it with the laboratories robot arm to physically reconfigure real modules.

By pursuing these steps, the project aims to showcase the feasibility and effectiveness of the planning program for autonomous assembly and reconfiguration of modular space systems, potentially paving the way for practical applications in the space industry.

C. Report Structure

This document serves as a comprehensive report of the research and development carried out during the Autonomous Re-Configuration of Modular Spacecraft with Manipulator Arm project. The report encompasses the following key components:

1) **Literature Review and Research:** A thorough examination of the current state-of-the-art in modular reconfiguration, including a review of relevant literature and existing technologies in the field.
2) **Detailed Design Development:** Creation of a detailed design plan outlining the implementation strategy for the reconfiguration planning program, specifying key components and methodologies
3) **Implementation Description and Specification:** Description and Specifications of the final implemented design, detailing the development and optimisation.
4) **Design Analysis and Results:** Analysis of the implemented design, records of performance metrics, solution generation times, and failure rates obtained through testing and simulation.
5) **Discussion of Results:** Interpretation and discussion of the analysis results, evaluating their significance and implications within the broader context of the area of study.
6) **Project Management Approach:** Examination of the project management methodology employed throughout the project lifecycle, documenting the evolution of the project plan and strategic adjustments made to achieve project objectives.
7) **Recommendations for Further Work:** Identification of potential areas for future research and development to build upon the findings and achievements detailed in this report, suggesting methods for expanding and refining the implemented system.

IV. Literature Review

This section builds, and expands, on material previously included in the project Initial Report (see Appendix D - Initial Report)

V. Overview of Modular Spacecraft

Modular spacecraft represent a design concept where the overall space system consists of interchangeable modules, each fulfilling specific functions such as propulsion, communication, power generation, or sensing. These standardised modules enable easy assembly to form a unified system, allowing for module movement or replacement to optimize craft efficiency and extend system lifespan. Adopting a modular design approach offers several advantages over traditional methods, including enhanced flexibility, adaptability, and simplified maintenance.

Modules feature standardised interfaces that govern physical and electronic interactions, facilitating seamless integration of modules with different purposes or manufacturers into the overall system architecture. While module sizes and shapes may vary across designs, standardisation principles ensure compatibility for integration. The scalability of modular space system architectures depends on the types and quantities of modules used, providing versatility and cost-effectiveness as the system can be tailored to suit specific mission requirements without necessitating a complete redesign.

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

This 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 space operations, there are limited existing cases of automated reconfiguration aside from the International Space Station (ISS). However, modular design principles have been integral in spacecraft development since the 1980s, notably with the introduction of the Multi-mission Modular Spacecraft (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.

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].

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

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].

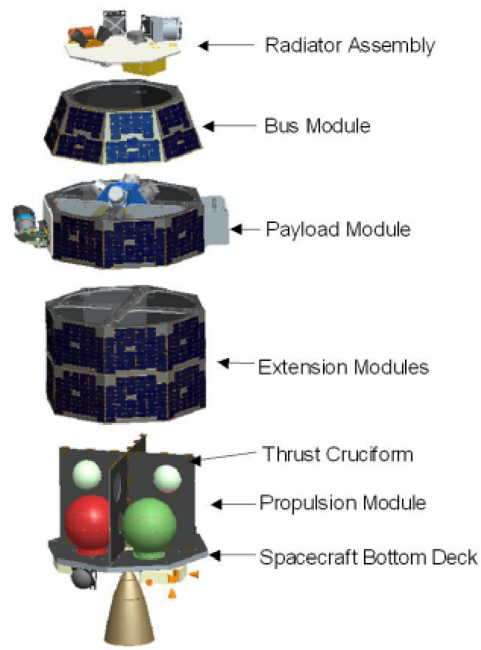

Fig. 2. LADEE Bus Modules from the MCSB Architecture. Image from [8]

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 microgravity 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.

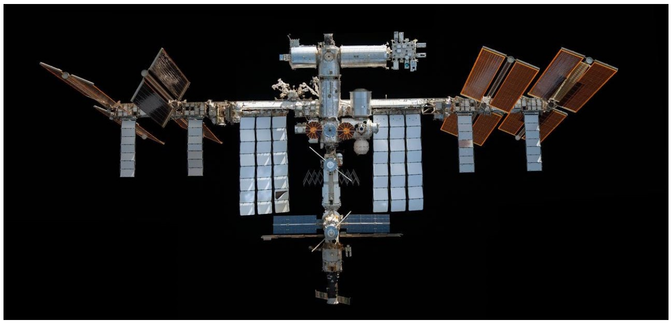

Fig. 3. The ISS pictured from the SpaceX Crew Dragon (Dec. 8, 2021). Image from [13]

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.

