Decentralized Control for 3D M-Blocks for Path Following, Line Formation, and Light Gradient Aggregation

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***Abstract*— This paper presents a decentralized control framework for lattice-based Modular Self-Reconfigurable Robots (MSRR) which utilizes a novel magnetic fiducial system to facilitate neighbor identification and to enable algorithms which promise scalable functionality for systems with many modules. In this system individual modules autonomously follow simple behaviors while periodically accepting input from a centralized controller. This system is demonstrated with three initial behaviors: (1) *Path following*: modules follow a three dimensional path based on magnetic fiducial tags embedded in their neighbors, (2) *Line formation*: modules transform from a 3D structure into a line following a partially decentralized control algorithm, and (3) *Light gradient aggregation*: the formation of a group of modules guided by a global stimulus (i.e. visible light). This paper provides details of the neighbor identification system, introduces the three behaviors and presents the results of physical experiments performed with a system of twelve 3D M-block robotic modules.**

I. Introduction

Modular Self-Reconfigurable Robots (MSRR) have been proposed as one method of autonomously creating general purpose robotic systems of arbitrary complexity. MSRR systems generally can be thought of as consisting of individual *modules*, which connect to either other active modules or passive modular elements through standardized *connectors* to create specific *configurations* in order to accomplish a designated task. Much of the existing work in the MSRR field has focused either on the preliminary development of novel hardware systems or general purpose algorithms which run on simulated systems. Few of the MSRR systems demonstrated to date have remained under active development long enough to develop and apply practical algorithms that can accomplish tasks using physical robots. This paper is focused on implementing and analyzing three separate practical partially decentralized "behaviors" with a set of 3D M-Block modules.

The conceptually simplest framework for controlling thousands or millions of individual modular robots is to have a centralized authority which dictates every move to each robot. However, centralized systems suffer from practical problems involved with maintaining the required number of communication links and in general lack robustness to disturbances and do not scale well. An alternative approach is to develop embedded "behaviors" or simple decentralized algorithms which each module can implement independently in the (potentially temporary) absence of centralized commutation. Several important characteristics that determine the

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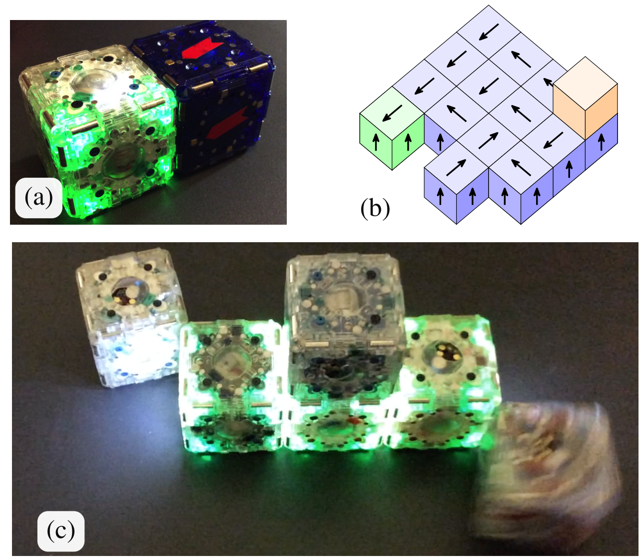

Fig. 1: This figure illustrates several of the behaviors implemented with the 3D M-Blocks robots. (a) Shows a photo of an active module connected to a passive module which contains a Magnetic Fiducial with embedded orientation information. (b) Demonstrates an abstraction of the magnetic fiducials as "arrows" which a module implementing the path following behaviour would move along. In this example, the module shown in *orange* would arrive on top of the *green* module after successfully implementing the path following behavior. (c) Shows several modules implementing the line formation behavior.

possible complexity and effectiveness of potential behaviors include the type of sensor feedback, the (un)availability and type of local communication, and the systems' reconfiguration implementation. This work focuses on modules which have information only about their direct neighbors, global input from a stimulus source (i.e. visible light), knowledge about gravity, and occasional wireless communication with a higher level controller. The initial behaviors that we introduce include: (1) Path following, (2) Line formation, and (3) Light guided aggregation. The ability for a MSRR system to delegate many of the details of each module's movements to be autonomously implemented by the individual modules based on local information, while still allowing centralized control when necessary, improves the system's ability to scale effectivly to large systems. While there have been similar proposed decentralized control strategies, several of which are discussed in Section II-B, this work focuses on defining and adapting these behaviors for an existing robotic platform.

