A Robot Capable of Autonomous Robotic Team Repair: The Hex-DMR II System

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Abstract Robotic systems are increasingly being used in hazardous environments and remote locations to safely extend human reach. However, these systems can be faced with unexpected events or system faults. Currently, the standard paradigm is to either leave a damaged robot in the field, or to rely on human invention for repair or retrieval. Therefore, a need exists for systems that offer long-term robustness in the face of such failures. In this paper, we present the Hexagonal Distributed Modular Robot (Hex-DMR) II System which is comprised of a team of several autonomous mobile robots capable of performing repair procedures on individual robots in the team. Hex-DMR II represents a potential solution to the longstanding problem of fragility in robotic systems in remote environments. First, we introduce the design elements of the second-generation system and contrast them to its first-generation counterpart. Then we describe the modular team members that result and summarize the repair process. Finally, we experimentally demonstrate the functionality of our system by performing two autonomous procedures necessary for repair.

Keywords Mobile robots · Modular robots · Multi-Robot systems · Robotic Self-Repair · Design

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X. Ding et al. (eds.), *Advances in Reconfigurable Mechanisms and Robots II*,
Mechanisms and Machine Science 36, DOI 10.1007/978-3-319-23327-7_53

1 Introduction

An increasing number of applications call for cooperative multi-robot systems to reduce variability and to mitigate risk in unknown environments (e.g. [8, 15]). In addition, if these robots are capable of repairing or reconfiguring themselves or other team members, the system may potentially be more adaptable to changing environments, more robust against unexpected events, and be able to operate over longer life spans. The research presented in this paper outlines the design of a second-generation robotic test-bed capable of repairing team members. The test-bed is an autonomous, cooperative multi-agent system (CMS) and is comprised of modular robots. The improvements and trade-offs of the second-generation system are discussed and are related to fundamental principles proposed in [1, 4] that are necessary for designing such a system. The functionally of the test-bed and its capability to perform a repair are verified through experimentation with a physical prototype.

A CMS is a team of independent agents, in this case robotic entities, that work together to accomplish some common objective. Such a system offers several advantages and additional capabilities over single agent implementations. For instance, agents in a CMS can be specialized for specific tasks possibly resulting in less complex and demanding designs and distribute work to team members to reduce mission execution time. Moreover, if several agents were to enter "fault states" their responsibilities could be reassigned to "healthy" agents, effectively increasing the robustness of the system. In many situations, the increased cost of multiple units can be offset by their more simplistic nature and added system efficiency and life [6]. The benefits of CMS have been realized in several areas of robotics. In particular, researchers have concentrated on swarm and modular robotics to demonstrate abilities of organization [14, 18], assembly [10, 16], and reconfiguration [2, 12].

Researchers in robotics have also sought to replicate biological processes such as fault recovery by team repair [9] to increase operational lifetimes. A "fault state" is described as any condition that leaves an agent unable to complete an assigned task. Common faults encountered in robotic systems range from physical damage to power loss to improper tooling and/or components for specific tasks. To overcome these faults and increase lifetimes, researchers desire systems with easily interchangeable components and agents. Bereton and Kholsa verified this claim by using reliability theory to model and analyze a system capable of limited team repair [5].

Therefore, modular robots, or robots comprised of elementary units (modules) connected together by docking mechanisms, have been the primary mechanism to showcase such fault tolerant systems. Modular robots can be divided into two distinct subgroups, homogeneous and heterogeneous, depending on the composition of the robotic agent. Not surprisingly, the repair process for each subgroup varies greatly. In homogeneous modular robotics, repair can be accomplished by jettisoning damaged modules [7, 19]. This process, while simplistic, can degrade the capabilities of individual agents. In contrast to homogeneous systems,

