Comprehensive Review on Modular Self-Reconfigurable Robot Architecture

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Abstract - *Self-reconfigurable modular robot is a new approach of robotic system which involves a group of identical robotic modules that are connecting together and forming structure that able to perform specific tasks. Such robotic system will allows for reconfiguration of the robot and its structure in order to adapting continuously to the current needs or specific tasks, without the use of additional tools. Nowadays, the use of this type of robot is very limited because it is at the early stage of technology development. This type of robots will probably be widely used in industry, search and rescue purpose or even on leisure activities in the future. Hence, this paper is written in order to review on self-reconfigurable modular robot technology that has been developed to this day for the purpose of the future researcher on this topic. This paper is structured as follows: modular robots hardware architecture, control architecture, modular robot challenges and open-source modular robot (Dtto) review.*

Key Words: modular, robot, architecture, self-reconfiguration, Dtto, technology, open-source

1. INTRODUCTION

Mostly in natural disaster situations for example an earth-quake, we will face a situation where people get trapped and unable to be found as soon as possible due to the unpredictable terrain. Due to that situations, nowadays researchers all over the world work on robotics technology that will give an impact to the search and rescue field. According to Robin Murphy cited by Carol Hamilton, robots are being seen as scouts that able to adapt and perceive; and robot will be small and can fit into small subhuman confines as they able to move as snake throughout rubble [1]. Hence, the idea of modular self-reconfigurable robot (MSR) based on CEBOT in 1988 [2] spark an interest to the researchers to fit the search and rescue purpose.

Self-reconfigurable modular robots can also be known as Modular Self-Reconfigurable (MSR) robotic system. Theoretically, MSR robots are able to change their own shape by rearranging the connectivity of their parts to adapt with a new circumstances or tasks. Conceptually, the best example of an MSR robot that shows how this robotic system works would be the robots called "Microbots" from the Big Hero 6 film directed by William Don Hall. In this movie, a character named Hiro create a lot of Microbots that able to be controlled by neurotransmitter. They are designed by Hiro to connect together to form various shapes and perform tasks cooperatively Hall and Williams [3]. The idea of that movie concept is multiple robots that able to change shape in group being controlled by human thought.

The MSR robot is build based on the electronics components, computer processors, and memory and power supplies, and also they might have a feature for the robot to have an ability to connect and disconnect themselves to perform various tasks. Having the quality of being "modular", in MSR robotic system, it is to have a basic intent to have an unrestricted number of identical modules or a specific small set of identical modules, in a mesh or matrix structure of self-reconfigurable modules. The advantage of combining multiple matrices into a single matrix is the ability to form larger or elongated, more complex structure. In the early 1990s, MSR robots were shown to have the ability to perform the task of locomotion. One MSR robot module by itself might not be able to move or locomote by itself, but the collective behaviour of the robots of many modules could move itself from place to place and achieve many different locomotion gaits [4] such as a slinky, caterpillar, or rolling. The development of prototypes for MSR robot derived from experience on basic locomotion. Majority of the module developed is based on available resource at specific time which sometimes restricted MSR capabilities due to slow technology advancements

A review on multiple MSR robots hardware architecture in this paper is done so that a better understanding on MSR robot can be achieved with better solutions for MSR robot provided with the latest technologies. It can be generalized that, re- search on modular robots is one of the challenges that provide opportunities in robotics field in term of automation, control, motion planning and the creation of the modular robot itself.

2. MODULAR ROBOT HARDWARE ARCHITECTURE

Nowadays, the MSR robots architecture is becoming better along with the technologies. As the first prototype MSR robot being developed called CEBOT, it is consisting of separate heterogenous units that capable of binding together. The research involving CEBOT was directed for development of different MSR robot structure that mimicking the biological organism such as snake [5]. According to Moubarak and Ben-Tzvi, MSR robots were categorized according to the locomotion of the individual modules and co- ordinated structures along with form factors. There are several ways of categorizing the MSR systems. Moubarak and Ben-Tzvi also stated that MSR system can be generally differentiated into hardware architectural groups based on the geo- metric arrangement of their unit and several systems exhibit hybrid properties, Mobile Configuration Change (MCC) and Whole Body Locomotion (WBL) [6]. The accepted classification is based on how frequent of attaching locations, which is based on the moving methods between locations or according to the perspective of possible structural formations when the MSR robots bind together. The accepted configurations or architecture for current MSR robotics system are brought together and categorized into several categories which are Chain, Lattice, Mobile, and Hybrid. MSR robots also being categorized as Stochastic, Deterministic, Trusses and Free-form system.

2.1 Chain Architecture Structured Systems

Modular units of this architecture connected in string and form chains. A chain based MSR system is consists of several modules that are organized in groups of serial chains connections. The chain architecture for MSR robot is always attached to the rest of the modules at one or more points, and they able to reconfigure by attaching or detaching from each other [7]. Compared to the other architectures, chain architectures are more versatile because their capability through articulation able to reach any point in continuous space. But to reach certain point, a chain form of several units is necessary, hence making it usually more difficult to accomplish a reconfiguration. It can be said that the disadvantages of this architecture is, it is more difficult to control and more difficult for computational analysis [8]. An example of Chain architecture MSR robot is PolyBot, which is inspired for capability of forming 3D structures [9][10]. Each module of PolyBot is equipped with a brushless flat motor and harmonic drive which provide a single rotational DOF. PolyBot also being developed with sensors for communication with neighbor PolyBot module. There are 3 generations of PolyBot [10][11][12]. There are actually four versions of G1 PolyBot which known as G1V1, G1V2, G1V3 and G1V4. The first 3 versions are a quick prototypes with modules bolted together. The G1V4 of PolyBot was developed as a test bed for experimenting with different gait modalities and sensors. Since it is not self-reconfigurable, the experimenting gait is needed for those gaits chosen autonomously to match environmental requirement for next generation of PolyBot [13].