This work is implemented and experimentally validated through a set of twelve 3D M-Block modular robots; which are one of the few MSRR systems capable of three-dimensional reconfiguration according to a generalized 3D lattice reconfiguration model. These 50 *mm* cubic modules use pulses of angular momentum and temporary magnetic hinges in order to implement lattice reconfiguration according to the Pivoting Cube Model (PCM). The M-Blocks were introduced for 2D movement in 2013 [1] and extended to three dimensions in 2015 [2]. In order to facilitate the implementation of new primitive behaviors, the 3D M-Blocks are further extended in this work to include a novel type of magnetic fiducial which allows modules to detect information about their neighbors. These fiducial tags, called MFTags, provide globally unique identification codes for each face of a collection of modules. MFTags include relative orientation of the connection between the reading module, and encode information passively, allowing the system to accurately determine its global configuration even when a fraction of modules are either disabled or are passive elements.

Specifically this paper presents the following technical contributions:

- Developed and characterized a new type of magnetic fiducial (MFTags) specifically designed to address the task of neighbor identification and determining connection orientation for MSRR. (Section III)
- Defined three separate primitive MSRR behaviors tailored for the 3D M-Block hardware system. (Section IV)
- Experimentally validated these behaviors on a system of twelve 3D M-Block modules. (Section V)

II. Related Work

Many papers provide a comprehensive overview of the MSRR field including the seminal article published in 2007 [10] in addition to several more recent updates, including [11] which focuses on the hardware systems, and [12] which focuses on algorithmic developments. In this section of the paper we investigate two different topics in the related work, (A) the challenge of configuration discovery in modular robotics systems, and (B) prior research on behaviors for MSRR systems.

A. Configuration Discovery in MSRR Systems

The ability for a modular system to discover the specific configuration of modules at any and all times is one of the most essential tasks for any modular robotic system. However, many of the modular robotic systems proposed to date have either built very limited and error prone methods for solving this problem, or have omitted implementation of such a system entirely. Any *connection* between modules in a modular system involves a minimum of three unique parameters (1) some form of identity or *ID* of the two modules in question, (2) the connector, or *face number* for each of the modules, and (3) the *orientation* of the connection, which in a cubic lattice is one of four possible 90 degree values. Much of the algorithmic work which concerns configuration discovery (e.g. [4] and in [13]), assumes that this information is accurately determined. However these works focus on the algorithmic challenges, abstracting away some of the details involved with implementing the algorithms on actual robots.

Connectors are one of the most significant design challenges in creating practical MSRR systems. Aside from their fundamental requirement of providing robust mechanical links, these connectors have been used in the literature to enable inter-module communication [14], [8], deliver and share power [15], and determine the presence and relative orientation of adjacent modules. However virtually all of the solutions for gathering presence and orientation information in MSRR require active communication between two robots, e.g. the inductive links in the SMORES systems [8] and CATOMS [9], or IR optical links used in many of the early MSRR, including MTRAN [16]. An ideal neighbor detector would work passively, essentially acting like a barcode. This would increase the robustness and scalability of the modular system, since it would allow passive elements to interact with active elements. There is a rich potential array of technologies which might be used to implement neighbor detection connectors, shown in Table I.

While there are many potential solutions for neighbor detection that allow passive identification of modules, few of these are practical for MSRR systems. RFID and NFC tags are one of the more promissing technologies, and are prevalent in robotics research, including in several fields related to MSRR, (e.g. [17]). However, due to the size and cost of the reader electronics these are currently impractical for MSRR systems with small characteristic dimensions. NFC is a technology related to RFID that looks promising for this type of application, but it remains a proprietary standard, and is not easily accessible at the present time. Additional passive methods, such as QR tags or April Tags [18] are effective in other fields of robotics, but require the use of a camera and sophisticated image processing techniques which at the moment are impractical to include in every active connector of a MSRR system.

