Development of a docking mechanism for self-reconfigurable modular robots

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Abstract—Self-reconfigurable modular robots are robotic systems consisting of a number of self-contained robotic modules that autonomously interconnect in different positions and orientations, thereby varying the shape and size of the overall modular robot. To facilitate reliable and efficient interconnection between them, constituent robotic modules must possess suitably robust and reliable docking mechanisms, based on a mechanically robust connector design, capable of facilitating sound inter-module power sharing and communication. In this paper, we briefly describe and discuss the prominent connector characteristics of existing self-reconfigurable modular robots, and in turn, describe the design, development and performance evaluation of a connector that possesses a combination of these prominent characteristics, with the intention to facilitate efficient self-assembly, self-reconfiguration and self-healing behaviors of a self-reconfigurable modular robot.

Keywords—Self-reconfigurable modular robot; robotic module; docking mechanism; connector

I. INTRODUCTION

Self-reconfigurable Modular Robots are robotic systems consisting of a number of self-contained modules that can autonomously interconnect in different orientations thereby varying the shape and size of the overall modular robot. This groundbreaking capability is what in theory, makes self-reconfigurable modular robots more suitable than conventional robots, for applications that involve uncertain or unpredictable challenges and tasks. These could range from navigation through unknown and unstructured environments, to autonomous 3-dimensional sculpture generation. In such surroundings, self-reconfigurable modular robots can autonomously self-assemble or reconfigure into differently shaped modular robots to suit the variable user requests or characteristics of their surroundings, thereby optimizing their usefulness. Moreover, the resulting self-reconfigurable robot could exhibit self-healing behavior where a malfunctioning module is easily replaced, thereby increasing the fault tolerance of the entire system. In this case, each connector should be able to individually engage and disengage the inter-module link, a feature referred to as single-end-operational capability.

To efficiently accomplish these self-assembly, self-reconfiguration and self-healing tasks, the constituent robotic modules require structurally robust and reliable connectors that facilitate reliable inter-module power sharing and communication. In addition, the docking procedure between any two robotic modules is required to be quick, energy efficient and accurate. This requires functional control and alignment processes, especially during autonomous self-assembly, where an initial pre-assembled structure of modules is yet to be formed. According to Nilsson [1] however, these control and alignment processes could be simplified if the docking mechanism of choice, aside from being robust, allowed for some misalignment. Given these constraints, a robotic module’s docking mechanism is a fundamental part of the overall self-reconfigurable modular robot, and its design must be carefully and properly established to avoid limiting the application of the entire system. Having said this, the design and development of such functional, structurally and electronically sound docking mechanisms is bound to be a complex and costly venture, which to date has significantly hampered the development of self-reconfigurable modular robots.

This paper however, primarily describes the design, development and performance evaluation of a functional docking mechanism, composed of a connector that combines and possesses the favorable characteristics of functional docking connectors of existing modular robots. Section II highlights the connector design fundamentals that form the basis of an ideal docking mechanism design, after which the docking mechanisms and connectors of existing modular robots are briefly analyzed in Section III. Section IV then describes the detailed mechanical and electronic design of the proposed docking mechanism and connector. Following the installation of two connectors on two robotic modules, the performance of the docking mechanism and the installed connectors is then evaluated and recorded in Section V. Lastly Section VI summarizes the findings of this work before proposing the focus of any future work related to this project.

II. CONNECTOR DESIGN FUNDAMENTALS

As highlighted in [1]–[3] there are several features of an ideal connector that form part of a functional self-reconfigurable modular robot. The first of these is genderless-ness, which refers to the structural similarity of all connectors such that any one connector can dock onto any other. A
second feature is 90° symmetry where two connectors can dock in one of four orientations about their central axes. The connector’s surface should also embody one boundary box, where all protruding artefacts are fully retractable to fit within the connector. Moreover, the connectors should be small in size, be able to tolerate docking guidance misalignments, and allow for fast and simple docking procedures and sensor integration.

