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Modular and reconfigurable mobile robotics

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ABSTRACT

With increasing demand on reliable robotic platforms that can alleviate the burden of daily painstaking tasks, researchers have focused their effort towards developing robotic platforms that possess a high level of autonomy and versatility in function. These robots, capable of operating either individually or in a group, also possess the structural modular morphology that enables them to adapt to the unstructured nature of a real environment. Over the past two decades, significant work has been published in this field, particularly in the aspects of autonomy, mobility and docking. This paper reviews the primary methods in the literature related to the fields of modular and reconfigurable mobile robotics. By bringing together aspects of modularity, including docking and autonomy, and synthesizing the most relevant findings, there is optimism that a more complete understanding of this field will serve as a starting ground for innovation and integration of such technology in the urban environment.

1. Introduction

1.1. Background

The term "modular robotics" refers to a family of robotic systems made of interconnected smaller units called "modules", joined together by docking interfaces. These robots are composed of relatively simple and self-contained building blocks that exhibit their own sensing, actuating and computing means. However, they are also equipped with docking interfaces that allow groups of these fundamental blocks to configure into larger or more capable robotic structures. Because of this ability to morph into different structures, modular robots are referred to as reconfigurable or self-reconfigurable, depending upon the level of autonomy associated with this process. Self-reconfigurability can therefore be defined as the reversible process by which discrete entities bind to each other without being externally directed [1].

Modularity offers significant functional and economic advantages over more traditional fixed-structure robots. The ability to reconfigure the morphology by rearranging the connectivity of their parts enables modular robots to adapt to changes in the environment. For example, a modular robot may be capable of changing its configuration from a legged robot, to a snake or a rolling robot depending upon the terrain layout. Modularity and reconfigurability also enable robots to perform tasks that a single module or a fixed-structure robot is unable to perform. This is achieved by docking additional specialized units to the original morphology in order to accomplish an assigned task. These specialized units can be grippers, batteries, or sensor units such as cameras. Modular robots also offer an economic advantage stemming from the potential of lowering the overall cost by building complex robotic structures from a single (or a few) rudimentary mass-produced module.

These advantages have yet to be practically validated [2]. With the current technology, a single fixed-structure robot tailored to perform a specific task is more likely to out-perform its modular counterpart. Nevertheless, the broad utility that modular robots can provide promises a change in the role they play in our society, most notably in enabling the integration of mobile robots in the urban environment alongside humans. Such efforts have long been hindered by the significant challenges imposed by the unstructured nature of the human-inhabited environment. Nevertheless, the adaptive faculties of modular robots represent the key technology required to achieve such integration, by endowing robotic systems with the morphological re-configurability that adapts their shapes to genuine architectural elements such as stairs, doors and furniture.

Modular robots also prove especially useful in environments that are deemed too dangerous or inaccessible to humans. The ability to adapt to unstructured terrains, coupled with the ability to repair or self-repair faulty components through self-disassembly, can potentially reshape the technology of extreme applications. Such applications include space exploration and deep sea missions where human intervention is not possible.

1.2. Motivation

The objective of this paper is to present, analyze and compare the research contribution made to the multi-disciplinary field of modular and reconfigurable mobile robotics. The content of

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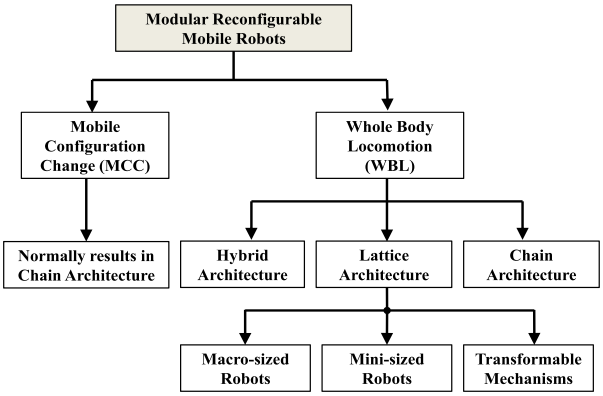

Fig. 1. Tree classification of reconfigurable robots based on structural properties.

the paper focuses on the methods that relate to advances in the structural characteristics of modularity, including mobility, reconfigurability and rigid coupling. The paper further assesses – where applicable – aspects of intelligence attributed to modular mobile robotics. These are discussed with respect to frames of application, such as shape formation, motion control and docking autonomy. The objective is to summarize the most recent and relevant advances in the field in order to formulate a general outline on the current state of modular mobile robotic technology. It should be noted however that, although modularity may apply to robotic structures that do not possess the ability to move, our primary interest is in robotic mobility. Therefore, this effort will be tailored exclusively towards the technical and scientific aspects related directly to mobile modular robotic systems.

2. Classification

Contributions to the field of modular and reconfigurable mobile robots can be traced back to the late 1980's (*CEBOT*, Fukuda et al. [3,4]), and are broadly classified within the research community into two major categories: *Mobile Configuration Change* (MCC) and *Whole Body Locomotion* (WBL) [5]. These categories are differentiated by the nature of mobility patterns and the reconfigurable properties of the robot. Further classifications can be seen under additional sub-categories based on the geometry, the docking interface and the modality of shape reconfiguration. These subcategories are: *Lattice* architecture, *Chain or Tree* architecture, and a hybrid combination of both. Fig. 1 visualizes a tree representation of these categories which will be further detailed in subsequent sections.

3. Modular robots with mobile configuration change (MCC)

The category of mobile configuration change (*MCC*) refers to modular robots where individual modules maneuver and interact with the environment independently, gather, and physically connect to one another to change the group configuration and augment the capabilities of a single module. This generally takes the form of a head-to-tail docking process. In this category, individual modules are self-contained and possess the sensing, computing and actuating capabilities to move and operate individually. The locomotion patterns of *MCC* modules are traditional, and are implemented using typical mechanisms that enable efficient mobility of individual modules such as wheels and treads. However, their structural morphology also encompasses means of coupling, referred to as docking interfaces, which enable a swarm of these modules to bind together into a larger configuration.

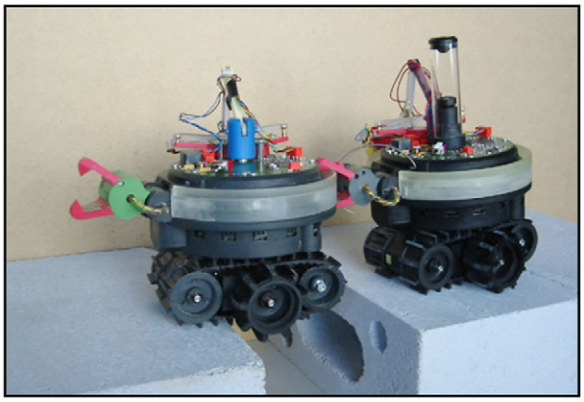

Fig. 2. Two S-bots docked together in a chain configuration using grippers [1].

3.1. S-Bots

One of the methods investigated to develop a docking interface for a swarm of robots was accomplished by implementing a robotic gripper on-board each module. S-Bots [1,6] illustrate such modular robots which combine collective team-work with reconfigurability accomplished via robotic grippers. Each module in the S-Bot swarm is autonomous, and is equipped with nine degrees of freedom (DOFs) that operate the mobile tracked-and-wheeled platform, as well as the manipulator arm and the gripper. To achieve reconfigurability, modules use their grippers to hold on to one another (Fig. 2). Partial gripping between two modules allows one to rotate on a horizontal plane with respect to the other, while full gripping restricts this motion but enables one module to lift the other off the ground in a chain-like formation.

In addition to rigid gripping, s-bot modules can achieve reconfiguration via semi-flexible connections. These connections consist of flexible arms actuated by three independent motors. One motor enables a lateral rotation of the arm; another motor moves the arm along the vertical direction, while the third motor provides extension/retraction maneuverability. This dexterity in connection enables s-bot assemblies to bend and create three-dimensional formations [1,7].

From an algorithmic perspective, the process of self-assembly is implemented using color rings incorporated around each module. These rings have the ability to toggle colors between red and blue. Red-colored rings are interpreted by the modules as a signal to avoid each other, while blue-colored rings signal docking. Hence, when assembly is initiated, one of the modules – referred to as the "seed" – turns its ring blue. This signals docking to the nearest module, which grabs onto the seed using its gripper and switches its ring color from red to blue, triggering other modules to bind to the assembly in the same scheme.

A chain configuration is therefore established with the objective of augmenting the actuation and manipulation capabilities of individual modules. This enables the assembly to perform arduous tasks, such as pulling heavy objects [6,8] or overcoming ditches and holes in the ground when navigating through rough terrain [9].