Although the examples provided are not exhaustive, they encompass significant cases of modularity in the history of space exploration. Currently, automated spacecraft reconfiguration remains unimplemented in the industry. This project aims to contribute towards the future widespread adoption of automated modular reconfiguration by developing a system that can be compared with other emerging systems, aiding to identify techniques that offer the most substantial benefits. These techniques can then be utilised to create increasingly advanced reconfiguration systems for space applications.

VII. Challenges and Limitations of Automated Reconfiguration in Space

The limited deployment of complex automated systems, like automated reconfiguration systems, in space is not due to a lack of interest, but rather stems from the formidable technical challenges and high-risk nature of space missions, which cannot afford failures due to their high cost and critical objectives.

Space systems must exhibit high reliability and operate effectively across a wide range of conditions. As system complexity increases, so does the number of potential failure points, making the validation, verification, and deployment of complex systems in the space industry a lengthy and costly process. Challenges that autonomous space systems face include:

- **Communication latency:** Delays in communications render real-time human intervention impossible, necessitating autonomous systems capable of operating independently without human oversight. Unlike terrestrial applications like self-driving cars that operate under human supervision, autonomous space systems must meet stringent autonomous reliability requirements.

- **Safety Requirements:** Systems will often be hosting valuable scientific equipment while operating in harsh, unpredictable environments with various hazards such as extreme temperature fluctuations, radiation, space debris, ice, and microgravity.

- **Limited Power Sources:** Autonomous systems rely on power sources that may not be constant or reliable. For instance, solar-powered crafts may experience power loss during eclipses or due to unexpected collisions with space debris. Autonomous systems must be capable of recovering from temporary power losses or have reliable backup power sources to prevent mission failure.

- **Isolation:** Unlike on Earth, space missions lack immediate external assistance or observation. Autonomous systems must possess robust sensing capabilities to self-diagnose issues, detect anomalies, and suspend standard operations when necessary to prevent further damage.

Overcoming these challenges demands cutting-edge technology, which has only recently become available, motivating research projects like this one. As computational power and materials sciences advance, we can expect a significant increase in autonomous systems within the space industry in the coming decades.

VIII. Emerging Advancements in Reconfiguration Technologies

A. MOSAR Project Outcomes

The MOSAR project has achieved several significant outcomes to date:

- Development of a standardized module framework utilizing the HOTDOCK adapter.
- Design and fabrication of a walking manipulator arm.
- Establishment of a related system architecture for remote control of the manipulator arm.
- Successful ground demonstration showcasing the manipulator arm's capabilities to move and connect modules.

At this stage, the MOSAR demonstrator could theoretically perform reconfiguration in orbit but currently requires manual transmission of reconfiguration instructions to the craft. Further work is needed to enable automated functionality, including:

- Automatic determination of a desired module configuration to meet mission requirements.
- Automated computation of manipulator instructions necessary to reconfigure the craft from one configuration to another.

The following review of automated reconfiguration literature will focus on identifying the best methods for the computation of manipulator instructions.

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.

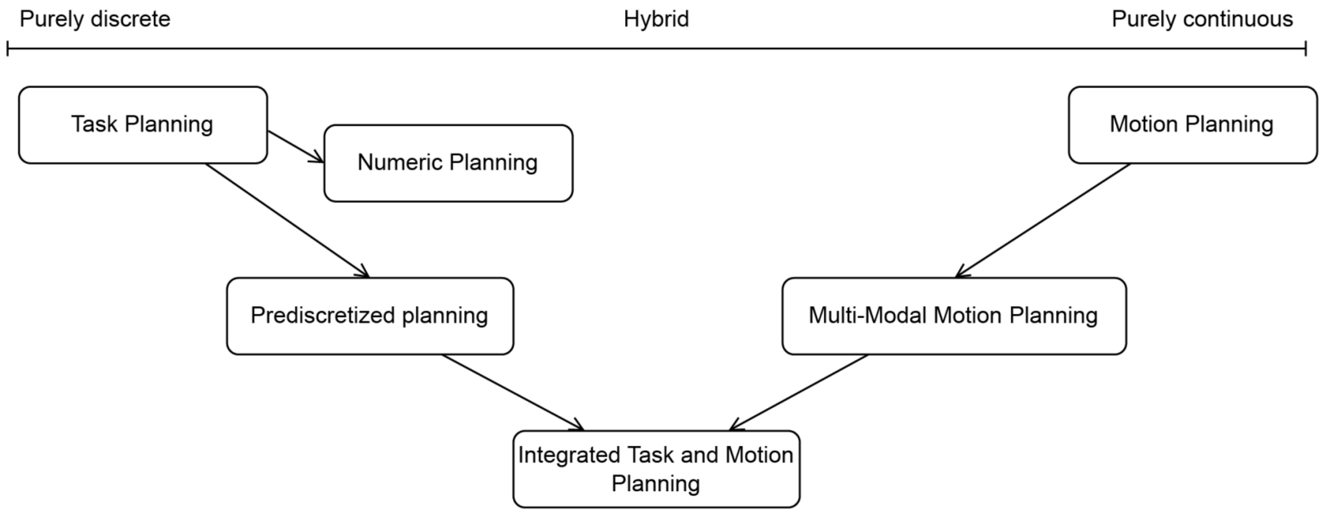

Fig. 4. Taxonomy of automated planning approaches based on their search spaces' characteristics. Image from [18]

C. Motion and Manipulation Planning

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 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].

