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Steps Toward Self-Assembly of Lunar Structures from Modules of 3D-Printed In-Situ Resources

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Abstract

This paper explores the idea of 3D printing entire self-assembling robots – structure, actuators, sensors and electronics – from lunar-derivable material. Such a capability would effectively bootstrap the construction of lunar bases and other facilities from the Moon itself with the launch of minimal material from Earth. Self-assembly has long been viewed as a highly desirable capability for autonomous construction of large space and planetary structures. There are two approaches: (i) the adoption of homogeneous modular building blocks that can be constructed in large numbers and can configure themselves into an array of different configurations – the cellular approach – including self-replicating blocks; (ii) a more practical approach that defines a small set of heterogeneous modules that can act as building blocks for constructing more functionally diverse structures such as lunar bases. We have focussed on the latter but the technology presented could be readily adapted to the former. In particular, the common features of all self-assembling modules are that the modules constitute a structure housing a computer-controlled actuator internally and a reversible latching mechanism externally. We have made significant successful steps towards self-assembling systems in which the modules can be manufactured from in-situ resources. We have demonstrated a 3D printed DC electric motor in which the only components that were not 3D printed are the wire coils. We are however working on the wiring aspect and shall present the challenges in achieving this while restricting ourselves to lunar analogue technologies. Indeed, this aspect is crucial to realising the next stage of implementing 3D printed computing electronics. We have married our 3D printed motor prototype to a 3D printed trigon-type panel developed as part of the trigon self-assembling system concept. The trigon concept underlies a modular approach to self-assembling planetary structures such as bases, etc. The 3D printed motorized panel system demonstrates that the motor aspect and structural aspects of robotic self-assembling machines are amenable to 3D printing. Furthermore, motorised self-assembling systems can be leveraged from local resources. This has significant implications for self-assembling systems in space in general.
Keywords: self-assembly; in-situ resource utilization; 3D-printed electric motors; flat-pack lunar bases

1. Introduction

It is desirable that robotic systems should automatically design and build other robotic systems enabled through the versatility of 3D printing (additive manufacturing). Most effort to date has focussed on the manufacture of structures through 3D printing. One goal of robotic 3D printing is to minimise assembly by 3D printing complex electromechanical systems such as robotic machines in as few steps as possible. Self-assembling systems are composed of objects that can be reconfigured for rapid assembly. 4D-printing introduces time to the 3D printing process. Hence, in the goal of automatic design and construction of robotic systems, little attention has been paid to the automatic manufacture of motor elements – to date, stereolithographically-fabricated high tolerance 3D structures have been printed with cavities and mechanical joints for the insertion of prefabricated sensors, electronics and actuators to build a simple mobile robot [1]. These components have not been 3D printed. We have been focussing on the 3D printing of electric motors as a necessary next step in the automatic manufacture of robotic systems.

The goal of this work is to 3D print entire self-assembling robots – structure, actuators, sensors and electronics. We have demonstrated a 3D printed DC electric motor in which the only components that were not 3D printed are the wire coils and the motor shaft (which shall be printed in a prototype under development). We have married our 3D printed motor with 3D printed TRIGON panels which are part of the TRIGON self-assembling system. The 3D printed motorized panel system demonstrates that the motor aspect of robotic self-assembling machines is amenable to 3D printing.

2. 3D Printing Electric Motors

Our electric motor was partially 3D printed by fused deposition modelling using a Prusa i3 3D printer.

Rotary electric motors for general applications offer: (i) good speed/torque versus stroke tradeoff; (ii) good volumetric compaction; (iii) robustness of performance. We selected a brushed DC electric motor as the test motor configuration as it is the most fundamental motor design from which all others are derived. As in all DC electric motors, it comprised four main components – rotor, stator, wiring and brush/commutator assembly. Both rotor and stator were 3D printed from commercially available ProtoPasta comprising 50% by mass magnetic iron particles in 50% PLA (polylactic acid) matrix (Fig 1). Previously built motor models indicated that heavier metal loading of 50% by volume increased the inertia of the rotor which was not offset by the increased magnetically induced torque yielding a reduction in rotation speed performance [2]. Energy losses in magnetic material are due to: (i) hysteresis loss which can be reduced by low coercivity; (ii) eddy current loss which can be reduced by low electrical conductivity and incorporating laminations; (iii) anomalous losses which can be reduced by using homogeneous material to permit magnetic domain migration. For these reasons, magnetic particles embedded in an insulating matrix ensure that eddy currents are minimised while magnetic field generation and threading is maximised. Both rotor and stator magnets were wire wound and the rotor windings were connected to the commutator through wire brushes using 24 MAG copper wire. This motor then constitutes a series wound self-excited DC motor. The commutator was a simple set of four thin contact copper sheets. The rotor was wound with 70 turns per pole while the stator was wound with 100 turns per pole. The main structure and commutator core were 3D printed from ABS (acrylonitrile butadiene styrene) which is more rigid than PLA. The only non-3D printed parts were the copper wire coils and the steel motor shaft (the thicker output shaft was 3D printed PLA). The motor was connected to a 30 Vdc power supply.

Fig. 1. DC electric motors with 3D printed stator and rotor electromagnets

We have been developing a photolithographically-printed wiring pattern to replace the copper wire which has been demonstrated in a pancake "air" motor configuration (Fig 2) but it has yet to be integrated into the 3D printed DC motor model. The four-quadrant design minimises the number of soldering points to four compared with a traditional radial pattern of pancake motors which require not far short of 100 solder points depending on the size of the rotor cross section. An interesting question that we shall not explore here concerns the trade between using a wire winder against photolithography equipment: a simple wire coil winding machine can be made from a rotary knife sharpener and a circular piece with three right-angle brackets for holding the coil form in place [3]. Another simple coil winder can be constructed from Meccano [4]. A more complex universal coil winding machine can also be readily constructed [5].

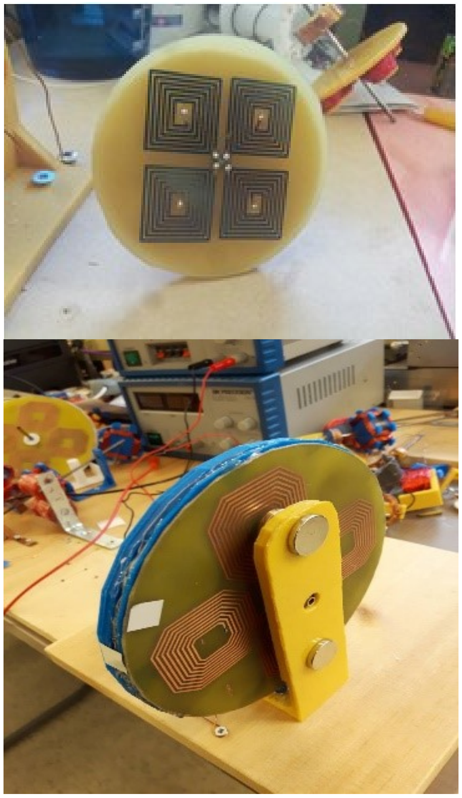

Fig. 2. Printed coil pattern and its implementation in a pancake motor

We have been exploring the use of 3D printed permanent magnets as the stators (manufactured by Oak Ridge National Laboratory) in our 3D printed motor, but they have yet to be integrated. Once this has been achieved, it would represent a fully 3D printed DC electric motor. Furthermore, to increase the volumetric performance of the motor, we shall be replacing the soft magnet closed stator with an open permanent magnet of 3D printed NeFeB from Oak Ridge National Laboratory (Fig 3).