B. MSRR algorithms

While there have been many simulated algorithms and control hierarchies that have been presented which accomplish distributed behaviors, e.g. [19], [20], [21] most of these works abstract away various challenges that real-world modules would face. There have been several works which present decenteralized algorithms operating on actual hardware, including the UBot [22], the ATRON system [23], and several others, e.g. [24], [25]. However few of these systems provide a clear path to being able to reconfigure according to a generalized 3D movement framework, which limits the reconfigurability and scalability of these systems. There are many works introducing various algorithms and control strategies similar to those we propose in this paper, and we are not claiming the behaviors we present are novel. This work from 2014 [12], provides an overview of some of the existing academic work involving decentralized control strategies for MSRR and robot swarms.

TABLE I: Comparison of attributes for several tagging technologies utilized by MSRR systems in order to determine the configuration of assemblies of modules.

	RFID / NFC	Optical	Electrical	QR Codes	Inductive	**MFTags**
Information Storage or transfer medium	radio waves	IR or visible light	direct wired connections	2D optical grid	inductive	permanent Magnet Field
Tag Cost	inexpensive	moderate	inexpensive	cheap	moderate	inexpensive
Reader Cost	expensive	moderate	moderate	expensive	moderate	moderate
Passive	yes	no	possible	yes	no	yes
Communication	possible	yes	yes	no	yes	not yet
Orientation	needs 4 tags	possible	possible	yes	needs 4+ points	Yes
MSRR Systems	[3]	CK-Bot [4]	Soldercubes[5], Ubot [6]	[7]	SMORES [8], Catoms [9]	3D M-Blocks [2]
Range	0-10+m	variable	0 m	1mm - 1m +	0-10mm	0-1mm

Light tracking behaviors can be traced to the canonical Braitenberg vehicles [26], and are implemented in simulation on M-Block like hardware in [27] and on the physical 3D M-Blocks in [28]. Other MSRR systems implementing light aggregation which we are aware of include the Polybot [25], and non-modular systems, e.g. the Kilobots [29]. Additionally there is some work detailing algorithms for line formation in MSRR systems, including [30].

III. Hardware

This section introduces the new magnetic fiducial tags, MFTags, which are implemented on the 3D M-Block Modules [2]. Basic information regarding 3D M-Blocks is presented in Table II. These modules can pivot on a cubic lattice using pulses of angular momentum from an internal reaction wheel according to the pivoting cube model [1].

TABLE II: Basic characteristics of the 3D M-Blocks robotic platform modules.

Actuation directions	6
Mass	163 g
Characterist dimension	50 mm
Total parts	216

The MFTagsfiducial tag system allows modules to detect information about their neighbors through magnetic fields, and an overview of their design is shown in Figure 2. The following design criteria were taken into consideration while creating MFTags, specifically that they should be able to:

- *be read passively* - information can be read even when the module is inactive.
- *be fabricated inexpensively* - necessary for systems with many (100+) modules.
- *identify many unique ID's* - needs to provide unique ID for many tags in large systems.
- *detect connector orientations* - the tag needs to determine the 90-degree angle of the tag relative to the reader.

MFTags are essentially specific arrangements of permanent magnets mounted on the connectors of each module. The orientation of the magnets which comprise a MFTag can be measured by simple absolute magnetic encoder ICs, thereby reading information encoded in the orientation of the magnets. Detecting the angle of the magnets is accomplished through using an absolute on-axis magnetic encoder IC. All of the active 3D M-Block modules have been outfitted with a circuit board that includes two Austrian Microsystems AS5048B absolute magnetic encoders, a light sensor, and several LEDs. The circuit boards are driven from the central processor through a TI PCF8575 I2C input output expander.

The underlying hypothesis is that low cost and lack of RF transmission make magnets an attractive choice for a technology that may have to be implemented thousands of times in a set of reconfigurable modules. The ability to use several sensors at close proximity prevents interference between reading faces, while still providing enough information to read tag orientation as well as indentify a unique tag identity. While the MFTags were designed and tested with the 3D M-Blocks modular robots, nothing precludes their use in other systems.