The increasing number of modules will also increase the cost and the robustness decreases as there is software scalability and hardware dependency issues. However, the goal for PolyBot G3 is to show 200 modules using robust autonomous locomotion, manipulation, and reconfiguration. Standardized BLDC motor with multi-stage planetary gear cannot satisfy the volume and form constraints of PolyBot G3. Hence, a modified custom Maxon pancake motor was developed for G3 [12]. The PolyBot G2 has been used to demonstrate some gaits implemented which resemble rolling track and straight sinusoid snake-like locomotion which proves PolyBot has variety of capabilities [12]. There are many applications of the PolyBot which is sufficient with a fixed set of configurations. Hence, pre- planned configurations can be made offline and stored for easier reconfiguration [9]. The comparison between three generation of PolyBot (G1, G2 and G3) are summarized in Table 1.

Fig -1: Structure differences between PolyBot (G1, G2 and G3)

Table -1: Comparisons of PolyBot (G1, G2 and G3)

Dimension (cm)	5 x 5 x 4	11 x 7 x 6	5 x 5 x 4
Reconfigurability	Manual	Self	Self
Bus	RS485 (G1v4)	2 CAN buses/ Module	2 CAN buses/ Module
CPU	PIC 16F877 (G1v4)	Motorola power PC 555+ 1M external RAM	Motorola power PC 555+ 1M external RA
Communication	50Hz PWM signal		
Sensor Applied		Infrared emitters and detectors, proximity sensor	Infrared emitters and detectors, proximity sensor
Connection Mechanism	Mechanic al	Electrical SMA actuator	Electrical SMA actuator
Reference	[13]	[7]	[10]

Fig -2: PolyBot versatile locomotion (left) rolling track; (right) snake-like locomotion [12]

Another type of MSR system by using Chain architecture is CONRO (CONfigurable RObot) designed by Castano et al. CONRO MSR robot was designed to form structures like snakes or hexapods in 3D. Each of CONRO module consists of three segments which are passive connector, body and active connector. The docking mechanism for CONRO and communication to each module are using feedback from IR transceivers which on the faces of active and passive connectors. The locking system in passive connector latches the module after docking which a pin/hole mechanism. Based on further research on docking and alignment issues for CONRO module, it is found that docking between independent groups of CONRO modules enables the merger of two or more independent self-reconfigurable CONRO robot [15].

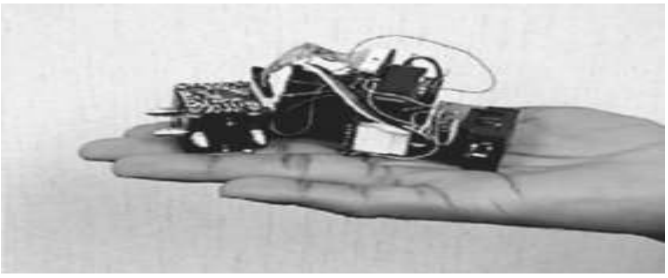

Fig -3: Self-sufficient CONRO module robot in motion [16]

Another MSR robotics system under Chain architecture is the YaMoR robot. YaMoR known as Yet another Modular Robot was presented by Moeckel et al. [17] in 2006. It is a semi cylindrical box structured robot that capable for forming a 2D chain structures. Each robot module has one DOF. Unlike CONRO robot, YaMoR does not support autonomous docking system. YaMoR robot is a complete integrated solution with a wireless communication using Bluetooth interface capabilities and FPGA for reconfigurable computation purposes. The casing of each modules is covered with strong velcros for correction with no restriction on angles between the surfaces of the modules and it being connected together by hand.

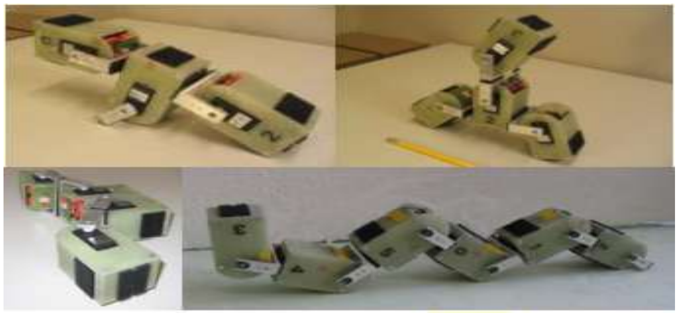

Fig -4: Different configuration of YaMoR robot [18]

2.2 Lattice Architecture Structured Systems

A lattice based MSR system can be categorized as their units connecting at docking interfaces and arranged in a grid structure in the form of 2D or 3D. For this category, a given module has discrete positions that they can occupy. This architecture network of docking interfaces is comparable to atoms and the grid to the lattice of a crystal [19]. The grid based structure of lattice systems generally simplifies the reconfiguration process compared to chain-based architectures where modules are free to move in continuous space. Kinematics and collision detection are comparatively simple for lattice systems. When lattice modules move only to neighboring positions, planning and control become less complex compared to when units move to any arbitrary positions [7]. Its architecture is able for simpler reconfiguration because control and motion can be executed in parallel [8]. This type of MSR architecture also demanding less programming. During self- reconfiguration, it exploits lattice regularity when aligning connectors for faster and easier self-reconfiguration. But, the lattice architecture system have a problem when it comes to big number of modules [20].

The first lattice structure category robotic design that capable of changing structures in 2D environment is metamorphic robotic system. A metamorphic robotic system based on Chirikjian [21], is a group of independently controlled mechatronic modules, each of which has the ability to attach, detach and climb over adjacent modules. Power and information are transferred through itself and being transferred to neighbor module. The locomotion of each module over its neighbors resulting change in the metamorphic root morphology. Hence, the metamorphic system capable dynamically self-reconfigure [22].

