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Modularity for the Future in Space Robotics: a Review

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Abstract

This paper presents a review of modular and reconfigurable space robot systems intended for use in orbital and planetary applications. Modular autonomous robotic systems promise to be efficient, versatile, and resilient compared with conventional and monolithic robots, and have the potential to outperform traditional systems with a fixed morphology when carrying out tasks that require a high level of flexibility. Based on a set of fundamental concepts in modular self-reconfiguring robotics, advances in applying modular self-organizing robotics technologies to aerospace applications and space mission concepts are summarized for the purpose of identifying relevant requirements and solutions. Based on this survey, critical guidelines for the implementation of in space assembly and operation using modular autonomous robotic systems are identified.

Keywords: modular robots, modular space systems, reconfiguration, planetary exploration, orbital servicing

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1. Introduction

The concept of modular robots and systems can be traced back to the late 1970's and emerged fully in the 1980's [1]. The concept of applying a common connection mechanism to an entirely modular robot was introduced by Fukuda with the biologically-inspired CEllular roBOT (CEBOT) in the late 1980's [2]. Since then, a growing number of research groups have been actively involved in modular robotics research projects. In particular, modularity is applicable to many aspects of space robotics, a field that faces greater challenges than terrestrial technologies in terms of environmental tolerances, adaptability without human intervention, and need for autonomy and system-level robustness. Modularity as a design method provides many advantages over monolithic design:

→ Efficient modification and upgrading of capabilities through partial replacement and reconfiguration;

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→ Improved explainability of operation, knowledge within the system, and organization of the system;
→ Better quality of individual components, being developed and tested atomically;
→ Rapid adaptation of capabilities and re-purposing of atomic hardware for different tasks;
→ Flexibility of operation to support many different missions through re-configuration of modules;
→ Reduction of overall system complexity through separation of modular components;
→ Increased robustness through simplicity of redundancy and self-healing capability;
→ Reduction in costs through re-use of standard components and forward compatibility.

However, modularity of space systems may also come with disadvantages that have prevented early adoption:
→ Increased up-front costs as each component must be separately interfaced and developed for interchangeability;
→ Higher per-component complexity to support networking and re-configurability;
→ Lower efficiency for single purpose-built tasks due to modularity overheads;
→ More complexity per-module compared to traditional components;
→ unfamiliar design principles for engineers with traditional system design training;
→ Additional practical challenges such as mechanisms for re-configuration and distributed architectures;
→ Exponentially higher number of potential system configurations that must be validated to ensure function.

Proposed future directions in applying modular robotics technology to space use are directed towards mitigating these disadvantages, while leveraging the advantages toward solving fundamental challenges in distant space operations such as orbital servicing [3]. Considering modular robots [4] and other technologies in the general sense, great progress has been made towards feasibility of modular technologies in practical applications. Through miniaturization, the ultimate evolution of modular robotics could be considered to be "Programmable Matter", in which thousands or more microscopic robot modules could collaborate, reconfigure, and accomplish tasks as a single morphable physical entity. Programmable matter as a concept has been present in the literature for 15-20 years, but only limited demonstrations with larger-scale modules have been accomplished so far [5]. Despite the progress made in modular robotics research, modular robots and systems in general have not yet become commonplace in fields where they might have the greatest benefit, such as space exploration and exploitation, and the environmental and validation challenges further complicate the use of Programmable Matter and other nano-scale technologies in space applications. This is partly because these technologies are not yet widely known, but to a much greater degree it is because they are not yet well-understood in terms of the trade-offs and fundamental capabilities they offer. In this paper, we critically evaluate both the fundamental capabilities and progress in modular systems with respect to their use in space applications, and make a set of recommendations intended to guide future development in modular robotics for space applications.

The remainder of this paper is organized as follows. Following this introduction, Section 2 includes a summary of fundamental concepts and terminology for modular robotics. In Section 3, a survey and analysis of modular space systems aimed mainly at planetary exploration and orbital servicing are illustrated with respect to these metrics. Through analysis of these systems, technologies for modular space robotics systems for orbital servicing will be elaborated on in Section 4, in which an analysis of challenges and a synthesis of directions and principles for the use of modular self-organizing robotic systems for in space assembly and operation will be given in Section 5. The paper is concluded with a summary in Section 6.

2. Fundamental Concepts and Terminology

To understand both the capabilities and limitations of modular robots, we must first define the fundamental concepts that modular robots embody. This list of fundamental concepts builds on an early list by Yim [6] and following characterizations by Chennareddy et al. [7] and Liu et al. [8].

2.1. Modularity

Modularity is defined as the characteristic of being constructed of a set of standardized components which usually can be interchanged. Considering the structure of a modular system, six kinds of structural modularity were recognized by Ulrich and Tung [9]: component Swapping modularity with different components combined within a module; component sharing modularity with core module(s) shared across different systems; cut-to-fit modularity in which one or more components/modules can be variable within preset or practical limits; bus modularity where a standard structure or interface accepts different components as modules; sectional modularity where any component/module can connect directly to any other via a standard interface; and the general term mix modularity which covers any combination of the above types.

Modularity also refers to more general design methodologies that can be applied to data, software and electronic hardware as well as physical form factors. It allows systems to be simpler by virtue of using general interfaces that can be applied to any type of functional element (interoperability) and more robust by virtue of increased interchangeability (replacement). This also is greater justification for autonomy in modular systems as it enables self-configuration and adaptivity to a much greater extent than traditional monolithic or purpose-built systems, which are highly complex to modify.

In the case of modular robotics, modules themselves are the modular components and generally exhibit Mix modularity of all of the above types to some degree, although modules may not be designed with certain structural modularity features for the sake of simplicity (for example, homogeneous modular systems do not generally exhibit Cut-to-fit modularity. For brevity in this review, we simplify structural modularity into the categories of Homogeneous (only one kind of module) vs. Heterogeneous (more than one type of module), and Static (fixed configuration) vs. Dynamic (changeable configuration while operating).

2.2. Reconfigurability

Reconfigurability has been used as a nebulous term in the past for describing dynamic properties of systems. In the context of reconfigurable modular robotics we will assume it refers to "the ability to rearrange a robot's physical components" in the case of static modularity, or "the ability of the robot to rearrange its own physical components" in the case of dynamic modularity [6]. By its general nature, reconfigurability must not only refer to the physical connection of hardware modules, but also the installation and configuration of software as a result of a modified physical configuration. Typical reconfigurable modular manipulators and several unit modular systems have been well studied by many researchers. Reconfigurability can be split into categories of Morphability (structure can change its shape at will), Connectability (how components can be connected), Scalability (system invariance to total size), Communication (information transfer between modules), and Self-Sufficiency (able to operate in isolation).

2.3. Topology

There are four commonly identified topologies for modular robotic systems. In a lattice topology, modules would have to fill the exact unit multiples of some minimum unit size, and for arbitrary orientation would have to be necessarily symmetric about the axes of re-orientation. Chain topologies typically require anisotropic modules with a principal rotation axis around which the chain is flexed. Using modules with a sufficient number of connected degrees of freedom, a lattice or chain "body" can be limbed using module chains that can provide mobility of the structure. Modules can also be attached by hinged connecting members in a truss, or be entirely "free-form". While swarms of independent robots are not usually considered to be "modular", they share many of the advantages of modular systems such as reconfigurability, resilience, and manufacturability. Realistically, modules may in a heterogeneous system may have different form factors, shapes, or sizes and may or may not be symmetric in form, e.g. some modules may rotate or extend in one direction and not others. This places a requirement that the module orientation may be important to the function of the system as a whole.

2.4. Actuation

Nearly all modular robots have some form of moving themselves or structures they are attached to. This can take the form of a motor or servo that moves a connector or moves the entire module as in the case of "hinge" style modules. We will use the terms "motile" to refer to a module/cell's ability to move by itself independently or structurally as part of a host, and "mobile" to refer to the ability of modules to move as part of a mobile host structure/organism. Typically any system that can form chain or legged topologies can be mobile by actuated movement of these topologies, while motility requires higher complexity of individual modules and is less common, but enables unassisted dynamic reconfiguration.

2.5. Resilience

Modularity usually implies highly redundant systems since many interchangeable modules are typically available, although this may not always be true of heterogeneous systems. Reconfigurability adds the characteristic that the system can incorporate self-repairability using redundant modules. Systems may also be resilient though morphability and change shape if needed. These two characteristics combine to produce robustness, an essential feature of space robotic systems. Redundancy alone does not necessarily increase robustness as adding redundant components also adds more components that can fail. There are two properties which mitigate against this. First, modules can each be made very simple in design which usually results in a higher robustness per module. Second, typically each module in a system has a limited effect on the overall performance; Thus the failure of one module is not catastrophic, and failures result in only a gradual reduction of capability. Resilience is also necessary in the reconfiguration process itself, particularly for large numbers of modules. Planning algorithms must avoid collisions, impossible configurations, and paradoxical reconfiguration sequences.

2.6. Manufacturability

Modularity is often cited as a facilitator for manufacturing and assembly, with large space structures such as the International Space Station traditionally being built and launched as interconnected physical “modules”. Shared with reconfigurability is the capability for self-assembly which usually requires some form of motility in the case of a robotic system. Reducing the number of functions for individual modules in a system increases manufacturability, making them easier and cheaper to build despite the overheads of modularity and interconnection. Breaking down large systems into separate and simpler modules is also key to reducing complexity. Complexity is becoming a primary challenge in robotics and the use of modular design philosophies to simplify repeated design is a key benefit.

3. Review of Modular Space Systems

Some modular and reconfigurable robotic systems have been proposed for use in space exploration and exploitation, and there are many diverse terrestrial modular robotic systems used for research and development [7] [8]. However, no actual demonstration missions have been performed with modular robot technologies as of yet. We focus in this review on systems that are specifically designed for space use or intended as prototypes for future modular space robots as the most likely candidates for further development. In general, the technological maturity of modular systems for space is low due to the harsh environment tolerances and extensive qualification testing required. Modular system use in space is generally separated into the application areas of planetary exploration and orbital servicing, although the system requirements are similar in many respects such as the need for extreme environment tolerance, adaptability to faults and changing mission requirements, and autonomous operation over long distances.

3.1. Planetary Exploration

One of the main foci of modular technology is the applicability of re-useable (and expendable) Commercial Off-The-Shelf (COTS) components to large systems, and this includes planetary surface infrastructure. The purpose of modularity is to simplify space platform design by developing versatile repeating units that have a range of common features and interfaces. For maximum benefit, the modular units should be non-mission specific, allowing for commonality even between space vehicles having different mission architectures [10]. Interfacing complexity becomes the core problem of such a multi-modal system. Several potential forms of modular space robots have been proposed for planetary exploration but they are far fewer and less developed than terrestrial modular robot systems, which are generally designed for education and research.