While the exact performance of the MFTag system is implementation dependant (i.e. different size/shape magnets, sensor ICs, etc), we performed several initial experiments to characterize their repeatability and functionality. Figure 3 shows a preliminary look at repeatibility of the MFTags and demonstrates that our implementation of the MFTag concept is feasible and useful in the context of modular robots. While the angular resolution of the magnetic angular encoders that we used is very high, 14 bits for the AS5048b used in this work, these readings are only repeatable under ideal conditions. There are many factors which influence the accuracy of the sensor readings in the context of the MFTags. We have identified the following factors that contribute to errors: (1) the relative alignment of the face containing the tag to the face containing the reader, (2) alignment of the magnetic sensor relative to the face of the reader module, (3)

TABLE III: Information content in the MFTags encoding specification. The current system is limited to 2 angle sensors due to practical considerations of the physical dimensions of the PCBa's in the 3D M-Blocks. Extending the reader to include four sensors would increase the number of unique tags by over 300 times.

	Current system	Future extension	Extended
Magnets	4	4	4
Digits	30	24	48
# Of Sensors	2	4	4
Unique Tags	**900**	331776	5,000,000

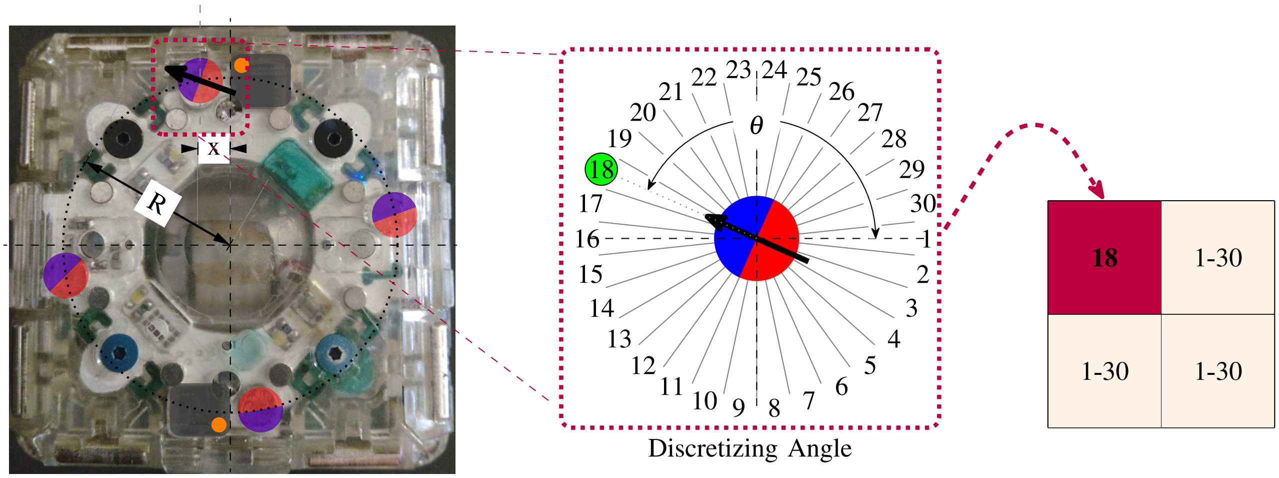

Fig. 2: Figure illustrating the MFTags system. A tag consists of four permanent magnets placed according to two dimensions, (R) is the circle diameter, and (x) is the offset from the y axis. The left half shows a photo of one of the m-blocks superimposed with the magnets and sensors. The absolute angle of the magnet, relative to a line extending from the center of the face is then digitized by an absolute magnetic encoder (black rectangle with orange dot).

variability of the magnetic field direction in the manufacture of the magnets, (4) accuracy of the mechanical alignment of the magnets in reference to the tag, and (5) effects of nearby external magnetic fields. While factors 2 and 4 appear to be a significant factor in the errors seen in this system, we think that much of this error is due to the inaccurate hand-assembled nature of this prototype system.

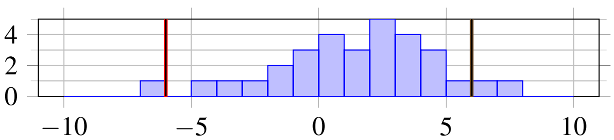

Fig. 3: Histogram showing one sensor face reading the same tag multiple times. The boundary lines represents tags that were misread. In this case about 9% of the tags were read incorrectly, however we believe that this can be significantly improved by improving the manufacturing process for both the reader PCBa's and the permanant magnets.

