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Mechanical Design in Modular Reconfigurable Robotics: A Literature Review

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Abstract

This paper reviews recent research on mechanical aspects of modular reconfigurable robots (MRRs). Many newe MRRs have developed unique designs and hardware updated from the older, basic designs. The author compile research of recent innovations in MRRs to include in the contents of this paper. The paper will first begin with reviewin the background of the MMRs and the influences it took on to create it. MMRs were inspired by the idea of one joinin together with others to achieve a task not possible for a single individual. Based on this idea, MMRs have modules tha form different structures by attaching to one another in different positions. With these unique differences to othe robotics, the paper then discusses the numerous benefits MRRs brings to the table compared to traditional robots. Th discussion of MRRs' benefits also goes into territory of applications in space as MRRs could be used for i extraterrestrial expansion. Further in this paper, reoccurring designs of MRRs are analyzed, comparing older design to recent ones. Here, the paper goes over recent MRRs and review their designs and mechanisms in depth, breakin down how they are built and how they work. The paper then examines the sensing in MRRs and recent innovations i making modules more aware of their surroundings. The differences between old and recent for both internal an external sensing used in modules will also be discussed and covered. Throughout this paper, the discussions of th similarity and lack of change/innovation from old MMRs to recent MRRs will be covered. Then finally, the paper wi conclude with key findings determined by the author and what further research needs to be done on the topic.

Keywords: Modular Reconfigurable Robots, Space Applications, Robotics, Modular Robots, Truss Robots, Bonding Robots, Lattice Robots, Modular Self-reconfigurable Robots, Chain Robots.

1. Introduction

Over the past four years, around 17,500 scientific articles covering modular reconfigurable robots (MRRs) have risen up at the time this was written. This style of robotics has been inspired by the idea of individuals joining together to achieve a task not feasible for a single individual (Liu, et al., 2021). MRRs are robots made up of individual modules that work together as a system (Seo, et al., 2019). Modules reconfigure themselves into different shapes and forms by connecting to and detaching from other modules of the system, in other words, reconfiguring themselves. With MRR systems being able to function properly no matter the number of modules there are, these robotic systems are able to be repaired easily and able to continue its tasks without certain parts (Zhao, et al., 2022). This makes MRRs better than non-modular robotics in certain applications where repairs might not be convenient or even possible. MRRs also bring a factor of versatility to the table as well. Because of their ability to reconfigure into all different shapes and sizes, MRRs can change their configuration to fit the task they need to accomplish next. However, there are some challenges to MRRs that traditional robotics often solves. Modular robots need to be connected with one or more modules, making a system, in order to work properly. A single module of a MRR by itself cannot function as intended. This makes the issue of needing to make perfect modules to have a steady fixed connection to communicate to one another (Zhao, et al., 2022). Imperfect manufacturing could result in a system failure because the system relies on a connection that could easily be broken with poor dock alignment as an example. However, with these disadvantages aside, MRRs show great potential to solve a multitude of problems that traditional single-body robots cannot as later presented in this paper.

One of the earliest pioneers of MRRs is Yim et al.'s PolyBot (2000). The PolyBot displayed the use of individual modules that could attach to and detach from other modules. The PolyBot has around one thousand citations at the time this was written and influenced many other current MRRs' designs. Yim et al. (2003) also remarks in another paper that the PolyBot and other articulated robots would be ideal in space applications as it met requirements in space manipulation.

As more MRRs start showing up in the robotics industry, this paper aims to cover the different examples of new MRRs and its applications. This paper is structured as follows: Section 2 will give an overview and explanation of the space applications of MRRs; Section 3 reviews common MRR designs by going in depth into each robot of each design, seeing how they functions with their design; Section 4 will cover the hardware inside the MRRs and how it works; and concluding the paper in Section 5.

2. Applications of MRRs

MRRs have and are being used in vastly different applications over the years it has been developed upon. One of the most prominent fields MRRs are being used for is space applications. With the commercialization of space by private corporations becoming more relevant in recent years, extraterrestrial living solutions often cite back to MRRs (Romanov, et al., 2021). Robots could be sent in swarms to other planets or moons to build shelter autonomously. This reduces the risks and resources required to have humans build shelter outside of Earth. MRRs are the most ideal type of robot for these missions as they carry their own advantages over a traditional robot too. MRRs are better at navigating through obstacles that might be abundant in other planets/moons and are easier to maintain. Because of their module design, they can adapt to the environment easily by changing their shape and size. This also help with maintenance as faulty or trapped modules could be easily detached to the system of modules and the robots would still function together fine with the remaining modules in the system.

