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Design of a Multi-Segmented Magnetic Robot for Hull Inspection

ABSTRACT

The use of a hull-climbing robot is proposed to assist hull surveyors in their inspection tasks, reducing cost and risk to personnel. A novel multi-segmented hull-climbing robot with magnetic wheels is introduced where multiple two-wheeled modular segments are adjoined by flexible linkages. Compared to traditional rigid-body tracked magnetic robots that tend to detach easily in the presence of surface discontinuities, the segmented design adapts to such discontinuities with improved adhesion to the ferrous surface. Coordinated mobility is achieved with the use of a motion-control algorithm that estimates robot pose through position sensors located in each segment and linkage in order to optimally command each of the drive motors of the system. Self-powered segments and an onboard radio allow for wireless transmission of video and control data between the robot and its operator control unit.

The modular-design approach of the system is highly suited for upgrading or adding segments as needed. For example, enhancing the system with a segment that supports an ultrasonic measurement device used to measure hull-thickness of corroded sites can help minimize the number of areas that a surveyor must personally visit for further inspection and repair. Future development efforts may lead to the design of autonomy segments that accept high-level commands from the operator and automatically execute wide-area inspections. It is also foreseeable that with several multi-segmented robots, a coordinated inspection task can take place in parallel, significantly reducing inspection time and cost.

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The focus of this paper is on the development efforts of the prototype system that has taken place since 2012. Specifically, the tradeoffs of the magnetic-wheel and linkage designs are discussed and the motion-control algorithm presented. Overall system-performance results obtained from various tests and demonstrations are also reported.

INTRODUCTION

Hull, deck plate, and tank inspection for corrosion, deformation, and fractures is a necessary part of ship maintenance to ensure functional integrity and proper operation of the ship. These inspections are labor intensive, expensive, and often dangerous. A multi-segmented magnetic-wheeled robot can assist the surveyors in these tasks. It can reach many dangerous and hard-to-reach passages and voids within maritime vessels. Various sensors can be accommodated to determine hull thickness, cracks, or general condition of the surfaces. With intelligence, surveillance, and reconnaissance (ISR) sensors, it can also provide a valuable remote sensing capability for Navy SEALs, Marine Force Reconnaissance, and Visit, Board, Search, and Seizure (VBSS) tactical teams.

The Multi-segmented Magnetic Robot (MSMR, Figure 1), currently in the second year of development, is designed to address these capability gaps by providing acoustically quiet climbing and turning ability over a typical ferrous hull that often includes discontinuities in the form of protrusions and indentations, especially where hull-plating sections meet. The key to its effective climbing lies in the design of its wheels and the multi-segmented approach. The wheels are designed to provide maximum magnetic adhesion while the multi-segmented body provides surface adaptability.[1]

Figure 1. Conceptual MSMR.

SYSTEM OVERVIEW

The MSMR is composed of the robot modules, linkages, and magnetic wheels (Figure 2) that provide attraction and traction with the ferrous surface being climbed. The robot modules contain the system electronics, motors, and batteries. The exterior of the robot module protects its contents from water, dust, dirt, and impacts with obstacles. The flexible linkages allow relative motion between robot modules so the system can turn, negotiate obstacles, and traverse around corners.

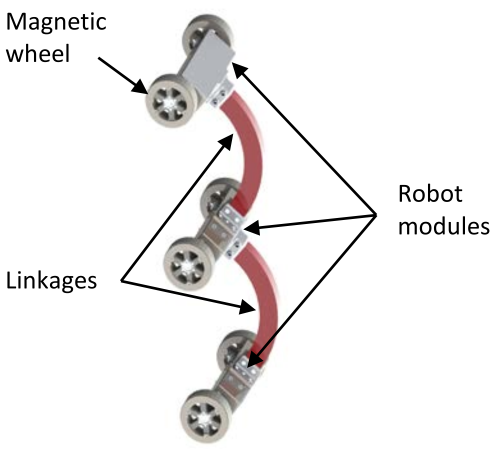

Figure 2. MSMR system overview.

ROBOT MODULES

Each robot module contains the control electronics, drive modules, and battery (Figure 3). The first iteration of the robot module was developed to accommodate rapid changes in design by using modular mechanical interfaces for the linkage and drive module. The addition of O-rings and seals to protect internal components from the elements were not included in the first iteration to save time and money during the conceptual development portion of the project. Future iterations will include environmental sealing. A plastic prototyping machine was used to fabricate the robot module chassis with a polycarbonate ABS blend to achieve a rapid turnaround time. Final versions of the robot module will most likely be machined from aluminum to increase strength and durability.

