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Versatile robotic platform for structural health monitoring and surveillance

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Abstract. Utilizing robotic based reconfigurable nodal structural health monitoring systems has many advantages over static or human positioned sensor systems. However, creating a robot capable of traversing a variety of civil infrastructures is a difficult task, as these structures each have unique features and characteristics posing a variety of challenges to the robot design. This paper outlines the design and implementation of a novel robotic platform for deployment on ferromagnetic structures as an enabling structural health monitoring technology. The key feature of this design is the utilization of an attachment device which is an advancement of the common magnetic base found in the machine tool industry. By mechanizing this switchable magnetic circuit and redesigning it for light weight and compactness, it becomes an extremely efficient and robust means of attachment for use in various robotic and structural health monitoring applications. The ability to engage and disengage the magnet as needed, the very low power required to do so, the variety of applicable geometric configurations, and the ability to hold indefinitely once engaged make this device ideally suited for numerous robotic and distributed sensor network applications. Presented here are examples of the mechanized variable force magnets, as well as a prototype robot which has been successfully deployed on a large construction site. Also presented are other applications and future directions of this technology.

Keywords: robotics; structural health monitoring; complex systems; sensor networks.

1. Introduction

Structural Health Monitoring (SHM) is vital to ensuring the integrity and longevity of civil structures, as well as providing data and design feedback for the modification or retrofit of existing structures, or the construction of new structures. By observing the performance and state of a structure through SHM techniques, much information can be obtained which quantify how a structure responds to its real world environment and its present state of health. Although computer simulations and analyses can predict a structural response to various loading conditions and environmental parameters, a vital step in the design process, it is also important to monitor the performance of the structure during its construction and throughout its life. SHM gives key information regarding structural condition and capabilities, provides feedback to help validate or invalidate the design models, highlights factors neglected in the modeling process, and provides insight into the condition and lifespan of structures. SHM also provides invaluable information for determining maintenance schedules and upkeep requirements. However,

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even with all the benefits SHM has to offer, the size, complexity, and accessibility of the structures themselves often makes monitoring difficult or impossible with conventional human based monitoring techniques. The use of mobile robots to deploy sensors and gather data in SHM applications provides alternatives to human based systems and greatly increases the feasibility of employing SHM in many hazardous, confined, or inaccessible structures or structural components.

Perhaps the most significant challenge to creating a robot platform for SHM applications is the diversity and variability of the structures themselves. Aside from creating small, specialized robots designed to travel across a single structure, or even a single aspect of a structure, utilization of robotics in SHM has been extremely limited. However, by creating a robotic platform which has the ability to traverse a wide variety of configurations and geometric complexities, robots can be applied to SHM of many different structures with only a few robotic platform configurations.

Many civil structures are made from ferromagnetic materials, predominantly steel. Being of major importance to civil infrastructure, monitoring of the health of these systems is critical. Also, recent developments in world politics and current events highlight the need for implementation of robust security systems on these important civil structures. The incorporation of security features is a natural extension of the sensing systems used in SHM applications, creating an integrated structural health monitoring and security system, or SHMS system. Typical examples of structures which can benefit from SHMS include bridges, coffer dams, pipelines, power stations, transmission towers, water towers, radio towers, construction sites, skyscrapers, offshore oil platforms, and many others. Utilizing a magnetic based robotic infrastructure traversing system to both inspect and patrol these structures allows for a robust, adaptive, and reconfigurable system. Also, utilizing magnetic based attachment methods eliminates the need for geometry-specific gripping, allowing a single design to be applied to a variety of structures.

2. Background

Employing sensor nodes and networks for structural health monitoring is not a new technique (Johnson, *et al.* 2004). However, utilizing robotic systems to traverse a structure and deploy sensors as needed adds considerable versatility to a nodal sensor network. In this way, such a system can be reconfigured as warranted to adapt to changing sensing conditions or parameters of interest. Having the ability to modify sensor locations, either in response to changing conditions or in light of newly collected data, has numerous advantages over a static system using permanently installed sensor nodes. For example, a detailed modal analysis of a bridge can be carried out with only a handful of sensors by gathering data at numerous locations and combining the results. Achieving this degree of detail with a static node system would require thousands of sensors, and would still not ensure that critical locations are being monitored. However, progressively modifying and fine tuning the node locations using previously collected data as a guide creates a system capable of providing information regarding structural condition and performance far superior to that of a discrete static network. The location, sampling rates, and sensor types can be chosen and modified as often as needed to provide a highly adaptive network.