3.1.1. Uni-Rover

This planetary rover has a main body with solar battery cell, communication devices, sample analyzer, battery chargers and tool changers that are used to equip a set of child rovers. Each child rover has a wheel for locomotion and an arm for manipulation. The main body can not move by itself - the child rovers hold the main body of the SMC rover by their manipulators and act as the active wheel of the main body, making this a bipartite modular system [11]. Each child rover can convert between locomotion mode and manipulation mode. The straight speed is 19.6cm/s. It can climb over gaps of 5cm of height. Problems remain with control of the orientation on rough terrain and the stability of manipulator motion.

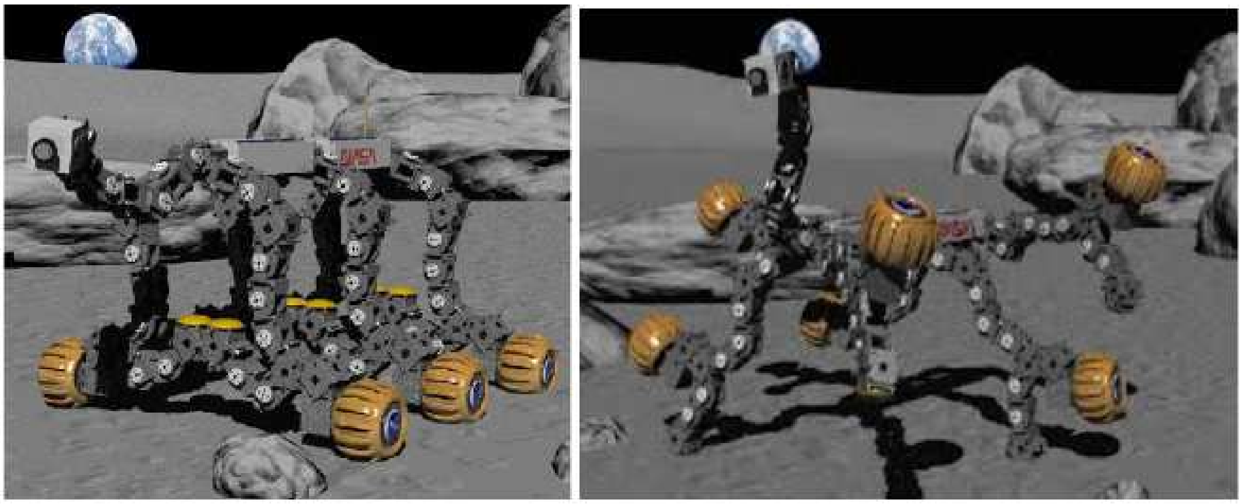

Figure 1. A modular robotic system with applications to space exploration in wheeled (left) and legged (right) configurations [12]

3.1.2. Modular Robotic System

Hancher and Hornby proposed a “Modular Robotic System” concept for exploration of other planets that is shown in Figure 1 [12]. Although still conceptual, notable points are raised regarding the need for a better understanding of the trade-offs of modular robotics for the advantages they provide in flexibility and fault-tolerance. The critical need for autonomous self-configuration and decentralized control are the main focus in their design. Most notably, they state about terrestrial modular robots: “These robots begin to flesh out the spectrum of modularity that lies between single-purpose custom-engineered hardware and pure homogeneous modularity. Unfortunately, no general-purpose heterogeneous modular architecture has yet been presented” [12], which supports other findings that have been presented above. While it is not explicitly stated to be heterogeneous, from the artist’s conceptions in Figure 1 it is inferred that the system will be heterogeneous to some degree.

3.1.3. Modular Mars Habitat Construction Concept

For the NASA 3D-Printed Habitat Challenge in 2018 ([13]), design studio Hassell and structural engineers Eckersley O’Callaghan (EOC) reached the virtual model stage of NASA’s 3D-Printed Habitat Challenge for Mars. Both companies partnered to design a shell, which could be constructed entirely by autonomous robots using Mars’ natural regolith, to protect the astronauts from the radiation, as well as micrometeorite strikes. In particular, the creation of the habitats used modular robots as pictured in Figure 2 to increase adaptability and autonomous capabilities. Although this concept did not reach the final stage of actual construction, the potential of modular robots for planetary construction was unique in this field and has great potential. Again, from the artist’s conceptions in Figure 2 it is inferred that the system will be heterogeneous to some degree.

3.1.4. Marsbee

Marsbee represents an example of aerial modular swarm systems for exploration. Marsbees are robotic flapping wing flyers of a bumblebee size with cicada sized wings. The Marsbees are integrated with sensors and wireless communication devices. The mobile base can act as a recharging station and main communication center. The swarm of Marsbee can significantly enhance a Mars exploration mission by: facilitating reconfigurable sensor networks; creating resilient systems; and sample or data collection using single or collaborative Marsbees [14].

3.1.5. Superbot

The Superbot robotic system (Salemi, B., Moll, M. and Shen, W. M, 2006) is focused on building and controlling self-reconfigurable robot modules for NASA space exploration programs that are autonomous enough to not require continuous monitoring. They can perform in both chain and lattice configurations. Power is shared through connectors and IR LEDs are used for inter-module communications. Design priorities were [15] to use sealed modules and

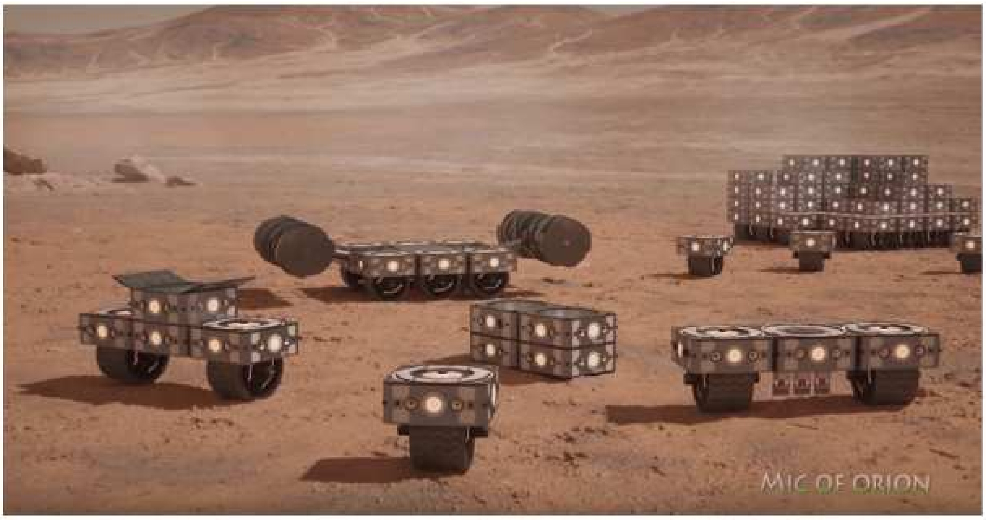

Figure 2. Hassell and Eckersley O'Callaghan Mars Habitat Concept, NASA 3D Printing Centennial Challenge (2018) [13]

Figure 3. Superbot, a single Three Degree of Freedom chain module [15]

connectors for harsh environments; retain sufficient dexterity for motility; appy sufficient torque for moving a "reasonable" number of other modules; be environment-aware through sensor arrays; manage power efficiently between adjacent modules; apply real-time, collaborative, dynamic, asynchronous, fault tolerant, scalable distributed control; and use genderless 90º symmetry connectors with integrated communications, power, single-sided disconnect, and docking sensors.

Modules have three degrees of freedom in 180º yaw, 180º pitch, and 270º roll. One half-module (the master) contains one interface, battery and controls one Degree of Freedom (DOF), and the other half-module (the slave) contains one interface and controls the roll DOF plus another DOF. Communications with the dock faces including a transmitter and 4 IR receivers and a 3DOF accelerometer for orientation determination are through a 1MB/s SPI bus. This allows basic orientation determination of faces through intensity comparison, and distance determination through reflection timing of the interface's own IR signals. Modules charge one at a time from a single source through docking face controllers. The microcontrollers used are ATMega128s running the AvrX real-time kernel, and communications between software is done through message queues. Titanium modules and space-qualified electronics were planned for future implementations.

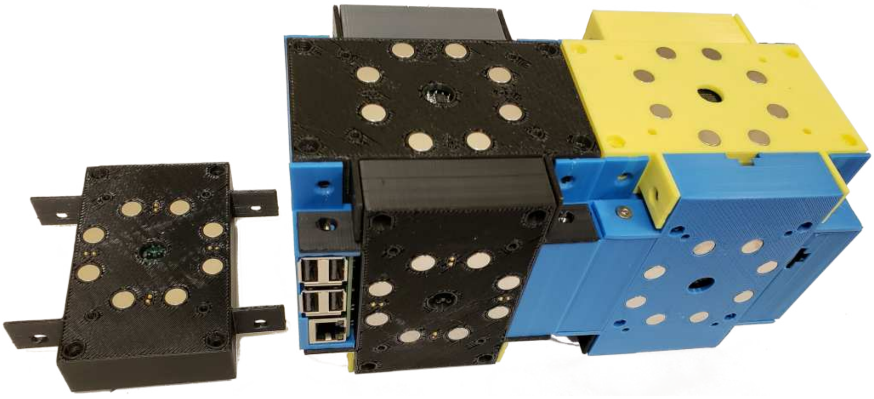

Figure 4. Sub-Modular Cube Prototypes, showing one tile (left) and two connected modules (right) [16]

3.1.6. Sub-Modular Cubes

This modular system [16] is at the time of writing under development as a means by which to develop self-aware autonomy techniques suitable for autonomous self-configuration of modular satellites such as those in the MOSAR modular satellite system. This modular system is the first in which modules are not atomic and identical units, but are themselves statically modular, being composed of 6 tiles fixed at manufacturing time at right angles, each of which can perform a different sub-modular functions. The purpose of this design is to reduce the number of modules necessary to build and also to create richer semantic information available through self-awareness for reasoning processes, in following with the large number of potential module types and specialties such as those used by MOSAR but with a common interface control unit (ICU) design. Modules are placed by a robotic arm, use magnets to aid in alignment and will be able to single-side disconnect themselves through magneto-mechanical actuation. The main advantages of this "sub-modular" approach is future-proofing by adding tiles to perform any function without module re-design, and economies of scale in construction, so that a broad diversity of modules can be created cost-effectively from relatively few tiles (Figure 21). Some tiles will feature a motorized connector and provide rotation so that dynamic movable structures can be created. The systems on each tile are also of suitable form factor to be re-used in other modular robotic research systems.