The connector’s latching mechanism should also be simply actuated, consume no power in static state, confer the ability to detach from faulty modules, and provide a stable connection with a manual override function. Structurally, the connector should have a high latch load and high impact strength to prevent easy breakage. It should also be protected from the environment and be composed of a minimal number of moving parts for easy maintenance. Lastly, the ideal connector should provide reliable inter-module power and signal transfer.

Existing docking connectors only possess and optimize subsets of the features described above. The goal of this project is therefore to integrate and combine of all these features into a single connector, a challenging task that is heavily influenced by the design of the robotic modules themselves.

III. BRIEF ANALYSIS OF EXISTING DOCKING CONNECTORS

Existing docking connectors can either be classified as: (i) Magnetic, (ii) Electromagnetic, (iii) Electrostatic, or (iv) Electromechanical. In this section, we briefly describe the suitability of docking connectors that fall within these categories. General schematic representations summarizing the existing docking connectors are shown in Fig. 1.

A. Magnetic

This connector category is shown in Fig. 1a. The most prominent of these are the M-TRAN I and II modules, that use permanent magnets to establish a connection and Shape Memory Alloy (SMA) coils and a non-linear spring to break the connection [4], [5]. Permanent magnets and non-linear springs however, require careful calibration and adjustment, thereby complicating the production process.

Modular Fracta [6] used a combination of permanent and electro magnets arranged in 120° intervals and separated into three layers. This mechanism facilitated inter-module infra-red (IR) communication via transceivers embedded in the magnets.

Telecube modules [7] exhibit connectors each made of an Ertalyte (semi-crystalline unfilled polyester) structure that holds a printed circuit board, sets of sliding magnets and magnetic iron alloy metal pieces to establish the inter-module connection, and IR transceivers for inter-module communication. Helical springs and SMA wires are then used to break the connection, and misalignment tolerance is achieved by 45° male/female matched surfaces. One major drawback however was the tendency of the magnetic pieces to corrode due to their high iron content.

B. Electromagnetic

This connector category, also illustrated in Fig. 1a, suffers similar drawbacks to those of the magnetic category. However, if module structure is simplified, and mass and volume minimized, electromagnets perform well as connection agents, as seen in original Molecubes [8] and Molecule [9] modules.

Robot pebble modules [10] are seen to use electro-permanent magnets, which are solid state devices that allow a magnetic field to be modulated by an electrical pulse. No electrical power is required to maintain the field, only to do mechanical work or change the device’s state. According to Gilpin et al. [10], the electro-permanent magnets also transmit power and facilitate inter-module communication.

C. Electrostatic

This connector category is shown in Fig. 1b. A lightweight electrostatic docking mechanism involving flexible aluminum foil electrodes coated with dielectric film is described in [11], where the electrodes are glued onto plastic panels and fixed onto several combs. A voltage applied to a module’s face establishes a connection with another module.

According to Karagozler et al. [11], power sharing and inter-module communication using the same electrostatic interface is possible but still inefficient. Shortfalls of this approach are a ‘peeling’ effect between charged combs that weakened and broke the connection, and residual charge and wrinkles in the flexible electrodes that introduced air gaps and minimized the contact area respectively.
D. Electromechanical

PolyBot G2 modules [12] incorporate a connector that holds electrical contact elements, grooved pins and holes, a latch return spring actuated with shape memory alloy (SMA) wires, and infrared (IR) transceivers for inter-module communication. No energy is consumed in static state.

As described in [13] and [14], CONRO robot modules exhibit gendered active and passive connectors. Each active connector is grooved and has a spring actuated latch for establishing a connection, and SMA wires to disengage the connection. Each passive connector has pins that penetrate the grooves of the active connector. It is reported in [15] that using the CONRO reconnectable facet, CONRO modules could exhibit self-healing behavior. This is however only attributed to the delayed response of SMA wires during connection disengagement. The connectors of PolyBot G2 and CONRO modules both fall under Fig. 1(c).