3.2. Uni-Rovers

MCC modularity has also been investigated for planetary rovers (Fig. 3). This has been accomplished by transforming the rover's wheels into self-contained mobile modules referred to as *child*. Each child provides manipulation capabilities and possesses a docking interface that enables it to connect (or disconnect) to the mother platform [10,11]. The manipulator arm of a *child* contains a gripper mechanism with a caster wheel at the tip, and serves

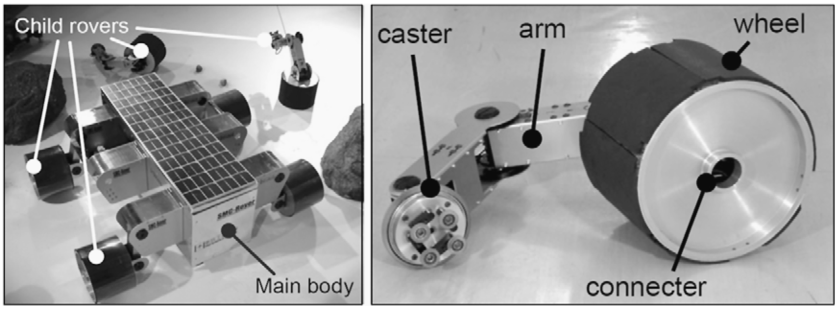

Fig. 3. Uni-Rover robotic modules with the *mother* platform and the *child* [11].

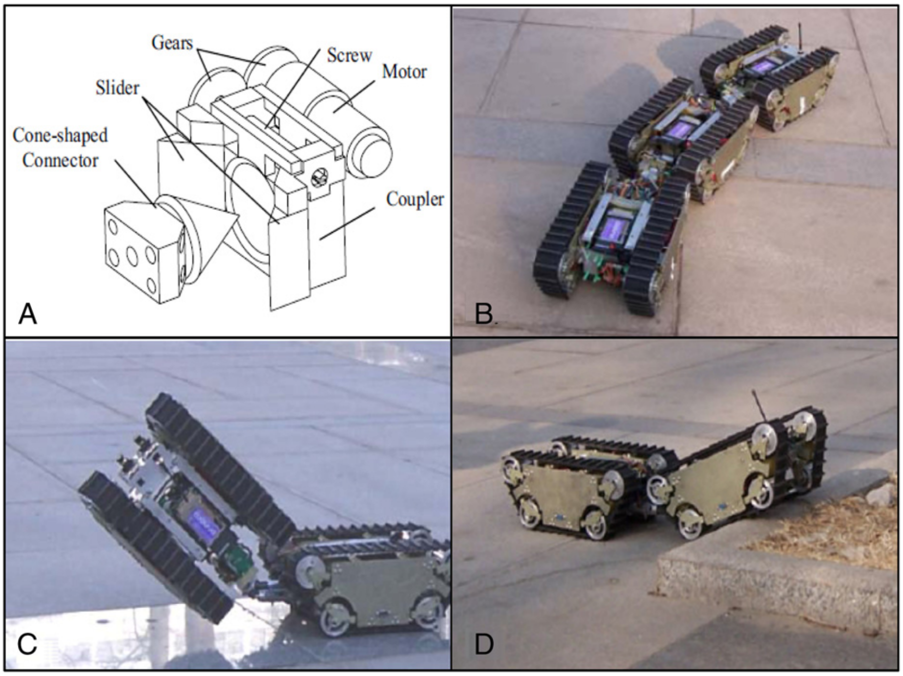

Fig. 4. JL-I robot [13]: (A) schematic of the docking interface, (B) train formation, (C) roll movement of one module relative to its neighbor, (D) obstacle climbing with two modules.

multiple purposes: (i) it enables the child module to connect to the mother platform via the gripper, (ii) it provides manipulation to the *child* module allowing rudimentary interaction with the surroundings, (iii) it enables the child to toggle between the locomotion and the manipulation mode.

Locomotion and manipulation modes are only enabled when the module is separated from the mother platform. In this configuration, *child* locomotion is provided by the main wheel (with its rotation axis parallel to the ground) in the front and the arm's caster in the back, with the caster wheel providing support and steering means to the *child*. The manipulation mode is also initiated by the arm. This is accomplished by pushing the gripper against the ground in order to flip the front wheel on its side such that its rotation axis becomes perpendicular to the ground. In this posture, the wheel acts as the manipulator's base housing the motors and complementary hardware.

Multiple wheel modules in the locomotion mode can dock to the mother platform using their manipulators. Because of the articulated joints of the arm, a closed-loop control strategy is implemented to enable *child*-to-*mother* docking on rough terrains which characterize the topology of planetary environments. This is accomplished by employing the joints of the arm to align the interface of the *child* with the interface of the *mother* in a spatial frame prior to docking on uneven terrains.

3.3. *JL-I and JL-II*

Another docking mechanism proposed and implemented onboard the JL-I robot [12,13], consists of a cone-shaped connector and a matching coupler incorporated in the center of the module between the tracked units. The matching coupler assembly includes a latching mechanism implemented with two sliding surfaces actuated by a power screw (Fig. 4(A)). During the docking process, the connector of one module aligns with the coupler hole of the other module. The connector is further thrust inside the coupler, guided by the funnel cavity, until the sliders latch onto the connector and lock the two modules together.

In the second generation of the JL robot (JL-II), the docking interface was modified to include a gripper [14]. This enabled individual JL-II modules to achieve rudimentary manipulation in addition to locomotion, which was not possible with the earlier module (JL-I). In both cases however, the relative motion of one module relative to its neighbor is still possible despite the rigid coupling.

This is achieved by incorporating a spherical joint within the connector assembly, which provides three revolute degrees of freedom for every module in the formation relative to its neighbor. Such articulation enables the chain assembly to exhibit a snake like morphology (Fig. 4(B)) with roll (Fig. 4(C)), pitch (Fig. 4(D))

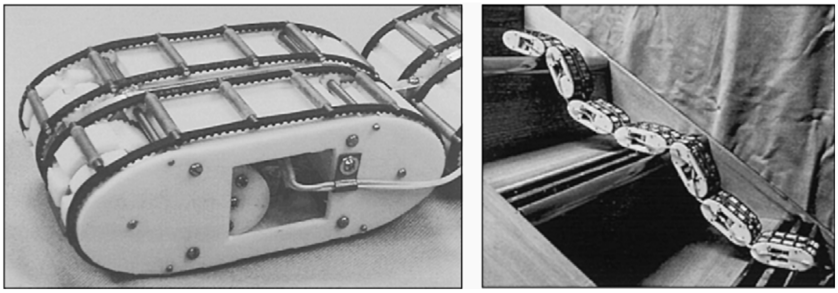

Fig. 5. A module of Millibots (left) and a seven-module train formation climbing stairs (right) [16].

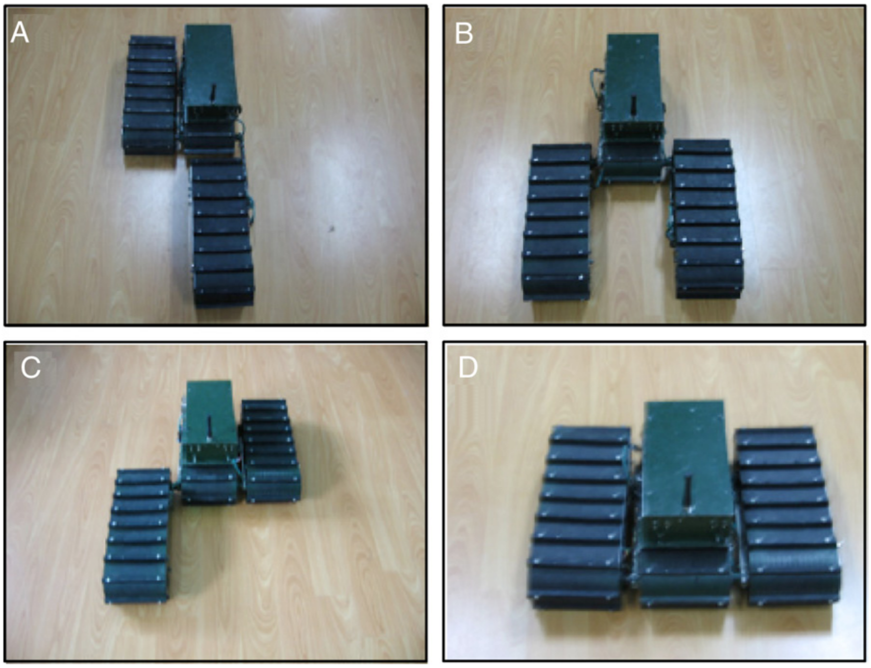

Fig. 6. AMOEBA modules in line, triangular and row configurations with link-type docking [21].

and yaw maneuvers. These maneuverabilities allow JL-robot to overcome obstacles taller than the module's tracks, by pitching modules above the obstacle one after the other [15]. Recovering from a fall is also possible, with experiments showing the ability of an assembly to recover from falling on its side (90° with respect to the ground) or its back (180° with respect to the ground).