The focus of the Sub-Modular Cube system currently under development is to address these significant design features that have not been addressed in previous modular robotic systems [16]: specialization of modules like cells in a certain function but unique from other specialized types of modules through different tile selections; autonomous reconfiguration of a heterogeneous group of modules and connectors while satisfying different requirements for location, orientation, actuation, and connectivity; sufficiently high processing power (e.g. Xilinx Zynq, NVidia Jetson microcontrollers) and speed/diversity of communications (100 Mbit/s Ethernet and Infrared) that state of the art robotic autonomy can be implemented with minimal restriction; conformance to the popular PC/104 size 10cm footprint and 1U CubeSat form factor standard for space use, including planar surfaces without protrusions allowing modules to tessellate cleanly on any surface; and simplification of design and operation to the level at which it would be feasible and inexpensive to manufacture in large numbers.

3.2. On-Orbit Servicing

The concept of on-orbit service of spacecraft can be traced back to the 1960s. The development of the Space Shuttle program made on-orbit servicing possible for spacecraft such as the Hubble Space Telescope. NASA's International Space Station Commercial Resupply Services programme, ESA's RemoveDEBRIS mission, DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) partnership, and the Mission Extension Vehicles (MEV) represent the state of on-orbit servicing technologies in the present [17], but all are designed to service traditional spacecraft that do not incorporate dynamic modularity. For large-scale complex spacecraft such as a large space station, it is very hard to launch the whole body in one mission. Therefore, the system must be divided into several parts to be launched into orbit in space, which directly leverages modular concepts as these "modules" must interconnect to form a complete system. Space manipulators that can undertake multiple tasks are the most important operating tools in assembling

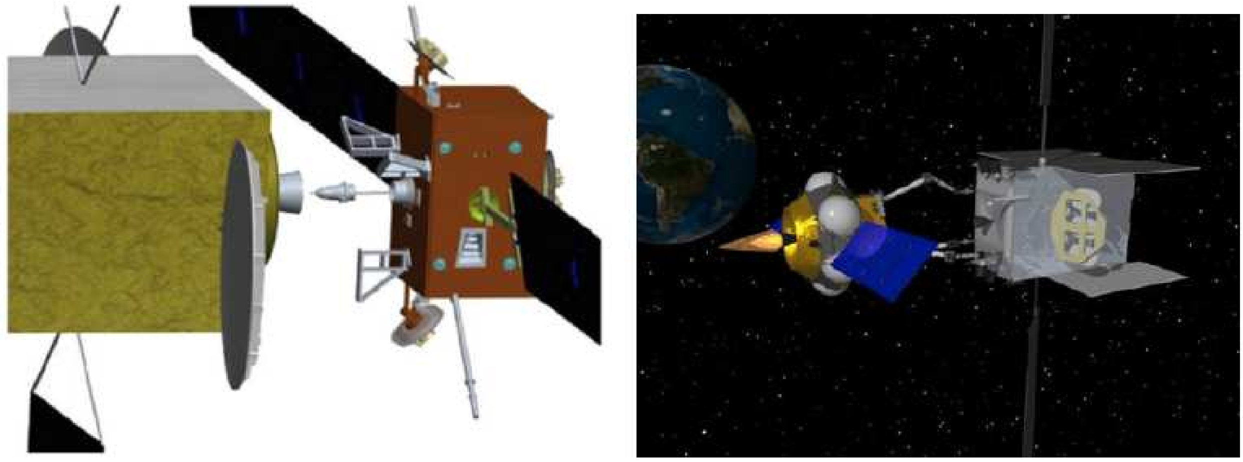

Figure 5. Servicing Spacecraft SMART-OLEV (Left) [18] and SUMO (right) [19]

and maintaining the space station. Because of the launch costs, the weight and volume of space equipment must be strictly controlled, placing limitations on the overheads that can be imposed by modular technology. A concept of using remote manipulators as the assembling tools for on-orbit services is envisioned so that astronauts only need to carry a certain number of modules to space and then assemble them into multiple modular robots to fulfill specific on-orbit assembly tasks. The advantages of modular reconfigurability with respect to adaptability and self-repair are similar to those on planetary missions. However, in most cases orbital operations also need to consider increased difficulty of capture and connection between modules due to the danger of zero-gravity collision/rebound scenarios and the additional interfacing requirement of controlled thermal transfer between modules.

3.2.1. *SMART-OLEV and SUMO*

In Figure 5, two concepts for orbital servicing satellites “SMART-OLEV” [18] and “SUMO” [19] are shown. SMART-OLEV was developed by Orbital Satellite Service Limited and once planned for launch in 2010. The satellite masses approximately 300kg with thrusters. SUMO is the “Spacecraft for the Universal Modification of Orbits”, intended to demonstrate the integration of machine vision, robotics, mechanisms, and autonomous control algorithms to accomplish autonomous rendezvous and grapple of a variety of interfaces traceable to future spacecraft servicing operations. Although these are not designed as “modular” missions, they represent a baseline for comparison with modular systems for orbital servicing and have explored the valuable concept of interoperability of replacement modules for spacecraft, and between spacecraft and servicer for autonomous operation.

3.2.2. *iBoss*

The iBoss programme supported by DLR has been focused for several years on structural design, operating components, and a universal mechanical, power, data, and thermal interface for modular spacecraft (shown in Figure 6). A parent company has been spun out to manage development and currently, stage 3 is underway to build more intelligent blocks and extend to the potential applications of on-orbit servicing [20]. It follows the conventions of traditional modular robotics in that each module element is cubic in shape with a side length of 40cm that can meet the installation requirements of most kinds of instruments for spacecraft. iBoss uses a a graphical user interface with a simulation and computer aided synthesis and validation process for facilitating modular reconfiguration with human oversight [56].

3.2.3. *MOSAR*

MOdular Satellite Assembly and Reconfiguration (MOSAR) [21] is a Space Robotics SRC project that is at the time of writing, developing modular satellite systems for in-space servicing (Figure 7). A set of re-useable heterogenous spacecraft modules are aimed at being a global ecosystem of interoperable components, with each dedicated to a specific function such as control, power, thermal management, or sensors. Standardized robotic interfaces are used

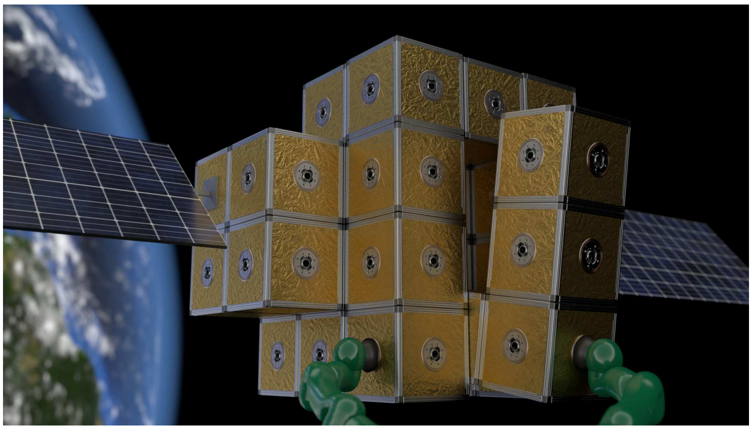

Figure 6. iBOSS Modular Satellite Concept [20]

to provide mechanical connection, data communications, power, and thermal transfer. A simulation is used to plan reconfiguration, and modules are captured, manipulated, and positioned with a symmetric robotic manipulator that "walks" over the modules with communications and power provided by the structure itself through the interconnections. Once assembled by the mobile manipulator, the spacraft is fully functional. It is notable that MOSAR cubes form a cubic lattice at rest, but the introduction of mobile manipulators as a built-in feature for reconfiguring the cubes could make it a bipartite modular system similar to the I-Cubes modular robots.

3.2.4. The Future: Programmable Matter

It is worth considering the potential of miniaturization and superscalar distributed autonomy technologies to eventually allow modular robotic systems to form Programmable Matter "metamaterials" for use in space. If the significant challenges in environmental tolerance, power production, autonomous coordination and manufacturing are overcome, future space hardware could in theory assemble, repair, and reconstruct itself endlessly in-situ without many of the limitations and overheads of discrete modular components. To date, MEMS based modular mechanical elements on the order of 1 millimeter diameter have been tested [22] and a large-scale modular self-reconfigurable robot composed of spherical micro-robots has been proposed as a testbed for Programmable Matter [23]. In [24], fast assembly of Programmable Matter is modelled with bonds between modules represented by stiffness matrices that follow the natural modular decomposition of the system. This shows that the arrangement of two types of bonds within a Programmable Matter systems enables programming of apparent elasticity of the structure and optimization of modular structures for desired mechanical properties such as load bearing ability and robustness. One advantage of these kinds of structures is that materials created from heterogeneous entities may have properties that vary over the structure as well, including stiffness, density, Poisson's ratio, thermal expansion coefficient, and friction coefficients. An efficient computation engine for simulation of the statics, dynamics, and nonlinear deformation of heterogeneous soft bodies in 2D and 3D is presented in [25]. Simulation is efficient enough that objects with thousands of degrees of freedom can be simulated on a modern desktop computer. If Programmable Matter becomes physically feasible in the future, these studies will help to open the door to truly revolutionary space systems.

3.3. Comparison of Modular System Designs for Space Use

The above modular space robotic system designs are compared in Tables 1 and 2 with respect to their use of fundamental concepts discussed. While dynamic modularity is well represented, not all are heterogenous systems, which is considered important as reconfigurable payloads are a key feature of modular spacecraft for on-orbit servicing. Also, the diversity of components required for space systems means that modules will not all be in the same form factor. Even more so than terrestrial systems, the module form factor will have to follow the stringent requirements for space systems, requiring flexibility in how modular components can be assembled. To the date of this writing, only MOSAR and iBOSS have performed terrestrial demonstrations, and dynamically modular components in space have not yet been flown.