SMA wires are described as slow and power consuming [5], with M-TRAN III modules employing hooks to establish a connection between gendered connectors of docking modules. These connectors can however completely retract their hooks beneath the connector’s surface thereby exhibiting a one-boundary box design. The hooks are motorized and geared, and are designed in such a way that position errors are absorbed during docking. The connector also houses IR transceivers for local inter-module communication, and electrical and communication contact elements. Furthermore, no power is consumed by the docking mechanism in static state.

Two other connector types very similar to those of M-TRAN III modules are the Active Connection Mechanism (ACM) [16] and the connectors of the Roombot robot [17]. The ACM connectors however, are genderless, with both hooks and grooves, and are designed to withstand larger misalignment errors, forces and torques than MTRAN III connectors. This increases their complexity and size. The Roombot connector however exhibits a simpler design than the ACM connector, with fewer hooks, but suffers from a reduced maximum load capacity.

Sambot modules [18] employ worm driven hooks to establish and disengage inter-module connections. In addition, IR transceivers for docking alignment sensing are also incorporated with the connector, together with network communication contacts.

The connectors of ATRON modules [19] also employed worm gear driven motorized hooks, but differed from all previously described ‘hooked’ connectors by utilizing a point-to-point hooking system as opposed to surface-to-surface. Though more complicated in design and development, the connectors created robust connections that facilitated power sharing through flexible printed circuit boards, and IR communication transceivers and proximity sensors. In summary, the connectors of M-TRAN III, Sambot and ATRON modules, together with the ACM connector design all fall under the connector type shown in Fig. 1d.

The Cone Bolt Locking Device (CoBoLD) connector [2] as used in Symbrion and Replicator [20] robot modules consists of a geared worm actuated locking wheel, cone shaped locking bolts and groves that serve to establish and disengage a connection between two robotic modules. The connector design allows for a one-boundary box, exposes electrical contact pins and consumes no power in static state. The CoBoLD connector is categorized as type c in Fig. 1.

Lastly, SuperBot modules employed the SINGO connector [21], categorized as the electromechanical connector in Fig. 1e. This connector utilizes motorized jaws that clench together to establish the connection and move apart to disengage it. The specialized shape of the jaws significantly contributes to misalignment tolerance. And finally, no energy is consumed in static state, and the connector exhibited single-end-operational capability.

IV. DESIGN OF THE CONNECTOR

Following a detailed review of the existing connectors described in Section III, it was decided that a new docking connector be designed, based on the existing design of the CoBoLD connector. This decision was made as the CoBoLD connector exhibited more of the ideal connector features detailed in Section II than any other analyzed connector. As seen in [2], these include having a simple design with a minimal number of moving parts, allowing for a one boundary box design, being genderless and 90° symmetric, consuming minimal power in static state, and exhibiting sound misalignment tolerance of 5 mm shear and 20° roll orientations. It is also seen to facilitate quick docking, taking about 3 seconds to establish a connection.

The task at hand was therefore to design and develop a docking connector based on a mechanism similar to the CoBoLD connector, but with the additional characteristics of single-end-operation capability, docking alignment sensor integration and reliable power and signal transfer facilities.

A. Structural design and development

Fig. 2 and Fig. 3 below show the inner and outer structures and mechanics of the designed connector. As illustrated, this connector is made up of four key assemblies:

1) The Faceplate assembly

The faceplate assembly is composed of a grooved 100 mm x 100 mm x 2 mm sheet of ABS plastic that forms the outer surface of the design connector, and supporting mounting brackets. As seen in Fig. 2 and Fig. 3, the grooves on the connector’s surface include structural fastening grooves, PCB attachment grooves, IR signal grooves, bolt movement grooves and a centrally located cross-shaped electrical contact groove.

2) The Motor and Worm gear assembly

This is simply composed of a geared DC motor with its shaft fastened to a plastic worm gear, all of which is securely attached to the inner wall of the connector as seen in Fig. 2. The worm gear is precisely placed in position to mesh with the gear wheel assembly.

