Emulating Self-reconfigurable Robots - Design of the SMORES System

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***Abstract*— Self-reconfigurable robots are capable of changing their shape to suit a task. The design of one system called SMORES (Self-assembling MOdular Robot for Extreme Shape-shifting) is introduced. This system is capable of rearranging its modules in all three classes of reconfiguration; lattice style, chain style and mobile reconfiguration. This system is capable of emulating many of the other existing systems and promises to be a step towards a *universal* modular robot.**

I. INTRODUCTION

Self-assembling and self-reconfiguring modular robot systems are capable of achieving varied complex tasks. Having the abilities of coordinated self-assembly and self-reconfiguration could allow a robotic system to adapt to different or changing environments on-the-fly. These robotic systems have the potential to exploit self-healing abilities with a reserve supply of low cost robot modules for increased system robustness. They are particularly well suited to situations in which they must adapt to tasks not known a priori such as search and rescue applications in unstructured environments, planetary exploration and deep space exploration. This paper presents the mechatronic design of a prototype robotic module for such a system.

There are dozens of groups who have constructed many versions of reconfigurable robots as included in a survey [19]. Over 800 papers and a book [15] have been written. These systems have exhibited a wide variety of locomotion and manipulation including: legged walking with two, three, four, six, and fourteen legs; riding a tricycle; snake gaits; manipulation of large objects with multiple arms/fingers; climbing stairs, poles, and pipes; self-reconfiguration between dozens of shapes; and many others.

There are three categories of reconfiguring systems: chain, lattice, and mobile [19]. Chain systems tend to be the most capable to do useful tasks, as they can form articulated limbs. Lattice systems tend to be the best at self-reconfiguration. Mobile systems have modules that individually maneuver on terrain. Of the systems that have been implemented to date, some that have been shown to be most capable (judging by number of demonstrations) are the hybrid chain-lattice systems: Superbot [13], MTRAN III [12] and ATRON [9]. Another recent interesting addition to the community is iMobot [7] and one from Johns Hopkins University which we will refer to as JHU [11] which are a hybrid chain-mobile system. Each module in these systems have the ability to travel on flat ground independently.

One feature that is inherent in all of these reconfigurable systems is that modules can attach and detach from other modules. Here, this attachment and detachment process is referred to as *docking* and *undocking* respectively. Methods for this process varies. Previously, systems have utilized retractable mechanical hooks, permanent magnets, Velcro™and electromagnets.

This paper presents a new module called SMORES (Self-assembling MOdular Robot for Extreme Shape-shifting) that aims to improve the versatility of self-reconfigurable systems. This system is able to replicate the movement abilities of many previously demonstrated systems. In one sense we are striving to develop a *Universal Robot* that is capable of emulating the movement abilities of other robots. This paper shows the SMORES modules' versatility in being capable of self-reconfiguration using lattice, chain and mobile module reconfiguration strategies.

II. DESIGN GOALS

The design goals for the robot can be broken into three parts: *System, Module and Docking* design goals.

a) System Design Goals: The SMORES system should be *polymorphic,* assuming many different shapes and configurations; *metamorphic,* changing between reconfigurations without physical human assistance and; *inexpensive,* not overly redundant so that the system becomes prohibitively expensive.

b) Module Design Goals: The dexterity of a system's modules limits flexibility of the whole robot system according to the Hardware Design Challenges suggested by Yim [19]. More specifically the modules should be able to reconfigure using lattice, chain and mobile style reconfiguration. The arrangement and number of DoF, number and type of docking ports, and geometric shape should enable the largest range of useful motions and configurations with the minimum number of actuators.

c) Docking Design Goals: The docking system should enable modules to connect in many useful arrangements. A system that can be manually placed in any configuration during experiments without needing power to the robot to connect/disconnect modules saves time during experiments. For this reason we want modules that can be easily manually docked/undocked. Another useful property we want for the connectors is impact resistance [20]. If a robot falls over or is subject to sudden impact such as an explosion, it is better if the modules disconnect rather than have the connectors physically breaking. For robustness, connectors should be able to disconnect from each other even if one of them is non-responsive. Finally, the docking connector should be fast