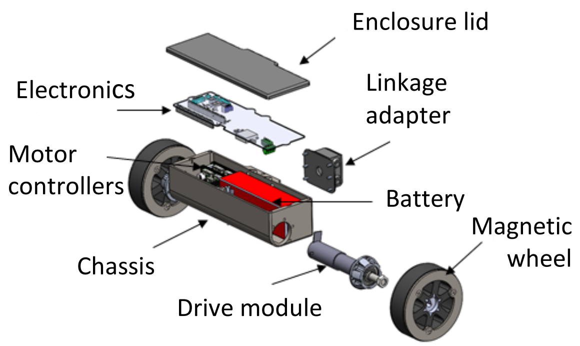

Figure 3. Exploded view of robot module.

MAGNETIC WHEEL

The magnetic wheel (Figure 4) provides the attractive force between the MSMR and the surface it is climbing, allowing the robot to traverse vertical and even inverted surfaces. The primary design attributes are adhesion force, surface friction, acoustic signature, shock absorption, mass, cost, manufacturability, ease of assembly, and serviceability. The wheel needs enough adhesion force to carry the weight of the MSMR and maintain enough friction to keep the wheel from sliding. The acoustic signature of a wheel while climbing a surface is important for operations where stealth is required. Flexibility of the wheel provides survivability for the entire system under high-shock loading seen during the inevitable cases where the robot falls from a vertical surface. Minimizing the mass of the wheel and MSMR, in general, reduces the required magnetic forces for climbing, motor output torque, and electrical power.

Figure 4. Multiple views of the magnetic wheel.

Two magnetic wheel designs were prototyped and tested.[2] The *conformal* wheel (Figure 5) consists of a high-flex elastomer wheel, radial magnet array, magnet locator, rigid hub, and elastomeric tread. The theory behind the design of this wheel is that the highly flexible structure of this wheel will allow the wheel to deform so that it flattens somewhat where the wheel contacts the ferrous surface. This flattened portion of the wheel creates a larger surface area of contact, increasing both adhesion force and traction. The high-flex elastomeric wheel provides the structure and flexibility of the wheel, with the magnets positioned radially with north pole facing toward the surface. The magnet locator is a highly flexible elastomer that holds the magnets in place and remains flexible to maximize the conformability of the wheel. The rigid hub transfers torque from the drive-shaft output to the wheel, and the thin elastomeric tread provides traction and constrains the magnets inside of the wheel.

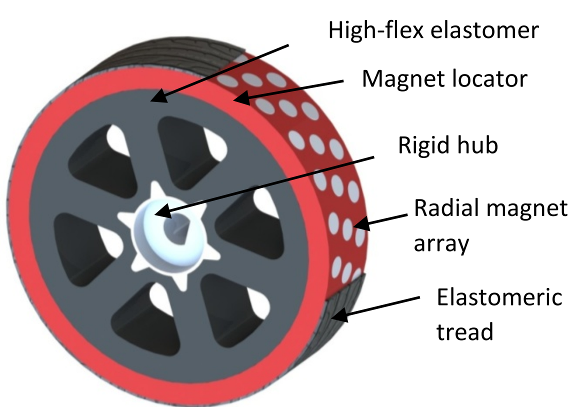

Figure 5. *Conformal* wheel.

The *flux-plate* wheel (Figure 6) consists of an elastomer wheel, two flux-plates, flux-plate locators, rigid hub, and an array of magnets oriented parallel to the central axis of the wheel. The magnets are positioned with all the north poles facing one side of the wheel and the south poles facing the other.

The elastomer wheel is 1-inch wide. In addition to locating the other components of the wheel, the elastomer is flexible, allowing the entire assembly to flex during impacts. The outer surface of the wheel has a high coefficient of static friction maximizing the traction with hull surfaces. The rigid hub in the middle of the wheel translates torque from the output shaft of the drive motors to the wheel assembly to facilitate motion. The flux-plates direct the magnetic flux of the magnet array through the surface climbed, providing adhesion. The flux-plate locators (not shown in Figure 6) help keep the flux-plates centered on the elastomeric wheel.