IV. Behaviors

The three behaviors described in Section I are described and presented in pseudocode in this section. These algorithms were designed for a system which meet the following assumptions:

- 3D cubic lattice movement according to either Pivoting Cube Model or Sliding Cube Model.
- Each module can detect a unique ID number and a relative orientation for each connector face.
- Modules are able to send simple messages through their connecting faces to other modules.

A. Path Following Behavior

The goal of this behavior is guide mobile modules to follow paths described by fiducials embedded in in adjacent modules' lattice connection points. This behavior requires that each module can determine from each of its neighbor connection interfaces a desired direction relative to its current absolute location that the module should move towards. The simplest implementation of this path following behavior involves passive hard-coded "arrow tags" in a lattice of passive modules, similar to arrows embedded along a road, as in Figure 1a-b. Path following behavior is then extended to modules which have connection face identities which are globally uniquely defined, and which contain some embedded "direction" or ability to determine the relative connection angle. Modules can then receive a mapping of ID numbers and "directions", and then can follow a virtually created path along a configuration of modules. A path could be defined along the surface of a large partially assembled aggregate of modules to guide modules to desired attachment points, similar to how optimization technique following gradient descent paths to reach a goal.

Algorithm 1 This algorithm attempts to drive a module in the direction of the embedded "arrow" defined by the MFTags.

initialization **while** *connected to valid module* **do**
  determine arrow direction **if** *flywheel plane is aligned with arrow* **then**
    Move in direction of arrow
  else
    Attempt to align flywheel with correct plane
  end
end

B. 3D Line Formation Behavior

The goal of this algorithm is to reconfigure an arbitrary 3D configuration of modules into a line using a decentralized algorithm. Initially a centralized or specially selected module selects to be the "seed" module for the line. In contrast to centralized line formation algorithms as in [30], this work implements the algorithm described in Algorithm 1. This behavior can be implemented in several ways, but in this work each modules uses knowledge of its direct neighbors, and very simple communication between the faces of adjacent modules. These communications are implemented as as a binary "connect here" or "keep moving," using visible light sensors and LED's on the modules' faces. Future versions could incorporate the path following behavior to optimize the movement efficiency (i.e. assembly speed) for a group of modules.

Algorithm 2 This algorithm attempts to turn a 3D shape configuration of modules into a line. The algorithm runs in a decentralized manner except for the initial step which uses a centralized "Server" block which communicated through WiFi which module is the "seed" of the line.

```
Initialization  while line seed not selected by Server do
    Modules send wireless information about their neighbors
    server searches for longest existing line
end
while Not part of line do
    Update sensors and state  if Neighbors = 1 and movement
    possible then
        Move in a consistent direction
    else
        Attempt to align flywheel with correct plane
    end
end
```

C. Light Gradient Aggregation Behavior

This goal of this behavior is to implement essentially a Braitenberg phototaxis behavior for lattice based modular robots, i.e. aggregating robots towards a light source. The algorithm assumes modules begin not connected to a lattice and continue to move towards light until they reach a specific "goal" structure defined by a specific aggregate of modules, which ensures that there is only a single successful aggregate. The modules move until they connect to a module that indicates it is part of the goal unit through some simple form of neighbor to neighbor communication, i.e. the face is lighted. With the exception of some method for selecting a single seed module, this algorithm is entirely distributed. This algorithm is based on the work from Claici et. al in [28], but is refined in this work to include functionality of the MFTags.

The experiments are implemented by placing a light source in a corner of a rectangular arena, and providing a *seed* module to designate the correct location to connect to. One possible biological inspiration for this experiment is to imagine that the modules are cells of a plant, and the algorithm is to grow a structure towards the light source as a plant. As far as we know this work would be the first to accomplish this task in 3 dimensions using modular robots.

V. Experiments

The three behaviors were implemented on a set of twelve 3D M-Block modules. The control system which is running the experiments is described in Figure 4.