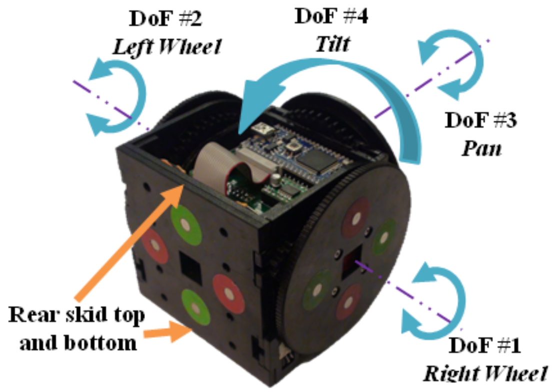


Fig. 1. Four Degrees of Freedom of a SMORES movement module

and power efficient, only using power when changing the state of its connections between modules.

III. MECHANICAL DESIGN

Mechanical design is focused on actuation and can be divided into, *module actuation* and *docking actuation*.

A. Module Actuation

There are two module motions of interest, one which moves docking ports relative to each other and module mobility in the environment.

SMORES has four active rotational DoF as illustrated in Fig. 1. DoF #1, #2 and #4 are parallel and coincident. DoF #3 is perpendicular to these three. Each module has three continuously rotating DoF (no angular limits on rotation), and one DoF (#4) limited to ± 90 degrees. DoF #1, #2 and #3 produce a twist motion of docking ports relative to the rest of the module. DoF #4 produces a bending joint.

In order to produce these motions, a geared drive train is used (Fig. 2). Here four identical gear motors with 9-tooth pinion gears drive four identical 48-tooth spur gears. A fifth 48-tooth crown gear is coupled to two of the previous gears. This fifth gear spins about the DoF #3 axis (pans) when the two inner ”Pan and Tilt” spur gears are rotated in the opposite direction. When the two inner spur gears rotate in the same direction, the gear rotates (tilts) about DoF #4. Note that this last action allows the torque of two motors to be combined to increase the torque for this DoF.

Mobile movement of individual modules has been achieved on other self-reconfigurable modular robots using wheels [6] [11], treads [8], the module’s DoF and geometric shape [13] [7], and external vibrations. On the JHU system, Kutzer et al. [11] include a docking connector on a wheel. This implementation requires trajectory planning to correctly align the connectors during self-assembly [16]. Orientation of the connectors is coupled to the module’s position on the ground plane in this design. Its two axially aligned wheels provide forward motion while the third wheel slips orthogonally to allow the module to move. iMobot [7] modules rotates two of its rounded square faces to produce an oscillatory, differential drive type motion. Scout [10] uses a differential drive design with treads.

SMORES has three connection plate disks on DoF #1, #2 and #3. The two opposing disks on DoF #1 and #2 are used as *driving wheels* and are slightly larger than the one on DoF #3. This allows differential wheeled drive locomotion of individual modules. Its advantages includes control simplicity, efficient forward motion, and a small turning circle. Driving wheels are fitted with rubber timing belts to provide grip. A third point of contact occurs on the edge of the square face of the module as a low friction skid, seen in Fig. 1. The center of mass is close to the geometric center of the module (over the wheels) so the skid see nominally light contact. There is also no rubber grip on the disk on DoF #3 which allows slip when contact occurs on this side. SMORES has demonstrated mobile movement on smooth flat surfaces and is capable of driving upside down. Some previous mobile module designs have not opted for this ability. Tilting the module (bending DoF #4) causes the skid and disk to make contact with flat terrain allowing SMORES to raise or lower the driving wheels. Raising the wheels allows SMORES to decouple connector orientation on the driving wheels without moving on the ground plane.

B. Docking Actuation

1) Number, Type and Arrangement of Docking Ports: A module’s number, type and arrangement of docking ports can influence the system’s overall complexity and versatility. The more space that is allocated to docking ports, the less space that is left for movement, or any other features on the module, if it is to remain the same size. The complexity of a module generally increases as the number of parts, and moving parts, increases. When designing a new module, the more connectors and DoF it has, it generally follows that module will have more moving parts and hence, could be more complex.