The key to achieving such a system is to have a robotic platform that can traverse a structure to deploy and move the sensor nodes as desired. Numerous specialized robots have been constructed for specific structures; however, these are limited in mobility and cannot be used on a variety of structure configurations. Instead, they are designed for single applications to a specific structure. Such robots include utility pole climbers (Hudson 2000) and I-beam traversing units (Huston, *et al.* 2003). “The Robotic Inspector” (ROBIN) was developed at the Intelligent Robotics Lab at Vanderbilt University to inspect man made structures (Pack, Iskarous, and Kawamura 1996). ROBIN is highly mobile and versatile, but is restricted by limited payload areas and a power cord. Visual/Inspection Technologies Inc. have a unit called SPOT that utilizes movable cameras for pipe inspection and has developed other robotic systems. Although SPOT can travel into areas where humans cannot reach, it still requires a human operator and is specific to piping applications. Other robots for pipe specific applications have been developed at North Carolina State University. Their proposed use is to crawl through pipes that remain intact after a building collapse and search for survivors trapped in the wreckage. They can also be used to detect gas leaks (Nadis 2000). However, a robot platform which has the capability to traverse a wide variety of structural and geometric configurations would add considerable versatility to a robotic SHM application. To create such a robot, a novel technique for attachment to the structure is needed to avoid designs based upon tracks or specialized mechanical gripping. An attractive solution to this problem is implementation of magnetic gripping which increases the kinematic flexibility and enables the fabrication of generalized mobile robots that can traverse more complex structures. A robot equipped with variable force magnetic feet is such a device and allows for deployment of a single design on a wide variety of structures. By designing an articulated robot with multiple joints and feet, an insect-like walker can be created with the ability to traverse and transition over all types of surfaces, joints, and geometries. Biologically inspired robots have been widely praised as having many features desirable in an automated platform, and rely on locomotion techniques which have endured millennia of testing and refinement through the evolutionary process (Taubes 2000, Bar-Cohen 2002). Creating a biologically inspired robot results in an effective platform of locomotion, however the means by which the robot physically attaches to the structure is still in question. A promising advancement in this field recently has been the development of a gecko-foot like material which utilizes van der Waals forces to cling to smooth surfaces, in the same way as the gecko lizard is able to walk up a glass window (Geim, *et al.* 2003). This material can grip non-magnetic surfaces, but disengaging its grip remains problematic. Also, its use and reuse on rough or scaly surfaces is severely limited. Other attachment efforts have utilized electromagnets, and have even included permanent magnet tracks for the inspection of underground storage tanks (Schempf 1994). However, none of these technologies possess the advantages present in the variable force magnetic attachment method described below.

3. The MOORAD

The use of magnetic devices which can be “turned off” by rotating a permanent magnet within a split ferromagnetic housing has been widely adopted by the machining and tooling industry since such a device was invented in 1934 by Eclipse Magnetics of the UK and patented in the United States in 1939 (Levesque 1939). However, their use in applications other than manufacturing and material handling has been very limited. Adopting this technology for use in a robotic system which can traverse a steel structure and deploy various sensor nodes also equipped with a similar permanent magnet based attachment device is a novel technique which can produce robust, low power robotic structural health monitoring and security systems. Utilizing actuators of various types, the magnetic device can be automated to turn on and off as needed to perform various tasks. This mechanized magnetic device, termed a MOORAD (magnetic on-off robotic attachment device), can be used as both an attachment means for a robot navigating a ferromagnetic structure, as well as for an array of sensor nodes to the structure. This technique has several advantages over other attachment methods, and can be used on a wide variety of steel structures and platforms.