3.4. Millibots

Millibots [16,17] represent another modular robotic system that shares common structural attributes with the JL-II robot. With Millibots (Fig. 5), the reconfiguration of the modules is accomplished manually through a SMA actuated latching mechanism. This mechanism consists of two male steel pins in the front of the module that couple with a female receptacle located at the back of the preceding module in a train formation. The rigidity of coupling is provided by a latching device actuated by a shape-memory-alloy wire which is triggered by a heating electrical current.

A module of the Millibots system fits into a cube with an edge length of 5 cm, and consists of a parallelepipedic mobile platform with two belts. Each belt is actuated independently from the other to provide mobility and skid-steering to the platform which carries sensing, power and communication devices. The coupling mechanism is further actuated by an additional motor that provides revolute pitch motion of the pins and the docking mechanism, enabling undulatory mobility patterns for a train of Millibots. This pattern demonstrated stair-climbing capabilities with a train formation consisting of seven manually configured Millibot modules as shown in Fig. 5.

Controlling the motion of Millibots is accomplished via a graphical user interface [18] which enables an operator-in-the-loop to control a swarm of modules, and receive sensor information over a wireless network. It is through this interface that Millibot modules can communicate with each other and share information about their surroundings, enabling the operator to perceive and build a global map of the explored environment.

3.5. AMOEBA

Further work on tracked *MCC* robots with link-type docking was done by Liu et al. [19–21]. AMOEBA-I and later generations are capable of docking from all sides of the central module via articulated links with pitch and yaw revolute joints. This enables AMOEBA to form a chain configuration with modules in line with one another (Fig. 6(A)), a triangular configuration with a central module and two offset side modules (Fig. 6(B) and (C)), and a row formation with modules stacked and aligned on the sides of one another (Fig. 6(D)). Each of these configurations is applicable to a specific terrain condition. For instance, AMOEBA's train formation was demonstrated in stair and obstacle climbing maneuvers, while

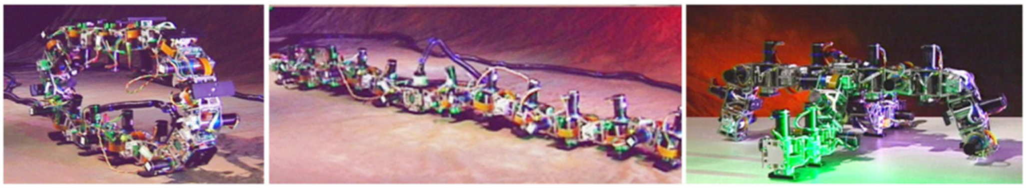

Fig. 7. PolyBot: a self-reconfigurable modular robot in a chain architecture providing whole body locomotion [33].

the mobility of a triangular formation was field-tested on snow, grass and debris as reported in [22].

From an algorithmic perspective, a unique binary representation is proposed to describe the possible configurations of an AMOEBA assembly with n-links [21]. Through this representation, all decimal numbers from 0 to $4^{n-1}-1$ are represented in an equivalent binary scheme. The resulting binary enumeration is further processed to eliminate configurations with adjacent link interference. This is achieved mathematically by eliminating the configurations described by the binary equivalent code, where at least one "10" sequence is depicted when diagnosing the binary code from right to left. The remaining $3^n - 1$ binary representations denote all possible configurations that can be accomplished with n-links without the possibility of adjacent link interference.

4. Modular robots with whole body locomotion (WBL)

The category of whole-body locomotion (WBL) relates to a family of modular robots whose morphology can provide different types of locomotion, such as walking, crawling and rolling. This is generally achieved by reconfiguring the DOFs and controlling the joints in order to reshape the structure into a desired configuration. The main difference between this category of robots and the mobile configuration change (MCC) is that the modules in the whole body locomotion can only provide *useful* mobility when connected together via docking interfaces. In contrast, in the MCC category, individual modules are independent entities that are capable of achieving individual *efficient* locomotion using traditional mobility mechanisms (wheels, tracks), even in the undocked configuration.

In general, the coupling patterns in the WBL category can be realized in three different architectures. The most common of these are the chain and lattice architectures. A third more recent pattern known as *hybrid chain-lattice* architecture combines the advantages of both categories and provides a unique leap into the potential mobility of WBL modular robots on rough terrain.

4.1. Whole body locomotion in a chain architecture

Chain modular robots providing whole body locomotion comprise many degrees of freedom. These highly articulated structures deliver complex locomotion patterns such as six-legged locomotion (*Tetrobot*, Hamlin et al. [23,24], Lee et al. [25]) and snake-like undulations in a spatial workspace (*ACM*, Togawa et al. [26], Mori et al. [27,28]). The reconfiguration scheme in the chain architecture is achieved by detaching an array of modules from one point of the architecture, and re-attaching it at a different point while maintaining the direct connectivity of the entire assembly. This is realized either autonomously, or under human supervision.

4.1.1. CONRO/PolyBot

CONRO [29–32], and later PolyBot [33,34] shown in Fig. 7, are two chain-based modular robots with actuated modules. These two generations of robots are capable of providing multiple whole body locomotion modes by autonomously rearranging the configuration of their joints. Rolling, undulating and walking maneuvers have been demonstrated with multiple modules in the assembly.

For CONRO, each module comprises two degrees of freedom actuated with two independent motors. Each module further carries its own battery source, microcontroller and infrared communication devices. For PolyBot however, every module comprises only one actuated degree of freedom, and its size is approximately half the size of a CONRO module.

Coupling between different modules of CONRO, as well as modules of PolyBot, is based on an interface that carries mating pins and holes with SMA latching mechanisms. In particular, for the third generation of PolyBot which builds on the earlier version of PolyPod [35], the coupling interface was designed with a set of four pins and four holes carried by each cubical module. These pins and holes are configured on two parallel sides of the cube, and are arranged on concentric circles, 90° apart. During docking, the pins from one module penetrate the holes of the adjacent module. A spring-loaded latching mechanism actuated by shape memory alloy (SMA) strings, rotates a scissor-like mechanism that latches onto the pins locking them in place. This process is reversible, where detaching the two modules is accomplished by actuating the latching mechanism in the opposite direction.

Controlling the process of docking in a chain architecture is arduous, especially when the chain comprises multiple modules, due to accumulations in positional error. In PolyBot and CONRO, the problem was addressed by splitting the docking process into three phases: long range, medium range and short range. The long range phase aims at bringing two modules from any position in space to within the vicinity of one another. Once the position sensors embedded in the mating faces sense the proximity of one module to the other, the medium-range phase is initiated. This phase has the objective of closing the gap that separates the two modules, guided by infrared sensing which determines the position and orientation of one module with respect to the other in six-dimensional spatial coordinates.

The final phase is only initiated at close proximity. Using only joint angle sensors and an open-loop controller based on a kinematic representation of the modules, compliant alignment between the pins of one module and the holes of the mating module is achieved. The pins are then guided to mate with the holes, and the two are permanently locked together via the SMA-actuated latching mechanism.

Furthermore, for CONRO formations, a high-level morphological control and communication scheme was implemented with a biologically-inspired hormone-based protocol. This enables modules in the chain formation to continuously discover changes in their local topography, and to collaborate via hormone-like messages to coordinate their actions and respond to these changes via self-reconfiguration. Such autonomous process, controlled by an online adaptive distributed control protocol, was tested on a physical formation of CONRO, as well as in a simulated environment with Newtonian mechanics [31]. This hormone-inspired control approach was further tested on SuperBot modules (Section 4.3.3) but not on PolyBot.

4.1.2. GZ-I

Whole body locomotion was also investigated for modular chain robots with assisted reconfiguration. Unlike CONRO and

Fig. 8. An assembly of CKBot modules with a top module carrying a camera and a light [42].

PolyBot that are capable of self-reconfiguration, the process of reshaping the morphology of these modular robots is not autonomous, rather accomplished by an operator. The underlying motivation is driven by the prospects of building complex electromechanical structures from simple building blocks. By homogenizing the structure of individual modules, repairing and maintaining faulty components becomes easier and cost-effective as any part can replace any other part in the assembly. Assisted or manual reconfiguration, as opposed to self-reconfiguration, further reduces the complexity of the controller and docking interfaces; however, it requires human intervention any time a reshaping of the morphology is desired.

GZ-I is one example of modular chain robots with manual configuration. GZ-I [36,37] robot is composed of Y1-modules which provide only one revolute degree of freedom and three connection faces. These faces provide docking means with adjacent modules in the assembly via bolts and nuts. Experiments showed the ability of these modules to reconfigure into snake and quadruped robots, with the snake formation demonstrating lateral rolling and full body undulatory maneuvers [38,39].