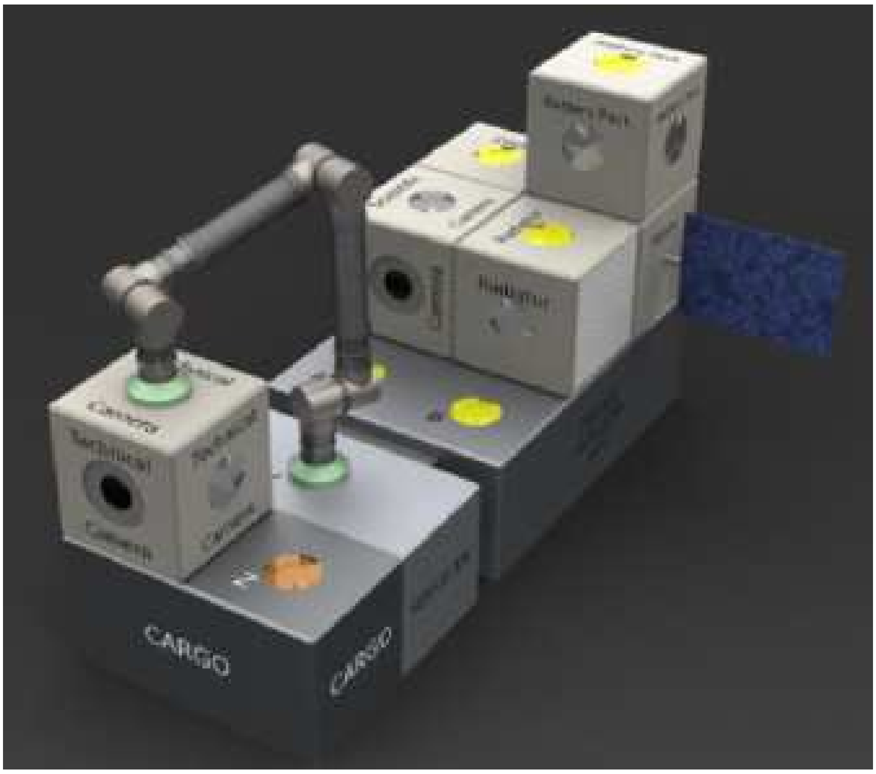

Figure 7. MOSAR Modular Satellite Concept, Space Applications Services NV/SA (https://www.h2020-mosar.eu)

Table 1. Comparison of Modular Space Systems by Fundamental Concepts

Robot	Modularity	Reconfigurability	Topology
Uni-Rover	Dynamic, Bipartite	Reconnectable	Free-form
Mod. Rob. System	Dynamic, Heterogeneous	Reconnectable,Rot.Morphable	3D Cubic Hybrid
Modular Hab. Const.	Dynamic, Heterogeneous	Reconnectable	3D Cubic Lattice
Marsbee	Dynamic, Homogeneous	Free-flying	Swarm
Superbot	Dynamic, Homogeneous	Reconnectable,Rot.Morphable	Double-Cube Chain
Sub-Mod. Cubes	Dynamic, Heterogeneous	Reconnectable	3D Cubic Lattice
SMART-OLEV/SUMO	Heterogeneous	Reconnectable	Single Connection
iBoss	Dynamic, Heterogeneous	Reconnectable	3D Cubic Lattice
MOSAR	Dynamic, Heterogeneous	Reconnectable	3D Cubic Lattice

Table 2. Comparison of Modular Space Systems by Fundamental Concepts (cont'd) (S-A: self-assembly; C-M: common modules)

Robot	Mobility	Resilience	Manufacturability
Uni-Rover	Mobile, Motile, sub-rovers only	Self-Repair by sub-rovers	Self-Assembly
Mod. Rob. System	Structurally Motile, Mobile	Robust, Redundant, Rep.	S-A, C-M
Mod. Hab. Const.	Motile, Mobile	Redundant, Repairable	S-A, C-M
Marsbee	Motile	Redundant	C-M (swarm)
Superbot	Motile by Manipulator	Redundancy, repairability	S-A, C-M
Sub-Mod. Cubes	Motile by Manipulator	Robust, Redund., Repair.	S-A, C-M, by tiles
SMART-OLEV/SUMO	Motile by Thruster	Repairable	Self-Docking
iBoss	Motile by Manipulator	Redundant, Repairable	S-A, C-M, by conn's
MOSAR	Motile by Mobile Manipulator	Redundant, Repairable	S-A,C-M, parts/conn's

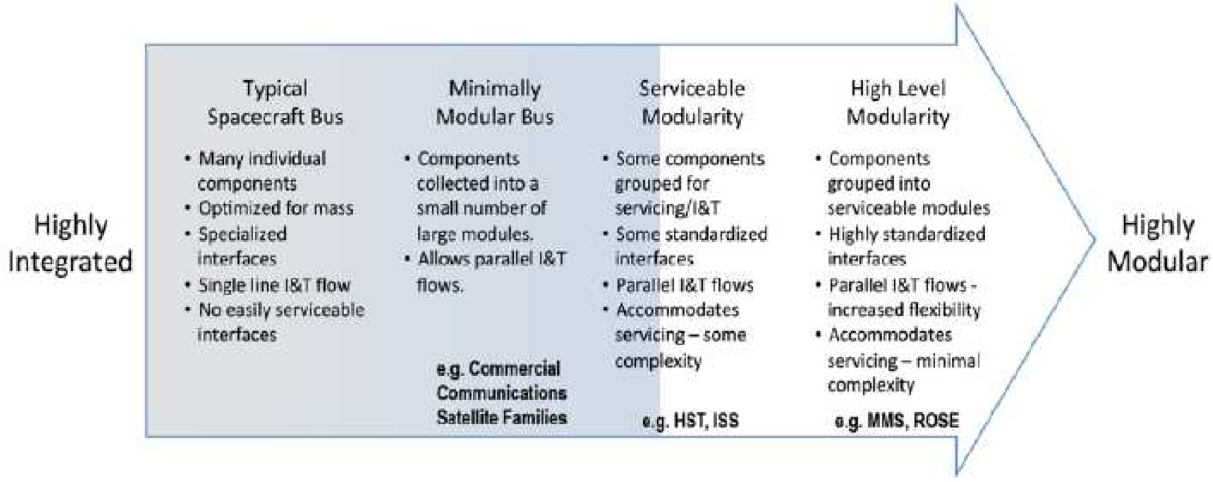

Figure 8. Modular Spectrum of Spacecraft [26]

4. Technology Considerations for Modular Space Robotics Systems

There are a variety of tasks that robots can do in space including manipulation (servicing in space), surface mobility (planetary exploration) and robotic colonies (preparatory for human colonies). They can perform simple tasks in place of humans such as scientific experiments and testing, and also work alongside humans as assistants. Due to economic and competitive pressures, the space community is now considering open architectures, digital data and engineering, deep analytics and trades, and automatic processes to build affordable, adaptable and flexible platforms. Figure 8 shows the modular spectrum of spacecraft divided at the present level of technological development in which we currently have only a degree of serviceable modularity [26], and a considerable distance to go to encompass high-level modularity of all components. It has been estimated that fully validating an autonomously self-configuring modular avionics system could take up to a decade [27]. However, it is evident that this shift must eventually occur to enable continuing improvements in design, construction, and autonomous operation. At the current pace it is estimated that ISA (in space assembly) and ISM (in space manufacturing) will be achieved within several decades. To fully exploit the benefits of modularity at this time, it will be necessary to consider modularity in all aspects of the system, including hardware, control, and software design.

4.1. Mechanical Hardware

4.1.1. Structural Topologies

Modular and reconfigurable robot units are generally considered to be constructed of repeated, regularly shaped modules and should be easy packed into a given space and can be arranged into different forms and perform a wide variety of tasks. Such systems might be a large redundant system and may be more robust. However as the number of modules increase, the possibility of each module failing also increases. The system will generally require control for different basic locomotion modes and manipulation abilities and must have a higher level of autonomy than conventional missions due to this extra complexity. The automatic adaptability of such a system usually is an open issue. The system also should be able to change with environmental conditions and to self-repair.

Systems may have varying degrees of unit-modularity, but there should be a fundamental “minimum unit” that makes up a system, which can be built on for more complex modules. For space use, there are also critical requirements such as compactness and lightness (the cost of sending equipment into space is proportional to its size and weight), and the “minimum unit” should have as few overheads as possible, as well as fundamental robustness (missions often have only one attempt to succeed) and versatility and adaptability (the environments are inherently unknown).

Chain-type self-reconfigurable robotic systems are made up of linear, looped, or branched chains of homogeneous or heterogeneous modules. This class of self-reconfigurable robots are able to separate locomotion from reconfiguration and for locomotion and manipulation these robots do not require continuous self-reconfiguration. This makes chain-type topologies uniquely suited to planetary operation, while in orbit there is little advantage to this topology unless it forms manipulators that are stabilized on a much larger platform.

Lattice-based self-reconfigurable robots consist of a set of modules that can only attach to other modules in discrete locations on a lattice. They require continuous self-reconfiguration for locomotion and manipulation, but for zero-gravity environments in which satellites and spacecraft operate there is little need for these features. Simplicity can be achieved by maneuvering solid lattice structures into position with thrusters and reaction wheels rather than altering the structure. If modular thrusters are technologically feasible, arms may be subsumed by detaching groups of modules that operate as a free-flying manipulator.

In addition to this, a critical consideration is that the assumption of repeated, regularly shaped modules is not necessarily realistic for space hardware. Space-qualified mechanical and electrical components are built to exacting standards and limited by technological constraints. As a result, their shape, size, and connectivity cannot be standardized to a modular form factor in many cases. Despite this, modular technologies are considered to be of great benefit to space hardware due to the benefits of interoperability, reconfigurability/deployability, and structural simplicity even if homogeneous form factors cannot be applied.

4.1.2. Actuation and Locomotion

There are only a few fundamental types of actuators used in existing modular systems, most often one degree of freedom per module but in some cases two degrees of freedom. Modular robotic systems typically use many more actuators than conventional robots by virtue of having many redundant modules. Motors, shape memory alloys (SMA), and other actuators used in space systems are very mature and can be used for these applications. However, the more actuators are used, the higher chance one will fail, consistent with probabilistic failure risk analysis, and it is important to use the redundancy of modular systems to offset this risk, and to apply fault tolerance by reconfiguration of locomotion modes and physical structure. Provision of fault tolerance can significantly increase the reliability of modular robots, allowing them to change their connective structure to assume different shapes that have different capabilities even when some modules may have failed.

There are two types of modular robot locomotion. One type is a repeating configuration change (for example, individually sending a module from the tail of the module structure the the head), Another is whole body locomotion, such as walking and crawling. A re-configurable robot would be able to reconfigure itself to use different modes of locomotion to adapt to different terrains, which is an essential feature for planetary exploration in complex and uncertain environments. This kind of sustainable planetary locomotion has three components: moving some incremental straight line distance; turning and or translating in multiple directions; path planning and navigation. Depending on the design of the robot, it is critical to use control algorithms that will result in efficient and safe movement over the desired terrain.

A variety of control algorithms have been used in modular robots for these tasks, including digital hormone control, sinusoidal controllers, central pattern generators (CPGs), layered control, and others that are morphology-dependent [28]. One planning methodology designed for both shape shifting and locomotion of cubic topology modular robots divided modules into two groups: fixed ones which build a rigid porous frame, and mobile ones which then “flow” through the frame, which is more efficient than common surface-flow approaches and could also be applied to other topologies and classes of modular robots [29]. Other techniques focus on “Collective Actuation”, or ensemble movements of many modules to achieve forces and movements larger than those that individual modules can achieve. Actuator capacity and range are usually fixed for a given module design, but in [30] they were made interchangeable by algorithm design and ensemble topology, allowing complex and large scale structures to bend and implement joints and actuators for larger structures. A new class of modular robotic structures was proposed in [31] to produce forces which scale with the number of modules using the concept of a spherical catom and a new connection type which is relatively strong but static.