D. Task Planning

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.

E. Task and Motion Planning

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].

F. Related Work

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.

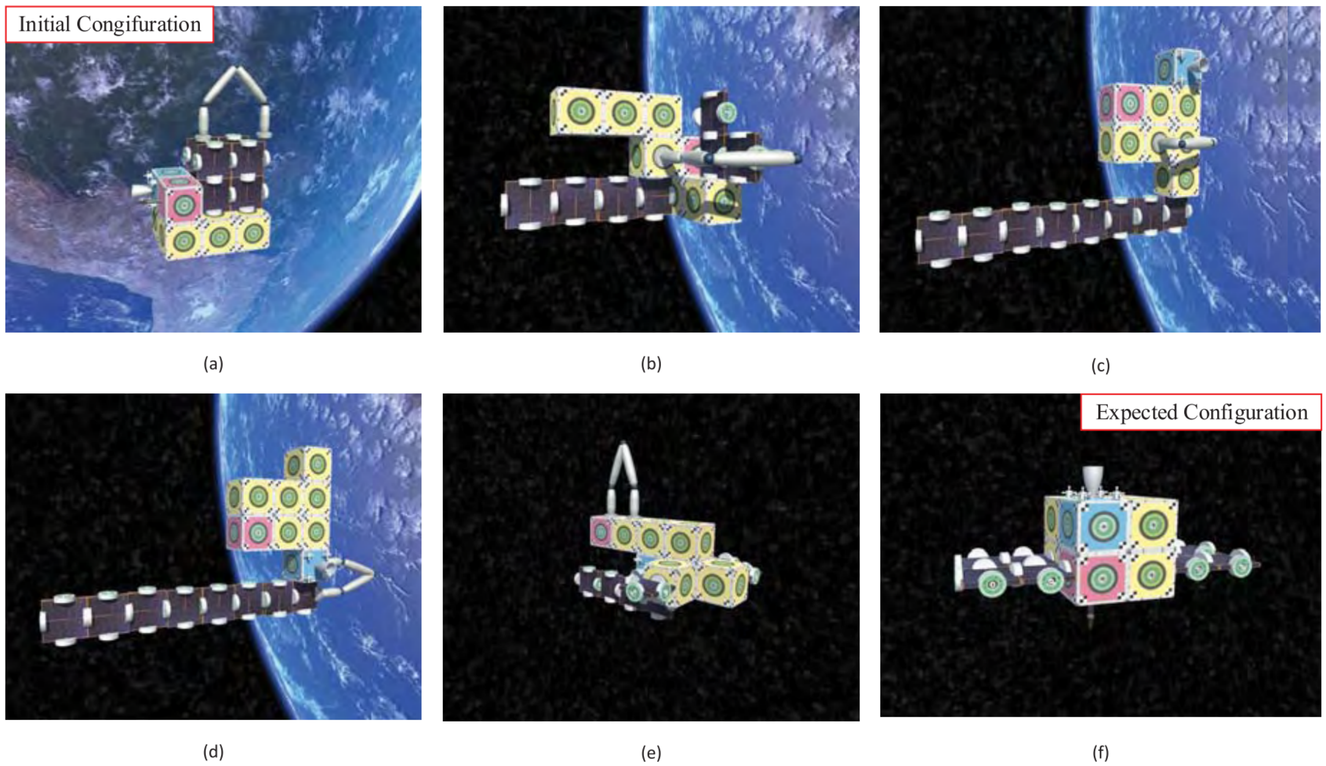

Fig. 5. Melt-Grow algorithm simulation results. Image from [25]

While proven to work, this method is shown to be highly inefficient for the 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.