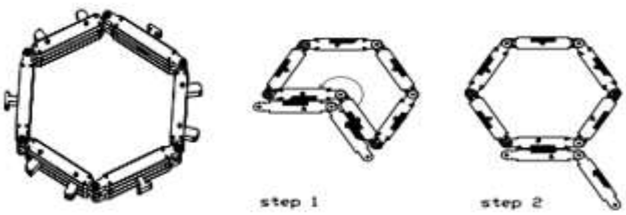

Fig -5: Design of a planar hexagonal module and module motion using electromagnetic coupling [22]

Besides that, another representation of MSR robot that employed this architecture is Crystalline module robot which is developed by Rus and Vona [23]. This module robot consists 3 DOF and formed by expand and contract movement each atom relatively to other atom. Crystalline capable to re- configuring in a dynamic fashion of any arbitrary geometric shape. By contracting and expanding a group of modules in coordinated way, Crystalline-module able to relocate. Without help, an individual atom module unable to relocate by itself [24]. The proposed algorithms for Self-repair only supporting 2D models and experimented in simulation [25].

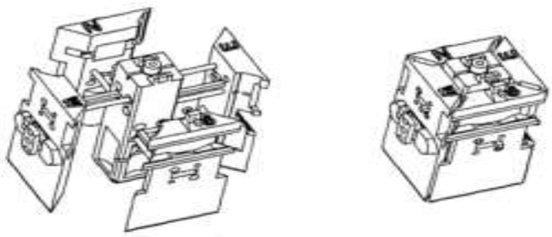

Fig -6: Design of a planar hexagonal module and module motion using electromagnetic coupling [22]

Another example of lattice architecture MSR robot is Molecule. Molecule robot was designed by Kotay [26] which is a 3D structure consists of two atoms and a right angle rigid bond binding them. The molecules exist in two versions, one with all female connectors and one with all male connectors. On side faces of each atom the connectors equipped with electromagnets. It has 2 degree of freedom as two-atom system bonded. The molecule MSR robot as a whole, able to provide for 4 DOF [27]. There are questions of the minimum number of Molecule robots that are required to satisfy the restrictions of known planning algorithms, as well as whether parallel transitions can speed up the planning and motion process.

Then, another lattice architecture modular robot is EM-Cube. EM-Cube was developed to have lattice architecture with 2 DOF. The appearance of EM-Cube is a cube shape of six tiles. Each module is utilized with a microprocessor, the Zigbee chip, electromagnets and permanent magnets. The modules are powered by wire and connecting modules with their movements are achievable by electromagnets with a soft iron core and eight permanent magnets [28].

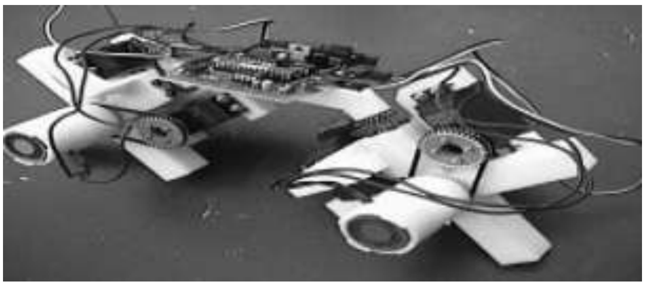

Fig -7: The molecule robot consists of two atoms and a right angle rigid bond binding them [26]

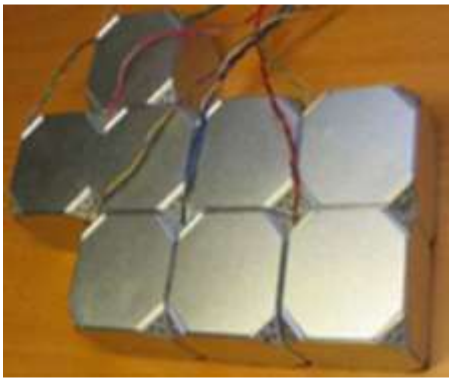

Fig -8: EM-cube which appear in cube shape of six tiles [28]

ATRON [20][29][30] is one of the modular robots in Lattice-based categories where its structures consisting of homogeneous modules. A module of ATRON is unable to move on its own unless with the aid of its neighboring modules. It's docking or connector mechanism is a mechanical type which is a point-to-point male/female hook scheme and the communication is establish by using Infrared diodes. The locomotion of ATRON is based on distributed control strategies. It is capable to perform locomotion in two type of categories which are fixed topology locomotion such as snake configuration and locomotion by self-reconfiguration which is cluster flow [30]. The robot is able to autonomously reconfigure between any reconfiguration as shown in Figure 9.

Fig -9: ATRON robot different configurations capabilities [20]

In 2011, a new homogenous lattice-based MSR robot has been proposed by Meng et al. [31]. The major feature of CROSS-Ball is as follow:

a) Several flexible reconfiguration capabilities, such as parallel, rotating and diagonal movements for forming 3D configurations.

b) A flexible and robust hardware platform and dedicated a motion controller works in a decentralized manner for MSR using more complex self-reconfiguration algorithms

c) The mobility of each individual module to simplify the configuration process under certain scenarios and potential applications to swarm robot

The docking mechanism for CROSS-Ball involving electromagnets which easily attach or repel from other module due to the dynamically changed of the poles of the electromagnets. Some configurations that can be built by CROSS-Ball can be seen in Figure 10.

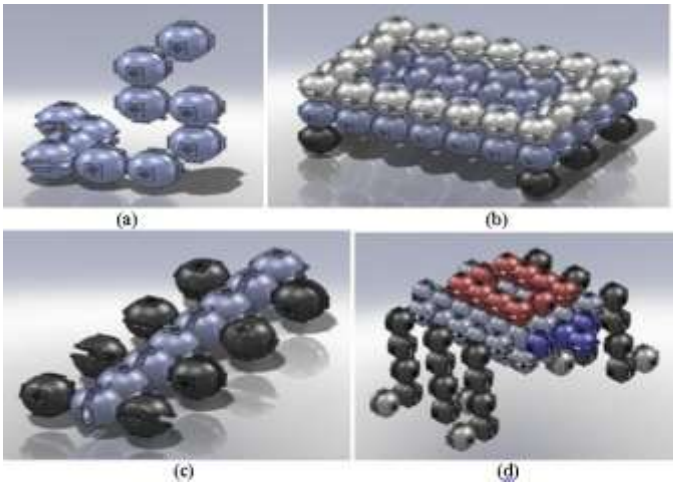

Fig -10: CROSS-Ball capabilities for propagate multiple configurations [31]