3) The Gearwheel assembly

This assembly comprises of a 5 mm thick ABS plastic gear wheel housed and precisely positioned to mesh with the worm
of the motor and worm assembly. Together, the motor and worm and gearwheel assemblies actuate the connector’s locking and unlocking mechanism, allowing it grab hold of and fasten onto another connector’s docking bolts, to establish a connection.

![Fig. 2. A CAD model of the inner structure of the docking connector mechanism that was designed for the UCT modular robot showing: (a) the motor and worm gear assembly as well as their support brackets; (b) the gearwheel assembly which is used to lock the docking bolts in place; and (c) the connector’s faceplate.](image)

4) **Four Spring Bolt assemblies**

Each spring bolt assembly consists of an ABS plastic mounting piece, a smooth metallic rod, a helical spring and a machined aluminum bolt as is depicted in Fig. 4. This design allowed for the retractability of a connector bolts into the body of the connector, thereby facilitating a one-boundary box design.

**B. Electronic design and development**

This section covers the printed circuit boards (PCBs) that were developed to sit on the connector’s inner surface, to facilitate docking alignment prior to docking, and inter-module power and signal transfer after docking. These include two IR PCBs and a Face PCB.

1) **Infrared (IR) PCBs**

A set of two IR PCBs are located on the left and right sides of the connector, whose functions are to receive and transmit the IR guidance signals necessary for the alignment of two modules prior to docking, as controlled by a docking alignment algorithm. Fig. 5 below illustrates an IR PCB, while Fig. 6 shows their placement on the developed connector.

![Fig. 4. A CAD model of one of the spring bolt assemblies designed for the robot, showing the aluminum docking bolt, spring, rod and mounting attachment.](image)

![Fig. 5. One of the infrared (IR) transmitter/receiver PCBs used to provide contactless docking alignment signals between two independent modules.](image)

2) **The Face PCB**

This PCB (i) facilitates power and signal transfer by exposing electrical contact elements through the centrally located cross-shaped groove in the connector’s faceplate, (ii) multiplexes sensor signals from the connector’s IR PCBs to a microcontroller that sits elsewhere in the robotic module, and (iii) governs the module’s dominance (ability to take control of a docked module’s docking mechanism) over another, thereby facilitating self-healing behavior of the robotic module.

The signals transferred between two docked modules include both input and output (i) dominance signals (DS), (ii) power and common ground, and (iii) pulse width modulated (PWM) motor control signals that facilitate self-healing behavior. These electrical contacts are arranged in such a way that the connector maintains 90° symmetry (illustrated in Fig. 6), able to dock onto another connector in any of four orientations.

Structurally, the PCB is intricately shaped, designed and placed to not only fit within the connector, but also to facilitate the retraction of the connector’s docking bolts via four outlet bolt grooves. Four additional groves on the PCB act as inlet bolt grooves, to facilitate the penetration of a
neighboring module’s docking bolts to reach the connector’s gear wheel assembly as illustrated in Fig. 3.

![Connector Diagram](image)

Fig. 6. A schematic of the electrical contacts found in the centrally located groove on each faceplate in the module. There are contact pins for power management, module control and docking signals.

V. PERFORMANCE EVALUATION OF THE CONNECTOR

Two fully functional connectors were developed based on the designs described so far. To evaluate their performance, they were installed onto the faces of two robotic modules that form part of the UCT modular robot. It should be noted that each module of the UCT modular robot has six faces onto which a connector can be installed. However, in this study only one face on each module was fitted with a connector, which was sufficient to evaluate the connector’s performance. This therefore limited the current version of the UCT modular robot to a chain-type architecture, which in turn limited its use to applications such as snake-like obstacle avoidance.

The robotic modules then underwent a series of tests that assessed the strengths and weaknesses of the developed connectors based on their design characteristics. These characteristics include:

1) Self-assembly, disassembly and reconfiguration

Self-assembly first required two undocked robotic modules to autonomously find each other in a controlled space and bring their connectors to within acceptable docking proximity, via their IR docking alignment guidance facilities installed on their connectors. At this task, the robotic modules successfully utilized their connectors’ IR guidance systems, but performed significantly poorly in aligning their connectors prior to docking. This was caused by the absence of accurate closed loop controlled locomotion of the robotic modules, and the general inaccuracy of the guidance algorithm utilized. When placed with their connectors fully meshed together however, with each connector’s docking bolts fully penetrated into the other’s, the two robotic modules were able to establish a connection within 3.8 seconds.

