Hardware Autonomy for Space Infrastructure

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Abstract—**NASA prioritizes autonomous systems development with the expectation that it will continue to drive significant improvements in human and science exploration capability. Crew operations benefit from a spectrum of machine assistance to complete replacement of dangerous or highly repetitive tasks. Many science operations have a teleoperation component, and similarly benefit from a range of autonomy implementations that make long distance applications feasible. As we consider longer duration deep space missions, we also consider higher levels of autonomy in order meet emergent safety, maintenance, and logistics needs. One of the challenges within this scope is installation and maintenance of infrastructure, such as large scale instrumentation and communications equipment, crew habitats, and operational facilities.**

We describe how a programmable meta-material architecture may shift the paradigm of how we design, build, and operate future space infrastructure and assets. A primary objective of this strategy is to free the design space from launch vehicle constraints and fundamentally shift how a mission is designed and conducted. This integrates advances in materials (mechanical meta-materials), manufacturing (cooperative mobile robotics), and autonomy (multi-agent planning algorithms). Engineering systems that utilize a modular and reconfiguration building block approach, such as digital communication and computation systems, currently lead in terms of size and complexity scalability. NASA is extending the benefits and flexibility of digital systems to hardware systems, to optimize materials lifecycle management and expand our space exploration mission capabilities to meet long duration and deep space infrastructure needs, in accordance with long term NASA goals of "in-space reliance" and "mass-less exploration."

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1. INTRODUCTION

NASA Ames Research Center's Coded Structures Laboratory (CSL) is developing autonomous construction, maintenance, and reconfiguration technologies to meet long duration and deep space infrastructure needs, in accordance with long term NASA goals of "in-space reliance" and "mass-less exploration." We seek to achieve these capabilities by utilizing a "programmable meta-material" approach that integrates emerging advances in materials (mechanical meta-materials), manufacturing (cooperative mobile robotics), and autonomy (multi-agent planning algorithms). Through the Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) project, we have shown assembly of high performance engineered cellular materials using cooperative mobile robotic assemblers. In this paper we describe a framework to assess the levels of autonomy for a structural assembly system and where the ARMADAS system fits into the framework.

2. BACKGROUND

Space Infrastructure Construction

As humanity continues to explore further into space and establish a more permanent presence on orbit and on planetary surfaces, infrastructure will need to be built to support such endeavours. Systems such as habitats, communication networks, power generation, and manufacturing facilities are just a few examples of what is needed [1]. Long-term success will be determined by our ability to adapt and "survive off the land", just like the early terrestrial explorers before us, albeit with a different set of constraints such as extreme environments, extremely remote locations, and limited resources.

To prepare for these challenges, we need to design systems that manage complexity, leverage robotic-based construction, automate material acquisition and manufacturing, and are self sustaining [2]. A system can reduce complexity by reducing the number of unique modules, "pre-loading" the complexity into modules, and reducing position and manipulation configurations. Reducing complexity ultimately leads to more efficient processes and higher reliability. Robotic-based construction can leverage autonomy, efficient material handling, and joining processes to create infrastructure at scale with lower risk. Raw material acquisition and part manufacturing capability would be incorporated in scenarios where we want to commit to more permanent and growing infrastructure. Self-sustainability in the context of maintenance and repair will extend the life of infrastructure and minimize human intervention.

With advances in robotic technology, much of the infrastructure can be pre-built before human arrival. To be able to achieve this, autonomous construction technologies need to be developed to adapt to changing environments, manage communication constraints, and increase reliability.

Autonomy

Autonomy enables a system to achieve its design goals while operating independently of external control [3]. This requires the ability to self-direct to achieve goals, and to be self-sufficient to operate independently. Autonomy can be applied to many systems including mars rovers, self driving cars, formation flying drones, air traffic management, and much more. Subsystems of a larger system can be autonomous as well, even if the system as a whole isn't autonomous.