2.3 Mobile Architecture Structured Systems

The configuration of mobile type MSR is basically based on the mobile robot that moving around in the environment. As the mobile MSR being attach, they can be form in the type of chain or lattice. It maneuver independently using the environment to attach with other module at new location to form a new con- figuration. Compared to the other architecture, mobile architecture is less explored as the reconfiguration difficulty of out- weighs the functionality gain [7][8]. The first modular robot was developed by using this architecture. CEBOT was developed by Fukuda and Kawauchi in 1990 that consists of units called "cells" [2]. These cells can automatically communicate, attach and detach to perform a function which allows the system to self-assemble and self-repair. CEBOT is belong to mobile category comprising heterogenous modules and has two hardware prototypes as Series 1 and Series 2. The differences between both series of CEBOT is shown in Table 2. Series 1 CEBOT require precise control and alignment for docking. Tapered connectivity surface of Series 2 CEBOT give an active latch mechanism instead of SMA while maintaining the same docking process.

Table -2: Comparisons of CEBOT (Series 1 and Series 2)

Characteristic	CEBOT (Series 1)	CEBOT (Series 2)
Connectivity Surface	Flat	Tapered
Couple actuator	SMA	DC motor

The wheel mobile cell having mobile capabilities to initiate docking with the necessary cell. The position sensors mounted on the cells provide time to feedback on the docking process [32]. Another example of mobile configuration of MSR is based on research by Lucian Cucu in 2015. The developed MSR is a mobile climbing robot which is for self-assembled structure [33].

Fig -11: Self-assembly robot describe by Lucian [33]

The robot designed using treaded root with flippers which are actuated extension of the treads. Most components are enclose inside the robot chassis with the treaded design, hence it gives low probability for the robot to entangle to each other. The uses of flippers for the robot module is for the robot to climb the other robot module which could be at higher position and it also can be used in correcting its position as the robot fall and turn upside down.

2.4 Hybrid Architecture Structured Systems

Basically, hybrid architecture is a combination of both lattice and chain architecture where each architecture has their own advantages. This robot architecture is designed in term of lattice recon- figuration with capability to reach any point in continuous space as in the term of chain architecture. One of the MSR robots by using hybrid architecture is the SMORES. Each module consists of a single semi cylindrical cubic structure on which three of four side faces of cube are equipped with circular discs. The locomotion of the modules was designed using orthogonally placed gears. Each face is equipped with four magnets with the same polarity magnets occupying alternate positions and hence at a time eight magnets participate in docking when the connection plates face each other. The docking keys selector present internally can extend through the center of all faces creating necessary gap for undocking [34]. It has 4 DOF and the module is able to move in three possible reconfigurations which are chain, lattice and mobile. Each module has its own battery and communicates with a central computer over 802.11 WiFi [35].

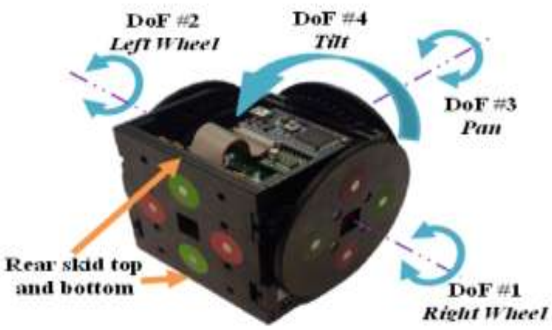

Fig -12: 4 DOF of SMORES modular robot [34]

Another modules robot with hybrid architecture is called M-TRAN which is developed by Murata et al. [36]. A module of M-TRAN was designed to have one passive and one active semi-cylindrical part which can pivot the link that connects between them and can form chains for performing tasks. When attempting to align with other module, two cubes of each module capable to occupy a discrete set of positions in space and attach to each other as in a lattice system for re-configuration. The connection surfaces designed to aid electrical connectivity between modules. The latching process is controlled by SMA coils by extending or retracting the mag- nets in passive units docked with magnets in links. M-TRAN has three versions which are M-TRAN (I) [36], M-TRAN (II) [37], and the latest module for M-TRAN is M-TRAN (III) which implementing new bonding mechanism with a mechanical latch that considered for stronger, faster and more reliable bonding mechanism compared to previous mechanism which is magnetic.

Fig -13: M-TRAN (I), M-TRAN (II) and M-TRAN (III) [38]

The M-TRAN (III) is an improvised designed in relation to previous version. The latching/delatching is replaced with hooks controlled by motor to provide better and more stable connection [39]. Further detail of M- TRAN, a series of software programs has been developed including a kinematics simulator, a user interface for designing configurations and motions sequences, and an automatic motion planner [36]. M-TRAN (II) is the second prototype where several improvements have took place to allow more complex reconfigurations. It has attach and detach mechanism with high-speed inter-module communication. The software also has been improved as well to verify dynamics simulation motions and to design self-reconfiguration processes [37]. The third prototype has been improved especially on connection mechanism. As mentioned before, the connection mechanism has been changed from the magnetic mechanism to mechanical mechanism where it used hooks controlled by motor to provide better connection. Several modes of modular robot control including global synchronous control, parallel asynchronous control and single-master control are made possible by using a distributed controller. 24 units are used for self-reconfiguration experiment by centralized and decentralized control [39].

Then, there is another Hybrid-based architecture of MSR robot which known as SuperBot robots, based on lattice and chain architecture. It is based on the features of others MSR robot which are M-TRAN, CONRO and ATRON and the SuperBot modules have three DOF [40]. Super- Bot is based on both Lattice and Chain architecture. It able to communicate and share power through their dock connectors. Besides that, SuperBot module have a position sensor and 3D accelerometer. The control of SuperBot is build based on previous work on [41]:

a) Hormone inspired distributed control

b) Table based control for fast prototyping

c) Phase automata for coordinating module activities

Benham Salemi et al. [41] also stated that, SuperBot control and coordination is based on distribute approach which is "Digital Hormone Control" [16][42][43].