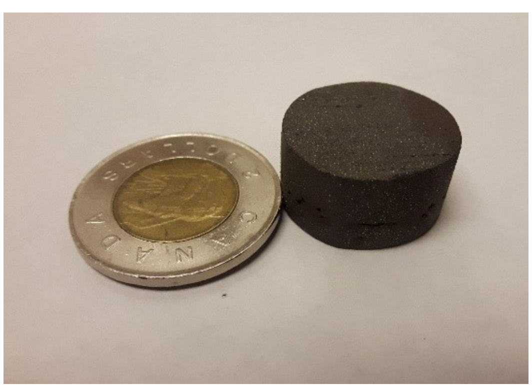

Fig. 3. 3D printed permanent stator magnet

However, these developments have yet to be integrated into a full motor assembly but are in progress.

3. TRIGON Self-Assembling Panel System

Self-assembly is the process where components automatically assemble themselves into specific configurations. The self-reconfigurable machine comprises a number of mechanical units (commonly homogeneous) which can connect to each other to alter their morphology and indulge in self-repair. Self-assembly of modular components provides robustness, reliability, reconfigurability, reusability and ease of development. One thing many self-assembling and reconfigurable systems have in common are either electromagnetic joining and/or motorised actuation. Rather than developing a 3D printed motor *in vacuo*, we have coupled the 3D printed motor concept with structural panelling as an example of reconfigurability with an extraterrestrial application. In general, the determination of the minimum number of tile types that can be assembled into a given shape (minimum tile set problem) is NP-hard, there are polynomial time solutions under certain constraints [6]. Furthermore, the assembly time can be minimised through partial ordering. We assume here that the number of panel is pre-determined by design. Assembly tasks require the mating of parts subject to contact forces and may be characterised by positional entropy as a measure of uncertainty in part position and orientation [7]. Part entropy can be reduced through fixtures, grippers and sensing. In a self-assembling system of modules, it is generally assumed that the modules are homogeneous and interconnect with each other using actuators. In flat-pack unfolding systems, the flat-pack configuration reduces part entropy by structuring the environment and acting as combined fixture/gripper with sensors are limited to motor sensors.

An example of this is PETSAT, a satellite concept based on a number of subsystem panels – onboard computer panel, battery panel, communications panel, attitude control panel and propulsion panel – that are assembled through plug-in connectors to form an integrated spacecraft [8]. Each panel has a standardised structural and thermal design (heat pipe with graphite insulation) while the interface provides reliable mechanical latching, one rotational joint/panel, electrical (power and data) interfaces (such as CAN bus) and thermal coupling. Multiple panels can be assembled into different spacecraft configurations.

However, we have been focussed on 3D printing the TRIGON (transformable robotic infrastructure-generating object network) panel system, a modular robotic construction system capable of self-assembling into trusses, domes, habitats, vehicles, factories and a variety of other structures (Fig 5) [9]. It is a modular robotic construction system comprising an adaptable kit-of-parts to realise the self-assembly of multiple habitat, rover and hybrid mobitat designs [10,11]. The TRIGON system is a panel-based self-assembly system in which each panel has motors integrated into each hinge on its edges linking it to other panels. The TRIGON system is a versatile self-assembly concept. Motors are integrated into hinges along panel edges with an offset so any two linked panels can be rotated through a full 0-360° range [12]. TRIGON panels are polygonal and designed to self-assemble from a stack of partially connected panels. The panels can accommodate payloads at the centre. Most self-assembling systems may be applied to a set of class 1 mobile habitats as a transition to class 2 habitats. Here, we consider class 3 habitats constructed from self-assembling panels.

There are two panel types, triangle and square panels, that can self-assemble into a variety of structures. We have been focussing on a dual set of linked motorised square TRIGON panels with an offset 3D printed motor. Our TRIGON panel however are much smaller versions than the full-sized version for demonstration purposes. The 3D printed square TRIGON panels and 1:27 reducing gears are constructed from PLA (Fig 4).

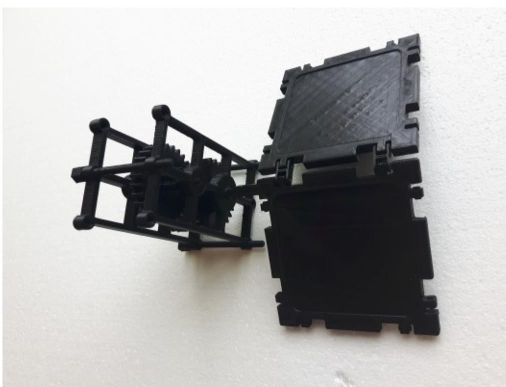

Fig. 4. 3D printed hinged square TRIGON panels and reduction gear

The hinged TRIGON panels and reduction gear were connected to the motor assembly (Fig 5) and successfully demonstrated opening and closing of the panel. Although a simple demonstration, this indicates that a complete motorized self-deployment system can be 3D printed using fused deposition modelling of PLA and derivatives thereof (less shaft and wiring).

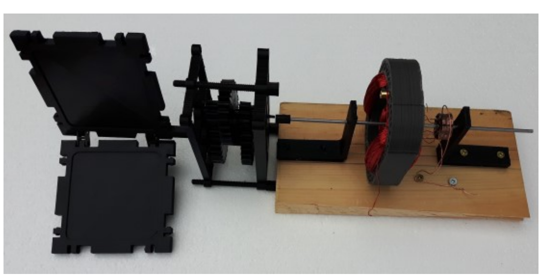

Fig. 5. 3D printed motorized hinged TRIGON panel assembly

TRIGON panels are designed as flat-packs that can construct 3D enclosure in two ways: (i) unfolding from pre-configured linkages with other panels from a compact stowed configuration; (ii) self-assembly where an integrated manipulator picks and places panels together for linking. It is the latter capability that differentiates TRIGON from most flat-pack concepts. The most flexible configuration involves the adoption of panel connector "arms" on each edge which act as motorized brackets that link two panels together. A each edge, a pair of connector arms act as manipulators to grapple neighbouring panel. They also possess sensors and controllers to permit sophisticated motion. The integrated motors from each panel operate in parallel to lift either panel with respect to the other. These grasping latches at the panel edges latch onto neighbouring panels and roll over the existing structure edge-over-edge. Hence, TRIGON panels can roll end-over-end to relocate into a growing structure of any arbitrary configuration [13]. However, the assembly of m parts by a manipulator of n degrees of freedom generates a configuration space of m+n degrees of freedom, i.e. assembly requires a path search through the m+n dimensional space.