SMORES has one passive and three active docking ports (mapping to the three outer spur gears in Fig. 1). Active docking ports control the attachment process and passive ports only provide a physical space for a neighboring module to attach. All connectors on the module are genderless. The SMORES connectors are coupled to individual DoF and decoupled from each other. This means moving any DoF on the module will result in moving just one docking port with respect to the others which simplifies control.

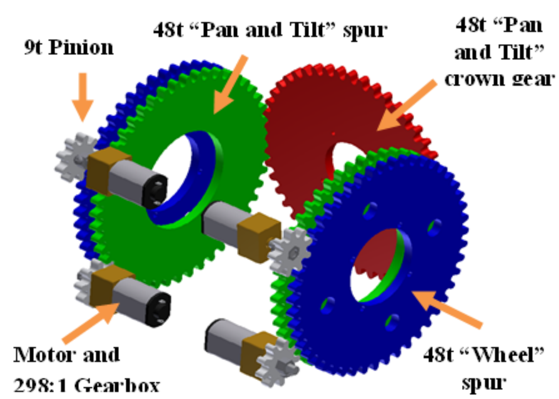


Fig. 2. Gear train and actuator arrangement

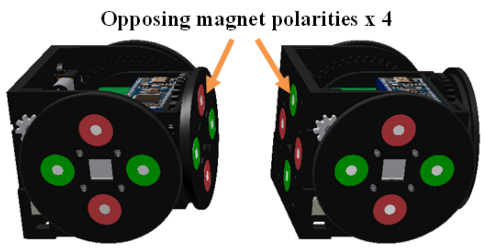


Fig. 3. Two modules prior to docking with opposite magnet polarity

The number of orientations that two mating docking ports can attach together can affect a module's versatility. For instance, M-TRAN [12], Polybot [18] and CKbot [20] modules can connect two mating connectors in four different orientations. ATRON [9] can connect neighboring modules in two orientations. In the case of the chain reconfiguration strategy, orientation can be limiting if connectors are not able to dock at arbitrary angles, even when the connectors are coincidently aligned. With SMORES and the JHU [11] design, the docking ports can rotate to any angle along the docking axis. SMORES can also do this with its active connectors to effectively connect active docking ports to neighboring modules in arbitrary orientations, as long as the docking ports have aligned the docking axis to be parallel and coincident.

2) Docking and Undock Sequence: The force provided to dock two modules together is provided by eight permanent magnets (four per connector). This allows for a connector that is easily manually reconfigurable, self-reconfigurable and impact resistant. Docking two ports together requires that the north (red circles) and south (green circles) permanent magnets are aligned. This is shown in Fig. 3. The pattern orientation keeps two passive docking ports from accidentally docking to each other while on the self-assembly plane. Connecting SMORES modules in a head-to-tail fashion prevents passive ports being docked together if it is desirable that all connections remain actively disconnectable.

To aid in the undocking process, SMORES uses docking *keys* (see Fig. 4). The docking keys on each module have been designed to serve several purposes. Firstly, the keys are used when modules need to undock. Secondly, they can be used to increase the docking strength of connectors in the shear and torsional direction. Lastly, we believe they can aid in the recovery of failed docking attempts though we have yet to experiment with this feature. To undock two modules, the appropriate key is extended to select which connector to undock (see Fig. 5). As the key is extended, it locates inside the opposing docking connector, securing it in the torsion and shear directions relative to the docking key. This is shown in Fig. 6(b). From this position, a module can undock from an attached module by rotating the respective DoF corresponding to the position of the docking key. The eight permanent magnets that were holding the two modules together are twisted apart. This motion is shown in Fig. 6(c). After 90 degrees of rotation, the magnet poles repel each other and the exerted magnetic force can be used to push the detached module away. If necessary, the docking key can be retracted to return the key to its previous position. This docking sequence is shown step-by-step in Fig. 6.