For orbital applications, locomotion is typically considered unnecessary but modular systems need to take into account structural mobility for moving modules around the outside of larger structures without the need for thrusters, and the associated conservation of momentum that will cause a large structure to rotate or translate in space whenever a mass attached to it is moved in zero gravity.

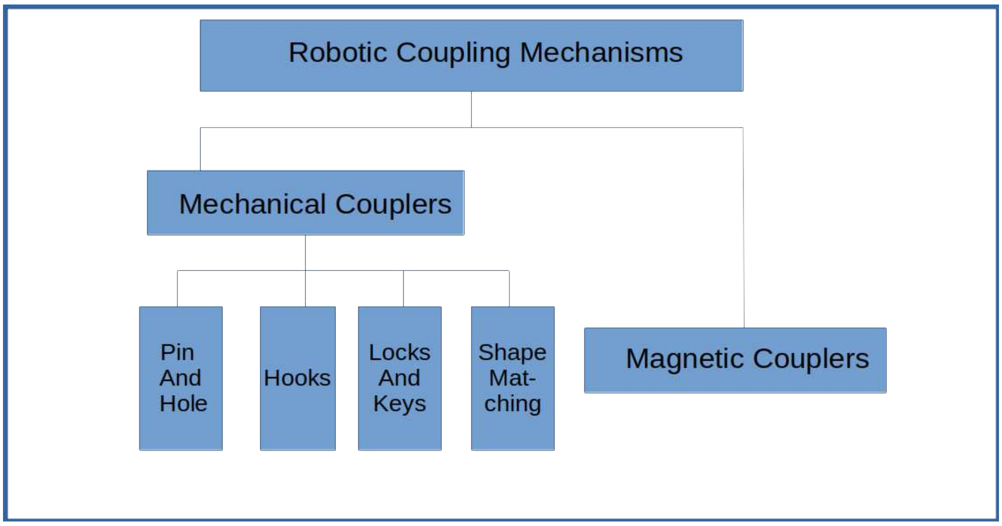

Figure 9. Classification scheme of coupling mechanisms for modular robots [32]

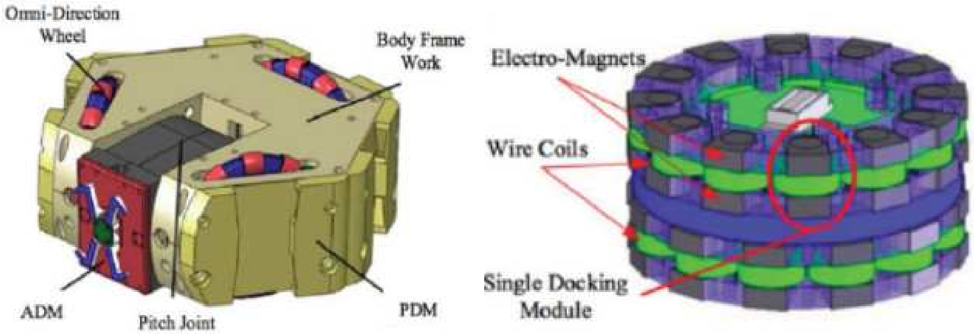

Figure 10. Trimobot platform and coupling mechanism using hook coupling mechanisms [33] (left); a Catmos module with magnetic coupling mechanisms [34] (right).

4.1.3. Docking and Coupling

Modular connection is also a significant challenge for any dynamically reconfigurable modular system. The precision by which a module can sense its relative location and the accuracy by which a module can be positioned by robotic means must determine the tolerance of the connector that mechanically, electrically, and optically interfaces two modules. Some form of self-alignment is necessary through alignment mandrels or magnetic clips.

Coupling Mechanisms used in Modular Robots: A wide variety of coupling and docking mechanisms have been used in the robotic systems surveyed here. These have been classified on the basis of mechanism [32] as reproduced in Figure 9.

The two main classes of couplers are mechanical coupling and magnetic coupling methods. Examples are shown in Figure 10. It is important to realize that mechanical coupling and magnetic coupling are not mutually exclusive, and can be used in concert to high effect. For example, magnets are highly effective for initial alignment, while mechanical coupling can be used after alignment to achieve a more rigid connection. For space use, mechanical coupling is required in nearly all cases. Magnetic coupling may be useful in planetary environments, but in most orbital scenarios magnets are not an option as they will interact with planetary magnetic fields to produce unwanted torque on a spacecraft.

Modular couplings as already stated need to be universal and interoperable in modular robotic systems. For space use, the consequence is that modular connections have very challenging requirements for combining many functions

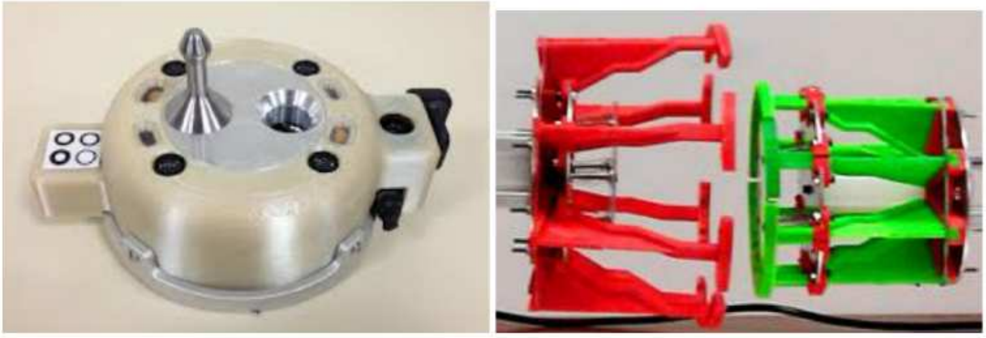

Figure 11. SPHERES Docking port (left) and CISAS G Colombo Semi-androgynous small satellite docking Interface(right) [35]

into a single unit. Robust and reversible coupling mechanisms are particularly important to the field of modular robotics due to the complexities of coupling robots in physical movement. Considerable work on connector design has been done and several challenges still exist in terms of the rigidity and overall reliability of the connections. Figure 11 shows some examples of small satellite docking interfaces [35].

Considering both the requirements for modular robots in general and the requirements for use in planetary and orbital applications, the list of desirable features for a modular connector for space systems include the following [28] [36]:

1. Capacity to transfer mechanical forces (the fundamental requirement for most connectors)
2. Capacity to transfer power
3. Capacity to transfer data
4. Capacity to transfer heat (thermal transfer)
5. Capacity to transfer fuel (if needed in some situations)
6. Active Latching and unlatching through actuators
7. Passive docking/capture to simplify zero-gravity rendezvous timing
8. Genderless (hermaphroditic) connection
9. Multiple orientations of attachment (radial symmetry)
10. Single-sided disconnect (SSD) as a fail-safe in case of failure of one module
11. Structural rigidity
12. Tolerance to mis-alignment when docking
13. Redundancy of function for greater reliability
14. Tracking features for autonomous docking
15. Re-useability of the connector itself

As a result of this extensive set of requirements, the universal connector is in many cases the most complex and critical part of a modular space robotic system. No single modular connector has been able to satisfy all these requirements simultaneously, nor likely will be due to cost and complexity constraints, but trade-offs must be made in such a way as to suit the requirements of the modular system. The geometry and features of modular connectors produce very different functionality of modular connectors in terms of the fundamental concepts of modularity, as well as the requirements of space systems. Accordingly, the most promising "universal" connectors now are designed with the ability to have variable functionality depending on the specific connector and the module it is attached to such as thermal transfer, without compromising compatibility with more basic functionality such as simple mechanical connection. This cross-compatibility with different levels of functionality can be considered a necessary feature of modular connectors for space.

Table 3 shows a matrix comparing the various modular robotic systems with respect to the features of their connectors. Headings correspond to the feature numbers listed above. It is also worth noting that there is much less value to a "universal" connector that is not used in cases where different trade-offs are required, so it is imperative to choose a connector that has the greatest cross-compatibility and future-proofing possible.

Table 3. Comparison of Modular Space Systems vs Selected Connector Features, numbered as above with legend: Y-yes, has the feature; N-no, does not have the feature; X:feature is not applicable

Robot	2	3	11	4	9	6
Uni-Rover	N	N	Y	N	N	Y
Modular Robotic System	Y	Y	N	N	N	N
Modular Habitat Const.	Y	Y	Y	Y	Y	N
Marsbee	X	X	X	X	X	X
Superbot	N	Y	Y	N	Y	Y
Sub-Mod. Cubes	Y	Y	Y	N	Y	Y
SMART./SUMO	Y	Y	N	N	N	X
iBoss	Y	Y	Y	N	Y	Y
MOSAR	Y	Y	Y	Y	Y	Y

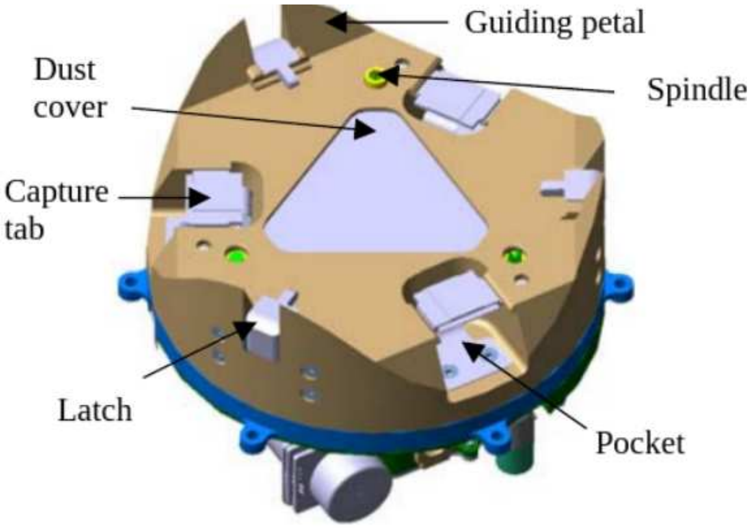

Figure 12. SIROM connector and main parts [37]

For use in the harsh environments of orbit and other planets, modular space robotic systems have been considered in the design of new modular connectors with tolerances suitable for space conditions and autonomy.

4.1.4. Connectors for Docking and Coupling of Modular Space System

SIROM: The SIROM (Standard Interface for Robotic Manipulation of Payloads in Future Space Missions) connector was designed to provide modular connection with a variety of interfaces including power, CAN bus, and SpaceWire for both orbital and planetary applications [37], and is shown as a CAD rendering in Figure 12.