Further development would involve the incorporation of integrated connector manipulator arms to deploy the TRIGON panels. We have yet to implement these more complex and challenging configurations necessary for self-assembly. Nevertheless, the deployment of 3D printed drive motors with the panels demonstrates that these more complex assemblies are achievable in the near term. Potentially, in the long-term, TRIGON panels could be deployed to construct a cassette factory manufacturing cell implementing 3D printing [14]. This would represent a step towards a self-replicating machine [15] beyond current state-of-the-art [16].

Our approach has implications for automated assembly of 3D structures from 2D flat-packs. Origami techniques may be employed to create 3D shapes by folding 2D sheets in different ways. Origami is the art of folding a flat sheet of paper into a 3D sculpture through folding but no cutting. The number of creases is limited and the most iconic origami model is the Japanese paper crane. The two basic folds are the valley-fold in which a sheet is folded upwards into a "V" with the crease at the bottom and the mountain-fold in a sheet is folded downwards into an "A" with the crease at the top [17]. All other folds are variations on these two. Folding in conjunction with cutting can form almost any sculpture. Miura-ori patterns combine valley and mountain folds to compress a large area sheet divided into parallelogram cells into a compact volume. The Miura map is a rigid fold that may be adopted to deploy large solar arrays.

This was demonstrated on the Japanese Space Flyer Unit (1995). Origami may be used to fabricate self-folding machines such as demonstrated with a crawling robot initially as a flat sheet with embedded resistive circuits to activate elastic flexures of shape memory polymer around thinned hinges [18]. Once folding has occurred, the hinge is cooled and the polymer hardens into position. Locomotion was enabled by two eight-bar linkage chassis, each driven by a single actuator to actuate forward and aft legs. Millimetre-scale robots are ideally suited to the combination of photolithographic (additive) printing, laser (subtractive) machining and origami construction methods [19]. Soft photolithography is used to pattern a photoresist which acts as a mould to create features in a polymer layer. Pulsed UV laser machining offers spot sizes ~1-10 μm with minimal heating damage. Millimetre-scale circuits with solder dots and wires on the faces of a polyhedron can form the basis of self-assembling multiple polyhedra into 3D electrical networks [20].

A programming language has been developed which generates a self-assembly process among agents emulating cellular morphogenesis and differentiation to generate a pre-defined global shape [21]. Epithelial cells differentiate into a wide variety of complex 3D structures from a 2D sheet of cells during embryonic growth – skin, capillaries, gut, neural tube, etc. A sheet of autonomous agents can execute instructions based on the local environment with no global coordination and only local communication. The 2D sheet can also form 3D structures through a folding process determined by origami axioms automatically compiled from the predefined global shape. There are six Huzita origami axioms for constructing all folded Euclidean shapes from straight line folds: (i) between points P1 and P2, we can fold a line between them; (ii) perpendicular bisector of line P1P2 folds point P1 onto point P2; (ii) bisector of angle between lines L1 and L2 folds L1 onto L2; (iv) line perpendicular to line L1 through point P1 folds L1 onto itself through P1; (v) for points P1 and P2 and a line L1, we can fold P1 onto L1 passing through P2; (vi) for points P1 and P2 and two lines L1 and L2, we can fold P1 onto L1 and P2 onto L2. A set of five biologically-inspired local primitives defining local interactions can be combined to generate global shapes – (i) gradients emulate chemical gradients where concentration relates distance to the chemical source; (ii) neighbourhood query collects information about neighbouring agents; (iii) polarity inversion to alter initial apex-basal polarity if necessary; (iv) cell-to-cell contact permits communication between agents in physical contact; (v) flexible folding to contract its apex or basal fibres to change the shape of the sheet. Complex 3D structures can be self-assembled from stacks of 2D panels with motorised joints along the folds. The combination of direct ink write assembly with wet-folding origami has demonstrated the construction of 3D shapes [22]. Metallic, ceramic or polymeric ink (in this case, TiH_2 particles loaded in an organic solvent that is subsequently dried and annealled) is extruded through a nozzle with three axis motion capability. Partially dried ink retains elasticity with E~30-110 MPa permitting folding. The origami structure of a crane was constructed in 15 steps as a demonstration. Hence, complex geometries can be created from origami.

A variation of folding/unfolding is contraction/expansion. The crystalline molecule is actuated by expansion and contraction of its four faces around a central core to simulate muscle behaviour [23-25]. It is cubic with connectors to other modules at the middle of each face encapsulating five Li batteries for power, a microcontroller and support circuitry. They do not move or rotate with respect to each other rather than moving relative to the complete structure. They move linearly in the plane of the modules. Each crystalline robot expands to 4 cm on a side from its contracted state of 2 cm on a side. Each expansion/contraction is activated by three binary actuators. All four faces form part of the connection mechanism supported by serial IR communications – two faces have active connectors and two have passive connection slots to form rigid connections. It can be used to create dynamic structures with shape-shifting (morphogenesis) capabilities using its expansion/contraction mechanism and its connectors to bond different bonds. It can realise any 3D cellular grid structure and indeed, units can relocate by travelling through the volume of the structure. A distributed control algorithm based on cellular automata (with similarities to hormone-based control) has been used to reconfigure the crystal robot into different shapes [26]. Telecubes is a cubic module with six prismatic degrees of freedom whose sides can expand to twice its dimensions similar to the crystal robot but expands in all three dimensions rather than in a plane [27]. Each of the six faces is driven by a telescoping linear actuator and each face has mechanical and electrical connectors with magnetic attachment. The metamorphic robot system is an extreme version of this approach in which the modules were deformable planar six-bar linkage modules that can dynamically reconfigure themselves individually [28].

4. Active Connectors Between Modules

Self-assembly may also be implemented through the linking of independent modules. The ability to 3D print magnets and magnetic devices – soft electromagnets, hard permanent magnets and electric motors – are the key components for imparting mobility/manipulation/bonding in 3D printed self-assembling systems, offering the prospect for 3D printing entire modular robots including their mechatronic components (though we do not address 3D printing electronics and sensors here). The advantages of multi-module reconfigurability from modular units include flexibility of implementation, robustness through self-repair and low cost through economies of scale. Self-assembly occurs at all scales with the common requirement that components must be sufficiently mobile to interact through relatively weak forces but there are two main processes – static self-assembly which exploits configurations with global or local equilibrium and dynamic self-assembly which dissipates energy to generate quasi-stable patterns [29,30]. Although the former is most commonly exploited in engineering self-assembly (as here), the latter is characteristic of biological self-assembly at the molecular level and will become increasingly important towards nanoscale miniaturisation at the molecular level but even at larger scales random external forcing can be useful.