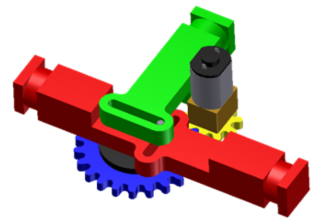
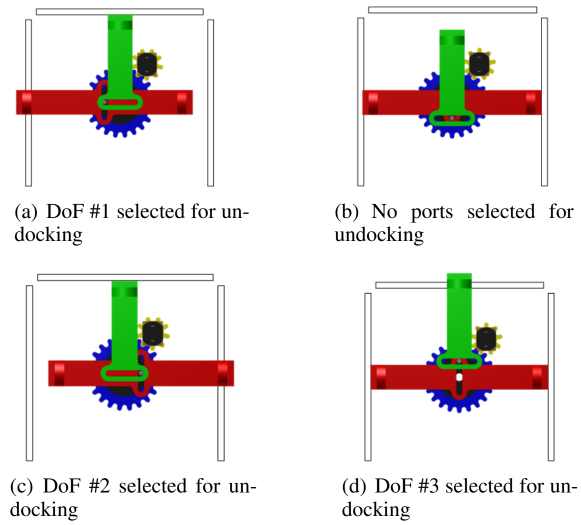


Fig. 4. Docking key drive mechanism



(a) DoF #1 selected for undocking

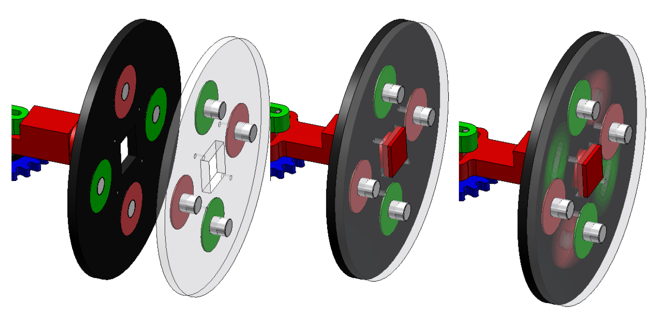
(b) No ports selected for undocking

(c) DoF #2 selected for undocking

(d) DoF #3 selected for undocking

Fig. 5. Docking Key Connector Selection

The docking key is actuated by one motor that sequences between four positions as shown in Fig. 5. One trade-off in using this method of docking is that a single module cannot undock two of its active docking connectors at the same time, though sequential undocking is allowed. To the best of the authors knowledge simultaneous undocking has not been a necessary feature of any existing system. As SMORES has predominantly active docking connectors, if simultaneous undocking is required in the future we believe it could be achieved through the coordinated action of neighboring modules. Connected modules could work together to undock at the same time to achieve the same effect as a single module undocking its connectors simultaneously.



(a) (b) (c)

Fig. 6. Module Dock and Undock Sequence. a) Docking. Neighboring connector shown in wire-frame for clarity, b) Magnets coupled and docking key is inserted. c) Coupled magnets are twisted apart to undock

One entire dock and undock sequence can take as little as 0.8 seconds and at most 2.3 seconds if the docking key is in the worst possible position to undock a connection. To the best of the authors knowledge, this is one of the fastest docking connector cycle times implemented on a self reconfigurable system to date.

If a system is to exhibit self-healing behavior, damaged modules need to be disconnected and eventually rejected from the robot. In the event of a module failure, it is possible SMORES modules can disconnect defunct modules, without sacrificing functional modules. Given the docking key is not extended and the connection consists of two active connectors, either module can break the connection without communication or coordination with its neighbor.

3) Docking Connector Strength: One goal for docking connectors is maximizing the strength of the connector when attached and minimizing the force required to disconnect. The SMORES system uses magnetic connectors which can be made to repel when disconnecting.

The holding force in tension between two docked modules is provided only by the attractive force of the permanent magnets. One pair of our neodymium-based magnets 6.35mm diameter x 6.35mm long, exert a pull force of $14.9N$. Two connected SMORES faces have four pairs resulting in a theoretical connector holding force of $59.6N$ in tension.