4.1.3. *CKBot*

CKBot modules [40] (Fig. 8) on the other hand provide two modes of docking. They can either be assembled manually with screws binding mating faces together, or they can self-reconfigure using permanent magnets embedded in these faces to exhibit walking, undulating and rolling capabilities (among others) [41]. The magnets of CKBot have enough strength to hold seven modules in a vertical position before the weight of these modules causes unintended chain disconnection.

Further experimentations demonstrated the ability of CKBot to self-repair after an impact resulting in the disconnection of the modules from the robot chain [41]. Using infra red sensors and cameras (Fig. 8), modules locate themselves on a flat terrain and crawl towards one another in order to reconfigure the broken configuration. This crawling maneuver is rather slow as the individual undulation of modules represents a relatively inefficient mode of locomotion. Once modules are gathered in the vicinity of one another, the mating faces are realigned, and the coupling between the broken modules is reinstated via the magnetic interfaces embedded in the faces of each module.

4.2. *Whole body locomotion in a lattice architecture*

Modular robots that adopt the lattice architecture reconfigure themselves by rearranging the position of the modules on the grid or lattice. This is achieved by moving a component from one initial position on the grid to another neighboring position in 2-D or 3-D space. The connectivity between one module and the neighboring ones is ensured via docking interfaces. Furthermore, the number of neighboring components to every module in the lattice is finite and known at any given time (*Molecubes*, Zykov et al. [43]). This aspect makes planning the motion of individual components on the grid relatively easier (compared to the chain architecture), as the ensemble of positions a module can occupy on the grid is finite and well defined.

Macro robots, mini robots and transformable mechanisms have been reported under the lattice architecture for different modular robotic applications. Although there exists no established threshold as to what constitutes a macro module and what constitutes a micro module, the literature seems to adopt the size of monetary coinage such as an American quarter (*characteristic dimension*∼25 mm) as a Ref. [44,45]. As such, in this survey, any modular robot with modules' dimensions greater than 25 mm belongs to the macro size category; otherwise, it is considered a mini robot. Readers should not confuse a mini robot with a micro-robot where the dimensions of the latter are less than one millimeter.

4.2.1. *Macro robots in a lattice architecture*

Most of the modular robots in a lattice configuration have cubic or parallelepipedic modules (*I-Cubes*, *EM-Cubes* (An [46]), etc.). This is generally advantageous because cubes and parallelepipeds possess large flat faces. These faces increase the contact area between one module and the other, and accommodate larger docking mechanisms that deliver rigid coupling. However, there also exist modular robots with near spherical, cylindrical (*Catoms*, Kirby et al. [47], *OCTABOT*, Shiu et al. [48–50]) as well as hexagonal modules (*Metamorphic*, Chirikjian et al. [51,52], Pamecha et al. [53,54]).

A. Crystalline

One of the examples that best illustrates a macro-sized reconfigurable robot in a lattice architecture [55] with parallelepipedic modules is Crystalline (Fig. 9) [56–58] which delivers planar mobility via whole-body expansions and contractions. This pattern of expansions and contractions is enabled by a rack and pinion mechanism, and generates planar linear mobility of a lattice of modules in a two-dimensional formation. The four sides of the module are each connected to one rack that engages a single central pinion actuated by one motor. In this design, all four faces can either expand or contract by the same rate at the same time, where the expansion phase doubles the original volume of the module.

Every module further contains four latching mechanisms. Two of these latches are passive, while the other two are active and actuated by gear-motors. In a lattice assembly, one Crystalline module connects to a maximum of four other adjacent modules. However, an individual module cannot relocate on the grid by itself. Instead, a series of coordinated group contractions and expansions enables a grid member to relocate relative to the structure. This coordinated mobility is controlled by an efficient planning algorithm for shape metamorphosis.

B. Odin

Shape reconfiguration via expansion and contraction of individual modules in a lattice architecture was also investigated for Odin [59] (Fig. 10). This modular robot consists of two main components: links and joints. The cylindrical links are either active or rigid, where the active links are telescopic modules actuated with an electrical motor embedded inside the body. The rigid links on the other hand can be batteries or sensor modules, or can act as passive components that contribute to the overall strength of the lattice. Every link further carries two flexible connectors, one at each end of the cylinder. These connectors mate with the joints

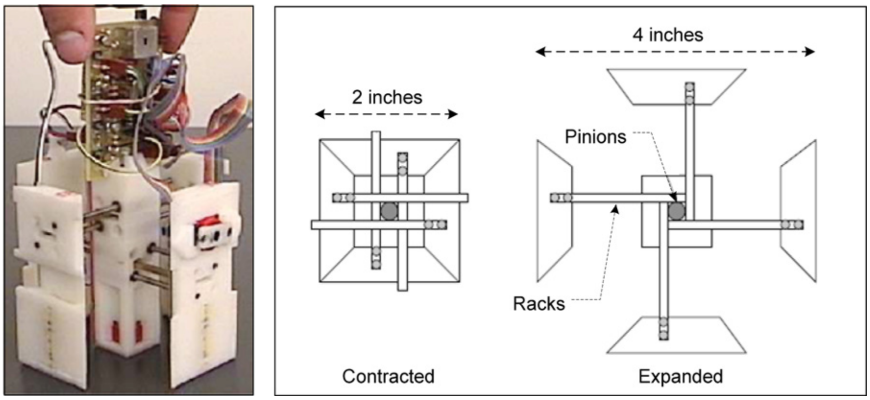

Fig. 9. Crystalline module (*left*) and a schematic of the rack and pinion mechanism and the expandable/contractible faces (*right*) [57].

Fig. 10. A lattice assembly of links and joints for the Odin modular robot [59].

of the lattice, where each joint provides twelve different female connection slots, and enables the lattice to deform in a three-dimensional space when the active links are either expanded or contracted.

Preliminary investigations on spatial contraction/expansion motion generation with Odin were undertaken as a constrained minimization problem [60], where the potential energy stored in the springs of the flexible links was minimized subject to kinematic constraints and joint limits. This generates the twist and deflection angles that define the shape of a specific configuration. In this analysis, the parallel connecting lattice of an n-link Odin formation, comparable to a Stewart platform, was modeled kinematically as $n \times n$ matrices that represent the interconnection between the links and the joints. Such approach is projected to being generalizable for the shape-estimation of an n-link Odin robot. However, in [60], shape-estimation was only reported for a tetrahedron formation of Odin.

C. I-Cubes

Other reconfigurable robots with cubical modules, such as I-Cubes [61–63] have been reported (Fig. 11). I-Cubes lattice architecture is bipartite, in the sense that the robot morphology comprises two independent structural components: links (active) and cubes (passive). The links are manipulators with three rotational degrees of freedom designed to self-assemble and hold the cubical modules together in the desired configuration. However, despite the rigidity of the connection that links can provide as compared to permanent magnets, controlling the motion of the assembly in the lattice architecture proves to be arduous.

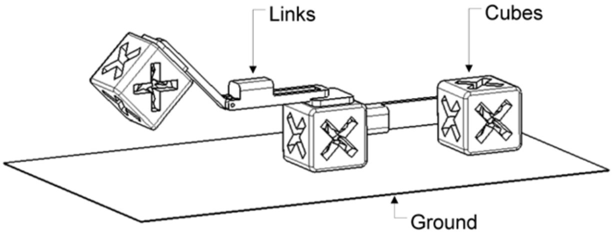

Fig. 11. Schematic of a sample I-Cubes formation with two links and three cubes.

An algorithm that plans the movement of the cubes on the grid is proposed to address this problem [62]. This algorithm dictates the motion and connection of the links and the cubes in order to match the morphology of the lattice to a predefined formation developed on a master computer. Through this assisted process, commands are initiated to the links in order to replicate the computer-designed configuration by modifying the pattern of link-face connections. This is accomplished by moving links from one cube's face to the other, from one cube to the neighboring one, or by carrying the whole cube to a different location in the lattice while maintaining direct connectivity with a neighboring stationary cube. The resulting versatility in docking enables I-Cubes to generate a variety of lattice formations that deliver non-traditional mobility patterns, such as dynamic grid rearrangements or train formations capable of climbing tall obstacles.

D. Catoms

Other modes of locomotion for lattice configurations include a two-dimensional translation achieved through expansion and contraction of the modular formation (*Telecubes*, Suh et al. [64], Vassilvitskii et al. [65,66] and *Crystal Robot*, Butler et al. [67,68]), and a planar rotation of individual modules (*Fractum*, Tomita et al. [69], Yoshida et al. [70]).