Assembly of modules requires the adoption of standardized fastener bolts in favour of moulded or welded structures. Robotic assembly requires grappling of two parts and using tools to join them with fasteners – in microgravity, solid fixtures are required to align parts prior to joining. An alternative approach to repair is the addition of plug-in modules. One of the key technologies is that each modular unit can make/break connections with other units, i.e. the docking interface in terms of mechanical strength and stiffness, precision of alignment and compliance requirements, power limitations and stability. The process of assembly and docking requires knowledge of tolerances in relative positioning and orientation with a controlled relative velocity vector. Most docking fixtures are variations on peg-in-hole tasks. Modular robotics evolved from quick-change automatic tooling using common connection mechanisms. Mechanical connectors should be mated/demated robotically which eliminates bayonet-style connectors unless a ratchet tool can be used. All structural connectors must possess alignment features such as alignment pins to ensure correct connector orientation with "soft-latch" prior to full positive locking. Robotic connector/interface mechanisms have four properties: geometry to provide simple and rapid self-aligning docking and release, latching robustness, stiffness and stability with high impact and load strength, power and data transfer, and small parts count for easy maintenance [31]. In addition, low mass and inertia are essential properties yet retain high impact and load strength. The geometry must support simple and rapid connection, yet the connection should be stiff and not buckle catastrophically with overload.

In self-reconfigurable robots, each module should be self-contained and inter-connectable with other modules. Modularity and interconnectibility offers the opportunity for modular, self-reconfigurable robots which may be configured according to their required tasks. Tesar & Butler (1989) provide an extensive review of robotic mechanical component design [32]: although there are six basic joint mechanisms (revolute, prismatic, double-revolute universal, cylindrical, ball-and-socket and planar), all can be represented by combinations of 1 DOF revolute and prismatic joints. Prismatic joints are rare in space systems, so revolute joints are the most general and common form of space robotic joint. Standardised joint systems (perhaps dual drive for redundancy) with dedicated electronics (including encoders, tachometers, torque sensors, motor controllers, brakes, signal conditioning, etc), structure and standardised interfaces offer the potential for modular off-the-shelf designs. Geared motors such as harmonic drive gearing are preferred over direct drive motors due to their higher torque-weight ratio and lack of power requirement at rest. Harmonic drives have high accuracy and repeatability, negligible backlash, high reduction ratio within a single stage (1:320) and high transmission efficiency ~90%. Links should have a circular cross-section to minimise biased bending stresses and torsional loads. A modular approach has been developed which integrated a motor, harmonic drive and encoder within a connector link [33]. Mechanical connections between robotic modules should enable direct longitudinal and perpendicular connections - each module provided a 45° connection scheme relative to the module main axis to provide this through 180° rotation relative to the connecting modules. There were two forms of motor - large motors of near the base with high torque output and smaller motors near the wrist with lower torque output. Clearly, to reduce the loading on the outboard links, all prime movers should be installed at the shoulder, perhaps through a series of bevel geared cable drives but such approaches suffer from large torsional and longitudinal deformations. The wrist also comprised of separate RPY joints. A revolute jointed 6 DOF manipulator similar to the PUMA 560 was constructed from these modules. The addition of another DOF would be readily achieved. Such a modular reconfigurable design may be optimally configured for a given set of tasks determined by workspace, tip velocity/acceleration, maximum tip deflection and external forces/moments on the tip. An early multipurpose high load precision connector was for the nuclear industry (Westinghouse) to enable 6 DOF modular maintenance robots to be built manually – the connector was a precision-fit quick-disconnect unit assembled through a single turn of a threaded collar with up to 20 O-ring based hydraulic seals and 100 electrical line connectors [34].

Active connectors are new innovations which provide electromechanical connections rather than purely mechanical connections. The latch should require low power during latching and unlatching but not require power during its static state. The latch should be disconnectable from both sides which suggests a genderless connection scheme. The DRAGON connector was developed for modular self-reconfiguring robots has the ability to self-align and has a high strength-to-weight ratio [35]. It comprises of three components:

(i) the guide shaped as two funnels and two mating cones to align the connectors on touching capable of correcting 45° offsets and 20% diameter offset
(ii) the thin Al outer shell to take the load
(iii) the steel latching spring blade inside its cavity within the inside of the shell to keep the connectors connected

The spring expands against the inside of the shell of the mated connector to lock it in place. It is actuated by a shape memory alloy wire along the inside of the spring which closes the spring with a force of 0.3 N to release the mating connector. Delatching may also be achieved by inserting a screw into one of four threaded holes in the shell to compress the spring. Two IR emitters within each guiding cone can act as beacons for docking and two IR receivers at the vertices of the funnels provide the basis for optically isolated electrical connections. Within the connector, 12 thick spring-loaded copper contacts provide a power conduit. The spring has a shear buckling stress of:

$$\tau = \left(\frac{k_s \pi^2 E}{12(1-\upsilon)^2}\right)\left(\frac{t}{b}\right)^2$$

where k_s=buckling coefficient>5.5, t=spring thickness, b=spring width, E=Young's modulus, ν=Poisson's constant.

The ACOR (active connector for robotic systems) comprises a plug and receptacle containing many flexible lamellae to provide the connection [36]. A shape memory alloy actuator moves the lamellae ends to control connection/disconnection. The lamellae are pushed together to latch. Connection can be controlled from both plug and/or receptacle side. ACOR can transmit axial/shear forces and torques. All ACOR connectors possess both a female receptacle and a male plug side-by-side which provide the mechanical and electrical connection. The male lamellae form a cylindrical ring around the male pin. A shape memory alloy wrapped around the lamellae when activated constricts the lamellae towards the centreline, thereby releasing the connection. The female receptacle for the pin also includes female lamellae in a cylindrical ring around the female receptacle. A shape memory alloy wrapped around the lamellae when activated releases the lamellae. When connected, the pin is surrounded by the female pins to provide shear strength. The male and female lamellae interconnect during engagement through their angled shoulders at the ends of the lamellae. Either the male or the female actuators may be activated to release the connection. The male pin may be constructed from conductive material to provide electrical power connection. Alternatively, the outer male and inner female lamellae may be conductive to provide electrical data connection. A universal connector comprising side-by-side male and female components provides the basis for exact alignment of genderless connectors.

5. Robotic Self-Assembling Systems

Self-propelled macroscopic self-assembling systems constitute mobile robots which have higher potential utility such as CEBOT, PolyBot, CONRO, M-TRAN, Swarm-bot, fractum and Super mechano-colony. These involve single general-purpose modules that can be adapted for all functions through self-assembly albeit at a cost in hardware efficiency [37]. Reconfigurable robotic systems can be classified into three architecture – lattice architectures with modules arranged into a cubic or hexagonal grid, chain/tree architectures where modules are connected serially, and hybrid chain/lattice architectures [38]. These architectures may be reconfigured either deterministically or stochastically. Reconfigurable robots comprise heterogeneous modules (a small variety of structural link and motorised joint modules) that are premised on mechanical, electrical, data and power interfaces [39-42]. For most reconfigurable manipulators, a heterogeneous set of modules includes actuator-driven and unpowered (prismatic and revolute) joints, (but all, like homogeneous modules, are equipped with common joint encoders, tachometers, accelerometers, microcontroller board, CAN bus network and electronic interfaces) [43]. The powered modules, in common with homogeneous modules, incorporate at least one DC motor, amplifier, gearing and brake. SMA actuators are typically used to open latches/connectors.