Current research includes autonomous navigation technologies, collective swarm spacecraft operations, and lunar space stations. In the next generation space stations like NASA's Gateway, autonomy is used to operate the vehicle for long periods of time while astronauts are away. For Gateway, autonomy is defined in six levels, 0-5, where 0 is full manual control, and 5 is full automation [4]. Other automation architectures such as self driving cars also have a similar scale, but is defined for how a user interacts with the car. Autonomy for different systems may have different definitions and understanding how the progression is developed helps designers work towards full autonomy. Current challenges being tackled by industry, government, and academia include situational and self awareness, reasoning and acting, collaboration and interaction, and engineering and integrity [3].

Programmable Meta-Materials

Programmable meta-materials is an field of study that merges mechanical meta-materials with programmable materials to create a system that has high-performance mechanical properties as well as the ability to reconfigure to various geometries to suit different needs [5][6]. The scalability in size and complexity of engineered systems achieved in computing and communications systems utilize a highly systematic approach to error handling and correction as well as a combinatorial and hierarchical approach to variability. Programmable materials (also referred to as programmable matter, digital materials) extends these principles to hardware systems [7]. Metamaterials push the boundaries of materials engineering at the micro/nano/macro-level to achieve extraordinarily effective mechanical properties [8].

Current research combines elements of research in both fields to demonstrate feasibility and capabilities to create assembly systems that are flexible and high-performing. Systems with discrete unit cells and inchworm-like walking robots are used to assemble lattice structures [9]. Robot swarms utilize collective robotic construction techniques to lay bricks to form structures [10]. Challenges in this field include being able to build "Big" systems, conduct self-repair, be self-sustaining, and many other challenges [11].

3. AUTONOMY FRAMEWORK

Overview

For an autonomous assembly system, there are four dimensions to consider with regards to autonomy: sensing, diagnostics, planning, and execution. Each dimension can be divided into 5 "Levels of Autonomy", as seen on Table 1. The first level is a rule based system (L1),in which automation relies on operator assistance. The second level entails partial automation, where there is some context awareness and retention by the system (L2). The third level describes a domain specific aptitude by the system leading to conditional automation (L3). This is followed by the more robust capability of reasoning or high automation (L4), and finally the fifth level, general full autonomy (L5).

Sensing

The first dimension to consider is sensing. Sensing refers to the ability of the system to detect the state of various components of the system during operation. At autonomy level 1, a rule based system, the state of components can be achieved through easily verifiable mechanism actuation. For instance, the status of a simple open-closed or on-off type of actuator can be determined by implementing basic sensing strategies. L2 utilizes a higher step of sensing automation where context awareness and retention enables partial automation. Here, the simple sensing information is used to update the knowledge of a subsystem or mechanism status, and bases subsequent actions on this knowledge. When all the robotic subsystems' processed sensing data is integrated and used to draw conclusions on the robot configuration, the system falls in the domain specific aptitude category, which is the third automation level, featuring conditional automation. In this case, the estimate of the robot configuration influences and determines the robotic system behavior during operation. The fourth automation level is based on reasoning. Here, the integrated robotic system has the capability to sense its configuration, and the structural components implement a configuration estimation based on sensing as well. Adding the structural component health sensing to the robot and component configuration sensing yields to a general fully autonomous system.

Diagnostics

Diagnostics refer to the ability of the system to identify anomalies via a continuous assessment routine. The five layers of autonomy for space infrastructure development systems have different levels of diagnostics capabilities. At the lowest level, the rule based system depends on dimensional integrated system assessment which involves periodic supervision, inspection and detection of errors in the process by an operator (L1). This is followed by context awareness and retention which entails automated fault detection in which the system performs a continuous self assessment and, through sensing, is able to detect faults (L2). The third level is the domain specific aptitude which utilizes autonomous fault detection to draw conclusions on the robotic and component system state. It performs online robot state estimation and infers structural system state estimation (L3). The next higher level automation is able to estimate the structural system state rather than inferring it (L4). A fully autonomous system (fifth autonomy level) is able to sense the environment, too, and to adapt to different conditions, such as a different build surface, or atmospheric conditions. It is able to achieve this through an online distributed system state estimation and mission environment prediction (L5).