Algorithm 3 This algorithm attempts to drive a group of modules to form a single aggregated group based guided by a light gradient.

```
while Not connected to Goal Configuration do
    Update State read sensors  if Numer of Neighbors = 0
    then
        Roll in direction of the brightest face that isn't on
        top
    else if Neighbors = 1, but not at Goal then
        Run algorithm to attempt to move towards light as a
        group
    else if Neighbors = 2, but not at Goal then
        Disconnect from structure
end
```

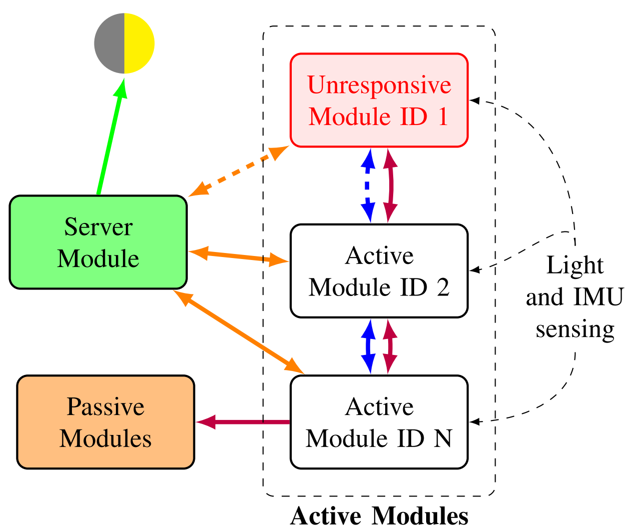

Fig. 4: This figure illustrates the various avenues of information exchange between the different elements of the experimental setup. The *orange* arrows represent bi-directional WiFi messages sent between the immobile *Server Module* and the active modules, with the dashed line showing a potentially faulty connection. The *blue* arrows show the simple light-based messages which active modules are able to send to neighbors which they are directly connected to. The *purple* arrows represent the reading of MFTags between an active module and a valid and properly connected MFTag. Note that MFTags can be read from both passive or unresponsive modules.

A. Arrow Following experiments

This experiment tested the ability of the modules to identify and follow the "arrows" embedded in in a set of passive and temporarily disabled active modules. The experiment consisted of a single module following the algorithm presented in Section IV-A.

B. Line formation experiments

These experiments aimed to transform 3D structures with several constraints: no holes, no modules connected by three or more connection faces, into a single horizontal line. These

TABLE IV: Experimental results for informal experiments testing the three behaviors. See the supplementary materials for a sample of the videos of the experiments.

	Path Following	Aggregation	Line
Experiments	15	3	11
Successful moves	104	-	81
Failed moves	15	-	10
Failed tag readings	3	-	4
Reached goal	16/23	15 / 30	64/84

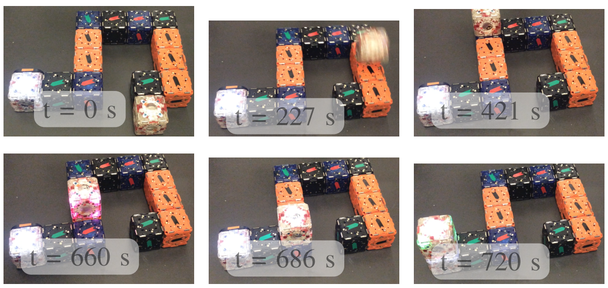

Fig. 5: In this experiment a single module moves according to "arrows" embedded in the MFTags in passive modules. The module moves along this path until it reaches a goal location, which is implemented as a module with its face LED's turned on.

experiments were run with the aid a centralized WiFi server - whose function is to identify which module is the "seed" for the line. The server receives WiFi status messages from the modules which includes information about their neighbors. The server attempts to find the longest existing line in the structure, and then picks one of the modules closest to the center of that line, and sends a message to that module indicating that it is the starting point for the line.

Fig. 6: This experiment shows a 3D configuration of six 3D M-Blocks reconfiguring into a line.

C. Light guided aggregation experiments

These experiments implement the photo-taxis Braitenberg behavior for a group of 3D M-Block modules. The experiment includes a single light source and a special target module indicating a initial connection location. If a module connects to a valid connection point it joins the aggregate structure and then signals to other modules that it is now also part of the structure through wireless and light signals. This essentially forms a single "crystal" of aggregated modules which grows as more modules join. In these experiment the modules are gradually released into a confined environment (0.5 m x 0.5 m) which is bounded by foam padded walls. The modules move until they either exhaust their battery or connect to the designated aggregate structure.