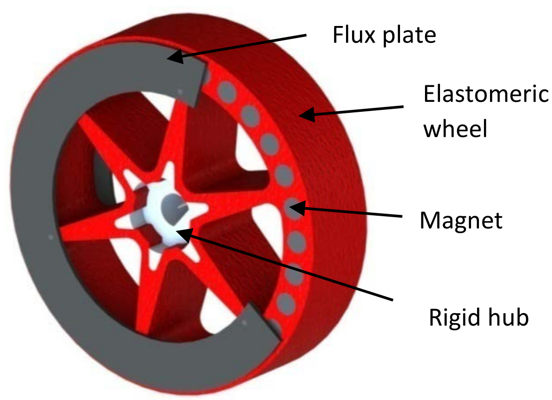

Figure 6. *Flux-plate* wheel.

Modeling and simulation, verified by prototyping and testing, demonstrated that the *flux-plate* wheel design was superior to the *conformal* wheel design in both performance and manufacturability.[2] Thus, an optimized *flux-plate* wheel design has been chosen for use on the MSM robot.

DRIVE MODULE

The drive module provides the torque to rotate the wheels and move the robot. The main components are the motor, gearbox, output shaft, housing, motor-shaft shock isolator, and bearings (Figure 7).

The primary design considerations for the drive module were torque output, speed output, shock absorption, weight, robustness, and modularity. The required motor torque, calculated by multiplying the weight of a robot segment by the wheel radius and a safety factor of two, was used to select an optimal motor-gearbox combination.

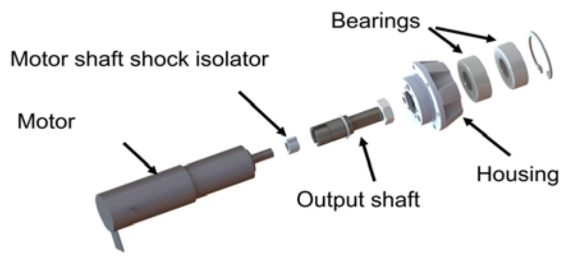

Figure 7. Drive module assembly exploded view.

To allow for ease of experimentation and prototyping, modular designs were used for the drive modules, allowing them to be quickly moved from one robot chassis design to another. The entire drive module can be quickly detached from any chassis by removing four screws around the perimeter of the housing (Figure 8).

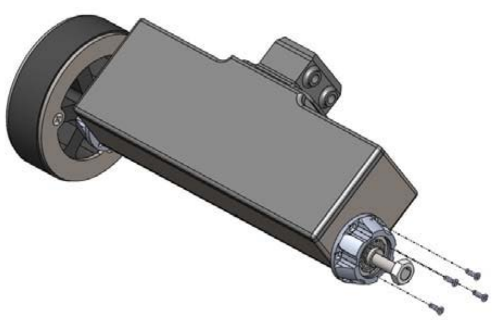

Figure 8. Drive module assembly.

The drive module was designed to mitigate the effects of large shock loads when the robot falls and lands on the wheels. The output shaft is supported by two high-load bearings (Figure 7) directly coupled to the drive module housing. If the wheel experiences an impact force, the radial loads are distributed through the output shaft to the drive module housing and back to the robot chassis instead of to the gearbox output shaft. The motor shaft shock isolator allows relative motion between the output shaft and gearbox shaft during impacts that cause the output shaft to deflect, while allowing torque to be transmitted from shaft to shaft for vehicle motion.

LINKAGE

The linkage, which makes the mechanical connection between the robot modules, must be flexible to allow the robot to turn and maintain wheel contact with the ferrous surface being climbed. It must also be able to transfer push (compressive) and pull (tension) forces between the robot modules so they can work in concert to overcome obstacles greater than the capability of any one robot module. Linkages with too many degrees of freedom (DoFs) may make control of the system overly complex and limit how force can be transmitted between robot modules. On the other hand, insufficient DoFs will limit the maneuverability and obstacle-traversing ability of the system. To better understand the linkage needs, four prototypes were fabricated and tested.

The elastomer-bow linkage (EBL) (Figure 9) was pursued because it appeared that it would provide both the flexibility for maintaining wheel contact and the transmission of forces for push–pull actions. At rest, the bow linkage is rainbow shaped, allowing the robot to traverse external corners more easily. The design is extremely simple, robust, and easy to fabricate. Linkages from three different durometers of elastomer were fabricated and tested. Testing showed the elastomer bow was effective at translating tension forces and providing flexibility to maintain wheel contact. However, during some cases when push (compressive) force was needed, the elastomer linkage started to buckle and the rear wheels caught up to the front, creating a situation where the robot stuck to itself.