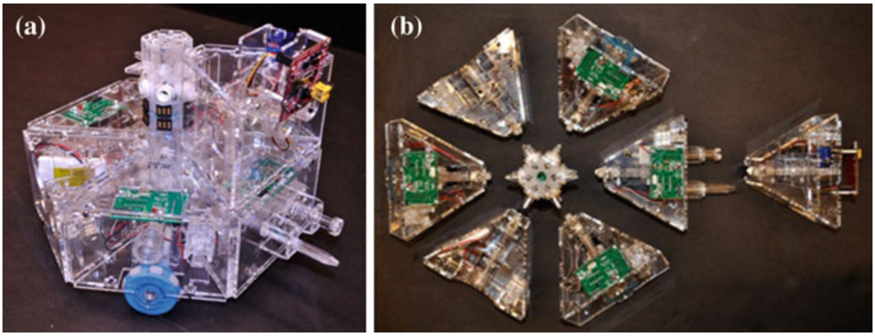

Fig. 1 Views of the Hex-DMR II system. **a** Isometric view of Hex-DMR II. **b** Exploded view of Hex-DMR II

heterogeneous robots can combine different functionalities, integrated as separate modules, into a single agent [13]. Repair in this systems is defined as replacing faulty modules with functional modules obtained from storage or by scavenging another damaged agent.

To our knowledge, only three projects exist where a team of heterogeneous modular robots can repair a team member. The first system, envisioned by Kutzer et al., was a robotic agent comprised of four heterogeneous modules connected together by rare-earth magnets [11]. However, this research effort concentrated on diagnosis of faulty modules rather than the design of repairable ones. Bereton and Khosla developed a system based around seven desirable constraints for exhibiting autonomous module replacement [4]. Their system consisted of a forklift-like robot equipped with a black and white camera to execute the repair and a repairable robot containing modules with fork lift receptacles [3]. Although Bereton and Khosla presented a repair process only certain subsystems were replaceable and important aspects, such as the locomotion system, were not addressed. By refining, combining, and adding to Bereton and Khosla's original constraints, we designed a first-generation robotic system (Hex-DMR) capable of remotely-assisted repair processes in [1]. Each robotic agent was constructed from six, large, trapezoidal-shaped modules. After analyzing the performance and design of Hex-DMR, we identified several areas of improvement related to reliability and robustness of the repair process. The resulting second-generation system (Hex-DMR II), pictured in Fig. 1, is smaller, more robust, and augmented with additional capabilities.

2 Design

The following section is dedicated to the discussion of the design of Hex-DMR II. First, we present our second-generation, team repair test-bed, Hex-DMR II, and then its key features are contrasted to the older generation Hex-DMR through the necessary and sufficient design constraints outlined in [1].

2.1 Hex-DMR II System Overview

The Hex-DMR II system is comprised of multiple agents constructed of heterogeneous modules. Each agent carries modules arranged in a radially symmetric fashion around a central hub that allows electrical and mechanical connections between every module. Agents of Hex-DMR II, can hold up to twelve modules, arranged in two vertically-stacked rings of six modules. Each agent requires a minimum of five modules and a central hub for minimal functionality; however, when equipped with seven modules it is able to perform all of its tasks (Fig. 1b, Table 1). The remaining five locations provide opportunities for modules to augment agents (i.e. expanding sensing and manipulation capabilities), as well as supplying additional modules to be utilized in the repair process.

2.2 Hex-DMR II Design Elements

The following subsections outline key design aspects that enable the Hex-DMR II system to perform reliable, autonomous team repair. In each subsection, the design features will be directly related to the constraints in [1] and the Hex-DMR II system will be contrasted with the first-generation system to highlight improvements. For the remainder of this section, Hex-DMR and Hex-DMR II will refer to both the overall system as well as individual agents in the system (where the distinction will be clear from context).

Table 1 Necessary modules for a functional agent

Module type	Function	Important components	No. Req.
Drive	When all three modules are operated together, it provides holonomic motion for the agent	Geared DC motor, omni-directional wheel, PIC board	3
Power	Provides power to all other modules	Polymer Li-ion battery	1
Control	Handles external communication, decision-making, and sends commands to actuated modules to perform kinematic and manipulation procedures	Atmega168-20PU micro-controller, Xbee wireless radio	1
Manipulator	Enables manipulation (attachment and detachment) of modules from the central hub	Current sensor, PIC board, geared DC motor for module manipulation	1
Camera	Provides a sensing modality for each agent	CMUcam4	1
Central hub	A passive structure housing mechanical and electrical connections for modules	Electrical bus	1

2.2.1 Modular Configuration

The modular configuration adopted by the original Hex-DMR system enabled a homogeneous repair process across all agents. That is, each module was designed to be removed by the same procedure, mainly the unlatching and lifting of a module by the manipulator. The only exception was the replacement of a manipulator module; in this case, the end-effector had to be removed before the manipulator module could be adjusted. This obstacle was avoided in the second-generation system by altering the manipulation mechanism and adjusting the layout of the manipulator such that it is anti-symmetric when facing another manipulator. Resolution of repair was also maintained in the Hex-DMR II system, thereby mitigating the resource cost of repair.