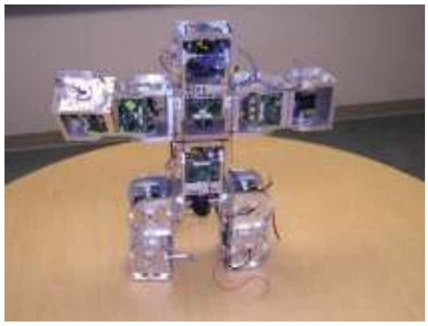

Fig -14: A network of SuperBot modules [41]

Another hybrid architecture which is based on lattice and chain is UBot [44]. It is in the cubic structure which has four docking surfaces and it is based on two rotational DOF. It has a hook-type docking mechanism and able to self-lock after connected with other UBot modules. As stated by Tang [45], sensor is need to be added to have the UBot able to interpret the environment information and make decision in real time whether to form a certain configuration or deform. Besides that, the module is being differentiated as passive and active module as in Figure 15.

Fig -15: UBot active module in black and passive module in white [44]

The UBot able to have different configurations such as snake-type and quadruped-walker without having hardware complexity of the robots. Hence, tradeoff between adaptation generality and high performance of robotic system can be avoided [45].

Another interesting robot that is categorized under Hybrid architecture is Swarm-bot or S-BOT. According to Mark Yim et al. in 2009, S-BOT was being categorized under mobile architecture [46]. As in Figure 16, the robot is a cylindrical shaped track robot, designed for swarm robotic research and it have a mobile characteristic. But, according to Chennareddy et al. [5], it is categorized as Hybrid be- cause of the capability of forming lattice structures in 2D and chain structures in 3D. It implemented with omnidirectional camera, sound emitters and receivers, torque sensors and traction sensors for physical contact information.

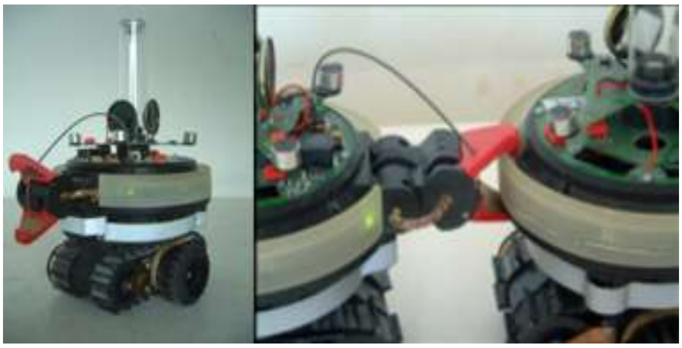

Fig -16: The S-Bot and S-Bot connection mechanism [47]

It employs with gripper mechanism for docking and there is an optical sensors present for feedback during docking process. It has a ring covering the periphery robot. The docking can be done from almost every direction as the ring present around the periphery. The robot able to navigate in uneven terrains. It has the same characteristic of modular robot such as reconfiguration and modularity [47] [48] [49].

Another modular robot which can be categorized as hybrid architecture is Sambot Instead of lattice and chain architecture, Sambot is a mobile and chain- based modular reconfigurable robot. Sambot has four degree of freedoms and the main body of Sambot is composed of two symmetrical halves (left and right) and the rotating mechanism of the active docking surface. The schematic diagram can be seen as in Figure 17. Sambot has been design to have each Sambot to be fully autonomous mobile robot and able to construct a robotic structure (such as snake-like configuration) which has the ability of locomotion and reconfiguration similar to chain-based reconfigurable robot. Sambot's communication is divided into two phases which are wireless communication in dispersed state and CAN bus communication in the communication state. The electrical connection being complete by CAN bus as the robots get connect to each other. Structure which is composed of multiple Sambot can have global communication through wireless communication that allows making autonomous decisions and realizing distributed control.

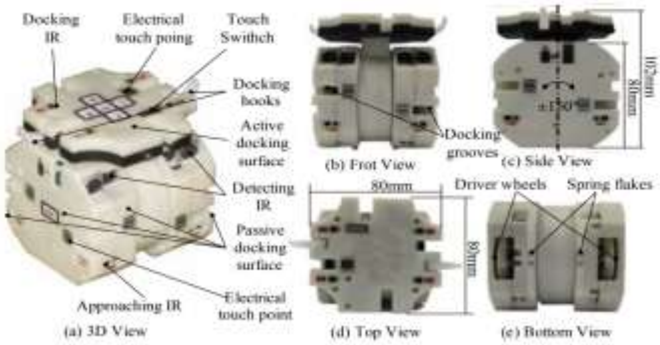

Fig -17: The Sambot schematic diagram [50]

2.5 Trusses Architecture Systems

Most of trusses system use scalable frame to change its topological structure. One of the first truss-type robotic systems that use telescoping links is Tetrobot robotic system. All links of the system can change length so that the system can easily change its shape [51]. Lyder et al. [52] developed Odin modular self-reconfigurable robotic system. Its module consists of heterogenous units: Cubic Closed Packed (CCP) joints and telescopic links along with capabilities to form structures in 3D.

Fig -18: Representation of ODIN modular robot [52]

The CCP has twelve female connector sockets, each with internal female PCB connector. The telescopic links are extendable cylindrical structures with flexible connectors on both ends equipped with male PCB connectors. In other words, it composed of three types of modules which are active strut module that can change length, passive strut module with fixed length and joint module that has 12 connection points [53].

The other truss-based architecture system has being proto-typed by Hamlin and Sanderson [51] [54]. It can forming random structures by using het- erogenous units which are links and joints. A three axis concentric multilink spherical joint is designed to hold three links together which capable of expansion and contraction in 3D. Joint is controlled using motors which reconfiguration is performed. Besides that, the conceptual truss design being prototyped by Ramchurn et al. [55] is called as ORTHOBOT. It is being simulated for structure such as hexapod which its locomotion is a coordinated system.