We briefly review some select activities in the broad field of self-assembly with particular emphasis on relevant actuation mechanisms that illustrate the value of 3D printing electric motors and magnetic devices. Self-assembly of millimetre-scale components subjected to random shaking using magnetic forces from permanent micromagnets has been demonstrated in a liquid medium [44]. The permanent SmCo and NdFeB micromagnets were 50-150 μm thick square, oval stripe, triangle and arrowhead shaped layers embedded into silicon substrates. Similarly, self-assembly of 3D objects such as a 3D conformed electrical circuit from elastomeric sheets embossed with magnetic dipole patterns has been simulated [45]. A flat projection of a sphere represented by a series of linked lenticular shapes (like orange peels) or a radial array of lenticular shapes (like a flower) magnetised into a magnetic dipole form a sphere. The magnets were mounted onto the sharp ends of the lenticules and a thin wire run between them to form a soft dipole magnet. The balance of mechanical and magnetic forces determined the shape and stability of the 3D structure. In general, macroscopic self-assembly requires external propulsion but this imposes a power penalty compared with environmentally-supplied movement in microscopic self-assembly [46,47]. Environment-supplied movement to macroscopic self-assembly tends to have limited practical utility such as artificially-agitated blocks, e.g. Penrose's template-based tiles [48]. As a development of this, self-reconfiguration of PCB-based units fitted with electromagnets for bonding has been achieved passively through Brownian motion implemented through a shaker table [49].

We describe only a few of the large number of the "yet another modular robot" systems that represent more sophisticated self-assembling systems. The use of artificial modular units which may self-reconfigure into larger and adaptable structures are generally of two types – chain/tree architectures which form serial topologies and lattice architectures which form cubical or dodecahedral grids [50,51]. They offer the adaptability and robustness through reconfigurability and self-repair [52]. There are only three regular polyhedral shapes that can construct arbitrary space-filling shapes – the cube and the dodecahedron – which provide maximum internal volume for any given surface area. The metamorphic Proteo assembly uses identical rhombic dodecahedral modules that can assemble into any overall topology including branched structures for different tasks [53]. Each module implements a finite state machine with limited memory while communication is limited to their immediate neighbours. They alter shape by rolling relative to each other's outer surfaces according to pheromone trails. A cubic structure is simpler and is commonly adopted for reconfigurable robotic modules from which arbitrary structures can be built.

CEBOT (cellular robot) was the first modular reconfigurable robot to adapt its kinematic configuration for specific tasks connected through pairs of hook/receptor interfaces that attach/detach [54-57]. It comprised of interconnected separable robotic modules (cells) which could dock with each other in different configurations. Each heterogeneous cell type performed a specialised function such as mobile modules with wheels, rotary and telescopic joint modules for manipulators and a hand module for end effectors but all had the same dimensions of width 90 mm by height 50 mm (mass range 1.1-1.3 kg). The mobile cell performed transport and alignment functions using infrared diode and ultrasonic sensors for module detection. Each module incorporated its own motor and processor but could communicate across modules. CEBOT could dynamically configure its optimal morphology for a given task defined by: (i) end effector position/orientation coordinates; (ii) end effector force/torque requirements; (iii) position accuracy; (iv) manipulator base coordinates; (v) end effector type; (vi) workspace constraints. They can be dynamically configured autonomously using simple rules whilst cooperatively negotiating with each other [58]. CEBOT used a genetic knowledge production algorithm to implement its distributed intelligence of knowledge cell units [59]. Each knowledge cell implemented a single task so that a network of knowledge cells represented a task plan. The knowledge network implemented a synaptic weighting matrix connecting knowledge cells, so any task may be represented as a task weighting matrix.

The rapidly reconfigurable modular manipulator system (RMMS) configures itself into different special purpose manipulators from a set of interchangeable link and joint modules of various sizes and performances [60-62]. Each module is self-contained including DC torque motor, brake, harmonic drive gearing, resolver/tachometer sensors and sensor interface, microcontroller, motor amplifier, RS-485 and RS-232 drivers, ADC/DAC circuits and VME-based communication interface using a message-passing protocol. Control of both power and data is distributed through each module to minimise wiring connections in 6 wires that passes through the hollow motor shaft. There are four types of module – manipulator base, link module, a set of pivot modules (for perpendicular offset configurations) and a rotary joint module (for parallel inline configurations). The base and link modules have no degrees of freedom while the joint modules have one degree of freedom. The quick-coupling mechanism provides secure mechanical connection between modules with a locking ring collar at the male end with keyed flanges on male/female ends for accurate alignment. The locking ring drives a cam to grip the mating flanges with gripping fingers. Within the locking ring is a modular male connector with 30 electrical pins that fit into corresponding female connectors for power and electronic signals. Infrared LEDs provide alignment feedback. A guide collar with six alignment pins prevented damage. From these modules, a large number of configurations can be constructed due to its integrated quick-coupling connectors. Its modular task-based software determines the optimal kinematic structure defined as a joint velocity trajectory for a given task over a Cartesian path – transformation via the Moore-Penrose pseudo-inverse is subject to kinematic limits, singularity avoidance, collision avoidance, and energy minimisation. The genetic algorithm was used to search for solutions subject to specific design knowledge constraints. Assembly of the control software re-uses reconfigurable software components from a software library based on the Denavit-Hartenburg matrix kinematic convention with inverse solutions being computed numerically. The RMMS may be constructed using another manipulator. RMMS was proposed as a fault tolerant satellite docking system [63].

CONRO is a cubic homogeneous module with three DOF that can autonomously connect with identical modules with connectors on each face to form different configurations of metamorphic robots such as snake-like chains, tree-like multiple-leg locomotion, track-like loops and multiple sub-robots [64-66]. Each self-contained module incorporated a microcontroller with ADC, four infrared LED/sensors for communication, onboard Li batteries, two servomotors and four connectors. The two motors in the main body of the module give two degrees of freedom for 90° pitch and 30° yaw rotations (to act as legs). CONRO exhibited hermaphrodite docking pins at each end with a spring-loaded latch to lock the pins and receptacles with shape memory alloy actuators to release the pins. The docking pins have a lateral groove limiting connection between modules in the same plane. Compliance in the connection mechanism is essential to accommodate alignment uncertainties which is accommodated in the genderless SINGO connector for the SuperBot successor to CONRO [67]. CONRO exhibited bidirectional infrared transmitter/receiver interfaces for communication between modules.