Planning

Planning autonomy is defined as the level of utilization of autonomous build algorithms to determine the system assembly instructions. For a structural assembly system, this could include component and module build order and robot motion planning. At the lowest level of autonomy (L1), the system relies mostly on the operator for manual assembly instructions. With additional autonomy (L2) the progression of assembly states are still user defined, but the software controls the motions between consecutive states. Mid-level planning algorithms are used at L3 to determine assembly instructions for a predetermined shape. A system at L4 used distributed planning algorithms and accepts high level parameters to calculate an output shape and the associated set of build instructions. At the highest level of autonomy (L5), the system utilizes highly complex algorithms for build plans. It receives a general set of desired parameters and the planning algorithms will design and optimize the final structure and plan, with the capability to adapt the design and plan based on new information.

Table 1. Levels of Autonomy

Autonomy Strategy	Sensing	Diagnostics	Planning	Execution
(L1) Rule Based System – assistance, automation	easily verifiable mechanism actuation	dimensional integrated system assessment	software guided manual assembly	finite tasks, verifiable guided workflow
(L2) Context Awareness and Retention – partial automation	critical mechanism actuation sensing	automated fault detection	software guided planning for automated assembly of user defined target states	user guided planning and remotely operated automated assembly
(L3) Domain Specific Aptitude – conditional automation	robust integrated robot configuration sensing	online robot state estimation, inferred structural system state estimation	planning algorithms for fully automated assembly of predefined target states	fully autonomous assembly of predefined target states
(L4) Reasoning – high automation	robust integrated robot and structural component configuration sensing	integrated online robot and structural system state estimation	distributed (finite state automata) planning for high level goals (e.g. enclosures)	fully autonomous functional system implementation
(L5) General – full autonomy	robust integrated configuration and component health sensing	online distributed system state estimation and mission environment prediction	algorithms for mission level dynamic optimization	fully autonomous exploration system

Execution

The execution dimension of the system refers to the ability of the system to execute tasks with varying levels of manual intervention. In a minimally autonomous system (L1), the assembly agents have a finite set of tasks to execute. This setup anticipates partial manual preparation of the system and some manual intervention as the operator sends individual commands to the agents. Increasing the level of autonomy (L2) supports partial automation of the task execution, where a user defined build plan is translated directly into commands for assembly agents. Higher levels of automation would enable autonomous assembly of a specific predefined target state in which the agents can use some reasoning to determine onboard what commands to execute (L3). More reasoning capability from the agents would allow a higher autonomous system which takes a specific high level command (L4). A fully autonomous system (L5) would accept a high level general command and complex reasoning system to determine requirements and optimize the execution of the mission goal.

4. STRUCTURAL SYSTEM EXAMPLE

This frame work is envisioned to be used for various structural assembly systems. In this section we discuss how the framework applies to the NASA Automated Reconfigurable Mission Adaptive System (ARMADAS) project in its current research phase, and how we envision the system evolving. A system can operate at a different level of autonomy in each of the dimensions of listed above. It could also be designed to operate in multiple levels of autonomy depending on design requirements.

Programmable Meta-material Assembly System

The core of ARMADAS's programmable meta-material architecture consists of 3 main technology sub-areas: the structure, the assembly agents, and the assembly algorithms. We co-design these systems to ensure an adaptable system that can create and reconfigure structures from a base set of building block components (Figure 1). From this core technology, we can branch out and expand the capability of the system through additional secondary component types and robotic agents to perform activities such as inspection, maintenance, repair, payload installation, or perform power and communications interconnect. As these technologies mature, future designers will be able to utilize the system to rapidly integrate and operate assets in space or on planetary surfaces from a set of well tested part libraries or create their own modules to integrate into the system (Figure 2). A core trait to the development of this system is the automation approach. Because of the modular and functional discrete (pixel-like) nature of the structural system, a diverse set of powerful algorithms for analysis, planning, and simulation can be adapted and leveraged to optimize construction, maintenance, and dynamic reorganization (as hardware with programmable form and function).