2.2.2 Holonomic Drive

To manipulate modules, a docking procedure between agents is needed. Depending on the design of the docking system, the agents may have to perform fine-tuned maneuvers to successfully dock. Nonholonomic approaches to this issue may result in a large number of corrections to generate small motions in constrained directions and, in general, cause difficulties [17]. Conversely, holonomic approaches allow instantaneous acceleration in any direction and orientation enabling more efficient docking procedures. In both Hex-DMR systems, we strove to simultaneously reduce the number of actuators present in each module to limit complexity. Several drive systems satisfy these constraints; however, only two options minimized the required number of drive modules. The first consisted of two drive modules containing steerable omni-directional wheels and a third module containing a passive castor for support. In this configuration, three modules and four total actuators are required. The second option, consisted of three, non-steerable, omni-directional wheels evenly spaced about the centroid of the robot. This configuration resulted in three identical modules with three total actuators radially spaced 120° apart. Clearly, the second option is preferable and is employed in both Hex-DMR systems as it limits complexity in the drive modules, increases overall homogeneity of the system, and improves maneuverability.

2.2.3 Hexagonal Geometry

In order to address the completeness of repair constraint, we must ensure that each module is easily accessible and replaceable. Convex geometries, such as rectangles or hexagons, provide collision-free paths to each module for external actuation. However, by increasing the number of modules in a set footprint, we effectively reduce the area available for external manipulation if overall scale is maintained. For example, consider a 1- by 1 unit square; if we place four modules in the square each face is 1 unit, if we place six modules each face is 0.5176 units, and if we place eight modules each face is 0.4142 units. Therefore, we must find a balance between the resolution and completeness of repair.

As stated earlier, we require three drive modules arranged in a radially symmetric fashion to implement a holonomic drive system and additional modules to power and control the robot. A square footprint cannot contain enough modules, while a pentagon cannot maintain the proper wheel spacing. The hexagonal footprint properly arranges the drive modules for the holonomic drive and also ensures more space over an octagonal footprint to perform docking procedures. Although Hex-DMR II retained the same hexagonal shape as Hex-DMR, the planar footprint was reduced by 32 %.

2.2.4 Evolution of the Central Hub and Electrical Bus

The passive central hub acts as the mechanical and electrical backbone of the Hex-DMR systems. The original system passed 20 signals through compliant electrical connections, on the back of each module, to the central hub. Power was shared by each module, but the remaining connections were independent digital signals specific for each actuated component, controlled by the centralized microprocessor.

Although Hex-DMR II retained compliant electrical connections, the complexity of the system was reduced by incorporating uniquely addressed PIC16F1825 microcontrollers into each actuated module installed on a "PIC board". In Hex-DMR II, addressed data packets are sent through asynchronous serial communication, in a hierarchical fashion to generate motion. This control architecture allows the central processor to concentrate on more general tasks such as navigation instead of constantly sending commands to each module and enables Hex-DMR II to require only four signals (power leads, RX, and TX) for operation. These signals are passed through compliant electrical connections, located on the rear of each module, that interface with the central hub (Fig. 2). Overall, the dramatic reduction in the number of connections and the altered control architecture increased the robustness of the repair process.

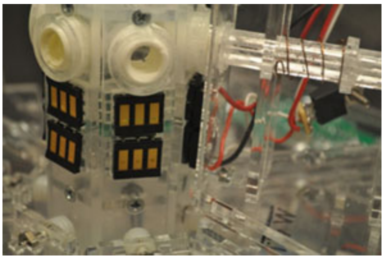

Fig. 2 Detailed view of a module docked with the central hub and the associated mechanical and electrical connections

2.2.5 Docking Mechanism

Hex-DMR II features a different docking mechanism than Hex-DMR. Mechanical connections between the modules and the central hub of Hex-DMR II (Fig. 3a) are realized using a screw mechanism and alignment pins (as opposed to a latching mechanism). Each module contains an identical mechanism comprised of a recessed sliding shaft that extends the length of the module. A threaded piece (screw) is attached to the posterior end of the shaft and is designed to mate with a corresponding threaded insert on the hub. As a module is maneuvered towards the hub, an alignment pin on the hub engages a corresponding feature on the rear face of a module (a), (b). The module is then driven forward until the screw engages the hub. Then the manipulator actuates the screw until the module it is carrying pulls itself into the hub (c). Springs are included on the sliding shaft and end-effector to ensure that there is constant contact during the docking procedure. Once screwed in, the alignment pins on the hub prevent the modules from arbitrarily rotating about the screw.