PolyBot is similar in concept to CONRO as a homogeneous modular approach to reconfigurable robot structures [68]. PolyBot is a chain-based reconfigurable robot system in which each cubic module has one DOF actuation enabling it to link up into snake-like, legged and tread-based locomotion systems. Each cubic module comprises a joint with a DC motor with harmonic drive for one rotary DOF with multiple sensors – joint encoder, force/torque sensors, contact and proximity sensors – and embedded PowerPC processor communicating over a CAN-bus. Two opposing connection plates either side of the joint include hermaphrodite mechanical/electrical connectors comprised of four grooved pins and four chamfered receptacles with LED/photodiodes for position/orientation feedback during docking. A latch of shape memory alloy holds modules together (passing current opens the latch) while pins/holes provide stability. Power is supplied via a tether. The G3 moduke is smaller than the G2 module due to the employment of a pancake motor with harmonic drive. Polybot has constructed a manipulator from 6 PolyBot G3 modules. Both CONRO and Polybot are chain-type self-reconfigurable robot constructed from connectable modules which can form snakes, hexapod legs emanating from a spine, and loops for locomotion [69,70] with potential space applications [71]. Genetic algorithms may be used to search through a small inventory of components (power, link, joint, foot/gripper modules) to determine serial/parallel kinematic configurations to realize specific tasks using constraining design rules to reduce the search space [72,73]. The configuration search problem is NP-complete so a hierarchical decomposition approach is favoured to provide further constraints [74].

MTRAN (modular transformer) is a distributed reconfigurable system of homogeneous two DOF joint modules has been developed which can be configured as a hybrid modular chain and lattice system [75-78]. Each module is constructed from two cubic sections connected by a servo-motor powered link whilst incorporating a microprocessor, power supply circuit, digital bus communications and pulse generator circuit. Each cube can rotate by 180° about the axis joining the link and cube. The three cubic faces comprise passive connection plates using permanent rare earth magnets. The magnetic force acts against a nonlinear spring and is slightly larger than the spring force. Active detachment is enabled by two antagonistic shape memory alloy coil torsion springs for high power-to-weight ratios which exceeds the force difference [79]. Electrical connection is enabled by two pairs of electrodes for power and one electrode for serial communications. Reconfiguration is achieved by detaching the module, rotating the link and reconnecting to a neighbouring module.

SuperBot is a set of modular 3 DOF cubical robots based on earlier MTRAN modules capable of self-reconfigurability [80]. SuperBot modules comprise two cubical units connected by a link with a central roll joint. Each cube was attached to one end of the link through yaw and pitch joints respectively. Each cube included electronics and batteries. Each cube had six genderless connectors, one on each side, which transmitted power and data – they required sensing and maintenance of tension while docked yet permit simple release. Each cube included a microcontroller for the sensors, motors, communications, power and docking. It adopted a digital hormone control system developed for CONRO to reconfigure itself. Robotic enzymes represent an alternative in which the robotic enzyme is a simulated module of two units linked together [81]. It has active sites (connectors) which it attempts to attach to other modules through movements in a simulated environment.

Tetrabot was a modular and reconfigurable robotic system offering reusability and reconfiguration of the same modular units [82]. CORBA (common object request broker architecture) provided the medium of control for the distributed network of modules. Tetrabot used three basic mechanical parts in which a control system defined the connectivity of parts and their kinematic structure. It was based on a multi-link spherical joint which allowed the interconnection of truss structures with an arbitrary number of struts.

I-Cubes is a modular self-reconfigurable robotic system that comprised of cubic mechatronic modules with a three DOF manipulator for relative position/orientation of the modules for attachment/detachment to other modules [83]. The link has a handle configuration with a short length d/2 perpendicular to one cube face which bends into a long length of 2d and then bends into a short length d/2 parallel to the first short length where d=length of side of a cube. The actuators are at: (i) the base of the first link with a 360° axial rotation axis along its length, (ii) a 270° elbow pitch halfway along the length of the middle long length a distance d from the inboard and outboard bends; (iii) the end of the final link with a 360° axial rotation axis along its length. The final link permits a cross-shaped twist-and-lock attachment to any cube face. Attachment provides mechanical, electrical and data interfacing. Much of the mechanical elements of the cubes and links were 3D printed. The I-Cubes form a dynamic graph where the links are edges and the cubes are nodes.

The 4 DOF Molecule robot unit comprises two atoms linked by a rigid right-angled connection (bond) similar to MTRAN [84,85]. Each atom has five inter-molecular connection points and two motorised degrees of freedom, one to rotate 180° relative to its bond axis and one to rotate 180° perpendicular to its bond axis. A gripper mechanism links the molecules together to replace the earlier electromagnets. Each molecule incorporates a microprocessor and motor driver circuits adopting RS-485 serial connections. Although the L-shaped molecule robot cannot be packed as efficiently as cube designs, they can configure into 3D structures as well as 2D tilings (tilings can be stacked) by moving over each other on the 3D substrate structure. They can also form locomotive or manipulative structures [86].

The basic fractum unit requires a minimum of three re-usable connectors, a mechanism of communication between neighbouring units, each unit must have an energy source, and for self-repair final configuration information must be stored in a distributed fashion [87,88]. Each 2D fractum comprises six connecting arms – three male and three female – each equipped with a male electromagnet and female permanent magnets. The fractum module housing an onboard microprocessor can connect and disconnect to other modules autonomously to self-assemble into different configurations. The polarity of the three electromagnets determines connection/disconnection so it can form up to six bonds with other units allowing 12 possible connection types [89,90]. The distance between two connection types is defined by the number of links in the shortest path between two nodes. Each module can connect with up to three other modules and coordination between modules is mediated through an infrared optical communications channel. The fractum comprised three layers, each layer comprising three fixed arms 120° apart mounted onto intervening bearings to ensure free spinning capability. Top and bottom layers incorporated three aligned permanent magnets on the arms paired together top and bottom. The middle layer has the same shape with three electromagnets mounted in each arm but oriented at a yaw angle of 60° with respect to the top and bottom layers. Control of the electromagnet polarity through H-bridge circuits determines either attractive or repulsive linkage to another fractum unit. Formations are changed by switching the electromagnets that permit morphing shapes.

Programmable parts involve modules subjected to random perturbations on a 2D air table so that they can collide and stick through switchable electromagnets [91]. Each programmable part comprises an equilateral triangle chassis with an actuated magnetic latch (to rotate 180° to generate attractive or repulsive polarity) and an infrared transceiver on each side, all supported by a microcontroller and control circuitry. Reconfigurable robotics involves varying the kinematic configuration of motors, sensors and control electronics – this yields flexibility in configurations of vehicle chassis, manipulator kinematics, end-effector/tooling, onboard computing and power systems.