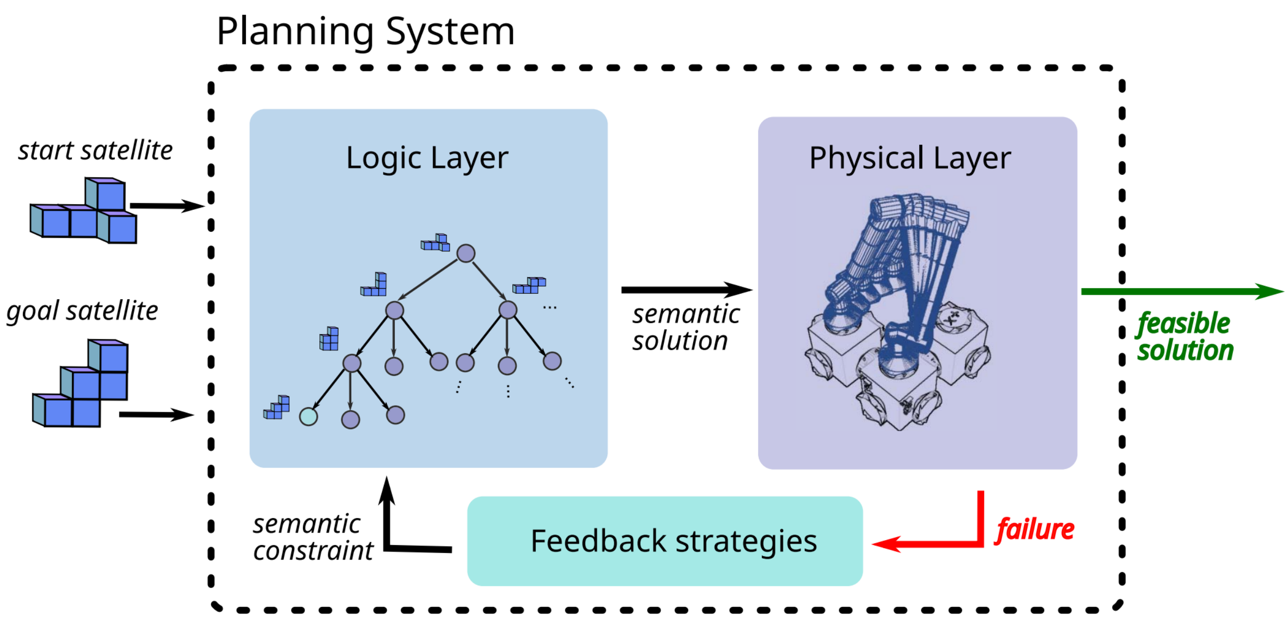

Fig. 6. "Architecture of the autonomous robot planning system. The system receives as inputs the start and goal satellite configurations, and iterates between the logic and physical layer until a solution is found." Image and text from [27]

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.

IX. Gaps and Opportunities

Modular reconfiguration defines a subclass of the generic planning problems usually addressed by TAMPs. 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.

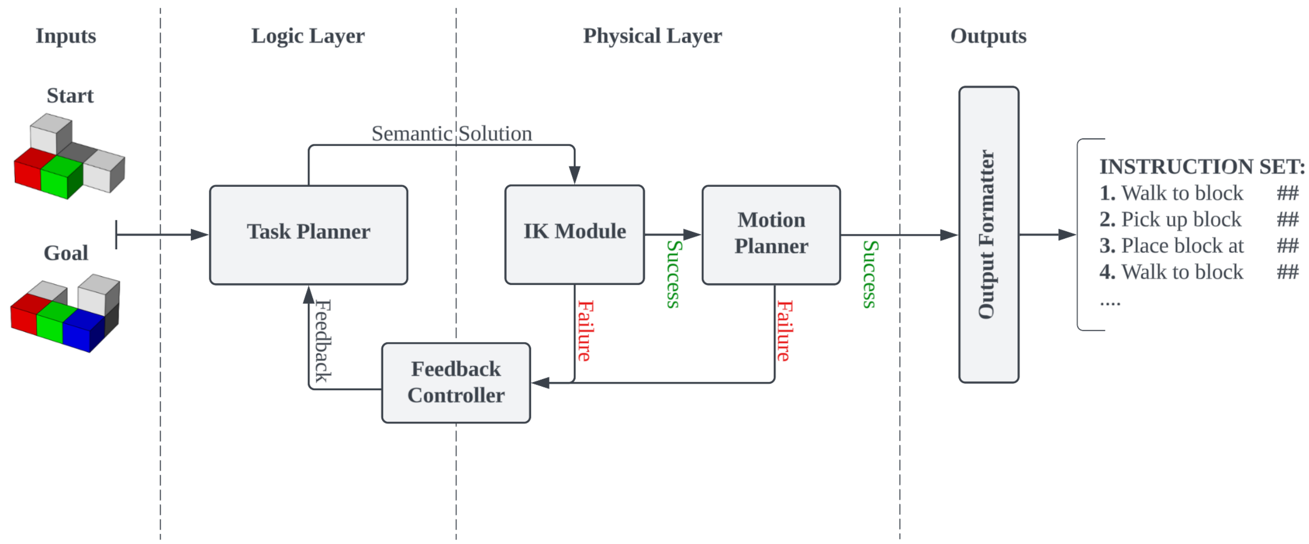

Fig. 7. High-level System Design

X. System Design and Development

test

XI. References

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XII. Appendix D - Initial Report

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