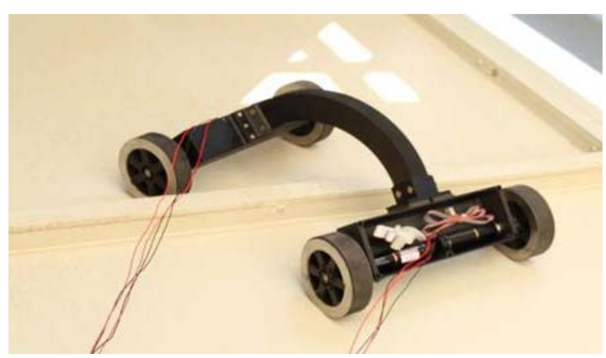

Figure 9. A two-segment prototype with elastomer-bow linkage.

A rigid-bow linkage was also fabricated for evaluation on the two-segment prototype robot. The linkage looked exactly the same as the EBL except that it was fabricated from a piece of plywood that made the entire robot structure rigid. The robot could traverse obstacles similar to those of the EBL as long as it was perpendicular to the obstacle. The rigid linkage did not perform well if the obstacles were approached at an angle because not all four wheels could maintain contact with the surface being climbed. It also provided very poor turning capability.

The third type of linkage that was designed, prototyped, and tested includes a three-DOF ball joint that can lock the pitch-and-yaw DOFs when compressed (Figure 10). This prevents the linkage from folding on itself when compressive (push) force is applied, but allows tension (pull) force through the joint. It was found that the range of motion of the ball joint was not enough to allow the robot to traverse external corners. Conceivably, the lockable ball-joint design could be implemented on a bow-shaped linkage to mitigate this problem.

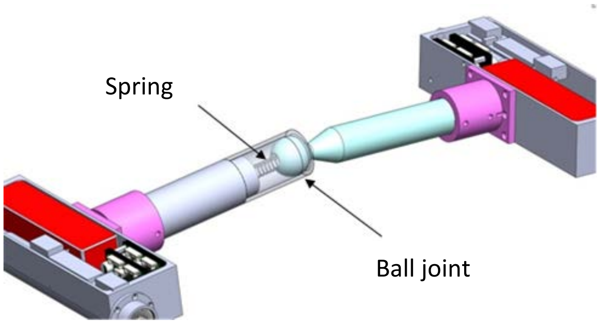

Figure 10. Lockable ball-joint linkage.

The fourth type of linkage designed and prototyped was a yaw bow with a limited-range-of-motion single-DoF leaf spring at the middle, which biases the robot towards an alignment of the wheels (Figure 11). The pivot and range limiting portions of the design worked well, allowing effective turning without allowing wheel-to-wheel contact. However, the wheels still had occasional problems maintaining full contact with the surface when the robot crossed obstacles diagonally. An improvement was then made to add a second DoF to the linkage, resulting in the roll-yaw-bow design (Figure 12). This design will be used in the development of the multi-module coordinated control software.

Figure 11. Yaw-bow linkage.

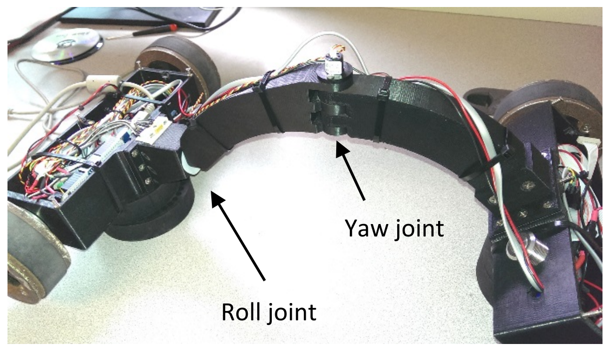

Figure 12. Roll-yaw-bow linkage.

ELECTRONICS

The electronics used in the MSMR can be grouped into four major categories: power, processing, sensing, and output. The power group consists of the battery and circuitry to manage and distribute power throughout the system. The processing group consists of the processor, radio, and circuitry to distribute communications. The sensing group includes the wheel encoders, linkage encoders, camera, and future payloads that may be added to gather information. The output group consists of the motors and motor drivers. The Gumstix *Overo FireSTORM* computer-on-module (COM) is used in each robot module to provide processing, sensing, and communication management. A high-level block diagram of the electronics is shown in Figure 13.