However in shear and torsion, the connection mechanism would be much weaker. The maximum shear strength of four pairs of coupled magnets was experimentally found to be $29.4N$. To increase the strength of our connector in the shear and torsion directions, the docking key is inserted into the docking port of the neighboring connector. Thus maximal strength in torsion and shear comes from both the magnets and the yield strength of the inserted docking key. The ultimate strength of ABS (docking key material) has been assumed to be $\tau_{max} = 28.3MPa$. The geometry used in calculating the shear and torsional strength of the connector is seen below in Fig. 7.

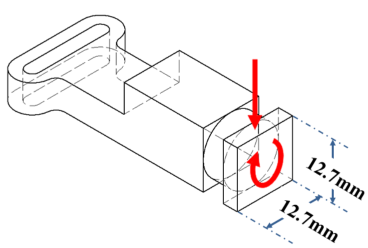


Fig. 7. Docking key geometry for calculating ultimate connector strength

Maximum direct shear:

$$F = \frac{\pi d^2}{4} \times \tau_{max} = 3.58kN \tag{1}$$

Maximum direct torsion:

$$T = \frac{J\tau_{max}}{r} = \frac{\pi d^4}{32}\frac{\tau_{max}}{r} = 11.4Nm \tag{2}$$

Thus, the ultimate shear and torsional yield strength limits of the connector were calculated to be $3.58kN$ and $11.4Nm$ respectively. This result is two orders of magnitude greater than using magnets alone to support shear forces.

Another figure of merit for modular systems is called the characteristic strength; the number of modules that can be supported in a cantilevered, serial chain of modules under gravity. Assuming that the center of mass for each module is at the geometric center, the number of modules we think we can theoretically hold in a cantilever configuration (due to strength of the connector only) is 3 modules.

IV. Electrical Design

Power is on-board and communication between modules is achieved wirelessly so the docking connections need only worry about mechanical attachment. Thus, the electronics on each SMORES module requires wireless connectivity, the ability to drive five motors, and to sense the angular position of the gear motors. There are no environmental sensing abilities on-board the module yet though this is planned for the future.

On-board processing is done by an MBED micro-controller that is based on the NXP LPC1768, with a 32-bit ARM Cortex-M3 core running at 96MHz. Five 298:1 gear reduced High Powered Micro Motors are driven with three TB6612FNG Dual Motor Drivers through PWM generated by the MBED. Angular position of the motors and the key drive is sensed using continuous rotation potentiometers. These are connected to analog inputs of the MBED and provide 5 degrees of positioning accuracy. The reason for this resolution accuracy is due to a blind spot on the wiper of the potentiometer which does not provide a full 360 degree resolution. Wireless data transmission between modules and a central controller is achieved with X-Bee radio transmitter/receivers. Given the slow speeds of the actuators, precision timing between coordinating modules should be achievable with this setup, but it has not been experimentally verified.

V. Experimental Results

Two prototype modules have been fabricated to date. Our first experiments showed the ability to self-assemble and successfully dock under manual remote control (Fig. 8). A demonstration of self-reconfiguration in 3D was achieved using a purpose built acrylic lattice structure of passive docking ports, to mimic a system of connected modules that SMORES could self-reconfigure its connections upon (Fig. 9). A summary of performance experiments is tabulated in Table I and Table II.

VI. SMORES as a Universal Robot

In this section we will compare SMORES with the current state of the art. Primarily we will focus on kinematics and connector topology rather than performance (e.g. speed, characteristic torque) though we will present the data we have available without discussion. Self-reconfigurable modular systems can rearrange their modules to emulate many fixed shape robot systems. We propose that one way to compare systems is to see how many systems a given modular system can emulate and how well it can do this.