Modules are removed from the hub by a slightly different procedure (Fig. 3b). The manipulator is aligned with and driven toward the module slated for removal (a). First, a long alignment pin extending from the face of the manipulator module engages a friction mechanism in the interior of the second module (b). This mechanism not only aligns both agents, but also has significant friction (from tight tolerances) to effectively mate both modules together (c). Once mated, the end-effector on the manipulator can unscrew the module from the central hub and then move it accordingly (d).

By the use of tapered alignment pins we have, theoretically, enabled our system to tolerate misalignments of up to 2.54 mm and 18°46′12″ during mating and up to 16°48′36″ during docking. In addition, we have reduced the complexity of manipulation in Hex-DMR II by reducing the degrees of freedom of the end-effector. These new features which were conspicuously missing from Hex-DMR greatly increase the robustness of repair of the new system.

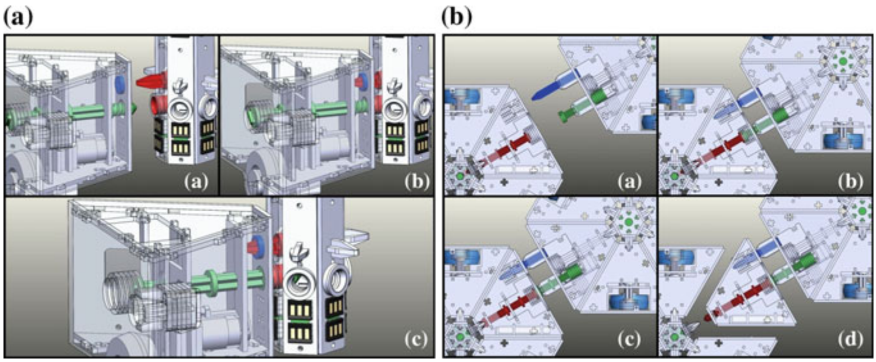

Fig. 3 CAD representation of repair procedures. **a** Module insertion into the central hub. **b** Module extraction from the central hub

2.2.6 Modular Redundancy

As previously mentioned, the central hub of Hex-DMR II is configured to dock with up to twelve modules arranged in two vertical layers of six modules. Additionally, each agent requires seven modules (three drive, one power, one manipulator, one control, and one camera) to achieve basic repair functionality leaving five additional locations on the hub for spare modules. These spare modules can be used to increase the versatility of the current agent, by providing a secondary power source, additional sensing capabilities, more complex actuation, or improve the robustness and self-sustainability of the entire system by providing extra modules to be used in the repair process. In general, the agents can be reconfigured during missions to adapt to varying requirements and to increase the probability of mission success.

Although no mechanism is currently implemented to transfer modules between layers, several viable options exist including a two-layer elevator module, an external elevator station, and multi-level storage racks.

2.2.7 Sensing

Unlike its predecessor, agents of Hex-DMR II feature an additional module for sensing. The camera module provides a means to identify individual modules on other agents through a 4-bit barcode and can also be used for navigation, thereby increasing the versatility of the system.

3 Methods

In this paper we define the repair process or the reconfiguration of an agent as a replacement of a faulty module with a new module (Fig. 4). A robot in a "fault state" (RIF) can be labeled as such for different reasons. As previously mentioned, the robot may be in fault because a module contains a broken component that needs replacing. A module may also have a component that is "temporarily" in fault (e.g. a dead battery). Finally, a robot may be in a "fault state" because it is not equipped with the necessary types of modules, even though all of the modules are technically functional. Determining if another robot is in fault and the specifics of the fault state is accomplished through a diagnostic process which will be discussed in a subsequent paper.