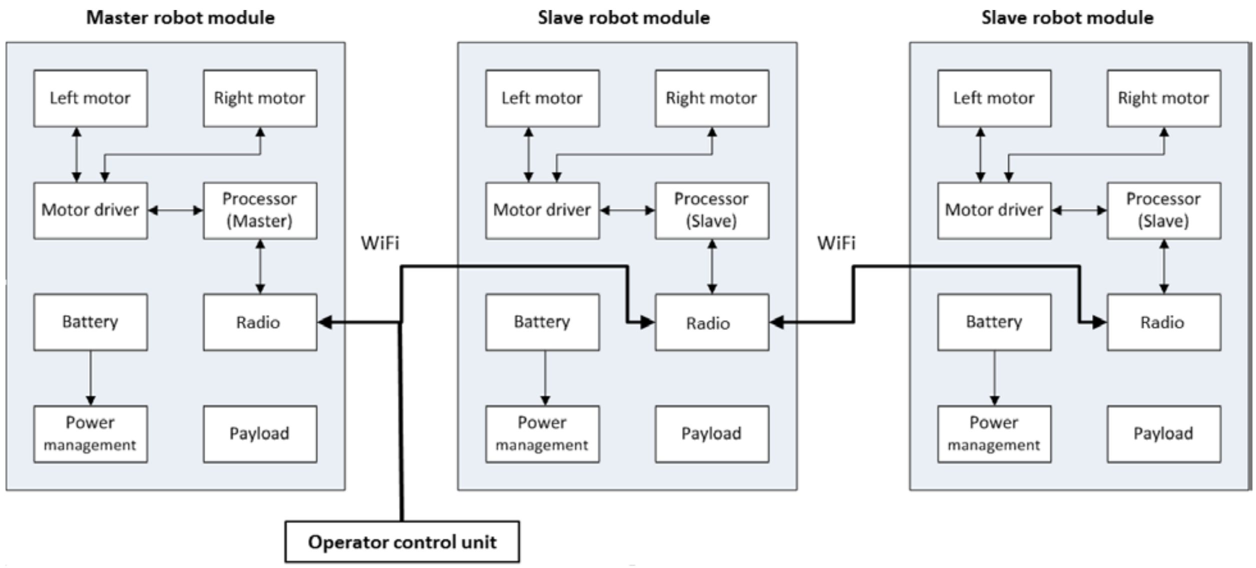

Figure 13. Electronics block diagram.

ROBOT MODULE SOFTWARE

Robot module software runs under Linux on the Gumstix *Overo FireSTORM COM* within each robot module. WiFi provided by the *Overo Fire COM* is used for communication between robot modules and the operator control unit (OCU). Software in the robot module executes low-level tasks and communications such as battery-level reporting, motor control, and sensor-data routing. Motor control software provides basic movement commands from the OCU via the *Overo* processor to the motor controllers.

OPERATOR CONTROL UNIT

The operator control unit will be a Microsoft *Windows* laptop or tablet running the *Multi-robot Operator Control Unit (MOCU)* application software.[3] Currently used for controlling a wide variety of unmanned systems, MOCU was designed from the ground up to be modular and scalable so it could be used with both existing and future platforms. The modularity has been extended to the user interface as well, making it possible to create the full gamut of user interfaces, ranging from headless to tiled windows to completely immersive game-like displays. While the modules are used primarily for interfacing to different protocols, specialized hardware, video decoding and the like, most of the user interface is defined in XML configuration files, making it relatively easy to customize what the display looks like and how the user interacts with the system, whether this be via mouse, keyboard, touchscreen, joystick, or other input devices (Figure 14). *MOCU* will provide video feedback and joystick control for the prototype system. In the future, feedback from new sensors, battery life, robot pose, and other relevant information and control interfaces may be added to provide semi-autonomous control.

Figure 14. A typical *MOCU* configuration for ground robots.

COORDINATED CONTROL

The coordinated control software (CCS) coordinates the motion of the drive modules to allow the MSMR to climb, turn, and scale obstacles more effectively. Each wheel on the MSMR is actuated individually, providing its own output speed. Individual control of each wheel by an operator is achievable but difficult. Development of a prototype MSMR with four wheels controlled through a standard radio controller (RC) clearly demonstrated the need for a coordinated motor controller.