3. Commonly Seen Designs in MRRs

There have been various different designs of MRRs, where all are designed to take on different challenges and problems. This paper will be discussing commonly seen designs in MRRs.

3.1 3D Lattice design

The 3D lattice design has its MRRs be connected in a web-like network where modules could be attached to another module in any angle that is 90 degrees away from another point of connection. One of the earliest pioneers of a 3D lattice reconfiguration design in MRRs were Romanishin et al. and the M-blocks (2013). Romanishin (2013) designed modules that were cubes that could be set next to or stacked on top of other modules and would magnetically attach to one another. These modules could move up and down vertically to a different plane by rotating 180 degrees in a certain direction and move horizontally in the same plane by rotating 90 degrees. However, this reconfiguration process is only able to be done locally. Modules are only able to move to a position where there is a neighboring module present already. In past years, there has been barely any innovation or change in the designs of the 3-D lattice MRRs. The use of the hybrid design in MRRs have caused the 3D lattice design to decrease in popularity due to the hybrid design utilizing features from 3D lattice MRRs and other designs. Nisser et al.'s ElectroVoxel (2022) and Leal-Naranjo et al. (2021) both use designs almost identical to the M-Block. Both researches proposed a cube shaped module that had the same movements as the M-Block. Also, 3D lattice MRRs all seem to use magnets to attach to other modules.

3.2 Chain design

The chain design has its MRRs be attached to one another in a chain-like architecture where modules connect to each other from the back and front, forming a link. A great example of this design is Murata et al.'s M-TRAN (2002). The M-TRAN modules are made up of two boxes attached with a link that provides the boxes to rotate. These boxes are of a semicircle prism shape with the rounded side of each box facing each other. On the flat side of each box, there are magnets that attach to the flat side of boxes of other modules. Murata (2002) designed the M-TRAN this way so it's modules can metamorphose into different configuration that can generate a walking motion without external help. The chain design offers length for the system of the MRR as modules could easily connect on either side and build a long structure. Other than the M-TRAN and other older MRRs, the chain design is not seen in newer innovations because designs of newer MRRs are usually of a hybrid design, a combination of 3D lattice, chain, and other designs.

3.3 Hybrid design

The hybrid design combines elements of the 3D lattice and chaining to assemble the MRRs. The best example of a MRR of this design is the SMORES-EP module by Liu et al. (2021). These modules are cube-shaped with four connectors that could attach to other modules on the sides of the cube. Three of these connectors are shaped in a circle and could work as wheels and rotators that spin the modules attached to it. The fourth connector functions as the bottom of the module and is square-shaped without the ability to rotate. They designed the modules this way to add vertical movement to the robot without have the modules stack on top of one another like Romanishin et al.'s M-blocks (2013). Hauser et al.'s Roombots (2020) are another example of the hybrid design for MRRs. Hauser's (2020) hybrid design takes 3-D lattice designs and added a new element to make it do so much more. Roombots modules have a rounded cube shape and are diagonally split into hemispheres. Each module has six connectors, one on every side of the cube, that can attach to other modules. The hemispheres of each module have three connectors on it and can rotate around the other hemisphere. The split in each module sets it apart from other designs of MRRs. Another unique hybrid MRRs design is found in Zhao et al.'s SnailBot (2022). As the name tells, Zhao (2022) designed his SnailBot modules to be snail shaped (sphere shaped) with a base that holds six wheels. These wheels are split into two trains, one with two sets of wheels and other with one set of wheels. Splitting the wheels into two trains makes climbing onto other modules possible. The train with two sets of wheels lifts up and rolls onto another module and the train with one set of wheels stays onto the surface it was originally placed on, whether it be another module or a flat surface. This way the module can attach to different modules magnetically and maneuver its way to different spots while on other modules. Zhao (2022) with the SnailBot takes older designs of 3-D lattice MRRs and their actuations and makes them smooth and less jagged, like how a snail would move. There seems to be a lot more variation in hybrid designs of MRRs compared to the other designs already covered. Like the 3-D lattice MRRs, hybrid MRRs are seen to have a more cube like shaped module with the exception of the SnailBot. However, hybrid designs tend to be used more in MRRs because of its versatility, getting the most range in motion and having the most convenient bonding motion. Additionally, hybrid MRRs, like 3-D lattice MRRs, also have magnets to assist the bonding processes or be the bond between two modules.