After the RIF is diagnosed, a robot is assigned to conduct the repair (RCR). The RCR must first locate the RIF by finding alternating colored markers on top of the RIF's central hub with the camera module. Once located, the RCR centers itself on the color located in the middle of its field of view (FOV) and approaches the RIF, while simultaneously ensuring that the centroid of the marker remains in a specified range relative to the FOV, until it reaches a specified distance. The RCR

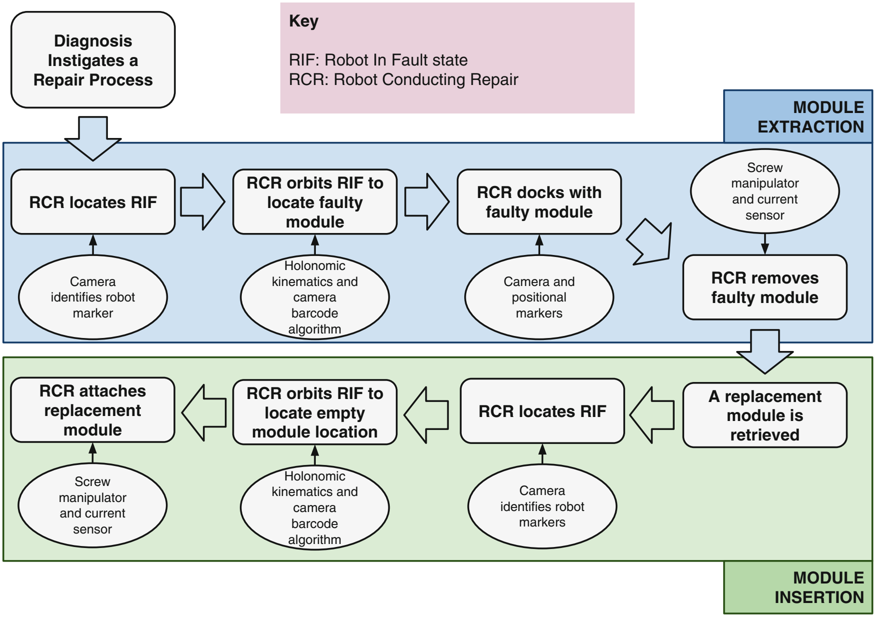

Fig. 4 Overview of the repair process

must then determine if the module it is facing is the "faulty" module by comparing a 4-bit barcode on the face of the module to the barcode of the "faulty" module. If the barcode does not match the designated module, the RCR orbits the RIF in the counterclockwise (CCW) direction until the alternatively colored marker, and hence the next module, is centered. This process repeats until the proper module is located.

Once the "faulty" module has been centered, a docking procedure is initiated. The RCR approaches the RIF, while correcting for errors, until it reaches a certain distance away. Then the RCR strafes to properly align its docking pin with the friction mechanism on the "faulty" module of the RIF. Once aligned, the RCR drives forward effectively mating both the RCR and the "faulty" module. The screw mechanism is activated and continues rotating until the screw has been released from the hub (indicated by a current sensor on the manipulator). Finally, the RCR backs away from the RIF completing the module extraction procedure.

Before the module insertion procedure begins, the RCR must drop off the "faulty" module and retrieve a "healthy" module from another agent (either by scavenging or using a spare module). Once the RCR is equipped with a "healthy" module it returns to the RIF and follows a similar searching procedure used during extraction; however, we now check for the absence of a barcode to determine the location for insertion. The search continues until the insertion location is discovered and then the RCR centers itself and drives forward to dock the "healthy" module with the central hub. Upon docking, the screw mechanism rotates clockwise

(CW) until the current sensor indicates motor torque saturation or stalling. Finally, the RCR backs away and is free to return to its original task.

Both module extraction and module insertion are essential for a successful repair process. The nature of our modular repairable design (Sect. 2) dictates a more robust extraction process than insertion due to the fact that during extraction, alignment and docking are completed for just the manipulator and not a manipulator holding a module (less complex) as well as the fact that the mating of a module to the manipulator can be less accurate and still successful.

4 Autonomous Team Repair Maneuvers

Since we previously tested these concepts through simulation and remotely assisted repair [1], we strove to demonstrate an autonomous repair process in this paper. First, we validated the new design by completing remotely assisted repair maneuvers with two agents. For the extraction and insertion procedures, the agents were placed 61 cm apart and the RCR was rotated 90° CCW from the RIF. The "faulty" module was located directly CCW from the module that the RCR was facing. Both remotely assisted procedures were performed; however, the success rate was noticeably lower for insertion due to the reasoning mentioned above.