The key to the MOORAD's operation is the mechanized rotation of a high strength permanent magnet within a split ferromagnetic housing. Rotation of a cylindrical magnet, polarized through the sides of the cylinder rather than the ends, within such a split housing allows for the magnetic field to be contained or released depending on the magnet pole orientation. The permanent magnet, or "hard" ferromagnetic material, influences the surrounding "soft" ferromagnetic material. Soft ferromagnetic materials have minimal magnetic hysteresis when an external magnetic field is removed, while hard ferromagnetic materials retain a residual magnetic flux density. Permanent magnets are "hard" ferromagnetic materials. When the magnetic flux created by the permanent magnet penetrates a ferromagnetic material that is below its critical, or Curie, temperature, the electron spins in the atoms of the material align themselves producing a net magnetic moment. This in turn results in an attractive force between the permanent magnet and the ferromagnetic material (Moon 1984). In the case of the MOORAD, magnetic flux can be directed through or around a soft ferromagnetic structure, thus changing the magnitude of the attractive force between the MOORAD and the structure. A diagram showing the on and off states of the device and the associated flux lines is shown below, Fig. 1.

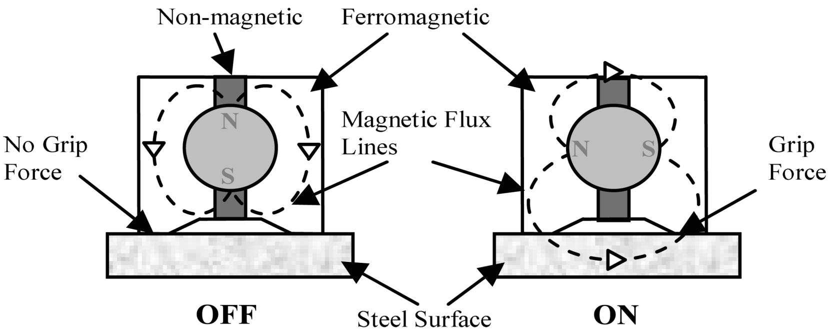

Fig. 1 Flux lines of the MOORAD device in ON and OFF states

The MOORAD is unique in that it only requires power to switch states, not to maintain them. This is in sharp contrast to conventional electromagnetic attachment devices, which must constantly draw electrical current to maintain a magnetic field. Rotation of the cylindrical magnet can be effected through a variety of means, such as linkages, gear trains, servomotors, and many others. Because power is only required when switching states, engagement of the MOORAD in contact with a ferromagnetic object is a neutrally stable change of states. The attachment can be sustained indefinitely without additional energy. A MOORAD-based robot can hang suspended from a structure ad infinitum without consuming power. Similarly, sensor nodes can be positioned and attached, and can monitor various parameters for an amount of time limited only by the power schemes of the sensors and microelectronics (including any data transmission). This enables structures to be monitored for long periods of time by small, relatively simple robotic platforms.

Prototype MOORAD devices have utilized servo actuated linkages, Fig. 2(a), and mechanized gearmotors, Fig. 2b. The MOORAD unit shown in Fig. 2(b) utilizes 25.4 mm long neodymium magnets attached to nylon gears that are held inside the split steel housing. A layer of acetal insulates the split housing to contain or release the magnetic field as desired for operation as outlined above. The split housings are the only magnetic components of the robot to ensure that there is no loss of field

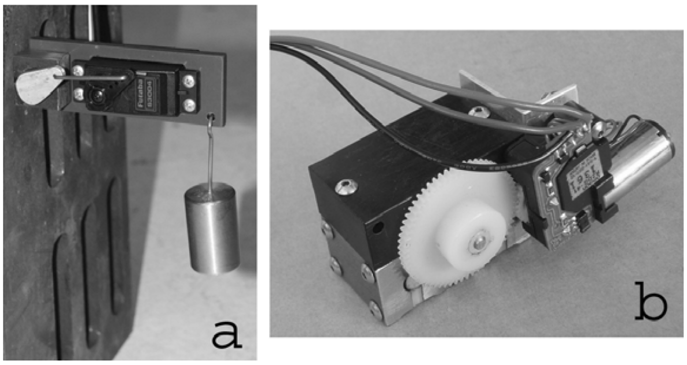

Fig. 2 Servo-linkage MOORAD (a), and gear motor driven double MOORAD (b)