2.6 Free-form Architecture Systems

Several research groups have developed modular robotic system that are not based on Chain, Lattice or hybrid of lattice and chain. These free-form architectures have the ability to group modules into at least semi random positions. A prototype developed by Tokashiki et al. [56] was capable of forming free-form structures in 2D. Transformable mobile robot were being developed that consist of homogeneous gear-type units, equipped with gear on top and bottom of the cylinder which actuated by motors. 6 pole magnets were equipped to a robot for bonding between robots through attraction. The robot module can move around when the gears of neighboring modules locked with each other for maintaining the structural [56]. Besides that, another free form structured architecture modular robot can be reviewed based on the MSR robot called Claytronics. It is being developed by Goldstein and Mowry which in it has a cylindrical structure for demonstrating various structure in 2D and being called as Claytronic atom or Catom [57].

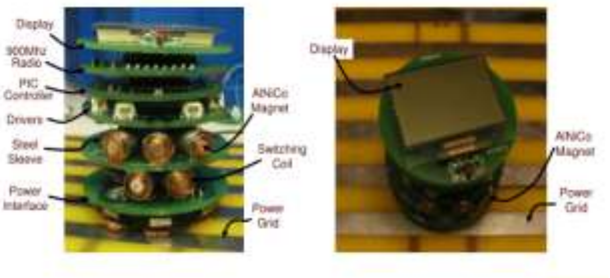

Fig -19: Planar prototype Catom [58]

Each Catom is 44 mm in diameter and equipped with 24 electromagnets arranged in pair of stacked rings. The module requires another module as it require support of neighbouring robots for forming structures and locomotion. The modules can implement various structures at much faster pace compared to rotating structures. The Catoms move around the other module and also adhere together as they are using forces generated onboard by either magnetically or electrostatically [57]. Another type of free form structure MSR robot is called Slime. Slime able to form structure that is similar to Claytronics. Each cylinder section is equipped with a Velcro to make contact with the neighboring robots. The spring action regulated by pneumatic air cylinders can extend and retract the cylinder for attaching and detaching between robots [59][60].

2.7 Other Classification

Another classification of MSR robot can be determined according to the way the units are reconfigured (moved) into place. It being categorized into two categories which are Stochastic reconfiguration and Deterministic reconfiguration.

Stochastic Reconfiguration

Stochastic reconfiguration system is involving the modules that able to move randomly and form structure by bonding in 2D or 3D environment. Modules move in a passive state in the environment. Once a module is in contact with another module, it will make a decision whether to bond or not. As the modules move in 2D or 3D environment, it uses a statistical process such as Brownian motion that used to guarantee reconfiguration times. The specific locations of every module are known only when it is attached to the main structure. The path taken to move between lo- cations might be unknown [8]. A stochastic MSR robot has been developed by Bishop et al [61] named Programmable Parts.

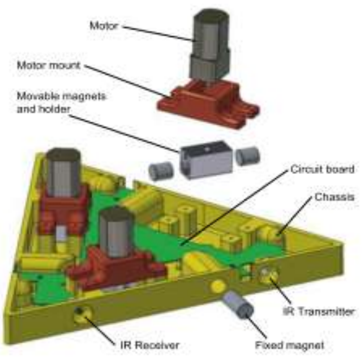

Fig -20: The component of Programmable Parts [61]

Programmable Parts can be assorted on an air table by over-head oscillating fans to self-assemble various shapes according to the mathematics of graph grammars. The modules can communicate and selectively bonding using mechanically driven magnets. Switchable permanent magnets are used for modules to bond to each other and communicates with the other module and decide whether to bonding with the module or reject the module. Programmable Parts are used in an experiment to show that it react similarly to chemical systems [61]. Then, kinetic rate data measurements are added by Napp et al. to produce a

Markov Process model by added the rate data to previous work of graph grammar [62].

Deterministic Reconfiguration

For deterministic MSR robot, the modules locomotion from one position to another position is in the lattice or chain form. Deterministic architectures modules move directly to their target locations during the self-reconfiguration process. The positions are known at all time for each module. For reconfiguration by this system, the amount of time it takes has been determined for a system to change its configuration. Macro-scale system is considered as deterministic and implementation of feedback controls needed to ensure an exact movement of MSR robot [63].

3. MODULAR ROBOT CONTROL ARCHITECTURE

The idea of MSR robot is for the system to work together to perform a specific task. Controlling a lot of MSR robot is a complex process as it is not the same as controlling one MSR robot in which theoretically it should be simpler. The establishment of a control architecture depends on the communication system built for specific MSR robot such as neighbor-to-neighbor communication by using infra-red (IR). The example of the modular robot that uses IR for communication between modules are PolyBot, CONRO and M-TRAN. Wireless communication is also possible, for example YaMoR module robot uses Bluetooth wireless as the sole means of inter- module communication [18].

Control architecture can be implemented by centralized control or decentralized control. Centralized control can be implemented on a local bus. Centralized control can be seen as it being implemented to PolyBot [9]. The local actuator positions of each module of PolyBot has its own controller. To set local behaviors, a master controller communicates to the module controllers. In other word, one specific unit sends commands to other unit modules and the action for this type of control system being synchronize. Centralized system is easier to be developed and analyzed. It can be said that the approach is straightforward to be implemented. The differences for the decentralized approach is that, all modules shared the computations. There are no specific unit to do the computation alone. It is determined as more robust than centralized approach and easier to be applied for MSR robot system that involve a lot of modules. Rather than have a master module, each module that being implemented with de- centralized approach will think for themselves as they being programmed with the same code. Unfortunately a complex task is hard to be achieved with decentralized approach. It is because behavior in distributed fashion is hard to be implemented [64]. Besides that, there is a proposed architecture that based on the biological hormone system. It had been proposed by Shen et al. [16]. Shen designed a control system that one or more modules need to start the hormone messages and this system is type of control which in between master and master-less. This type of control architecture is involving modules to communicate to each other locally where they receive, act or change the passing message. This approach for control treated all the modules identically hence it lends itself well to simple locomotion control.