Planar rotations in particular were investigated for modular robots with vertical cylindrical modules called Catoms, shown in Fig. 12 [47,71,72]. This mode of locomotion is a planar rotation of the modules around each other, resulting in a two-dimensional motion of the lattice formation via a dynamic rearrangement of modules on the grid

To achieve such mobility, electromagnets are incorporated in a series of rings along the circumference of the cylinders. The role of the electromagnets is to hold the modules together in a specific configuration, and provide anchor points for power and data transmission between one module and its neighbors on the grid. Actuation, and therefore movement, is also generated via these electromagnets. Using a controlled process of enabling and disabling the magnets, one module ("the mover") in the configuration rotates around a stationary neighbor acting as a pivot. The

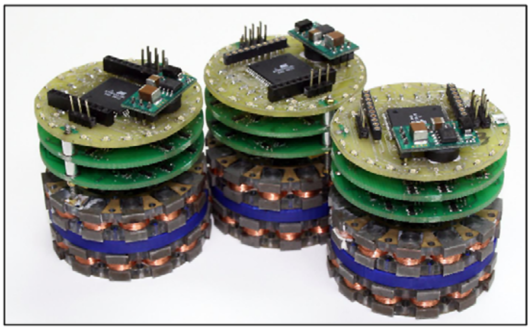

Fig. 12. A formation of Catom modules using radial electromagnets to dock and rotate around one another [47].

remaining modules surrounding the pivot hold the latter in place as the mover rotates around it. In the case of the Catoms, the controller energizes only one magnet on each module at any given time.

This process of enabling and disabling the magnets and the subsequent rotation of the mover is accomplished in under 100 ms. This enables an *n*-formation of Catom modules to deliver reasonably fast rotary mobility patterns for practical applications. Further developments on Catom robots seek to accomplish reconfiguration at the micro scale, with the mobility of individual modules provided via electrostatic actuation as reported in [73].

4.2.2. Mini robots in a lattice architecture

Interest in mini-scale reconfigurable and modular robots increased over the recent decade, sustained by the potential military and civilian applications. Although no reconfigurable mini-robots have been reported operating in such real environments, the possibility of building very small and cheap robots that can operate in a swarm formation has been envisioned for military intelligence applications from as early as the 1970's (ESL Inc.). Applications include exploration in environments that are too small, inaccessible or too hazardous for humans or larger robots. These include search and rescue missions inside the rubbles of a collapsed building, as well as diagnostic operations inside the digestive track.

Major technical challenges related to the field of mini-sized reconfigurable robotics persist, especially in terms of actuators' size and power supply. Catoms, presented earlier in this section, constitute an on-going project of robotic miniaturization [73]. However, the demonstrated reconfigurable modules of Catoms are still large enough not to belong to the mini or micro robotics category. Stochastic 3-D [74,75] represents a second mini robotic system designed to operate in fluidic environments. The robot's cubical modules have a face length of 15 mm but do not possess individual actuation means. Instead, modules of Stochastic 3-D require the movement of a fluid in a tube or container to pull them together in order to generate stochastic structural reconfiguration.

One of the reconfigurable robots reported to possess modules' individual actuation with an overall mini-sized morphology is developed by Yoshida et al. [76]. The prototype module evolved from a larger predecessor [77] and currently holds a near-parallelepipedic volume of less than 2 cm^3 (Fig. 13).

Actuation is provided via shape memory alloy coils that operate two latching mechanisms configured diagonally on the rectangular footprint. The process of mobility and reconfiguration is similar to the one provided by Catoms. That is, the latching mechanisms connect modules together in a 2-D or 3-D lattice architecture, and enable them to revolve around one another via a well controlled process. Such individual rotations generate an overall planar rotary mobility for the assembly by recurrently rearranging the location of the modules on the grid.

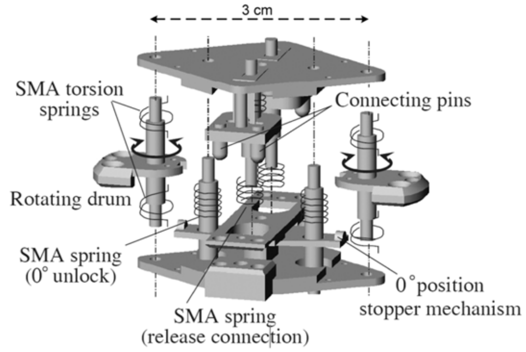

Fig. 13. A schematic of a mini-sized module with SMA-actuated latching mechanism [76].

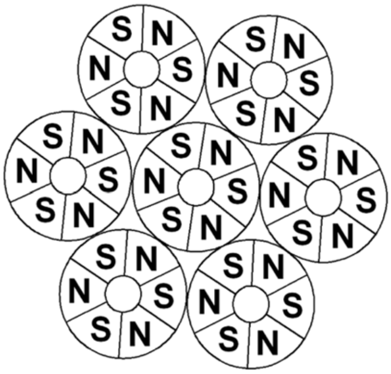

Fig. 14. Reconfigurable geared mechanism with peripheral multi-pole magnets providing radial coupling between adjacent gears.

4.2.3. Reconfigurable mechanisms in a lattice architecture

In addition to macro and mini-sized modular robots, standalone mechanisms capable of generating reconfigurable mobility have been investigated. One of the proposed mechanisms [78] comprises multiple magnetic gears in a lattice architecture, where each gear is actuated by one motor that provides individual rotation around the gear's central axis. A multi-pole magnet with a total of six poles (3N, 3S) is used on each gear unit as shown in Fig. 14. These magnets create attractive forces between opposite poles of two adjacent gears, allowing them to maintain radial distance while rotating around one another in a planetary way. This planetary movement enables the assembly to provide group rotary or wheeled-like mobility by rearranging the gears location on the lattice.

Movement of the assembly is generated by actuating one gear at a time. Starting from the furthest gear to the destination, each gear is rotated by its own motor around a stationary adjacent gear until contact with a second stationary counterpart is established. Once such contact is accomplished, the control algorithm that dictates the operation of the swarm then actuates another gear in the same fashion, and the alternating actuation process continues in a cyclic scheme until the final destination is reached.

4.3. Whole body locomotion in a hybrid architecture

Combining capabilities from both the chain and lattice architectures has been proposed for modular robots providing whole body locomotion in a hybrid architecture. Such architecture was investigated for mobile reconfigurable furniture applications (*Roombots*, Sprövitz et al. [79,80]), as well as for other highly adaptive mobile systems.

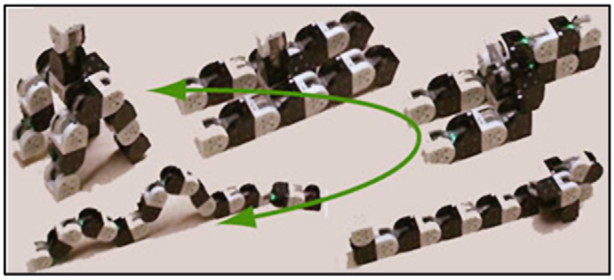

Fig. 15. M-TRAN robot in different whole body locomotion configurations.

4.3.1. *M-TRAN/i*Mobot

In the context of adaptive mobility, M-TRAN (I, II and III) [81–87] shown in Fig. 15, represents a highly maneuverable hybrid-morphology robot consisting of semi-cylindrical modules attached together in either a lattice or a chain architecture. A module of M-TRAN is composed of one passive and one active semi-cylinder capable of pivoting around the joint that connects them together. The passive semi-cylinder contains four permanent magnets (S pole) embedded on each of its three faces. The active semi-cylinder includes, in addition to four permanent magnets (N pole) configured on the docking surfaces, a connection mechanism actuated by a central coil made of shape memory alloys (SMA).

The role of this mechanism is to detach the magnets of the connected surfaces by expanding to push the faces apart. The controlled actuation of this coil is achieved by an electrical bias in the first generation of M-TRAN (M-TRAN I), and with miniature heat-generating light bulbs in the second generation of M-TRAN (M-TRAN II). However, because of the slow performance of the SMA coil requiring around one minute to heat up and expand, a mechanical latching mechanism replacing the SMA coil and the magnets was proposed for the third generation of M-TRAN (M-TRAN III). This mechanism resembles the one implemented onboard ATRON modules, and consists of a hook incorporated inside the active part and a corresponding cavity in the passive part. The hooks are engaged inside the stationary cavity following a series of rotations and translations providing firm binding of adjacent modules in the assembly.

M-TRAN modules are self-contained, where all hardware, electronic boards and batteries are housed inside the semi-cylinders and the links. Data communication and power sharing among modules is achieved through electrodes implemented on the mating surfaces. Data sharing in particular is important to control the reconfiguration of the modules and plan the motion of the assembly. This is realized through a utility graphical user interface and a CPG controller [88], where an operator designs a shape formation on the simulator and validates the kinematics and dynamics of the assembly, before relaying the commands to the real hardware to realize the desired configuration. A sequence of locomotion patterns, from legged locomotion to undulation and crawling (Fig. 15), was demonstrated in a laboratory environment where reconfiguration of the morphology from one preset formation to the other was achieved autonomously via a motion planner [89].