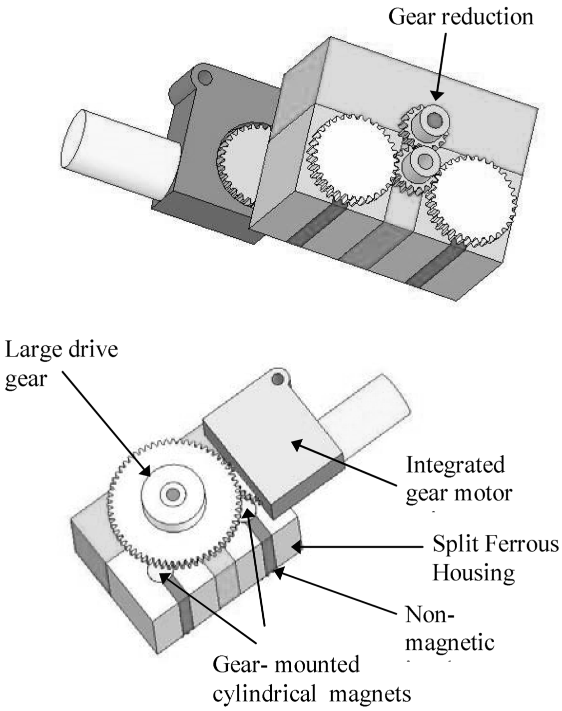

Fig. 3 Double MOORAD diagram

strength due to possible alternate flux paths, which may decrease the holding power of each unit. The MOORADs are actuated by a specialized gear motor which turns one complete revolution in response to an input pulse generated by the control system. A 4:1 gear reduction integrated into each unit causes the cylindrical magnets to rotate 90° for each pulse, thus switching states and requiring only one direction of motion. Two rotating magnets are connected to one main spur gear, which is driven by the gear motors, creating a double MOORAD foot, Fig. 3.

MOORAD based magnetic attachment has many advantages over conventional electromagnets. As mentioned, once engaged the MOORADs are stable and require no power consumption to remain

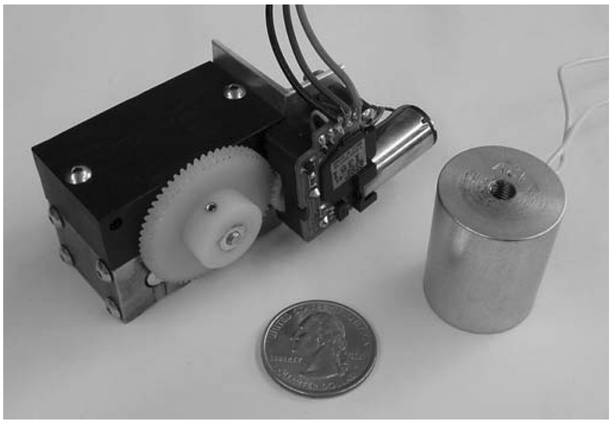

Fig. 4 Double MOORAD and electromagnet, U.S. quarter shown for size reference

attached. This not only is attractive in terms of operating time, efficiency, and onboard power requirements, but also improves safety by reducing the chances of the robot or sensor node detaching unexpectedly. The double MOORAD shown in Fig. 2(b) and Fig. 3 requires approximately 110 mA of current to actuate at a potential of 5 V, which takes about 1.75 seconds. This results in a power requirement of 550 mW, consuming just 960 mJ of energy for each change of states (Off to On, or On to Off).

A commercial electromagnet of similar scale is shown in Fig. 4, next to the comparable MOORAD unit. This device draws 330 mA at 12 V, consuming 4 W at all times while the device is engaged. Therefore, the energy required to operate the electromagnet for just one minute could be used to switch the state of the MOORAD 250 times.