A stepped approach is being used for development of the coordinated control software. The first step is to develop a simple leader-follower control scheme, where the operator directs the front drive module to go forward, left or right. The rest of the drive modules will then follow the drive module in front of them using a simple proportional, integral, and derivative (PID) controller (Figure 15). In the case where the operator commands the robot to go backward, the rear robot module will take the lead and the rest will follow using the same scheme. The required inputs for the leader-follower control scheme are motor speed and relative (yaw) angle of the robot modules to the one in front. The motor speed is obtained from the encoders integral to the drive modules. A sensor is being added to the linkage to collect the relative yaw angle between drive modules. This approach assumes that the roll and pitch variations between robot modules is not enough to significantly influence the control output.

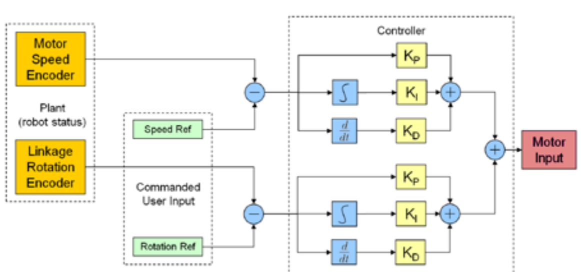

Figure 15. Robot-module PID controller.

If the leader-follower controller is inadequate because of the pitch and roll DoFs, or if the linkage design to support the leader-follower approach is overly complex, a more complex model-based controller will be pursued. In this case, the PID controller developed for the leader-follower may be reused within the model-based controller.

SYSTEM PROTOTYPES

Two prototypes have been developed. The first, a two-segment robot with RC components, was intended to quickly test different variations of subsystem components such as the drive module, magnetic wheels, and linkage. The second, a three-segment system with integrated processors, is being fabricated and will be used in the development of the coordinated control software for the system.

The RC prototype was tested with a variety of different linkage concepts. The yaw-bow linkage only provided a single DoF in the yaw axis, but proved the most effective of those tested with the RC controller. The system successfully climbed at 0.5 ft/sec and negotiated internal corners, external corners, and obstacles as high as 3 inches. It could also turn on vertical, horizontal, and inverted horizontal ferrous surfaces (Figure 16 and Figure 17). The linkage did not provide a roll DoF, resulting in the loss of wheel contact if an obstacle or angular transition was not traversed orthogonally to vehicle motion. Often, when wheel contact was lost the robot would fall from the surface being climbed.

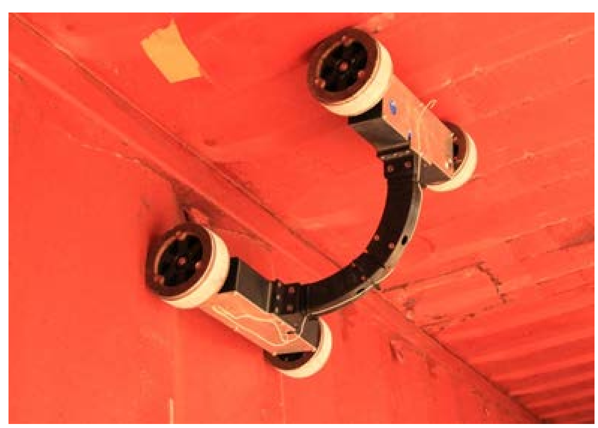

Figure 16. RC prototype traversing internal corner.

A second prototype was built implementing the lessons learned through experimentation with the RC prototype. This second design incorporates the roll-yaw-bow linkage and houses the full electronic suite described earlier. It is being used in the development of the coordinated control software.

Figure 17. RC prototype climbing exterior corner.

A three-segment computer-controlled prototype is planned, and an image of the CAD model is provided in Figure 18. It is expected to be more mobile than the two-segment system, but will require a full implementation of the coordinated control system.

Figure 18. Rendering of a three-segment MSMR.

CONCLUSION

The prototype MSMR systems developed at SSC Pacific have demonstrated that a multi-segmented magnetic robot with two DoFs between modules can effectively climb and negotiate ferrous surfaces with discontinuities, obstacles, and internal and external corners. Coordinated control of the modules is being developed to enhance operator control of the system. Additional development and maturation is required before the system is ready for testing in operational scenarios. The technology is promising for use in maritime interdiction operations and vessel hull and tank inspections, with the potential to significantly increase safety, effectiveness, and efficiency of personnel involved.

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Aaron Burmeister is a mechanical engineer with SPAWAR Systems Center Pacific, where he has 12 years of experience developing robotic systems for the Department of Defense. He has co-authored 13 published papers, been a guest lecturer at the University of California, San Diego, and holds five patents. He received a Bachelor of Science degree in Mechanical Engineering from UCSD.

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