The ARMADAS strategy is to replace diverse traditional infrastructure implementation and maintenance logistics problems with computational problems. Conventional autonomy development efforts focused on state estimation are simplified for the ARMADAS system due to the high degree of structure and predictability inherent to these robots' environment. This has allowed us to focus our autonomy efforts towards high level planning, and we have published analyses of assembly parallelization with multiple robots [12], planning and scheduling determinism and flexibility through centralized or distributed (e.g. finite state automata) approaches according to mission needs [13][14], and proven orders of magnitude scalability through programmable assembly algorithms [15]. Scalability with parallelization is known to be achievable within reasonable compute and operations time. The reversible nature of the ARMADAS structural system offers many error correction based algorithms, based on strategies for robust digital computation, and offers scalability

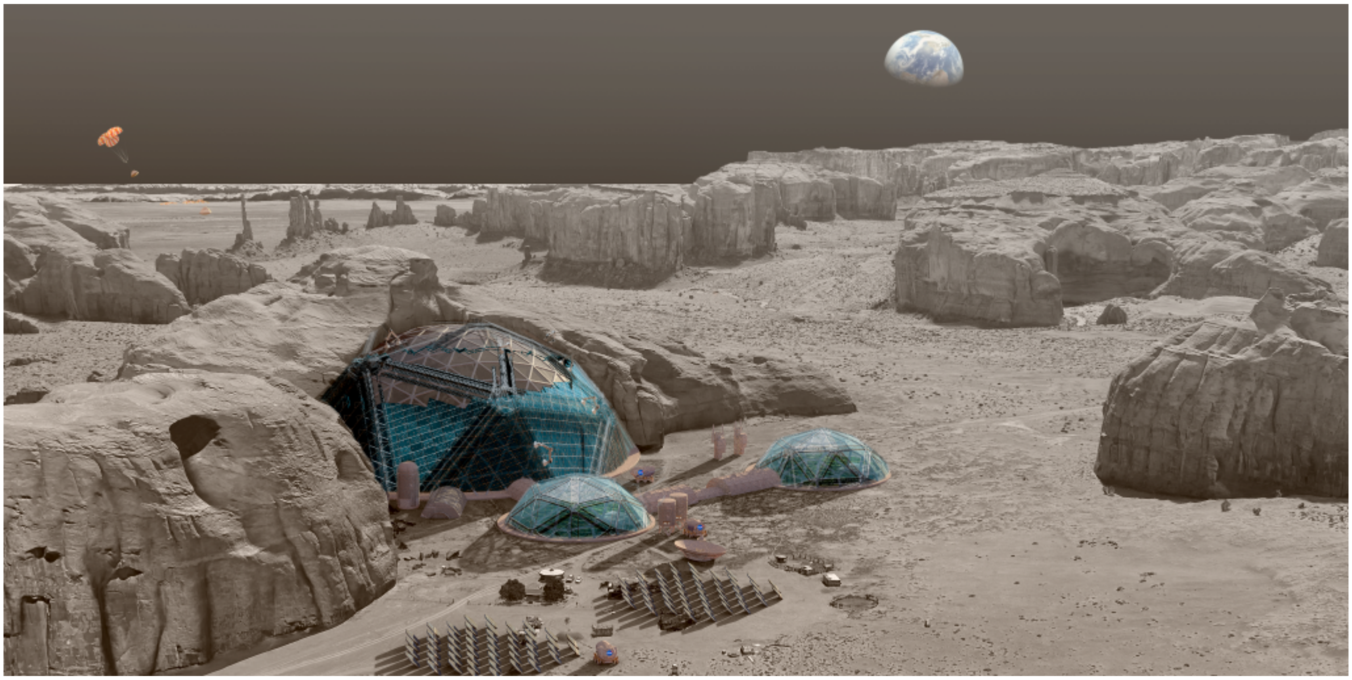

Figure 1. **Concept art of lunar base built using a programmable meta-material architecture**