Not only are the power requirements significantly less in the MOORAD than in the electromagnet, but the holding force is superior as well. Tests of both units were performed on an Instron testing machine to determine the maximum holding force of each device. The electromagnet was capable of providing an average of 60 N of magnetic attractive holding force when placed against a mild steel surface. This electromagnet has a mass of 77 g, therefore the force to mass ratio is approximately 0.78 N/g. The MOORAD was capable of an average maximum force of 182 N. The mass of the unit, including the gear motor actuator, is 183 g, resulting in a force to mass ratio of 0.99 N/g. It is noted that this preliminary design was not optimized for minimum mass, and a device having similar holding power could be built with a significantly reduced weight. These tests clearly exhibit the advantages of MOORAD based gripping over electromagnetic based gripping in terms of both force to weight ratio and power requirements.

4. MagGIE robot

The gear driven MOORAD unit described above has been successfully implemented in a robot platform utilizing biped locomotion to traverse a flat steel structure in any orientation. Fig. 4 shows this robot, named MagGIE (Magnetic Gripping Infrastructure Explorer), climbing a vertical steel plate in a laboratory environment.

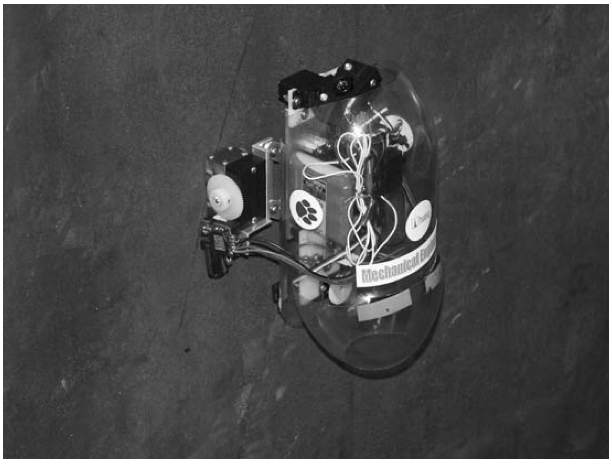

Fig. 5 MagGIE MOORAD based robot climbing steel plate

As this robot is a novel design, it was completely custom fabricated. The robot has two double MOORADs as feet, which are connected to a central control chassis and each other through a 5 bar parallel linkage. Other components are constructed of acetal, 6061 aluminum, and 18-8 stainless steel. Although 18-8 stainless steel can be slightly magnetic, our particular hardware selection exhibited minimal magnetic properties. The five bar linkage is actuated by a centrally mounted metal gear servo. This servo holds a specific position based on the duty cycle of a pulse width modulated (PWM) signal, generated either from an onboard microcontroller or through a RC radio receiver. The robot shown in the figures above uses a Futaba 9 channel remote transmitter operating at 75 MHz to control the unit manually. This transmitter system is designed for robust communication over a multi-mile distance, and although no tests have been conducted regarding range, no problems have been experienced to date regarding loss of operation or control. The feet can be switched independently to allow for either locomotion or for static operation (i.e. both feet magnetically engaged for maximum grip while in observation mode). The linkage angle is also controlled by the remote unit, and can be used to move either forward or backwards. Nylon bushings are installed at all linkage pivot points to reduce friction and increase robot efficiency. MagGIE is equipped with a remotely panning camera which transmits video of the structure and surrounding area to an observer via a wireless 2.4 GHz telemetry system. The camera serves as both a means for inspection and for tele-operation of the robot. The camera is mounted to a micro servo on the front of the robot's control chassis with integrated white LEDs for illumination, enabling the camera to pan as needed for both inspection or tele-operation. See Fig. 6 for a CAD model of the robot.

The robot accomplishes its locomotion by selectively turning on and off the feet on each side of the platform, and sliding the deactivated side forward or back as desired. This allows for vertical, inclined, or completely inverted operation. The high strength of the rare earth magnets provides excellent traction on all but the smoothest surfaces. The mild corrosion often found on and in steel structures provides a surface well suited to both MOORAD gripping and sliding.