HOTDOCK: The HOTDOCK connector, with an engineering model shown in Figure 13, is an androgynous mating mechanism developed by Space Application Services NV/SA for use in modular in-orbit and planetary applications, particularly with automated control of remote manipulator arms. It is an improvement on MOSAR in terms of simplicity, flexibility, and reliability for connect and disconnect cycling under small positional or rotational errors. Specific applications include quick changes of arm end effectors and tools, including electronic and mechanical devices requiring power, data, and fluid interfaces. It also is designed with a high load coupling capacity using a compact co-radial structure for manipulation of more massive objects such as spacecraft modules and payloads. It is also hermetically sealed, self-aligning, and provides single-sided disconnect capability [38].

In both of these connector designs, a major advantage is their scalability for heterogeneous modular systems. Not all modules will require certain complex interfaces (e.g. thermal transfer or fuel transfer), and the connectors are designed such that a variable number of interface options can be implemented on each connector, from inexpensive

Figure 13. HOTDOCK connector (https://www.spaceapplications.com/products/hotdock 2020) [38]

"dummy" connectors with no actuated latching or interfacing, to complex connectors with every type of interface. A key consideration is that the "dummy" connectors still have to mate physically with more complex connectors.

4.2. Electronic Hardware

The main characteristics of the modular robot control systems are directly derived from the characteristics of self-reconfigurable robots. The following characteristics have been stressed in the literature: Robustness - the control algorithm should be robust to module failure and communication errors; Adaptability - the control system should exploit sensor input to adapt the robot to the environment; Versatility - the control system should enable the robot to perform many different tasks; Scale Extensibility - the control system should allow for changes in the number of modules; and Scalability - the control system should be able to handle systems consisting of many modules.

4.2.1. Optimization of Modular Systems for Electronic Hardware

Control systems are mainly used for movement in a planetary scenario, or self-reconfiguration in an orbital scenario. Existing control systems can be divided into two main categories: centralized systems and distributed systems. Nearly all space hardware has been based on highly-reliable and redundant centralized system design such as the use of triple modular redundancy (TMR). However, modular systems are naturally suited to be naturally distributed and redundant, and changing the way that systems are designed from a centralized-redundant system to a decentralized-redundant system will greatly simplify and lower the cost of individual components that will regardless be duplicated throughout a modular system as there is no need for TMR if the system is fully modular and decentralized. While this increases the complexity of system design by some degree, it is critical for enabling high modularity that is predicted as the future of space systems, and also facilitates the use of decentralized systems in other domains such as Integrated Modular Avionics.

In a decentralized and reconfigurable system, configuration representation methods include the use of encoding, assembly incidence matrices, directed graphs, and a configuration matrix for managing the configuration of multiple modules. The configuration design that is used will need to be optimized and should satisfy performance tests before being selected as the target configuration This kind of optimization is currently done on the ground, but could be made autonomous with some advances in safety-assured autonomy for reconfigurable systems. Brute-force optimization, simulated annealing algorithms, genetic algorithm and other well-known methods are used for configuration of modular robots and can potentially be used in space with further work in this area. There is no currently no "general" algorithm for self-reconfiguration planning because the particular module structure designs will lead to different planning results. Thus, the algorithm needs to be chosen to suit the particular system.

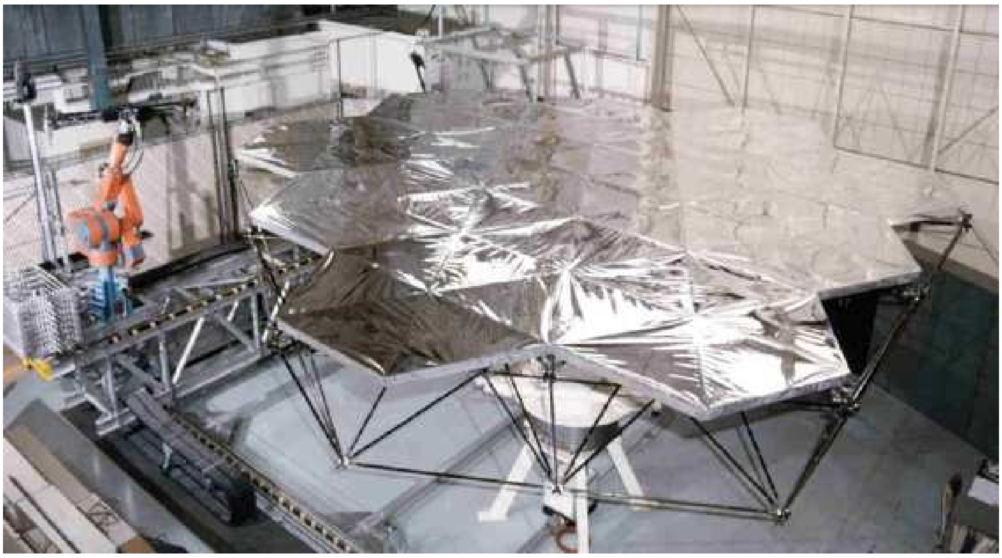

Figure 14. NASA Robotically Assembled Tetrahedral Truss Structure with Panels [39]

The evaluation index that is used to determine the optimal configuration will also need to combine several factors as a form of online multi-disciplinary optimization (MDO) including but not limited to: accessibility, operability, reconfigurability, mobility, obstacle/hazard avoidance, the number of modules/degree of redundancy. Progress has already been made on algorithms that are capable of autonomous self-assembly of modular elements. Figure 14 shows a truss structure assembled on a rotary motion base of 8 metres diameter using supervised autonomy in which the assembly sequence can be paused or reversed at any time.

4.2.2. Integrated Modular Avionics (IMA)

Avionics systems for aerospace vehicles, primarily aircraft but potentially also spacecraft, have evolved from the distributed digital architecture with a central system computer, to the federated digital architecture that allows multiple computers for different systems, and are now transitioning to Integrated Modular Avionics (IMA) systems [40]. The DO-297 standard provides IMA guidelines for civil aircraft, and an Open Systems Architecture (OSA) standard is a directive from the USA Department of Defence for military aircraft. These standards are essential bridges between stakeholders in the aerospace industry. The Airbus A380 usees an IMA system with ethernet-based AFDX communications between shared processing modules to facilitate standardized integration of all on-board systems between different locations, components, and industrial suppliers. The next generation of civil IMA systems are described as Advanced IMA (A-IMA) and next-generation military systems are described as A-OSA.

All IMA systems are considered to have the following characteristics [41]: Current OSA and IMA architectures have the following characteristics: Common hardware and software elements based on commercial off-the-shelf (COTS) or domain specific parts; Integration of networks, modules, and input-output devices partitioned by bandwidth, performance, safety, and security; Layered software architecture to hide hardware and applications from one another and enable code reuse and portability; Reconfiguration of applications on the modules, either static (aircraft not in use) or dynamic (in flight); An operating system and middleware environment to manage applications; Provisioned processing growth based on a notional roadmap of future functionality by subsystem; Refresh of key interfaces with bridges to legacy interfaces; Protection mechanisms to allow applications to be inserted and resources shared by criticality level; Deterministic scheduling to meet the deadlines of all applications for each viable configuration and when system is upgraded across the end-to-end distributed processing chain; Design artifacts to facilitate incremental certification of modules for initial certification and future growth.

The challenge of an IMA architecture is mapping system and subsystem level real-time, safety, and security constraints to a target architecture of a processor card or system module. Networks of over 100 processors interconnected with unified but diverse communication systems are not uncommon. At present, all fielded IMA systems are statically modular with pre-mapped redundant failover between components. Fully autonomous reconfiguration is not yet used in flight systems due to the complexity of validation and planning. Two approaches that target lower effort for self-reconfiguring "plug-fly" avionics are "model-based configuration" that removes ambiguity by storing configuration in a formal domain-specific model and applying automated checks, completions and conversions, and "automated configuration" that can generate large portions of the configuration from system architecture data and applying model transformation languages to produce architecture stubs from this data [42] [43].

4.2.3. *Fractionated Aerospace Systems*

In the field of avionics, similar trends to distributed robotics architectures are very evident. To increase reliability while minimizing complexity and retaining the advantages of a distributed architecture, Integrated Modular Avionics (IMA) architectures focus on the networking of standardized Line-Replaceable Units (LRUs) to perform a wide range of tasks in many different locations on an aircraft [44]. While static IMA networks designed and configured manually have already been successful in reducing complexity, power and mass, they do not realize the full potential of a fractionated system. The use of configuration-free "Plug-Fly" avionics [27] requires a common description of what each component's capabilities and connections are so that the system is sufficiently "self-aware" to perform this design and configuration autonomously given a set of simple rules. Fractionated architectures have a similar role in space systems, promising improved responsiveness and tolerance to uncertainty, though qualification and use of fractionated systems in space is even more difficult due to the field being costly and highly risk-averse [45]. Autonomic computing concepts have been proposed as valuable for use in space [46], but largely for reasons of risk and complexity, no large-scale missions have yet made full use of them.

Software and hardware architectures for robotics have gradually experienced a trend toward decentralization and fractionation. This is exemplified by the design of robotic middleware in recent years, which began with monolithic robotic software stacks and has evolved from server-based systems such as Player [47] through networked systems such as ROS [48] and now is focused on entirely decentralized software networks such as YARP [49]. The frequent interfacing and porting of software between these systems is testament to the value of being able to build heterogeneous systems that can interact seamlessly. Autonomic computing has been applied to the design of robots primarily as a means of fault tolerance but with the fractionation benefits of better modularity and flexibility as well (Melchior and Smart 2004). Autonomic computing has been proposed for use in underwater vehicles as a means of applying a bio-inspired methodology of robotic self-management based on the human autonomic nervous system (Insaurralde, 2013). This work has been focused entirely on designing autonomic behaviors for robots, and does not address the problems of fractionation or reconfiguration at the system level. Other experimental improvements in autonomic-style self-management such as the ROS-based RoSHA multi-robot self-healing architecture [50] have been developed. However, these self-management features are implemented as add-ons such as failure diagnosis, coordination, and re-configuration to the basic middleware and do not address the fractionation challenges in terms of underlying system design, which is ultimately necessary so that failures in the underlying middleware and communications strategy may be handled.

4.2.4. *Communications Systems*

For space use, the SpaceWire bus is the most popular modular bus for space systems and is suitable for routed communications in statically modular systems. However, it is not designed for dynamic on-line system reconfiguration, and this is a necessary feature for a modular space robotic system. SpaceWire is capable of being adapted for limited re-configurability using a form of "plug and play" implemented with its RMAP protocol [51]. However, this is not a long-term solution for dynamic systems, and the new SpaceFibre protocol provides much more flexibility with its implementation of virtual channels for dynamic routing of high-rate data. However, due to the cost and complexity of SpaceWire, only MOSAR has implemented SpaceWire as a core bus, and most modular prototypes use terrestrial technologies. Superbot used infrared transciever-based communications between modules with the stop-and-wait ARQ (Automatic Repeat reQuest) protocol [15].