6. Control of Self-Assembly

Challenges in assembling modular components into kinematic structures revolve around kinematic and dynamic analysis to match the optimal structure to the required task [92]. This requires consideration of multiple metrics such as manipulability measure, kinematic error metrics, torque limits, joint excursions, etc [93]. Modular robotic manipulator systems comprise standardised link and joint modules that may be assembled into different kinematic configurations optimally designed for a specific task. Joint modules may be revolute, prismatic, cylindrical or screw joints that connect to link modules through ports to form a kinematic tree. A task may be represented as a series of end-effector positions defining a cartesian trajectory. Genetic algorithms may be employed to search for an optimal assembly configuration for that task based on an assembly fitness function quantified as the manipulability measure $m = min\left[\sqrt{det(JJ^T)}\right]$ assessed on an inverse kinematics-based workspace check [94]. The search space for kinematic design can be pruned substantially by applying physical rules to eliminate inappropriate solutions [95]: (i) all configurations require a power/control module; (ii) modules are assembled into serial chains only; (iii) all configurations terminate in an end effector; (iv) all modules do not need to be used. The genetic algorithm can then be applied to search for feasible kinematic assemblies of connected modules [96]. The genetic algorithm may encode a tree-based representation tested within a dynamic simulator environment. An ontogeny – be it biological or artificial – constitutes an assembly plan of sequential procedures that prescribes how to construct an organism by exploiting the physics of its environment [97]. A two-level genetic algorithm can search for the optimal kinematic configuration including revolute/prismatic joint selection, link lengths and total number of degrees of freedom from a task specification [98]. The upper level GA determines the overall topology while the lower level GA determines the inverse kinematics solutions based on the Denavit-Hartenburg matrix representation. The fitness function may be expanded to incorporate six criteria:

$$F = exp(-(w_1R + w_2L + w_3A + w_4I + w_5O + w_6D))$$

where w_i=weights, $R = \sum_{i=1}^{m}(d_j - \sum_{i=1}^{n} l_i)$ =reachability of end effector to task, l_i=length of link i, d_j=distance of task j from base, n=maximum number of DOF, m=number of subtasks, $L = \frac{|p^d - p|}{|p^d|}$=linear distance to goal, $A = \frac{|R^d - R|}{|R^d|}$ =angular distance to goal, $O = \sum_{i=1}^{n}\sum_{j=1}^{o} c_{ij}$ =penalty function, $c_{ij} = \frac{(s_i - d_{ij})}{s_i}$ =collision penalty if obstacle exists within a safe area otherwise c_{ij}=0, d_{ij}=distance of link i from obstacle j, s_i=security distance, o=number of obstacles, $I = \frac{\sum_{i=1}^{n} l_i + r_i/20}{e}$=minimum complexity measure, r_i=1 if joint i is R but 0 otherwise, e=end effector distance from base, $D = \frac{1}{1+m}$ =dexterity measure, $m = \sqrt{det(JJ^T)}$ =manipulability index. In CEBOT for example, the optimal minimised criteria for the assembled configuration was defined as [99]:

$$F = \sum_{j=1}^{m}(w_1 e_j^T e_j + w_2 T_j^T T_j + w_3 D^T(j+1)D(j+1)) + w_4 C$$

where w_i=weights, m=total number of task points j, e_j=position error at task j as a function of link and joint rigidity, T_j=required end effector force/torque at task j to support payload and outboard links, D(j+1)=drive function transformation from task j to j+1, C=cost parameter typically total joint torque or motor energy consumption. This acted as a performance measure for an optimal controller for self-assembly. Task-based design is an approach to the design of optimally configured manipulators for specific tasks such as Space Shuttle tile servicing on-orbit [100]. In swarm-bots, neural networks implemented in each s-bot module may be evolved to perform integrated sensorimotor coordination and decision making [101]. This implements a local behaviour-based controller that requires no inter-agent communication or coordination. Three primitive collective behaviours based on measuring distance to neighbours can form arbitrary shapes [102]: (i) edge-following; (ii) gradient formation; (iii) localisation. A set of stigmergic if-then rules for automated self-assembly from bricks has been simulated similar to potential force fields [103]. Artificial gradients provide the means for coordination. Simple local control rules can generate emergent behaviours to grow different global structures according to resulting (scent) gradients [104]. Self-assembly may proceed hierarchically at multiple levels (nested hierarchy) through rule-based interactions of simple modules to generate new emergent properties at each level [105].

Control of reconfigurable modules is generally distributed with limited information exchange between modules. Market-based communication, interaction and coordination of resources and scheduling are based on negotiation (auction) through the contract net protocol or a variant thereof. Agents typically interact through negotiation mediated by the contract net protocol based on a call for bid, bid submission and contract award [106,107]. The contract net protocol is a simple coordination mechanism that has been commonly adopted but it has been supplemented for more recent market mechanisms, auctions and other trading mechanisms. The disadvantages to a market system are the complexity of the bidding process and cheating through collusion. Vickrey's auction in which the highest bidder wins but pays the second highest bid price promotes fairness. The multirobot task allocation problem – a variation on the multiple travelling salesman problem - is best solved using optimisation such as simulated annealling or genetic algorithms over a market-based auction approaches such as the contract net protocol (in which cooperation is negotiated in a bidding process) [108,109].

Self-assembling robotic configurations from homogeneous modules may be controlled through several different mechanisms based on some form of distribution of information. In the fractum module system of self-assembly, diffusive communication between units represents the average difference between units which forms the basis for self-assembly and self-repair [110]: $x(i, t+1) = x(i, t) + K\Delta x(i, t) - L$ where K=diffusion coefficient, L=leak constant. CONRO and SuperBot implemented an adaptive distributed control mechanism to provide global control of the kinematic configuration through hormone-inspired asynchronous message passing between modules for dynamic coordination [111,112]. Hormones are characterised by having no specific destination by propagating through the network with different effects on different receivers. Some organisms use hormones for morphallaxis to regenerate limbs through self-organisation of remaining cells, e.g. lobsters and hydra. The digital hormone model is based on the Turing reaction-diffusion equation as the basis for chemical morphogenesis. A set of differential equations model pattern formation in a ring of modules (cells) which communicate through hormones (morphogens). The diffusion rate dynamics of the ring of i=1,..,n cells are given by:

$$\frac{dx_i}{dt} = f(x_i, y_i) + u(x_{i+1} - 2x_i + x_{i-1})$$

$$\frac{dy_i}{dt} = g(x_i, y_i) + v(y_{i+1} - 2y_i + y_{i-1})$$

where x_i=concentration of hormone x in cell i, y_i=concentration of hormone y in cell i, u,v=cell-to-cell diffusion rate of x and y hormones, f(x,y),g(x,y)=chemical reaction rate increase. According to this model, artificial hormones are propagated from module to module. The CONRO topological network implemented a loop of receiving and sending hormones between neighbours and acting on the local instructions based on these messages. Hormones are distributed messages without a specific destination and trigger different actions in different subsystems. It reduces the communications cost to O(kn) where n=number of modules yet maintains global synchronisation at a local level. There are special types of hormones such as probe hormones that monitor local connection topography. On receipt of a hormone, a module relays it to all its active links (except the receiving link) thereby propagating the hormone through the network. To ensure that each hormone is received only once for each module a stored rule-base selects and executes actions determining how the module reacts to hormones. Although each module possesses the same rule-base local action vary according to local topology and internal state. Hormones implement actions such as gait control by commanding actions and polling sensors. They have a finite lifetime after which they become inactive. The use of pheromones is not strictly necessary – ants successfully build nests from small stones without the use of pheromones [113]. In this case, ants respond to the density of small grains which act as an attractor thereby constructing the nest brick-by-brick. Furthermore, as stones accumulate, building accelerates until the nest is complete.