Power for the system is supplied by a low cost ni-cad battery pack, with an output of 4.8 volts and 600mAh. This provides all the power for the camera, camera servo, illumination LEDs, linkage servo, gearmotors, and the remote receiver. Depending on the distance traveled to a specific sensing location,

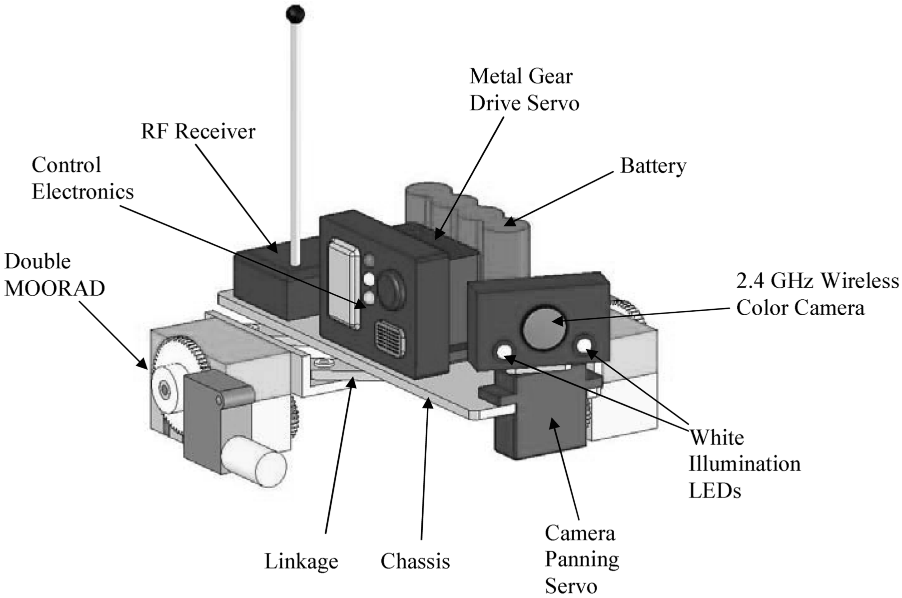

Fig. 6 CAD rendition of MagGIE robot

the unit can operate for hours on a single charge. This runtime can be significantly increased by implementing higher performance batteries and incorporating on-board energy harvesting techniques, and may even offer lower weight as well. The entire robot assembly has a mass of only 0.8 kilograms, with a holding capacity of over 150 N with both double MOORADs magnetically engaged. Incorporation of a safety factor and realizing that locomotion of the robot relies on one MOORAD holding the entire load, robot payloads of up to 3 kg can be accommodated provided the coefficient of friction between the MOORADs and the structure is sufficiently high. Increasing this friction using techniques such as knurling or applying a thin layer of a viscoelastic material to the MOORAD's contact surface should increase the payload capacities but have not yet been investigated.

Applications of this or future generations of the MOORAD based robot systems are many. In terms of monitoring and surveillance, this system has applications to bridges, dams, pipelines, power stations, water towers, naval vessels, and any magnetic structures, large or small. Also, small robots can be created which travel through building ductwork to provide video monitoring, and can incorporate the ability to deploy various sensors within the air handling systems to monitor for the release or presence of various chemical, biological, or nuclear (CBN) agents. Because the MOORAD devices require no power to maintain their state, they are an attractive solution to sensor deployment as well. Attaching sensors to a single MOORAD with remote transmission capabilities enables the deployment of a highly specialized sensor network throughout or within a structure. In this way, a robotic MagGIE can be utilized to disperse the sensor nodes to the key locations, and can be used to retrieve or reconfigure the sensor placement as needed. Large infrastructures can be monitored from a single location (which can be either on site or remote) while utilizing highly configurable and adaptable network configurations.

MagGIE has been successfully deployed on a large hospital construction project for its initial field testing. Specifically, it has been used to inspect pressure vessels, Fig. 7, and navigate HVAC ductwork Figs. 8 and 9.

Fig. 7 MagGIE robot inspecting a pressure vessel

Fig. 8 MagGIE traversing galvanized ductwork

The application to galvanized steel ductwork is an extremely useful example of the benefits of this technology. Generally, these environments are far too constrictive and not nearly strong enough to permit a human to safely move throughout a duct system. Additionally, the length and complexity of the duct systems complicates the use of telescopic or tethered inspection and sensing systems. MagGIE's light weight and tele-operation capabilities make it ideally suited to such an application. Inspection of joints and fittings, observing fan and baffle operation, and blueprint generation or verification can all be carried out with ease. Also, a robot outfitted with an anemometry sensor can be used to determine flow rates through ducts, and can be used to track down problems with air circulation systems and mixing boxes.