Valuable lessons can be learned from the adoption of communications systems for terrestrial modular robotic systems to guide the adoption of communications strategies for modular space robotics. The most prevalent medium for modular communications is infrared, which despite its commonly low speed is robust across free space without the potential unreliability of physical connections. CAN bus is also popular due to its need for only two wires and its ease of implementation for multi-drop bus devices. Bluetooth is popular for convenience of support on devices, but for space use dedicated short-range wireless that is more similar to ZigBee may be appropriate for modules that are physically separated. Infrared and other free-space optical links hold scalability advantages if many modules are simultaneously transmitting close together. The IBOSS connector makes use of a free-space optical coupling for short-distance high-rate communications across the isolated connector, and it is this kind of application in which SpaceFibre could ultimately be most valuable due to its flexibility and potential reconfigurability. If SpaceFibre is adopted as the medium of choice for modular space systems in future it would also be beneficial to have analogous protocols and routing systems available on less expensive wired hardware for use on lower-specification space devices such as CubeSata, and for prototyping and testing at lower cost. Work is currently underway to use an Ethernet physical layer for low-cost transport of the SpaceFibre protocol and enable a broader adoption of the protocol in the process [52].

4.3. Software for Modular Space Systems

4.3.1. System Design

Due to the need to build a distributed system to exploit the value of modularity, significant challenges still persist with all aspects of hardware, software and experimental validation in mission-critical modular robotics. The simultaneous needs for high safety and reliability assurance, and autonomous operation with fault tolerant adaptability have not been fully addressed yet. Full autonomy for large assemblies of space hardware modules cannot be achieved under the current requirements for safe space qualification, and new approaches are needed to enable self-managing of modular robots and satellites. These approaches will likely be driven by the synthesis of complex designs into verifiable models using high-level design languages such as AADL, SysML, and SDL to build a degree of self-awareness into autonomous systems, and then the application of formal methods for validation of these models during autonomous operation [53] [54]. Formal testing of a system using semantic system modelling and requirements capture such as in the ASSERT toolchain [55] is an important part of the simulation step for ensuring software and hardware performance. While formal modelling is still a challenge for robotic systems of conventional complexity, progress is being made in this area for the benefit of modular space hardware.

4.3.2. Autonomic Elements

There is a great body of interest in modular architectures for autonomous applications, in which software tasks can be ideally spread arbitrarily across a distributed network of similar hardware processors for parallelism and redundancy. At the same time, the complexity of the resulting system must be somehow managed to prevent the number of potential configurations and interactions from becoming impractically difficult to understand and predict. One of the first steps toward fractionated architectures in general computing was made with the definition of Autonomic Computing. The concept of Autonomic Computing is central to dealing with complexity in large-scale systems and has been conceptually present for over 15 years [57], mainly focused on self-management of complex Information Technology systems such as corporate networks as addressed in IBM papers [58] [59].

As envisioned, an autonomic system must "know itself" sufficiently well to embody four characteristics:

1. Self-configuration: systems can install functions and set parameters following high-level rules;
2. Self-optimization: parameters can be tuned and performance improved autonomously over time;
3. Self-healing: localized software and hardware problems can be detected and repaired/bypassed;
4. Self-protection: large cascade failures or malicious attacks can be quickly identified and defended against.

Being features of multiple, networked components, these aspects drive the design and behaviour of so-called Autonomic Elements, which function as fractionated components capable of managing themselves and their tasks within the system. In the broad context of autonomic systems, four additional characteristics are often cited [57]:

5. Self-awareness: the system is aware of its state, capabilities, and topology;
6. Context-awareness: the system is aware of its configuration, its goals, and its environment;
7. Open: localized software and hardware problems can be detected and repaired/bypassed;
8. Anticipatory: large cascade failures or malicious attacks can be quickly identified and defended against

Autonomic elements form a well established framework with which to design modular self-managing systems in software.

4.3.3. Complexity of Modular Space System Software

The key to enabling autonomous operation of modular systems for the space industry is the management of software complexity. Commercial software source code has doubled roughly every 4 years since the 1990s (Software Engineering Institute, Carnegie Mellon University). The amount of effort in terms of workstation power times personnel required to maintain and update this code base, much less build new software based on it, has commensurately increased by 100 times since the 1990s [60]. The avionics software code base specifically grows by roughly 400% every 2 years and correcting errors in already-deployed flight code costs approximately 900 times more than correcting it in early code [61]. This illustrates that it is essential for commercial competitiveness to both design a slim, efficient software code base with emphasis on simplicity and to be able to deterministically predict and isolate potential faults and errors in advance of flight implementation. Reduction of complexity also facilitates remote manufacturing of space robots, not yet feasible but potentially valuable. One of the most compelling reasons for modularity of space systems is in support of the goal of remote manufacturability. Manufacturing of systems using in-situ materials on planets and raw/recycled materials in orbit is a challenging but extremely rewarding capability in terms of reducing resources for launches, mass in transit from Earth, and extending mission durations. This will require simplicity of components, easy interoperability, and self-assembly capabilities, which are all provided as part of module-level simplicity.

4.3.4. Reconfiguration Planning and Execution

For large and especially heterogeneous modular systems, autonomous planning is essential due to the complexities of reconfiguration, but and existing platforms such as MOSAR rely on human oversight of each reconfiguration step in simulation before a planned reconfiguration sequence is sent to be executed. For metamorphic systems such as Programmable Matter, current solutions to the shape formation problem are still a long way from meeting the requirements for space use. An extensive survey of the current state of the art of self-reconfiguration algorithms and underlying models in modular robotic and self-organizing particle systems is given in [62]. One of the most established algorithms is the "MeltSortGrow" algorithm by Fitch, which decomposes the structure into a straight line, which is then sorted to order them in the order required for subsequent assembly of the goal structure [63]. However, MeltSortGrow is not distributed by design and easily scaleable to hundreds or thousands of modules due to the time and movement required to position a large number of modules for sorting before repositioning. The reconfiguration problem becomes hugely complex with a large number of modules, as discussed for the 2D case in [64]. A distributed graph-based algorithm for the modular robot SMORES was tested for a small number of modules that performsconfiguration decomposition iteratively using virtual modules and virtual connections [65]. Gradient field algorithms have also been proposed, though implementation is more complex than the above algorithms [66]. Machine learning through trial and error has also been proposed to help overcome the complexities of reconfiguration planning for space-based applications, using fitness scores to evaluate potential solutions [67]. This method is both computationally intensive and difficult to verify suitably for space use, but given the popularity of machine learning in terrestrial applications, may be considered suitable in future for space exploration.

The prediction of unsafe movements for modular structures is also an essential function of planning, particularly in mechanically-demanding planetary gravity fields. Considering the reconfiguration of Programmable Matter as a large-scale case, the simulator VisibleSim has been used to predict whether each planned reconfiguration step of a modular robot will mechanically overload the structure. This model considers intermodular connections to be beams and assumes no-sliding contact between the modules and the ground, and was physically verified in small scale using the modular robotic system "Blinky Blocks" [68]. The concept of "Cellular Automata" has also been used as a guide for reconfiguration strategies in a simulated three-dimensional modular lattice where the desired configuration was "grown" from an initial seed module that produces growth by creating a gradient in the system [69]. In all the above approaches, there is still the problem of validation against mission and technological requirements and verification of the reconfiguration solution, which will likely require human oversight at least at the high level of reconfiguration for the foreseeable future.

4.3.5. Modular Software Architectures

In addition to the advantages of modular hardware, modular software systems and architecturing tools have compelling reasons for use in space. Due to the flexibility and reprogrammability of software architectures, there is already some use of modularity in space software. NASA's CLARAty (Coupled Layer Architecture for Robotic Autonomy)

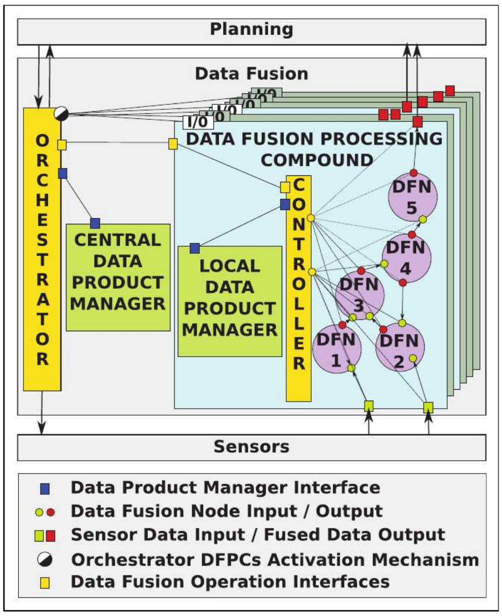

Figure 15. InFuse modular software architecture highlighting the assembly of modular DFNs into a DFPC, managed locally by a controller to produce data products that are cached in a Data Product Manager. DFPCs are centrally managed by an Orchestrator [72].

was envisioned as a robotic software framework to facilitate re-use and co-development of space robotic software components through modularity [70]. More recently, ESA has supported European Strategic Research Clusters to develop open-source software frameworks that are designed to be modular and re-useable in nature, including the European Space Robotics control and Operating System (ESROCOS) middleware [71]. One key framework that uses ESROCOS is the Common Data Fusion Framework (CDFF) created by the InFuse robotic data fusion SRC project. The CDFF reads sensor data and provides “data products” processed though sequences of Data Fusion Nodes (DFNs), each one an algorithmic step in a Data Fusion Processing Compound (DFPC) that is custom-assembled for each data product, which is then cached in local and central Data Product Managers for distribution via ESROCOS [72]. Figure 15 illustrates the structure of the CDFF. While DFPCs are statically modular and reconfigurable to an extent through parameters, they are not fully dynamically reconfigurable and distributed to reduce overheads in implementation.

4.3.6. *Distributed Software Systems*

Modular robotic systems and their fundamental concepts as discussed are a natural fit to distibuted software systems, particularly those that use autonomic elements or IMA architectures to achieve distributed operation for increased resilience, efficiency, and interoperability. Distributed systems have been researched and designed since the earliest networked computers, and as a field extends to as many application domains as computing itself, as well as being used in robotics frequently [73]. However, these systems are more complex to design than monolithic software systems due to the necessity of communications and coordination between multiple processes, which may also be located on different hardware. Focusing only on the domain of modular robotics, robotic middlewares are generally decentralized and fractionated as stated in Section 4.2.3, making them in many cases better suited to implementation on distributed software systems. New software systems such as the Drona framework for mobile robots [74] focus on making algorithms and control processes autonomous, distributed and decentralized in a safe manner, such that time desynchronization and communications faults will not impede operation. Other visions of how distributed self-managing systems have been similarly formulated to address complexity and reliability such as that of Organic Computing, which focuses on the effects of emergent behavours in massively connected self-organizing systems [75]. Another concept of computing related by the goals of system fractionability and complexity minimalization is that of Wide Computing, in which concurrent tasks are spread horizontally across a network of visible, connected elements in a peer-to-peer fashion [60]. It is expected that robotic systems, including space robots, will in future be designed as distributed and decentralized systems and the software platforms that support them will in turn be distributed in nature.