From our validation testing, it was clear that we could demonstrate the autonomous extraction and insertion of a module. Both the RCR and RIF were placed with the same configuration as during the remotely assisted repair. Autonomous removal of a power module is illustrated in the first column of Fig. 5, while autonomous insertion is displayed in the second column. The procedure for extraction is as follows: (a) the RCR rotates CW until the RIF is located; (b) the RCR approaches the RIF and checks the barcode of the module it is facing; (c) the RCR orbits until it finds another module and confirms that the module is slated for repair; (d) the RCR docks with the RIF and unscrews the module; (e) the RCR drives backwards to extract the "faulty" module; and the procedure for insertion is as follows: (a) same as before; (b) the RCR approaches the RIF and checks to see if the module it is facing contains a barcode; (c) the RCR orbits until it finds another module location and confirms that there is no barcode; (d) the RCR inserts the module; (e) and drives away.[1]

Through our experimentation we were able to continuously and repeatably demonstrate that an agent of the Hex-DMR II system could locate the RIF, identify modules by their barcodes, locate the "faulty" module or lack of a module, and either remove or insert modules in the central hub. Although we were able to autonomously insert a module, the process did not always prove to be reliable.

[1]Video of the repair procedures is available at https://www.youtube.com/channel/UC11bvIH6byvI1ecPsgr0XGA.

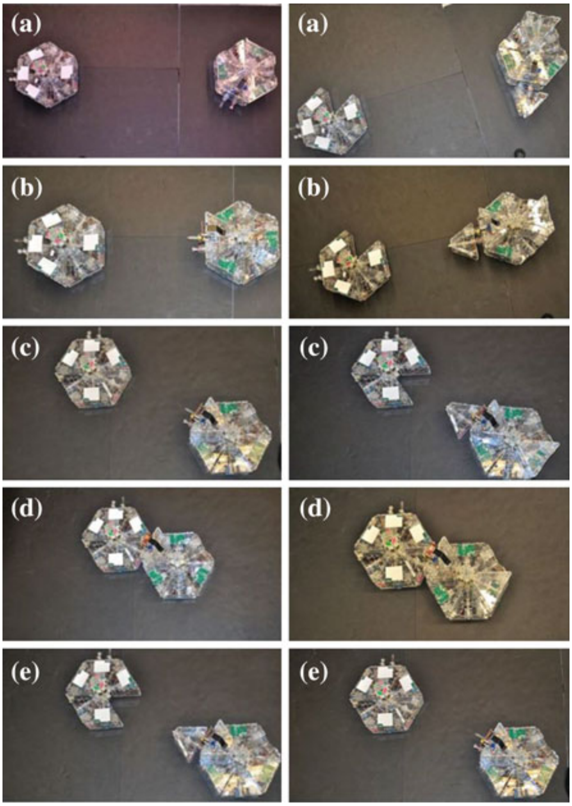

Fig. 5 Repair procedures: The first column demonstrates an extraction procedure, while the second column demonstrates an insertion procedure. The corresponding text that outlines each of these procedures is included in Sect. 4

5 Conclusions and Future Work

As multi-robot systems become more important, and more prevalent, efforts to improve their long term autonomy and versatility in the field, in the absence of humans, are critical. One step in this process is to develop designs and strategies that allow teams of robots to autonomously recognize and address fault states through reconfiguration. In this paper we have proposed a method to achieve this using a modular robot design. This system improves on our previously published work and experimentally demonstrates the system conducting elements of autonomous repair. Work still remains to assure a more reliable total repair process—as issues still arise in the final phase of module insertion. We will test possible solutions and constraints centered around re-examining the weight distribution of the modules, refining the tolerances of the manipulator screw mechanism and adding an additional degree of freedom to the manipulator module.

In parallel to autonomous repair of an agent in a CMS, we will also concentrate on developing robust algorithms for self-calibration and visual diagnosis of fault states in other agents. With the addition of these algorithms, we will be able to showcase the full functionality of the Hex-DMR II system.

Acknowledgments This work was supported by NSF Grant RI-Medium: 1162095. In addition, the work of Joshua Davis was supported by an ARCS Foundation Scholarship. Chirikjians contribution to this material is based upon work supported by (while serving at) the National Science Foundation. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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