Another example application of this technology is for temporary site monitoring, such as a construction site. A MOORAD equipped robot can climb to a high lookout location, and with a wireless

Fig. 9 MagGIE entering a large air duct

Fig. 10 MagGIE climbing to an ideal lookout location

camera can provide surveillance of the project, including incremental progress and construction practices. When the project is nearing completion, the robot can simply walk back down the structure and move on to the next site. Fig. 10 shows MagGIE attached to a steel I-beam near a potential lookout location. Utilizing the panning feature of the camera allows for surveillance of a very large area from a single location. Having multiple mobile robots on a site allows for remote monitoring of a sizable area from a few key vantage points, which can be changed as necessary to accommodate varying observation requirements. The applications of this video based monitoring are many. Project managers have instant access to the state of the project, and can document the timelines of progress and material deliveries. Similar technology can be used to monitor security at critical locations for short periods of time, such as large sporting events.

5. The future

Implementation of MagGIE in a real world construction site demonstrates the viability of this technology to SHMS and other surveillance and inspection applications. However, MagGIE's mobility is limited to straight locomotion on flat or relatively high radius of curvature surfaces. It is desirable to increase the mobility of the robot for applications on more complex geometries, such as the ability to negotiate sharp curves and corners. This can be accomplished by increasing the number of degrees of freedom of the robot and its articulated joints. Utilizing two MagGIE type units connected in the center with a three degree of freedom joint which can flex in two dimensions and also rotate, a device known in the industrial robotics field as a robotic wrist, Fig. 11, is the first step in realizing this enhanced mobility (Sclater 2001). Further enhancements of this model would increase the mobility and capabilities of the robot even further, accomplished through the implementation of three or more MagGIE type sections connected with the wrist type joints, and by adding another degree of freedom to the MOORAD feet, specifically the ability to rotate the gripping surface around an axis. This biologically inspired design mimics the caterpillar and its locomotion capabilities. Such a system would have the ability to traverse and transition a huge variety of complex ferromagnetic structures and components, and would even allow for the transitioning between non-contiguous components, such as adjacent trusses on a bridge. This is similar to the way in which a caterpillar can climb from a stick to a leaf suspended above, but not touching, the stick. The robot could reach out to other surfaces, engage its front feet, and pull the rest of it up behind it. A simple diagram of such a system making this type of transition is shown below in Fig. 12.

The speed of such a robotic system is also an important design consideration. MagGIE's speed is limited by the speed of the mechanical actuation, and is on the order of 1 meter per minute. However, as this is a proof of concept prototype, this has not been maximized. Refinement of the control system and selection of higher performance electromechanical actuation components could easily yield an order of magnitude improvement in speed. Future designs will have speed characteristics based on a