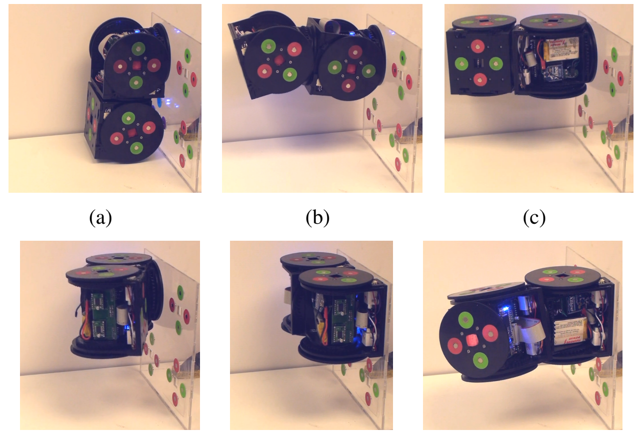
The SMORES system can be classified as a hybrid system that can adopt lattice, chain and mobile self-reconfiguration

TABLE I
SMORES MODULE DATA

Specification	*Value*
Wheel Speed (No Load)	23 RPM (9V)
Pan Speed (No Load)	23 RPM (9V)
Tilt Speed (No Load)	23 RPM (9V)
Maximum Land Speed	1.1 Body Length/s
Wheel Torque	1.2 Nm
Pan Torque	1.4 Nm
Tilt Torque	2.3 Nm
Static Module Power Dissipation	1.7 W (9V)
Overall Dimensions	100x100x90 mm
Maximum Angular Resolution	5 deg
Module Weight	0.52 kg
Modules cantilevered under gravity (DoF strength)	2 Modules
Cost	$300 USD

TABLE II
SMORES DOCKING PERFORMANCE DATA

Specification	*Value*
Average current draw	0.85 A (9V)
Holding force in tension	60 N
Max. holding force in shear	3.6 kN
Max. torsional load	11 Nm
Modules cantilevered under gravity (connector strength)	3 Modules
Min. time to undock	0.8 seconds
Max. time to undock (worst case docking key position)	2.3 seconds

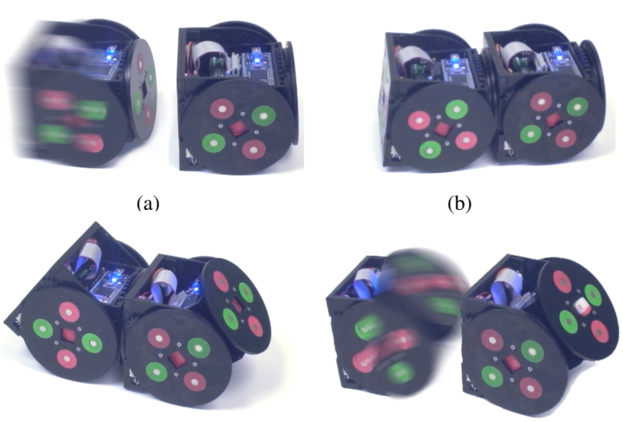


(a) (b) (c) (d) (e) (f)

Fig. 9. Self-Reconfiguration in 3D space on a passive lattice test piece. (a),(b) and (c) shows one module lifting another, moving it into a new position; (d), (e) module is docked to a new position; (f) a module undocks, and is moved into a new position

strategies. The system from JHU [11] claims to be the first that does all three. The SMORES system can approximate the JHU system matching orientation and axis of active DoF though the geometry has some offsets. The SMORES system can also emulate many others much more precisely as well. By emulating we mean providing connection points (CP) with the same active DoF between each CP and similar geometry at arbitrary scale. We do not claim to be able to replicate the same scaled performance of these existing implementations. For a comparison of performance against some previous systems, we have included Table III. Fig. 10 shows SMORES emulating several chain style robot systems. Many modular systems can emulate other modular systems [5]. One question is, how efficiently can they do it?