For self-disassembly, the two docked robotic modules had to sever the mechanical and electrical connection between them and physically separate from one another. The task of severing the mechanical and electrical connection was found to be consistently successful, taking on average 3.5 seconds to complete. The maneuver to physically separate however, was found to be successful 2 out of every 3 times, due to unintentional lodging of one connector’s docking bolts within the other’s faceplate.

Lastly, self-reconfiguration required only successful motion and gyration of the UCT modular robot to change its overall shape. The developed connectors provided the necessary mechanical and electrical stability to successfully facilitate these maneuvers.

2) Misalignment tolerance

This is a connector’s ability to successfully and securely mesh with its complementing connector given uncorrected misalignments following the docking alignment of their robotic modules. These misalignments could be described as (i) Linear shear, with the connectors misaligned in the direction perpendicular to their central axes, (ii) Rotational shear, with them misaligned about their central axes, or (iii) Linear gap, with them misaligned in the direction of their central axes, and therefore having a space between them prior to docking.

Following experimental analysis, it was found that the developed connectors could successfully mesh together with misalignments of up to 3 mm linear shear, 10° rotational shear and 2 mm linear gap.

3) Power and signal transfer, and self-healing

Following experimental analysis, it was found that power and signal transfer between docked robotic modules was only functional in one direction, due to improper meshing of the connectors’ electrical contacts. It is proposed that more efficient, smooth-tipped and spring-loaded electrical contacts be installed in future, instead of the tulip connectors currently in use. This shortfall adversely affected the modules’ single-end-operational ability, rendering the modular robot’s self-healing behavior only functional in one direction.

4) Steady state energy efficiency

It was found that the power consumed by one connector was 3.6 W while not sharing power, and 3.7 W when sharing power, all in static state. Although minimal compared to the entire module’s power consumption of 26.7 W and 26.8 W respectively, this did not meet the ideal connector requirement of not consuming any power in static state.

5) Structural stability

For a structural stability test, the two robotic modules were docked end-to-end, and suspended from one module’s undocked end. The connectors were able to withstand the hanging weight of one robotic module, which is 8.4 N.

6) Other general ideal connector characteristics

The developed connectors are genderless, 90° symmetric, occupied minimal space measuring 100 mm x 100 mm by 25 mm, affordable, relatively easy to manufacture, and simple with a minimal number of moving parts. They also provide sensor integration and protection. However, their moving parts are not easily accessible, and the retraction of the docking bolts to within the connectors’ bodies was slightly hampered by the frictional forces between the spring bolt assemblies’ helical springs and the surrounding artifacts. This prevented the connectors from exhibiting a one-boundary box design.
Fig. 7: A photograph of the inner and outer structures of the designed connector, showing (a) the docking mechanism, (b) IR PCBs, (c) the face plate, (d) four protruding docking bolts, (e) face plate grooves, (f) the connector’s Face PCB, and (g) a Face power PCB that distributed power to the connector’s other PCBs.

VI. CONCLUSIONS AND FUTURE WORK

The docking connector developed in this project successfully combined and fulfilled most of the ideal characteristics of a connector, as described in Section II. It is recommended that spring loaded electrical contacts be used in future designs of the power and signal transfer facilities, and a more friction-independent docking bolt retraction mechanism be investigated and installed. These changes would optimize power and signal transfer, self-healing modular robot behaviour, and the achievement of a one-boundary box design.

Improvements on the closed loop controlled locomotion of the UCT modular robot should also be considered so as to successfully utilise the IR docking guidance systems installed on the connectors.

The developed docking connector prototype and its implementation in the UCT modular robot therefore proved to be successful and viable bases for further study, investigation and research.

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