Fig. 7: This experiment illustrates the light guided aggregation behavior. The goal location and the light source are both in the upper left hand corner. If modules form aggregates that are not connected to the goal location (e.g. at t = 220s), they dissassemble and continue trying to reach the goal location.

VI. Discussion

This paper presents a new magnetic fiducial, the MFTag, for Modular Self-Reconfigurable Robots, and introduces three behaviors which utilize it to accomplish specific tasks. The MFTags's use of permanent magnets is inexpensive, functionally simple, and allows for the reading of passive or inactive modules. While other technoligies including NFC tags are also promising for this application, they are more complex, more expensive (when considering both tags and reader) and are a proprietary standard. One additional advantage of MFTag is its scalability in modular robotics applications that involve RF communications. Many magnetic rotary position sensors are immune to stray magnetic fields, and have a very short detection range. A large number of magnet-sensor pairs can be used within a system of many modular robots without any RF interference or confusion. In contrast, RF-based technologies may interfere with one another when densely packed, or interfere with other communications devices in EM-noisy environments including outer space and industrial applications.

The experimental results and behaviors presented in this work are based on preliminary hardware, and have relatively high error rates due to manufacturing and design limitations. Additionally the 3D M-Block robots which this system is tested on has relatively unreliable movement abilities due to electronic and manufacturing problems. However we believe that this system provides justification that this technology could provide a framework that future work could follow to create an effective system to identify the configuration of and control systems with millions of modular elements.

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Supplementary Material

`https://youtu.be/Y94J9ONjKD8`

References

[1] J. W. Romanishin, K. Gilpin, and D. Rus, "M-blocks: Momentum-driven, magnetic modular robots," in *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*. IEEE, 2013, pp. 4288–4295.

[2] J. W. Romanishin, K. Gilpin, S. Claici, and D. Rus, "3d m-blocks: Self-reconfiguring robots capable of locomotion via pivoting in three dimensions," in *Robotics and Automation (ICRA), 2015 IEEE International Conference on*. IEEE, 2015, pp. 1925–1932.

[3] J. Werfel and R. Nagpal, "Extended stigmergy in collective construction," *IEEE Intelligent Systems*, vol. 21, no. 2, pp. 20–28, March 2006.

[4] M. Park, S. Chitta, A. Teichman, and M. Yim, "Automatic configuration recognition methods in modular robots," *The International Journal of Robotics Research*, vol. 27, no. 3-4, pp. 403–421, 2008.

[5] J. Neubert and H. Lipson, "Soldercubes: a self-soldering self-reconfiguring modular robot system," *Autonomous Robots*, vol. 40, no. 1, pp. 139–158, Jan 2016. [Online]. Available: https://doi.org/10.1007/s10514-015-9441-4

[6] Y. Zhu, D. Bie, S. Iqbal, X. Wang, Y. Gao, and J. Zhao, "A simplified approach to realize cellular automata for ubot modular self-reconfigurable robots," *Journal of Intelligent & Robotic Systems*, pp. 1–18, 2014.

[7] K. Lin, J. Rojas, and Y. Guan, "A vision-based scheme for kinematic model construction of re-configurable modular robots," in *Intelligent Robots and Systems (IROS), 2017 IEEE/RSJ International Conference on*. IEEE, 2017, pp. 2751–2757.

[8] T. Tosun, J. Davey, C. Liu, and M. Yim, "Design and characterization of the ep-face," in *IEEE Intl. Conf. on Robotics and Automation (ICRA)*, 2016.

[9] B. T. Kirby, B. Aksak, J. D. Campbell, J. F. Hoburg, T. C. Mowry, P. Pillai, and S. C. Goldstein, "A Modular Robotic System Using Magnetic Force Effectors," in *Intelligent Robots and Systems*, 2007, pp. 2787–2793.

[10] M. Yim, W. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, and G. S. Chirikjian, "Modular self-reconfigurable robot systems: Challenges and opportunities for the future," *Robotics and Automation Magazine*, vol. 14, no. 1, pp. 43–52, 2007.

[11] S. Chennareddy, A. Agrawal, and A. Karuppiah, "Modular self-reconfigurable robotic systems: A survey on hardware architectures," *Journal of Robotics*, vol. 2017, 2017.