3.4 Truss design

The truss design in MRRs has its modules connected to one another in at least two points of contact and more often than not are connected to several other modules. Connections between truss modules are also manipulatable, which is the main method for the MRR moving. This way, when the modules change their size and/or degree they are connected to the other modules, the whole system is moved like that. One example of this design is Qin et al.'s TrussBot (2022). The TrussBot modules are triangular pyramid shaped. Qin (2022) designed each corner of each module has a hook with a rubber band that is used to attach to other modules, so that the connection flexible between the two modules. There are two different types of modules depending on object on the inside: battery modules and actuated modules. Each battery module holds a battery that supplies power to the whole system of modules with the other battery modules. Actuated modules have a servomotor in the center of the module that pulls in and releases a fishing line that is connected to other modules. This is for moving the system of modules by contracting and stretching the fishing line like a tendon. Another innovation in truss designs in MRR comes from Stuart et al. (2021) and the Balloon Animal Robot. Modules of the Balloon Animal Robot are untraditional where they don't make up the MRR shape but instead are cinches that are wrapped around an inflated tube that makes up the MRR. Stuart (2021) designed the Balloon Animal Robot to be soft so that the robot would be able to reconfigure into varying landscapes in vastly different situations. Each module is straw-shaped with rollers on the inside side that rotate with a drive mechanism. This way modules can move up and down the inflated tube they are wrapped around on. Each module also has a winching mechanism and a cinch mechanism. The winching mechanism is a motor attached to a string that is attached to other modules' winching mechanism on the other end. This is for pulling and pushing parts of tube closer or farther together by pulling in and releasing the string. The cinch mechanism is a motor also attached to a string, but the string is wrapped around the inflated tube and both ends of the string are attached to the same module. This is for closing the tube to make joints for bending the tube by reeling in the string. The combination of these mechanism makes the inflated tube be to twist and form structures from a previously straight inflated cylinder. Truss design in MRR vary in structural build up, but seem to have string to actuate movements. This design tends to be applicable in more specific situations and is more difficult to work with.

4. Hardware

When it comes to MRRs, the hardware that is needed to make the design come to life is equally as important as the design. In this section, the paper covers how modules bond together, move from rest, and sense their orientation and environment.

4.1 Actuation

Every MRR has a method of action physically interact with other modules or the environment around it. This action is known as actuation. In this sub-section, the paper will talk about actuations and the actuators, the mechanism that made the action happen, that MRRs employ for bonding and movement.

Bonding Actuation

Bonding actuation is the action that physically connects or attaches one module to another module. MRRs, similar to design, have vastly different methods for bonding to other modules and different mechanisms to do so. One common method of bonding is by using magnets. Romanishin et al.'s M-Block (2013), Murata et al.'s M-TRAN (2002), and Zhao et al.'s SnailBot (2022) are some examples of this bonding actuation, both using permanent magnets to bond modules together. However, Liu et al.'s SMORES-EP (2021) also uses magnets to bond modules together, but SMORE-EP uses electro permanent magnets instead of the popular permanent magnets. Liu's use of electro permanent magnets allows SMORE-EP modules to easily attach and detach by just turning on and off the magnet instead of having a separate mechanism to break the bond between modules that is needed for modules that use permanent magnets to bond together. This trend of using electro permanent magnets in bonding actuations is rising as Nisser et al.'s ElectroVoxel (2022) noted that they would research into the use of electro permanent magnets in the future for the ElectroVoxel. Putting aside this small difference between the uses of permanent magnets and electro permanent magnets, the actuation process for both of them are similar. Magnets are put on the surface of a module that is meant for attaching to other modules and magnetism holds the modules together. Another common method of bonding is using a hooking mechanism. Hauser et al.'s Roombots (2020) and Qin et al's TrussBot (2022) are some examples of this bonding actuation, both having their modules use hooks to latch onto other modules. Hauser (2020) has his modules hook onto connection plates of other modules and Qin (2022) has his modules hook onto rubber bands in other modules to physically attach both modules together. The use of hooks compared to magnets has its arguments. Hooks provide a stronger link between modules and more degrees of freedom for movement between the two linked modules than magnets do. However, magnets give modules an easier and faster method for attaching and detaching to other modules. It is ultimately dependent on the situation and task the MRR is in or tasked to do that determine which actuation is favored.