5. Discussion and Recommendations

This paper has presented a review of modular robotics, modular space systems, and their relevant technologies that will be essential for making high-level modularity widespread in space applications over the next decades as it is predicted to be [26]. A key message from this review is that modularity is not just a design, it is a methodology behind design that enables beneficial interoperability, reliability, and autonomy.

5.1. Challenges of Modularity

It is clear that modularity is not a panacea. The capabilities of modular robotic systems come at the cost of significant overheads in mass, volume, power, and complexity, that have prevented most modular robots from leaving the laboratory and achieving the maturity required to be used actively in space. To some degree, this is due to a lack of breadth in application of these systems. Previous work in terrestrial reconfigurable modular robotic systems in [7] and [8] indicates that most heterogeneous modular systems are not dynamically reconfigurable or self-repairable. The additional complexities related to autonomous self-reconfiguration of heterogeneous systems have been explored algorithmically [64] but practical application has not yet been done, partly at least due to the associated problem complexity [64]. Significant challenges also remain with the practicality of modular systems. Modular self-reconfigurable robots are in theory versatile, adaptable, robust, and cheap for their complexity compared to an equivalent monolithic robot. However, these features are usually realized to a limited degree in actual implementation [1]. Laboratory modular robots have, in contrast, historically been 1) unuseful, 2) expensive, and 3) unreliable [76], and as prototypes are nearly always homogeneous and lacking the diversity or payload space for performing useful tasks either due to design without a specific application, or due to physical modularity overheads of additional hardware. In addition, the elements of mass, reliability, and complexity that are critical to driving up costs of space systems are considered to be inherent overheads of modularity, and designers of space hardware will therefore generally eschew fully modular and reconfigurable approaches in favor of single mission-specific designs that are cheaper in the short term, particularly in the case of limited-term orbital and planetary missions that are planned to be simply abandoned.

The requirements placed on space hardware and the priorities of the space community are slowly changing, though. It is now desired to maintain a permanent presence in space, either by robots alone or in concert with human workers and explorers, which will likely in time make re-useable and modular systems more economical than single-mission designs. Servicing missions like SMART-OLEV and SUMO and new technology projects such as iBoss and MOSAR indicate that the benefits of modularity, re-useability, and reconfigurability may soon be considered to outweigh the drawbacks. This paradigm shift is necessary to allow modular reconfigurable robotic systems to fulfill their potential as noted above: costliness can be overcome by production in quantity; versatility is achieved by universal connectors such as HOTDOCK; adaptability and robustness are achieved through repeated application and design refinement. In pursuit of these advances, some guidance in application of future modular space robots.

5.2. Recommendations for the Future

The following recommendations apply the results of our review to future development of modular space robotic hardware and software, so as to maximize the value of modularity to a system and ensure it is space-worthy. Through review of modular platforms and technologies, these are the authors' recommendations for enabling maximizing benefits from the fundamental concepts of modularity presented in this paper.

Modularity: Modular systems should enable forward-thinking heterogeneity. Fully-actuated modular robotic systems are constrained by the space required to house actuators and mechanisms for mobility and actuation of joints, particularly homogeneous modular systems. This greatly limits the usefulness of these systems and increases modularity overheads as all modules must contain all functions. Making a modular system heterogeneous in both form and function allows some of the modules to contain components that would not normally fit in a module such as fuel tanks and solar panels, which in turn is facilitated by interoperability of standard connectors. For this reason, heterogeneous modular systems are considered to be an essential design consideration. In general, such systems are more future-proof for the addition of new modules and functions. Dedicated actuators can be used for positioning and movement of modules with no actuation themselves. Modules with non-standard form factors can be accommodated by ensuring that they have at least two standard connectors placed in such a way that they can be both manipulated and attached to a host structure.

Modularity: Connectors should be minimalist but maximize interoperability. As heterogeneous modules are necessary to perform different functions within a system, it is also necessary to accommodate different levels of functionality in a connector so that modules without a need for certain connectivity are not encumbered with unnecessary hardware. At minimum, both active and passive connectors are necessary for active modules to connect with passive ones that do not have space for a mechanism, but must be genderless and still require single-sided disconnect. The natural extension of this concept is that some connectors may only need a small component of a face-size connector, enabling fraction-sized modules and umbilical cables that do not require a full-sized interface. The restriction on the design of such connectors is that they must ultimately scale up and be compliant with a minimal, standard interface organization physically and electrically in any orientation, ideally with 90 degree symmetry or less so that a cube lattice is possible in three dimensions. This is also facilitated and made more robust by reducing connector counts through the use of free-space optical dynamic communication interfaces such as SpaceFibre.

Reconfigurability: Fully decentralized and self-sufficient architecture. Despite the higher effort required in design and validation, a completely decentralized control and software architecture is essential to obtaining the benefits of modular space robotic systems, as most of the “soft” advantages of modularity in general are only achieved through decentralization. The fractionation of robotics middlewares, proliferation of distributed systems and cloud data technologies, and commitments to IMA in aerospace are clear indicators that future systems will inevitably become more decentralized, and effort needs to be made to propagate these advances in the space systems field. Decentralization and the use of distributed systems is also the key to enabling both simplicity at the module level, and the flexibility to support many different configurations that were not considered in initial mission planning and system development. This decentralization should include the necessary degrees of independence to facilitate the use of autonomic elements and by extension, the capability of the system to self-manage and be robust as well as dynamic and reconfigurable.

Reconfigurability: Formal testing capability of reconfiguration using semantic system modelling. It usually requires capture. Reconfigurability creates a more critical need for formal modelling and validation of a system. Frequently, component-level testing of deployed hardware is feasible while exhaustive system-level testing in hardware is impractically complex. In many cases, a dynamically configurable “module” may incorporate statically configured elements within itself, and also may form unique structures within the form of a larger structure. This multi-level organization capability should be taken into account in modelling the system, and could help to simplify it into smaller minimum functional units for validation. Modern tools for system formal modelling, synthesis/analysis, and simulation are essential for abstracting the complexity of modular adaptive models into tractable results for Engineers to use as well as validation and verification of systems in advance of launch and deployment.

Topology: Flexible hybrid structure considering planetary and space applications. Heterogenous hybrid topologies are the most forward-thinking and practical as they can serve a variety of potential missions. Chain/limbed hybrid topologies are suitable for planetary exploration and require many redundant modular actuators, while orbital applications only require modules with basic structural motility or external manipulation methods. The same connectors and fundamental module technologies can be used for both scenarios in a heterogenous system. While free-form topologies are attractive for their flexibility and generality, the technical complications that they entail in a high-reliability modular system make them less feasible and more complex.

Actuation: Motility requirements for assembly and reconfiguration. Motility is an essential component of space modular systems given that host robots that perform assembly may not be reliable unless they themselves are modular and redundant. Self-configuration requires structural motility (and if feasible, thrusters for independent motility) in an orbital modular satellite scenario. In a planetary scenario, independent surface motility is considered essential for at least some core modules of a robotic system, to ensure that modules are not “lost” and so that core modules could at minimum aggregate with modules that do not have motility, though the less modules that are motile, the less efficient assembly will be. Flying motility opens up possibilities as in the Marsbee concept, but the overheads on higher-gravity bodies do not leave much space for payloads or mission functionality. Structural motility may require actuated degrees of freedom in each module, and robotic movement requires at least some actuated modules to serve as joints. Dynamic control algorithms may require significant effort to develop.

Resilience: Design of autonomic elements. For resilience, modules will need to survive at least for short periods of time without communications and power (e.g. when in transit by motility) and should embody the concepts of self-sufficient autonomic elements. In an autonomous system, to ensure that unexpected faults, environmental changes, or system anomalies do not have destructive results, each element of the system needs to have its own survivability measures. Self-awareness and localized adaptivity complements the distributed system by ensuring that each module can either contribute to the well-being of the system or remove/defend itself and notify the system if failures occur. Communication needs to take plug-and-play style dynamic reconfiguration of elements into account, which generally requires packet-based locally intelligent routing. Software should follow wide computing principles if possible to facilitate simplicity of design, increase modularity, and allow accessibility to distributed resources throughout the system.

Manufacturability: Minimization of complexity in construction. The diverse number of potential configurations for a self-configuring modular system means that each module and component must be as simple as possible to reduce modularity overheads and ensure that component-level validation is easy and also translates reliably to system-level validation. This also facilitates the production of many modules cheaply and/or by automated means in future missions, and implies that environmentally tolerant technologies should be applied to ensure that modular systems can function as much as possible without shielding and protection overheads. Design methodologies should seek to simplify the components of each module by leveraging the use of a distributed system of modules in which hardware-software equivalence allows reconfiguration of functionality and redundancy of functionality to other parts of the system dynamically.

Manufacturability: Leverage cost-effectiveness and economies of scale. One of the most compelling business cases for modular self-organizing robots in orbit is re-useability of components. To accomplish this while retaining the advantages of heterogeneity, space systems will have to break from the trend of modular robots to be highly complex, single types of modules and construct them from smaller, more unit testable components. This also will lead to better quality in larger runs of components, and allow modules to be less expensive and more forward-compatible and modifiable in development effort through a reduction of complexity.

6. Conclusions

In this review, we have described a set of fundamental concepts in modular robotics as Modularity, Reconfigurability, Topology, Actuation, Resilience, and Manufacturability, and in doing so shown how they benefit future space robotic systems. Currently, modular technology for space use is still in its early development stages, and careful design and integration work that takes into account management of overheads, requirements, and modular design philosophies will be needed to make it feasible for long-term use in space. It is like that high-level modularity will need to feature prominently in future space systems both in orbital and planetary applications due to the benefits of modularization of satellites and planetary robots, and many significant innovations will be needed to reach this point, which could arrive in a matter of years. Future research in this area needs to focus on modular methodologies for design, implementation, and operation of distributed, self-managing and formally modelled interoperable hardware and software in space robotic systems. Enhancing manufacturability and reducing modularity overheads and complexity can ensure that modular systems are competitive with monolithic systems from an industry viewpoint and perform at or above the levels of traditional space hardware. Ultimately we will be able to create self-managing colonies of modular robots in space and on other planets to support, complement and to assist human explorers.

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