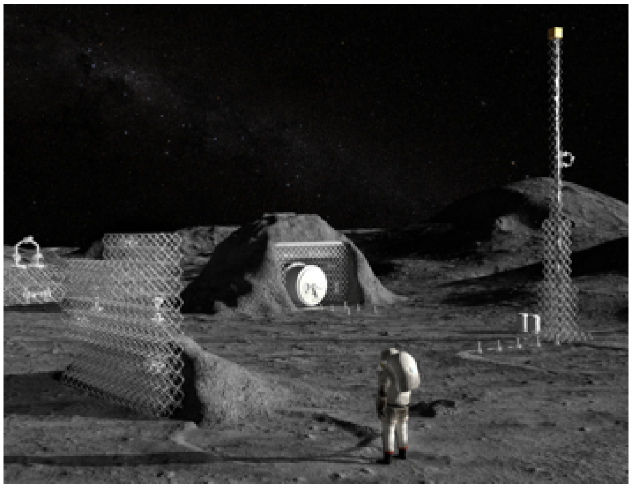

Figure 2. **Concept art of lunar infrastructure built using a programmable meta-material architecture**

and decentralized control, with rapid extensibility to diverse structural applications. We believe that this is a pathway towards full hardware autonomy.

In the current phase of autonomy development of ARMADAS, the system has been able to demonstrate L3 Domain Specific Aptitude autonomy level in each of the 4 areas. The system uses conditional automation to achieve autonomy. In terms of the sensing automation, multiple sensors including encoders, limit switches, and current sensors, are employed to have robust integrated robot configuration sensing. In diagnostic autonomy, sensors from the robot system can be used to infer the state of the structural system and assembly success and progress. For example, in the current system, placement of unit cell success can be inferred from sensors on the robot, and the success of the joining process can also be inferred from current sensing data from the joining mechanisms. Planning algorithms are implemented to translate a pre-designed structure into a build sequence, and then translated into a set of robotic motions to assemble the designed structure. Algorithms to achieve L4 have been demonstrated in the literature. Execution is at L3, fully autonomous assembly of predefined target states, but current implementation reverts to L2 autonomy when faults occur, requiring an operator to remotely resolve the anomaly.

In the next phases of development, elements of the system will work together to push automation to a higher level. We envision a system that is able to monitor system health of assembly agents, health of the structure, and be able to repair or replace robots and repair or replace structural units. As the system matures, we can leverage developments in distributed geometric algorithms to adapt assembly planning instructions to changing mission environments. As the programmable meta-material architecture becomes more ubiquitous and integrated with external payload and systems, the eco-system can be used to achieve L5 execution with fully autonomous construction capabilities with just a limited set of inputs.

5. CONCLUSION

Autonomous assembly of infrastructure is an enabling capability that will help pave the path for future explorers and help establish a persistent presence further in space. The framework proposed in this paper is envisioned to be used to assess and compare various structural assembly systems. The framework is divided into 5 levels of autonomy, with 4 dimensions to be considered at each level. They include sensing, diagnostics, planning, and execution. A system can be implemented at various levels across the 4 dimensions. The ARMADAS system, which is a programmable metamaterial assembly architecture, is assessed to be nominally operationally at L3 in this system. The jump in each level of autonomy is a significant hurdle to overcome that requires notably more effort than advancements in lower levels. There is still much to be done in the field of autonomy for assembly systems, and having a framework and understanding of the direction to work towards will help designers focus their efforts.

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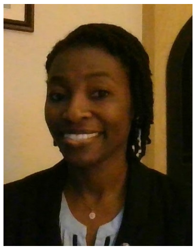

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