The more relevant systems are perhaps the hybrid systems, several which have only recently been introduced. These systems are already capable of several classes of reconfiguration and SMORES also falls into this category. Fig. 11 shows SMORES emulating these systems to different degrees. While the SMORES system wasn't designed specifically to emulate other systems, the design turns out to be well suited to it. In some sense it has a set of properties that encompass the minimal set of kinematic features with respect to CPs that most systems use. A deeper study of this *universality* is required to understand kinematic relationships between connection points, active DoF, number of actuators, cost and complexity of modules. This study would yield a more meaningful comparison between systems and would hopefully provide a metric of equivalence for such systems. However, the focus of this paper is to introduce the SMORES design so finding the metric for universality is left as future work.



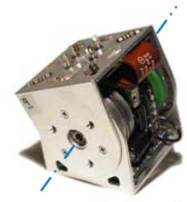
(a) (b) (c) (d)

Fig. 8. Mobile modules self-assemble in (a). Cluster movement of two modules in (b) and (c) before disassembly of two docked modules in (d)

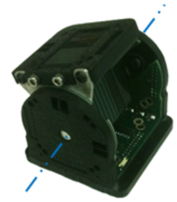
TABLE III
PERFORMANCES OF SELF-RECONFIGURABLE MODULES

Specification	*SMORES*	*ATRON*	*PolyBot G3*	*M-TRAN III*	*SuperBot***	*JHU*
No. of DoF	4	1	1	2	3	3
No. of Actuators	5	6	4	5	9	6
No. of Mech. Parts	132	145*	43+*	162*	-	-
DoF Speed (RPM)	23	5	30	10	20	4
DoF Torque (Nm)	2.3	2.4	1	2.3	6.38	4.6
Dock Cycle Time (s)	2.3	4	30	5	50	-
Weight (kg)	0.52	0.83	0.16	0.42	1.2	0.8
Data derived from		[2]	[17]	[4], [3]	[13]	[11]

* Estimated values from figures
** Fitted with six SINGO connectors [14]

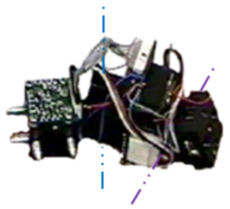


(a) PolyBot, 1xDoF, 2xCP[18]



(b) CKBot, 1xDoF, 4xCP[20]

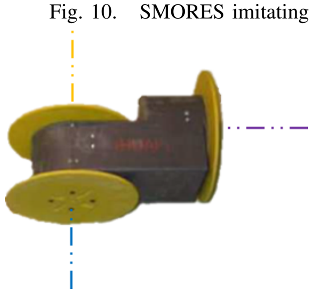
(c) SMORES identical geometry



(d) CONRO, 2 orthogonal DoF, 4xCP[1]

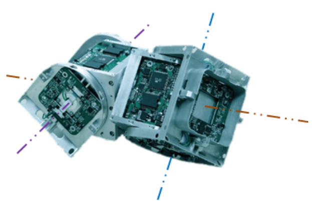
(e) SMORES nearly identical geometry

Fig. 10. SMORES imitating previous *chain* style systems



(a) John Hopkins University module with 3 wheel CP [11]

(b) SMORES approximate geometry



(c) SuperBot, 3 DoF, 6 CP [13]

(d) SMORES identical

Fig. 11. Systems that use hybrids of *chain*, *lattice* and *mobile module* reconfiguration strategies

VII. CONCLUSION

SMORES uses five identical motors to achieve a module that has four DoF, three active docking connectors, and module movement that can utilize lattice, chain and mobile module movement strategies. The SMORES modules can drive upright and upside down. We have shown that it is possible for the SMORES design to emulate the CP arrangement and DoF of many existing systems in our efforts to realize a more universal robot.

We hope in future revisions to begin replicating existing system performances. We would like to implement local communication between the docking ports of neighboring modules using perhaps slip rings or future vision capabilities. Several environmental sensing abilities could be implemented including motor torque feedback (current sensing) and tactile sensing abilities. An IMU could be implemented which may lead to the removal of the skid contact if the modules were programmed to self balance on its two outside wheels. Uneven terrain performance needs to be investigated for improving mobile module movement. Developing a metric for the *Universality* of modules would lead to a meaningful way of comparing modular reconfigurable systems.

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