3.1 Self-Assembly

One of the main benefits of modularity is the capability of self-assembly, which is the natural construction of complex multi-unit system using simple units governed by a set of rules. However, it is uncommon in technical field, be- cause it is considered as a new concept relatively in that arena although it could help in lowering costs and improving versatility and robustness, which are the three promises of modular robotics. The element may be homogenous or heterogenous; their binding properties may be fixed or dynamic; and they may have a range of capabilities such as ability to detect bind- ing events or exchange information with neighbours [65].

Based on the research done by Yim et al. [66], the ability for the modular robot to reassemble into one connected component has been demonstrated. Having different disconnected module requires decentralized control approach. The modules combination have its movement to be act in a coordinated manner. The modules facilitate a global CANbus which being included with electrical header and the modules also facilitate IR communication without electrical header. The global CANbus communication used as the modules is attached using screw but the IR communication module is connected to each other using magnet faces. This is the hybrid architecture for control method within a cluster using global CANbus and in between clusters by using local IR communication.

White at al. [67] studied stochastically driven self-assembly 2D systems in 2004. Algorithms and hardware for few systems were developed by them. The systems developed are triangular modules with swiveling permanent magnets that self-assembled into a line and then changed their sequence within the line. Another system that they developed was a system that uses square modules with electromagnets that self-assembled into an L-shape and then self-reconfigured into a line. Each unit had been distributed with configuration map for determining locally of its free bonding sites to activate in order to form a specific geometry. An alternative to the previous approach is to temporally moderate the formation such that cavities do not form through layered construction [67].

3.2 Self-Reconfiguration

Modular robotics spark an interest to researcher in the robotics field due to their ability to self-reconfigure [68]. Modular self-reconfigurable robots involve robot modules to combine with each other to perform specific task under certain [69]. This adaptability enables self-reconfigurable robot to accomplish tasks in unstructured environments;

such as space exploration, deep sea applications, rescue mission or reconnaissance [70].

4. CHALLENGES OF SELF-RECONFIGURABLE MODULAR ROBOT

The challenges that being face for the development of MSR robot is the hardware design of the MSR robot. Even though MSR robotic system has high adaptability, generally it is unsuitable for manufacturing applications because [71]: (1) High loads is involve in manufacturing environment and MSR can only maintain small force and the connections between 2 units cannot support large force transfer. (2) Real-time control involving complex kinematics and dynamic as it involve a large number of units and possible configurations. (3) As there are many bonding among the robot modules, it is difficult to achieve a high accuracy. (4) Impractical for autonomous robot configurations in industrial environment. Besides that, according to Yim et al. [8]. The self-reconfigurable robot also face a challenge in term of control and planning. As self-reconfigurable modular robot system involve multiple modules, high level-planning is needed to overcome realistic constraint such as: (1) parallel motion for large-scale manipulation, (2) optimization of reconfiguration planning, (3) handling failure modes such as misalignments, nonresponding units and units that behave unpredictable, (4) determining optimum configuration for given task and (5) synchronous communication among multiple units.

5. Dtto, AN OPEN-SOURCE MODULAR ROBOT REVIEW

Dtto MSR robot is being designed based on the hybrid architecture MSR robot called M-TRAN. The robot has been minimized as much as possible to have a large free space in half of the robot, so that it can be used by users to set up their preferred sensor such as Infrared (IR) sensor or install more actuators. It is 3D printable and at low cost. Dtto is modular robot built with 3D printed parts, servo motors, magnets, and readily available electronics. Each module consists of two boxes, rounded on one side, connected by a bar. The module can join with each other in many different orientations using the attraction of the magnets. It can be fully printed with 3D printers and has been designed using FreeCad software. The robot communicate to each other by Bluetooth and radio communication.

The idea of Dtto modular robot is to be designed so that it has the adaptability. The motivation idea for building Dtto robot is, by changing its configuration DTTO robot can move through a small area, then transform into a wheel like robot to move faster, then transform to a centipede robot when there is no vertical space and finally build a bridge to get to the other side of the hanging floor Dtto is groundbreaking in its ability to make modular robots experimentation available to roboticists everywhere by sidestepping what has traditionally been a high-cost undertaking [72]. Dtto robot can be seen as in Figure 21.

Fig -21: Dtto-Explorer Modular Robot [72]

To review Dtto modular robot in detail, we can review and compare between other 3D printed robot and M-TRAN robot because as mentioned before Dtto robot is inspired based on M-TRAN robot and it is being designed to be 3D printed.

According to Onal et al. [73] new method for robot fabrication is being called printable robot which can be used to rapidly fabricate capable, agile and functional 3D electromechanical machines. This printable process has been demonstrate that address the robotic area and it shows that 3D printing can be used for creating a robot-printing machine that requires no technical knowledge on the part of the user after automating some fabrication steps that were performed manually in the proposed system.

3D printed also being used for fabricating the components of a robotic arm. Qi et al. [74] has used 3D printing for robotics arm and it provide huge cost and time saving in fabrication. Besides that, 3D printing provided more precise dimensions for the robotic arm component. The robotic arm designed by Qi et al. [74] has 4 DOF and equipped with 4 servomotors to link the parts and move the robot arm. It is programmed for light material lifting tasks in order to assists in the production line in any industry. Besides that, another example of 3D printed robot is a modular underactuated hand developed by Raymond et al. [75]. The robot is a low-cost design with built in joint for being made through 3D printing. It is stated that the motive of this research is to have an open-source hand design that it can be reproduced and customize. By having this idea of design for public use, it will motivate researcher and quicken the innovation in the robotic field. As it is being compared between the open source designs with the existing commercially robotic hands, it is found that the open source hand presented compares favorably with the commercialized robot. The grip force of 10N was measured and the grip force will vary with respect to the selected finger parameters [75]. Another example of an open source 3D printed robot is a robot called Poppy which is the first complete 3D printed open source and open hardware humanoid robot. Poppy is designed to conduct robotic experiments and integrate several key abilities in an easy-to-use robotic platform. It is easy to duplicate and affordable. Basically, this robot also allows anyone to customize or extend it for their own use [76]. Actually, from the review of those 3D printed robot, we can conclude the same with the open source Dtto modular robot. The purpose of building the robot is different but the goal for having a 3D printed method for robot fabrication is same.