[12] T. Abukhalil, M. Patil, and T. Sobh, "Survey on decentralized modular swarm robots and control interfaces," *International Journal of Engineering (IJE)*, vol. 7, no. 2, p. 44, 2013.

[13] S. Funiak, P. Pillai, M. P. Ashley-Rollman, J. D. Campbell, and S. C. Goldstein, "Distributed Localization of Modular Robot Ensembles," *IJRR*, vol. 28, no. 8, pp. 946–961, 2009.

[14] J. Liedke, R. Matthias, L. Winkler, and H. Wörn, "The collective self-reconfigurable modular organism (cosmo)," in *Advanced Intelligent Mechatronics (AIM), 2013 IEEE/ASME International Conference on*. IEEE, 2013, pp. 1–6.

[15] C. Chen, T. Collins, and W. Shen, "A near-optimal dynamic power sharing scheme for self-reconfigurable modular robots," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, May 2016, pp. 5183–5188.

[16] H. Kurokawa, K. Tomita, A. Kamimura, S. Kokaji, T. Hasuo, and S. Murata, "Distributed self-reconfiguration of m-tran iii modular robotic systems," *International Journal of Robotics Research*, vol. 27, no. 3-4, pp. 373–386, March-April 2008.

[17] J. Werfel, Y. Bar-Yam, D. Rus, and R. Nagpal, "Distributed construction by mobile robots with enhanced building blocks," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*. IEEE, 2006, pp. 2787–2794.

[18] J. Wang and E. Olson, "AprilTag 2: Efficient and robust fiducial detection," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, October 2016.

[19] C. Jones and M. J. Matarić, "From Local to Global Behavior in Intelligent Self-Assembly," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2003, pp. 721–726.

[20] Z. Butler, K. Kotay, D. Rus, and K. Tomita, "Generic decentralized control for a class of self-reconfigurable robots," in *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, vol. 1. IEEE, 2002, pp. 809–816.

[21] K. Stoy and R. Nagpal, "Self-reconfiguration using directed growth," in *In Proc. 7th Int. Symp. on Distributed Autonomous Robotic Systems*. Citeseer, 2004.

[22] Y. Zhu, D. Bie, S. Iqbal, X. Wang, Y. Gao, and J. Zhao, "A simplified approach to realize cellular automata for ubot modular self-reconfigurable robots," *Journal of Intelligent & Robotic Systems*, vol. 79, no. 1, pp. 37–54, 2015.

[23] D. J. Christensen, U. P. Schultz, and K. Stoy, "A distributed and morphology-independent strategy for adaptive locomotion in self-reconfigurable modular robots," *Robotics and Autonomous Systems*, vol. 61, no. 9, pp. 1021–1035, 2013.

[24] P. Levi, E. Meister, and F. Schlachter, "Reconfigurable swarm robots produce self-assembling and self-repairing organisms," *Robotics and Autonomous Systems*, vol. 62, pp. 1371–1376, 2014.

[25] M. Yim, B. Shirmohammadi, J. Sastra, M. Park, M. Dugan, and C. Taylor, "Towards robotic self-reassembly after explosion," in *Intelligent Robots and Systems*, 2007, pp. 2767–2772.

[26] V. Braitenberg, *Vehicles: Experiments in synthetic psychology*. MIT press, 1986.

[27] S. Claici, "Aggregation for modular robots in the pivoting cube model," Master's thesis, Massachusetts Institute of Technology, 2016.

[28] S. Claici, J. Romanishin, J. I. Lipton, S. Bonardi, K. W. Gilpin, and D. Rus, "Distributed aggregation for modular robots in the pivoting cube model," in *Robotics and Automation (ICRA), 2017 IEEE International Conference on*. IEEE, 2017, pp. 1489–1496.

[29] M. Rubenstein, C. Ahler, and R. Nagpal, "Kilobot: A low cost scalable robot system for collective behaviors," in *International Conference on Robotics and Automation*, May 2012, p. In Press.

[30] C. Sung, J. Bern, J. Romanishin, and D. Rus, "Reconfiguration planning for pivoting cube modular robots," in *Robotics and Automation (ICRA), 2015 IEEE International Conference on*. IEEE, 2015, pp. 1933–1940.