Graph grammars have been proposed for modelling the motion of large numbers of particles and their mutual interactions – they capture local interaction rules for exhibiting specific behaviours for each particle but although useful for large numbers of particles does not appear to offer great advantages over alternative methods [114]. Cellular automata representation has been used to control reconfiguration by modelling growth from an arbitrarily selected initial seed from a random population of modules through a gradient descent of artificial chemical concentrations created using local communication between neighbouring modules [115]. The hormone control approach may be combined with artificial embryogenesis both of which exhibit diffusion processes to model growth [116]. Programmable parts are homogeneous modules that self-assemble into a global configuration based on local "chemical" interactions rules [117]. The interactions rules are defined by a graph grammar associated with each programmable part that models the logical physics of particle bonding (polymerisation) between two particles (particles representing each robot module):

|a…a→b-b (rule 1 - r_1– two unbounded particles a and a can bind together to form b-b)

Φ=|a…b→b-c (rule 2 - r_2)

|b…b→c-c (rule 3 – r_3)

The state of the system evolves as a labelled graph G=(V,E,L) according to the initial assignment of labels a,b,c where V=vertex set of integers to index the particles (vertex set represents latching connectors), E=edge set of edge pairs from V, and L:V→Σ=labelling function that associates a label L(i)ϵΣ with each particle iϵV where Σ={a,b,c,…}=set of labels. The final assembly is reachable if there a graphical trajectory from the initial assembly through the sequential application of the interaction rules: $G_0\overrightarrow{r_i^1}\ldots G_j\ldots\overrightarrow{r_i^k}G_k$. There is a considerable range of options for controlling the self-assembly process in which bio-inspiration plays a dominant role.

7. Applications of Self-Assembly

A small number of reconfigurable modules can yield a fleet of ISRU rovers for different functions at low cost and enhanced system reliability but without loss of performance. These modules may include actuated joints with integrated motors, links which may be connected serially or in parallel, a variety of end-effector tooling compatible with a standard wrist plate, sensors with dedicated signal processing electronics, wheels with integrated motor control units, etc. These components may be configured into rover/manipulator platforms for different roles. Such configurations must be performed autonomously – there must be interface modules capable of moving to and manipulating other modules. This system could provide the basis of robot colonies to perform coordinated functions. Swarm-Bots are composed of modular s-bots which are unique in adopting two integrated differential tracks with wheels (treels) for rough terrain mobility [118,119]. S-bots also have a rotational upper chassis turret, a single DOF pitch arm and a gripper to attach to another s-bot's turret, a suite of sensors and onboard microprocessor implementing a neural network controller and battery. An autonomous self-replicating Lego robot comprised of six modules in which the replicating robot self-assembles the modules into a growing structure [120]. Module 1 comprised batteries, touch sensor and contact sensor; module 2 comprised state machine and contact sensors; module 3 comprised left motor and motor drive circuit; module 4 comprised right motor and barcode reader; module 5 comprised a relay circuit; and module 6 comprised a tracking sensor. The robot possessed three simple behaviours – forward line-tracking, reverse and left turn - to run a circular circuit guided by a line around a pre-structured environment with modules placed at specific locations. It required both a complex set of modules and a structured environment limiting the adaptability of the self-assembly scheme. This work was akin to a physical instantiation of the low-complexity replication without universal construction.

Both formation flying and self-assembly of spacecraft requires high degrees of control. Formation flying is reminiscent of many types of animal groupings (swarming) which is commonly modelled as a diffusion process constrained by repulsive and attractive taxes (nominally modelled as a Fokker-Planck equation) [121]. On-orbit assembly of large composite spacecraft has been considered essential for large modular space structures [122]. One example is to employ more compact structurally connected versions of ESA's Darwin and NASA's Terrestrial Planet Finder without the need for formation flying [123,124]. Although this reduces the interferometric baseline achievable to ~10-50m, station keeping issues are eliminated (although additional problems such as structural vibration become important). Traditionally, this has involved the use of astronauts to perform such operations but robotic self-assembly has become feasible using swarm control and self-organisation techniques of distributed robotics [125].

The ultimate example of self-reconfiguring robots in space for self-assembly of large space structures (such as solar power satellites) is the freeflying intelligent fibre/rope (FIMER) robot concept that uses a tether between two robot freeflyer robots to autonomously dock them [126]. The two freeflyers at the ends of the tether can be reeled in and out. Each freeflyer unit is a complete spacecraft functionally including ion engines with a tether winch, reconfigurable connector and flexible robot arm for grasping as payloads. The large-scale self-assembly process may be controlled through the digital hormone model [127]. In FIMER, components to be joined broadcast a docking requirement signal to which appropriately located FIMER(s) respond by grasping the components and reeled them together. For fine assembly tasks, positional entropy may be used to quantify assembly tasks in terms of uncertainty in position/orientation which in turn determines contact forces during mating of parts [128]. Positional entropy is based on the probability distribution of parts position/orientation defined by an ensemble of repeated assembly tests. Positional entropy may be reduced by fine manipulation with sensory feedback, jigs and fixtures.

8. Conclusions

We have made significant headway in demonstrating the feasibility of 3D printed self-assembling robotic machines. The key to this is the development of the 3D printed electric motor which is near completion. We have demonstrated a 3D printed system of the (near) 3D printed motor with the TRIGON panel which has the versatility to be both self-deploying and self-assembling. Although much remains to be done, we conclude that we are well on track without any significant showstoppers. The chief limitations in homogeneous self-assembling robot modules are in the strength of the intermodule bonds (typically magnetic), motor torque capabilities and dexterity. This limits number of modules that can be lifted in a serial configuration and so limits the practical applications of reconfigurable robotics. For example, M-TRAN is based on a lattice of cubic modules, each of which comprises two blocks connected through rotary joint to an intervening link [129]. Earlier magnetic connections of M-TRAN had been replaced by motor-driven mechanical latches. Most of these issues may be addressed through modular manipulator approaches by introducing heterogeneous modules with a range of motor torque capabilities. The 3D printed motor offers the prospect of in-situ manufacture of electric motors to fit the task considerably widening the applicability of reconfigurable robotics.

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