Other modular robot designs adopted the M-TRAN module as a basis for their development. *i*Mobot [90] is one such example with a module's shape that resembles that of M-TRAN's, and which can provide manipulation in a serpentine modular formation (Fig. 16). However, unlike M-TRAN's modules that cannot provide individual mobility, *i*Mobot's modules are capable of moving independently from one another in a disconnected configuration. This is achieved by implementing two additional revolute joints (four DOFs per module) on two opposite sides of the parallelepipedic module that enable the differential rotation of the wheel-like connecting faceplates. The rotation of these faceplates provides wheel-like mobility and steering for the individual module.

Fig. 16. A serpentine assembly of *i*Mobot modules with a gripper [91].

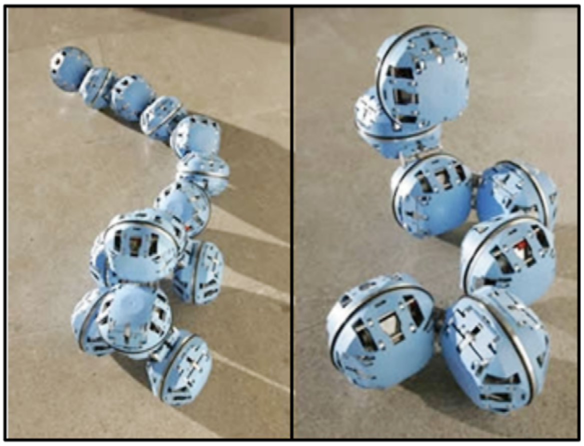

Fig. 17. ATRON robot with near spherical modules [95].

4.3.2. *Molecubes*

Cubical modules were also used in modular robotics, in particular for Molecubes [43], where each module (10 × 10 × 10 cm) is split into two parts along an inclined plane perpendicular to the cube's long diagonal. The revolute joint that connects both parts is actuated by an embedded motor that enables one half-cube to swivel around the other. Each face of the cube carries an electro-magnetic interface that enables two adjacent modules to dock into a lattice assembly. The polarity of these electromagnets can be changed electrically so as to attract, repel or act as a neutral element to the neighboring module.

The reconfiguration of a Molecubes' assembly is achieved manually via a simulator, and replicated on a physical formation. Several mobility patterns were demonstrated with this manual replicator, such as a quadruped formation with multiple grippers. An attempt to automate the self-replication process was also investigated through an evolutionary fitness-based algorithm as reported in [43].

4.3.3. *ATRON*

Additional module shapes were investigated for ATRON [92–96] (Fig. 17) which represents an example of a modular robot with near spherical and pyramidal modules. Every ATRON's module is composed of two four-sided pyramids with edge carvings that enable the module to exhibit a near spherical geometry. A spherical design in ATRON's case is favored over a cubical design because the geometry of the sphere provides smoother and more continuous mobility patterns. However, with a spherical design, the connection between one module and its neighbors is point-to-point, as opposed to a surface-to-surface connection with cubical modules, which provides more stable and rigid connectivity between different components in the lattice formation.

ATRON modules are therefore built with one rotational degree of freedom, as well as active and passive connectors that emulate

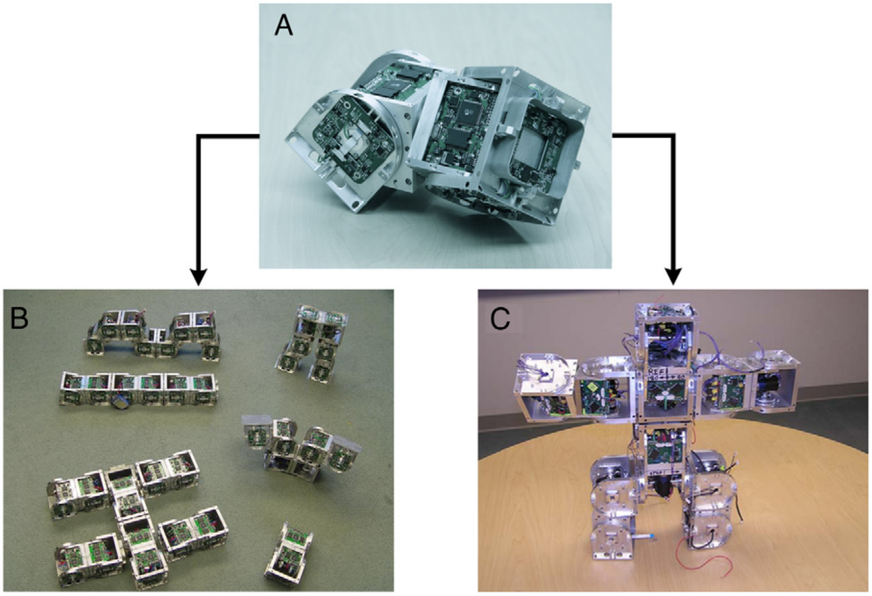

Fig. 18. SuperBot modular robot in different configurations: (A) single unit module, (B) legged, Quadruped and Train formation, (C) legged formation in a standing posture [105].

surface-to-surface connectivity. During docking, three active connectors from one module latch onto the passive connectors of the neighboring counterpart to bind and enable modules to share battery power and communication data amongst themselves. Once docked, one module rotates around its central axis to establish contact with other stationary modules in the configuration. Connection with the old module is then released, and a new connection with a new module is established.

This cyclic process of attaching and detaching connectors in the lattice is controlled by online pattern generation algorithms [93], such as an artificial co-evolution algorithm supplemented by virtual-reality simulations on Vortex [96], in order to generate autonomous mobility patterns for the full assembly. Different ATRON's formations were also abstracted using an anatomy-based algorithm [94] which generated anatomical formations of ATRON such as muscles, bones and hinges. These capabilities were equally simulated on a formation of multiple Catom robots for mobility, collaborative actuation, grasping and manipulation applications.

4.3.4. YaMoR

Another modular robot with one revolute degree of freedom per module is YaMoR (Yet Another Modular Robot) [97,98]. YaMoR is a chain-lattice based reconfigurable robot with a module's length of 94 mm. Each module is a self-contained entity of the assembly with its own power, computing and communication means, and is capable of exchanging information with the swarm members over a network established via a Bluetooth protocol [98].

In the YaMoR robot, as well as in other hybrid architecture robots such as Thor [99], self-assembly is not possible. In fact, modules can only be assembled manually using screws and nuts to create different configurations such as quadruped and train undulatory formations. The motion control of a chain of YaMoR modules was proposed through a combined framework of online optimization and central pattern generation (CPG) [100,101]. In this framework, each module runs a nonlinear oscillator to control the oscillations of its servomotor. Individual oscillations are coupled together in the chain formation over the wireless Bluetooth network to synchronize and smooth the motion pattern of the assembly.

With this synchronization, different stable gait patterns can be demonstrated by tuning the parameters of the CPG that defines the frequency, the amplitude and the phase of oscillations. An online optimization routine running in parallel with the motion generator and implemented using Powell's algorithm, updates the parameters of the CPG in order to smooth-out the motion of the oscillators by converging to the limit-cycles of the motion after a short transient phase.

4.3.5. SuperBot

A final example of a hybrid whole body locomotion reconfigurable robot is the SuperBot system [102–105] (Fig. 18). Following the M-TRAN design for space exploration missions, SuperBot modules possess a similar structure with two half-cubes pivoting around a central link. However, in the case of the SuperBot, the link that connects the two half-cubes is capable of rolling around itself enabling the module to achieve rotation around three different axes. Each of these three rotations is actuated separately by a geared DC motor embedded inside the cubes along with complementary control boards and electronics.

To enable connectivity and power and data sharing among modules, docking interfaces with electrodes are incorporated on all three faces of every half-cube. These interfaces are genderless, in the sense that any connecting surface of one module is capable of docking with any other face of an adjacent module in all 90° orientation intervals.

The control methodology in the case of the SuperBot was implemented using table-based and hormone inspired distributed controllers [106], with a software hierarchy separating low level device-specific code from high-level assignment driven routines. A special-purpose simulator was also developed to validate the kinematics and dynamics of any desired formation on a virtual terrain prior to real-time reconfiguration. With this control and simulation approach, SuperBot modules are among the few *WBL* modular robots that were tested in a real environment, such as on sand dunes [107] in uphill and downhill maneuvers replicating space terrain conditions.

5. Comparative analysis

In the previous paragraphs, the characteristics of different modular and reconfigurable mobile robots were presented separately,

Table 1
Benefits and shortcomings of reconfiguration categories and architectures.