Movement Actuation

Movement actuation is the action that moves modules of an MRR to other modules or to the environment. With varying designs, MRRs have many different ways of moving from one place to another. One common movement actuation is rotating a part of a module. Whether this be wheels on Liu et al.'s SMORES-EP (2021) or hemispheres of Hauser et al.'s Roombots (2020), many MRRs just use a motor to rotate parts of a module to alter the module's position. In the case of Liu and Zhao et al.'s SnailBot (2022), their MRRs have wheels to roll to other places, whether it be to another module or the environment. Another movement actuation in MRRs uses string. Qin et al.'s TrussBot (2022) and Stuart et al.'s Balloon Animal Robots (2021) both use string to move their modules closer together or farther apart. In both robots, two modules that are distanced apart are physically connected via string and have a winching mechanism to reel in or let go the string to move their respective system. Lastly, another movement actuation in MRR is internal actuation. This type of actuation has its MRR move to different places without interacting with other modules and the environment physically. This is the case for Romanishin et al.'s M-Blocks (2013) and Nisser et al.'s ElectroVoxel (2022). Romanishin (2013) designs his modules to move from its bonded modules by using a flywheel inside each module to create torque strong enough to break away from the force from the magnets and move to a different location. On the other hand, Nisser (2022) designs his movement actuation mechanism to use magnets on each module to repel and attract other magnets on other modules to move the module to a different spot. Movement actuations in MRRs, more so than bonding actuations, are heavily dependent on the design of the MRR.

4.2 Sensing

In order to have physical actuations function correctly, MRRs also have to have some method of detecting other modules and the environment. Without sensing, modules would not know where to traverse to and bond with other modules if they were out of their initial positions. In this section, the paper will address innovations in internal sensing and external sensing.

Internal Sensing

Internal Sensing in MRRs is seen to be needed to do two things, provide precision for docking and track the position of each module's degrees of freedom. Degrees of freedom (DOF) stands for the parts of a module that have actuated movement (Liu, et al, 2021). Precision docking is incredibly important to ensure self-reconfiguration of MRRs as modules in order to connect to other modules reliably have to dock accurately. Docking is often seen being assisted by infrared and linear hall-effect sensors, for example in Hauser et al.'s Roombots (2020). The infrared and linear hall-effect sensors on each module of the Roombots detect the existence of other modules in the area and the distance it is from other modules or the environment. With the sensors put under the connection plates of the Roombots modules, the combination of infrared and linear hall-effect sensors with magnets guides the connection plates of modules to the perfect position for the bonding actuation. The position of each module's degrees of freedom is needed in order to know the next actuation for reconfiguration or moving. To know the positions of these degrees of freedom on each module, sensors such as encoders and estimation algorithms are used to calculate the positions. For example, Liu's SMORES-EP (2021) uses customizable sensors and an algorithm to predict each module's wheels'/connection plates' orientation. SMORES-EP modules use this info to determine how much to rotate each wheel/connection plate to get to the system's desired configuration or location.

External Sensing

External sensing in MRRs helps modules detect the environment and other modules in the area. External sensing is less essential to the MRRs function compared to internal sensing, but this doesn't excuse its existence. A great example of external sensing in MRRs is Hauser et al's Roombots (2020). Hauser (2020) proposes incorporating a camera to modules of the Roombots to enable computer vision for the robot. This could be used for detecting the environment, for example human beings, that could be useful for the furniture applications, what Roombots is intended to be applied to. However, most MRRs use a bus system where modules can communicate to one another as long as they are directly connected to a system of other already interconnected modules.

5. Conclusion

This paper reviews recent research of modular reconfigurable robots (MRRs), focusing on the mechanical aspects. Many newer MRRs have developed new, unique designs and hardware. This paper reviews and highlights the vastly different designs used and hardware implemented in recent MRRs, updating the repeated designs and hardware of older MRRs. Key findings in recent research of MRRs prove that mechanisms ideal for assisting in bonding or being the bond between two modules are dependent on the task the MRR is aimed to complete. Also, cube shaped modules are found to be more popular in design because its shape helps with the MRR's simplicity. However, further research needs to be done on external sensing of the environment. With space applications possible for MRRs, research should be conducted on MRRs being able to sense and adapt to its surroundings. Additionally, further research could be done on chain MRR designs, as there was a lack of chain MRRs compared to other designs like the popular hybrid design. With the chain design offering the option to be lengthy that other designs can't do as easily, research should be conducted to use the length of chain design MRRs in unique applications.

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