Table -3: Similarities of 3D Printed Robot.

3D printed robot characteristic	**Review of the 3D printed robot**
Cost	All 3D printed robot were developed at low cost compared to the commercialized robot.
Motivation	To motivate researcher in term of the innovation of robot in research and educational setting in open source format. Also, simplify the assembly and manufacturing requirement.
Fabricating Method	3D printed fabrication

Besides that, as Dtto robot being inspired based on M-TRAN robot, hence it is necessary to review and make a comparison between those two robots for future robot analysis. First of all, the design of Dtto robot and M-TRAN robot is almost similar. It can be seen as in Table 4.

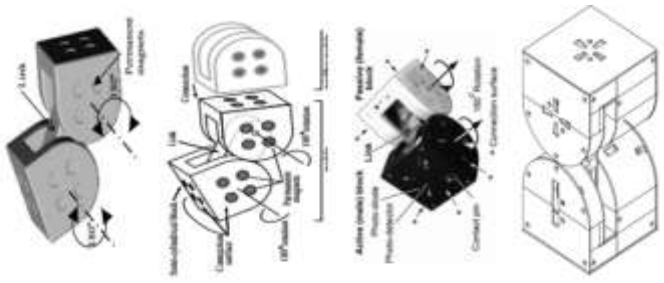

Fig -22: The design differences between M-TRAN I, M-TRAN II, M-TRAN III and Dtto robot

According to Mark Yim et al. [46], M-TRAN robot has 2 DOF. Hence, it makes Dtto robot also possess 2 DOF. Based on the design of the M-TRAN robot series with Dtto robot, the design is almost similar except the dimension of the robot. The module consists of two semi-cylindrical parts that can be rotated about its axis and with a link. At this moment, Dtto robot ability seems to resemble the M-TRAN module but the component use in Dtto robot is being minimized to only a basic state. Dtto modular robot need further improvement in term of its design so that it has ability to attach and detach with other module. Besides that, another improvement that can be made to Dtto robot is the ability for the robot to produce a twist motion relative to rest of modules like SMORES modular robot [34]. So, it will become more versatile and increase the number of configuration that can be made for Dtto robot. Other than that, basically DTTO robot has the same principle as other modular robot and it can be applied to robotic research purpose in term of hardware design, planning and control of the robot.

Table -4: Comparisons of DTTO and M-TRAN Robot

Dimension (mm)	66 x 66 x 132	60 x 60 x120	65 x 65 x 130	64 x 65 x 130
CPU	BasicStamp II	Neuron chip (Echelon Corporation) Three PICs	HD64F7047 HD64F3687 HD64F3694 (Renesus Corp)	Arduino Nano v3.0
Communication	Asyncronous serial	LonWorks & RS-485 (Global Communication) Asyncronous serial (Local Communication)	Bluetooth wireless modem (Zeevo ZV3001Z)	Bluetooth wireless RF24L01
Battery	DC 12V	Li-ion	Lithium-polymer	Lithium-polymer
Sensor Applied		Acceleration sensor	IR proximity IR diode IR sensor Acceleration sensor	InfraRed LED Emitter-Receiver (Optional)

6. GENERAL DISCUSSION

Generally, the size of the MSR robot modules is on the order of centimetre. Actually, several researcher have a goal which is to rescaling the modules to be in milimetre or micrometre scale. As an example, the Claytronics atom or CATOM modular robot has been visualized to be on nanoscale [57][58][77].Most of the reviewed MSR robot in this paper is based on the homogeneous modules but there is a heterogenous modules which including Odin [78]. Basically, the modular robot concept has fascinated researcher and it can be seen that there is an evolutionary path of the MSR robot system and basically in term of their system architecture from Chain or Lattice configuration only to Hybrid configuration. Besides that, there is a MSR robot which being designed for 3D printed which creates an opprtunity for mass production of MSR robot. But there are some inescapable aspects of MSR which create limitations and challenges for the researcher. At this point, the robot is being control to have its multiple configuration externally and the capabilities to change their configuration is limited to hardware constraints (Mechanically) besides some configurations that is difficult to achieve. Several type of configurations have been done for the MSR robot such as Snake or Quadruped walker. To ensure the robot is not being controlled externally, multiple sensor have to be implemented so that the robot can perceive the environmet

condition as information in real-time and able to make decision on their own in term of choosing their configurations. Most of the MSR robot are autonomous as each modules have their own processor and power supply. Each modules sensing abilities include sensing position, orientation, contact, proximity and gravity. Docking mechanisms of the MSR robot is based on electromagnets, permanent magnets, hooks and lock-key mechanism. It is believe that in future, MSR robot able to be implemented in real life as it have various potential such as space exploration, search and rescue, cooperative transportation, assisting the disabled and manipulating objects.

7. CONCLUSION

Nowadays, modular robot is a new technology that have a very high potential for application and making significant technological advances to the robotic architecture in general. It would lead to a changes as the system have high versatility and high robustness in term of automation. This technology has been developed as it is being identified with various possible future application such as for human machine interface and hence, lead to more specific research in term of algorithm and prototype validation. The details on scope of this paper are summarized within modular robots hardware architecture, control architecture, modular robot challenges and review of Dtto, open source modular robot. Summary from researcher in this field review have been addressing several challenges for modular robot, in term of hardware design and planning and control. Some improvements have been made but there are still a lot of improvement and new application by this system can be done. Besides that, this technology also being implemented with 3D printing method which create a potential for rapid fabrication of modular robot at low cost. This paper also reviewing the first open source modular robot called Dtto which developed by a team lead by Alberto from Hackaday.com. This paper intends to provide to provide a preliminary studies for researcher prospective by providing necessary information in term of innovations and technologies employed for modular robot research.

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