	Benefits	Shortcoming
Mobile Configuration Change (MCC)	• Modules have individual efficient mobility which enables them to operate as a swarm in addition to reconfigurable capabilities	• Re-configuration is limited to specific locations on the grid which reduces the versatility and mobility patterns of the assembly. • Efficient individual mobility makes the modules more complex and expensive
Whole Body Locomotion (WBL)	• In a reconfigured formation, modules have a better versatility and can generate multiple locomotion patterns • The simplicity and under-actuation of the modules makes them simple and less expensive to build	• Modules are generally under-actuated and unable to provide efficient individual mobility. • Self-assembly after an accidental disconnection may be time consuming
Chain architecture	• Provides a higher versatility in reconfiguration where a chain formation can reach any point or orientation in space	• Control and motion planning is arduous since the number of neighboring components to every module in the chain is not necessarily finite and known at all time
Lattice architecture	• Control and motion generation is easier because the ensemble of positions a module can occupy on the grid is finite and well defined • The simpler computational representation allows scalability to more complex formations	• Discrete motions are often associated with inefficient mobility patterns since the formations are reconfigured in 3D patterns, such as a cubical or parallelepipedic lattice, providing mobility via continual relocation of individual modules on the grid
Hybrid architecture	• Combines the benefits of both chain and lattice architectures in terms of versatility, task space and parallel control	• Higher versatility and hybrid formations complicate the mechanical infrastructure and pattern generation protocols of the robot

and the related discussion was organized based on reconfiguration approach, architecture, and size considerations. In this section, a cross-assessment of the capabilities of each robot is presented in order to establish a comparative scheme that highlights critical aspects of existing modular robots.

In Table 1, a comparative analysis is summarized to highlight the broader benefits and shortcomings of the two reconfiguration categories identified in this paper (WBL *vs.* MCC), as well the benefits and shortcomings pertaining to the different architectures that define the shape formation of modular robots (chain, lattice, hybrid).

In Table 2, the robots discussed in this survey are aggregated based on the configuration (WBL *vs.* MCC), the architecture (chain, lattice, hybrid) and the size (macro *vs.* micro). The docking interface for each robot is also highlighted – in addition to the year of invention – in order to expose the different approaches adopted to implement the key enabling component of modular reconfiguration (docking).

In Table 3, five selected aspects of modular robotics are emphasized for each robot presented in this paper. The first aspect denotes the shape of the module, while the second highlights the number of DOFs incorporated on each module. This second aspect accounts for the DOFs that generate mobility or movement for the *module*, and does not take into consideration the DOFs that actuate the *special-purpose* docking interface.

The third aspect highlights the mobility and manipulation capabilities of every robot through a True(1)/False(0) scheme that reflects whether a given robot is capable of providing mobility and manipulation (1/1), or whether its capabilities are only limited to mobility (1/0). Through this scheme, it becomes a simple observation to note that, in general, current modular robotics technology falls short of combining both aspects in a single platform, where most robots tend to favor mobility over manipulation.

The fourth aspect reflects the autonomy of reconfiguration for each robot. A scale of 1-to-3 is adopted to highlight this aspect, with scale "1" denoting manual reconfiguration accomplished by an operator assembling the modules. Scale "2" denotes a semi-autonomous reconfiguration where – for example – a formation is designed on a graphical interface and commanded to the robot to replicate it in real-time. Scale "3" denotes an autonomous reconfiguration where an embedded algorithm accomplishes such shape formation without direct human intervention. In the latter, it is important to note that such level of autonomy was only demonstrated through carefully selected and controlled scenarios.

The fifth aspect reflects the *major* mobility patterns that can be delivered by every robot. Such comparison was established with a numeric scheme that highlights the versatility in mobility (*i.e.* the nature and number of patterns) that characterizes every robot.

6. Future directions and opportunities

The comprehensive discussion and the tabular comparison of the state-of-the-art modular mobile robotic systems presented in the previous sections exposed critical limitations that delineate the current status of the modular robotics technology. These limitations can be recapitulated into five major challenges that refer to the hardware and algorithmic infrastructure of the technology.

6.1. Docking and coupling

Docking mechanisms represent the key enabling component of modular robotics. It is the rigidity of this interface that defines the applications of a modular robot, and the maximum number of modules that can be docked in a specific formation without causing undesirable disconnection as a result of the robot's weight [108]. Therefore, when the coupling mechanism is developed with a technology that provides no rigid connection between modules on the grid, the practicality of the modular robot becomes questionable, and its applications will be limited to carefully controlled environments such as inside research laboratories.

As this survey shows, three-dimensional *self-reconfigurable* rigid docking remains an unsolved problem as equally noted in [109]. In fact, current coupling techniques such as the ones summarized in Table 1 are – for the most part, with the exception of manual reconfiguration – characterized by the non-rigidity of their docking interfaces which are predominantly developed using unreliable mechanisms such as magnetic or SMA-actuated latching devices. These devices significantly limit the number of modules in the formation, the payload capacity, and the maneuverability of modular robots on rugged terrain. Such limitations make rigid-structure robots a more favorable choice for real-time applications, despite the superiority in functionality that modular robots exhibit.

Addressing this issue starts at the module's level by investigating novel approaches for docking interfaces that provide rigid, reversible, and non-back-drivable three-dimensional coupling between modules. Mechanical systems, such as the ones demonstrated with ATRON, represent a step in the right direction for this investigation, where traditional non-back-drivable passive components – such as lead screws and worm gears – can be employed as

Table 2
Docking interfaces of different reconfigurable robots in the chain, lattice and hybrid architectures.

	Reconfiguration type	Architecture	Structural attribute	Robot name	Year	Docking interface
Reconfigurable robots	Mobile Configuration Change (MCC)	Chain architecture	Macro-size	S-Bots	2006	Robotic gripper
				Uni-Rover	2002	Robotic gripper
				JL-I, II robot	2006	Mechanical connector/coupler mechanism
				Millibots	2002	SMA actuated latches
				AMOEBA	2006	Link-type interface
	Whole Body Locomotion (WBL)	Chain architecture	Macro-size	Tetrobot[a]	1996	Multi-link spherical joint
				ACM[a]	2000	Revolute joint
				CONRO	1998	Magnets and SMA connectors
				PolyPod[a]	1994	Bolted connection plates
				PolyBot	1998	SMA latching connectors
				GZ-I robot	2006	Bolted connection surfaces
				CKBot	2007	Magnetic docking interface
		Lattice architecture		EM-Cubes[a]	2008	Permanent and electro magnets
				OCTABOT[a]	2007	Electromagnets
				Metamorphic[a]	1993	Electromechanical male/female connectors
				Crystalline	1999	Mechanical latching connectors
				Odin	2008	Manual with flexible connectors and joints
				I-Cubes	2000	Interconnecting links
				Catoms	2005	Electromagnets
				Telecubes[a]	1999	Permanent magnets
				Crystal robot[a]	2002	Rotating channel-key type connectors
				Fractum[a]	1999	Permanent and electro magnets
			Mini-size	Stochastic 3D	2005	Latching mechanism
				Robot by Yoshida et al.	2000	SMA latching connectors
			Transformable mechanism	Robot by Tokashiki et al.	2003	Permanent magnets
		Hybrid architecture	Macro-size	Roombots[a]	2010	Mechanical latching fingers
				MTRAN-I	2002	Permanent magnets and electrically actuated SMA detaching mechanism
				MTRAN-II	2003	Permanent magnets and thermally actuated SMA detaching mechanism
				MTRAN-III	2005	Permanent magnets and a rotating latching mechanism
				*i*Mobot	2010	Manually connected faceplates
				Molecubes	2005	Permanent and electro magnets
				ATRON	2003	Electromechanical male/female connectors
				YaMoR	2004	Manual screw and nut connection
				Thor[a]	2010	Manual genderless magnetic connectors
				SuperBot	2004	Mechanical connectors

[a] Robot was featured in the context of the paper without being thoroughly discussed.

a fundamental underlying technology to provide rigidity and non-back-drivability in coupling for real-terrain applications. Such interfaces encompass a broader industrial component, where they can benefit other applications that require system-to-system rigid, reversible and non-back-drivable coupling such as space docking and air-to-air refueling maneuvers.

6.2. Autonomy

Autonomy in mobile robots has always remained at the core focus of a broad research thrust in robotic applications. Specifically, for modular mobile robots, the need for autonomy is fundamentally magnified because of the large number of articulated joints that constitute a modular grid in the docked configuration. If the robot does not possess some aspects of autonomy, a very elaborate involvement of a human operator would be required for the motion-generation process and the execution of tasks, where the robot depends directly on operator-initiated directions to carry out assignments. Without these commands, most existing state-of-the-art robots cannot operate and become incapable of executing the fundamental task of self-reconfiguration.

Developing a modular robot that is fully autonomous however is beyond the reach of the current technology. This is because autonomous behavior, in general, is a multi-disciplinary research that depends significantly on the evolvement of other scientific disciplines such as mathematics and statistics. Without this underlying evolution, intelligent behaviors in mobile reconfigurable robotics remains limited to very specific aspects of modular autonomy, on the account of fully autonomous systems.

To address these challenges, a long-term objective of future investigations should first focus on the integration of existing individual autonomous algorithms as a stepping stone for a higher level of modular intelligence. The aggregation of these algorithms would deliver a more independent generation of modular robots, and in the process, unveil critical unforeseen shortcomings that would instigate new findings in the underlying science that supports the development of fully autonomous systems.

6.3. Locomotion patterns

For many modular and reconfigurable robots, the locomotion patterns of individual modules or small-chain assemblies are not practically efficient. For instance, a cubical module with one revolute degree of freedom sharing connections with two other similar modules in a chain architecture exhibit limited maneuverability on a flat terrain. This maneuverability is reduced to either in-plane or out-of-plane undulations. In the event of an accidental disassembly, such locomotion pattern proves considerably slow in gathering sub-assemblies of modules together in order to repair the original configuration, such as in the case of the CKBot.

For real-time applications, these inefficient mobility patterns are detrimental to the accomplishment of an unsupervised task on a real terrain. Thus, albeit a debatable subject, future research direction should take this challenge into consideration, and evolve modular locomotion to patterns that provide reasonably efficient mobility and practical maneuverability at the module's level, as well as at the assembly level.

Table 3
A comparison of different selected aspects of modular robotics.

Robot name	Module's shape	DOFs per module[a]	Locomotion/manipulation[b]	Reconfiguration autonomy[c]	Mobility patterns[d]
S-Bots	Cylindrical	9	1/1	3	1, 2, 8 [1,6]
Uni-Rover	Manipulator arm	5	1/1	1	2 [11]
JL-I robot	Trapezoidal	4	1/0	3	1, 8, 9 [12]
JL-II robot	Trapezoidal	4	1/1	3	1, 8, 9 [14]
Millibots	Parallelepipedic	3	1/0	1	1, 8, 9 [16]
AMOEBA	Parallelepipedic	3	1/0	1	1, 8 [22]
Tetrobot[h]	Truss	1	1/1	1	3, 6, 7 [23]
ACM[h]	Wheeled frame	1	1/0	1	2, 8, 9 [26,27]
CONRO	Cylindrical	2	1/0	3	3, 6, 7, 9 [29,30]
PolyBot	Cubic	1	1/0	3	3, 6, 7, 9 [33]
PolyPod[h]	Cubic	2	1/0	1	3, 6, 7, 9 [35]
GZ-I robot	Cubic	1	1/0	1	6, 9 [39]
CKBot	Cubic	1	1/0	3	3, 6, 9 [40,41]
EM-Cubes[h]	Cubic	0	1/0	2	4 [46]
OCTABOT[h]	Cylindrical	0	1/0	3	4 [49]
Metamorphic[h]	Hexagonal	3	1/0	3	4 [52]
Crystalline	Cubic	1	1/0	3	4, 8 [56]
Odin	Cylindrical	1 or 0[e]	1/0	1	10 [59,60]
I-Cubes	Cubes and links	3	1/0	2	8 [61]
Catoms	Cylindrical	0	1/0	3	4 [47]
Telecubes[h]	Cubic	6	1/0	3	4, 8 [66]
Crystal robot[h]	Parallelepipedic	2	1/0	3	4, 8 [67]
Fractum[h]	Triangular	0	1/0	3	4 [70]
Stochastic 3D[h]	Cubic	0	1/0	2	5 [74]
Robot by Yoshida et al.	Near-cubic	0	1/0	3	4 [77]
Robot by Tokashiki et al.	Cylindrical	1	1/0	3	2, 4 [78]
Roombots[h]	Near-cubic	3	1/0	2	5, 6, 7 [79,80]
MTRAN (I, II, III)	Rounded parallelepiped	2	1/0	2	3, 6, 7, 9 [81,83]
*i*Mobot	Rounded parallelepiped	4	1/1	1	2, 4, 6, 9 [90,91]
Molecubes	Cubic	1	1/1	2	3, 5, 6, 9 [43]
ATRON	Near-spherical	1	1/0	3	4, 6, 8 [94,95]
YaMoR	Parallelepipedic	1	1/0	1	3, 6, 7, 8 [97,100]
Thor[h]	N/A[f]	1 or 0[g]	1/1	1	2 [99]
SuperBot	Cubic	3	1/0	2	3, 6, 7, 9 [102,105]

[a] Number of DOFs does no account for the actuation of the special-purpose docking interface.
[b] Numbers denote the following convention: 1: True, 0: False.
[c] Numbers denote the following autonomy scale: 1: Manual, 2: Semi-autonomous, 3: Autonomous.
[d] Numbers denote the following mobility patterns: 1: Tracked, 2: Wheeled, 3: Rolling, 4: Planar Linear or Rotary, 5: Biped, 6: Quadruped, 7: Spider, 8: Train formation, 9: Undulations, 10: Spatial contractions and expansions.
[e] 1—DOF for an active link, 0—DOF for a passive link.
[f] Thor modules are heterogeneous. Thor robot is assembled manually from an ensemble of different modules and connectors.
[g] 1—DOF for an motor module, 0—DOF for others.
[h] Robot was featured in the context of the paper without being thoroughly discussed.

6.4. *Modular manipulation*

Manipulation in robotic applications is a genuine need that has become a common denomination of rigid-structure robots. In modular robotic applications however, manipulation is often regarded as a secondary asset to locomotion as reflected in Table 3, where only few reconfigurable robots are capable of combining the two attributes in the same modular morphology.

Without a gripper and a manipulator arm, the interaction of the robot with its environment is limited to sensorial perception with no ability to act upon its surroundings, which further restrains the practicality of modular robots in real-time applications.

Future research developments should focus on addressing this shortcoming by incorporating manipulator arms as an integral body of modular and reconfigurable robots. This will extrapolate the value of modular robots to include, not only multiple and exotic locomotion patterns, but also scalable and reconfigurable manipulation enabling the robot to interact with its surrounding and execute useful tasks such as object placement and multi-arm manipulation.

6.5. *Field testing*

One of the most significant shortcomings of modular and reconfigurable robotic research is the inaptitude of most existing technology to operate on a real terrain. Field testing reported in the literature is predominately restricted to carefully controlled environments such as inside research laboratories. While this represents a necessary preliminary step towards further developments, laboratory testing is in general not sufficient to demonstrate the feasibility and practicality of a prospective modular robot on complex terrains.

Future investigations in the field of modular and reconfigurable robots should integrate field testing as a complementary component of this research, evolving in tandem with other considerations of coupling mechanisms, modules' size [108] and algorithms aimed at integrating modular robots in unstructured topologies. This is ultimately the environment where these robots are projected to operate (planetary exploration, inspection, search and rescue in collapsed buildings, life support on other planets, etc. [110]), and thus the practicality of a candidate design should be evaluated in the real environment in addition to preliminary laboratory testing.

7. Conclusion

This paper reviewed the state-of-the-art contributions to the methods and algorithms related to the field of modular and reconfigurable mobile robotics. A classification of such contributions was proposed under two major categories: mobile configuration change (MCC) and whole body locomotion (WBL). The *WBL* category was further divided into three sub-categories: chain architecture, lattice architecture, and a hybrid combination of both.

Under the lattice architecture, a distinction between macro robots and mini robots was suggested based on the characteristic dimensions of the modules in the assembly. The survey discussion further highlighted stand-alone reconfigurable mechanisms for modular robotic applications, and presented a tabular comparison of different aspects of modular robotics, including docking interfaces, mobility patterns and level of autonomy among others.

Despite the achievements accomplished in the field of modular and reconfigurable robotics based on the current state of the technology, significant challenges still persist with regards to all aspects of hardware, software and experimental validation. Those shortcomings relate primarily to docking interfaces and autonomy, which represent the enabling element of modular and reconfigurable robotics. Without autonomy, rigidity and non-backdrivability in coupling, large reconfigurable assemblies are not possible, and modular robots will remain vulnerable to the constraints of a real-terrain, where the ruggedness of an unstructured topology represents a major challenge for reliable mobility and maneuverability in practical applications.

For many prospective research developments in this field, understanding the current state of the modular robotics technology will be an invaluable starting point. Henceforth, the authors hope that the material presented in this paper will originate a better understanding of the challenges and limitations attributed to modular and reconfigurable robots, and from that, initiate further developments with the objective of integrating modular robots in a real, urban and unstructured environment.

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