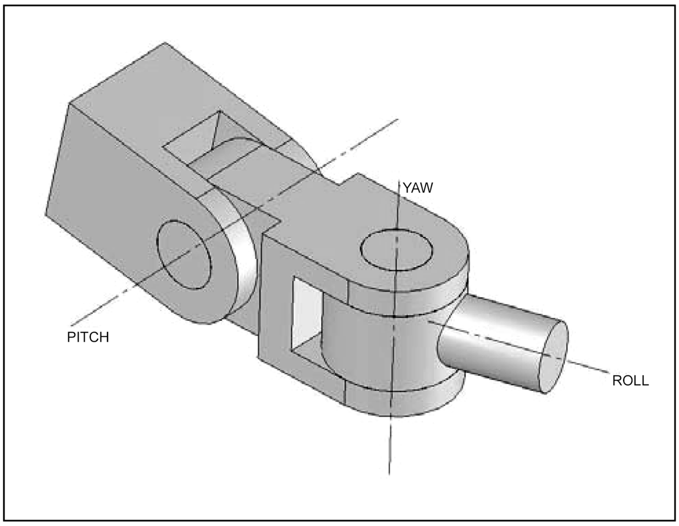

Fig. 11 Three degree of freedom robot wrist

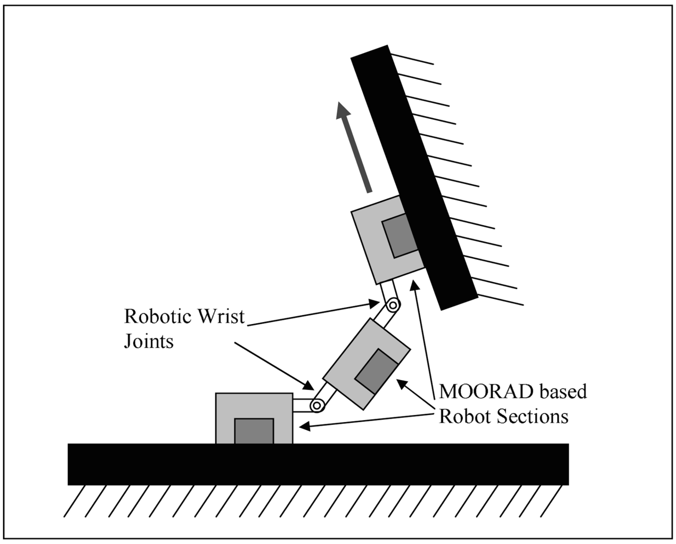

Fig. 12 Caterpillar inspired MOORAD climber

compromise of monitoring requirements, power requirements, size, and cost. The speed at which a robot moves also influences the number of robots required for each application. For example, MagGIE, moving at 1 m/min and with a 10 centimeter wide field of view, can inspect about six square meters per hour, or about 150 m^2/day. In a simple inspection project, this may be more than adequate. However, applications requiring faster data collection or rapid reconfiguring of sensing nodes may require faster robots, groups of robots, or both.

Aside from increasing the mobility and flexibility of the robot, developing an array of deployable sensors is an important stepping stone to a complete robotic SHMS system. Utilizing sensor nodes which also incorporate the MOORAD attachment method is an attractive solution to sensor deployment. These sensors can be specific, having only one measuring parameter, such as acceleration, or can be more complete nodes incorporating an entire array of sensors and detectors. Recent advancements in sensor technology have enabled the production of extremely efficient and small transducers. Packing many sensors in a compact node creates a very versatile and capable monitoring system. Examples of sensors which can be incorporated into such a system include video, audio, temperature, humidity, acceleration, strain, GPS, CBN detectors, and even miniature mass spectrometers. Ideally, the robot would have a small army of these sensor nodes which it could deploy and reconfigure as necessary throughout a structure or region of interest. To deploy the sensors, the robot could simply climb to the desired location, engage the node's MOORAD through a simple robotic actuator, and release the sensor node. The magnetic forces would cause it to grip the structure until the robot comes back to deactivate the MOORAD and retrieve the node.

Collecting data from the deployed sensor networks can be accomplished through a variety of means. The most attractive of these is the use of radio frequency (RF) communications. Utilizing RF transceivers, the robot can communicate with the individual nodes and sample data as needed. Bi-directional communications can be used to program the nodes to send data back on specific parameters of interest at specific time intervals. This type of system utilizes the robot not only as a means for sensor deployment, but as a central pipeline for the sensor data also. Utilizing addressable RFID (radio frequency identification) type technology, many sensors can be deployed each with unique addresses, allowing for a very large amount of data to be gathered in a highly organized and reliable fashion. This technique has been successfully used in human deployed SHM applications (Galbreath, *et al.* 2003), and would certainly be a beneficial technology to robotically deployed SHMS systems.

Once data sets are collected, they must be sifted through to reveal the critical information. Generating overly large and cumbersome data sets with SHM systems is easy, however efficiently extracting the useful information out of these data sets is much more difficult and time consuming. Some methods of doing this include various data fusion techniques, preset alarm levels, trend identification, and others. The advantage of using sensor nodes which can be relocated and reconfigured by the robot is that the system can be tuned and tweaked continuously while still gathering data on the structure, without the need for continuous human involvement. Future research and field trials will be used to help determine at what level the robot operates on its own and how much human input it needs to make decisions. For example, a human might tell a robot where to go but not how to get there. This type of configuration allows for efficient operation but also incorporates the human attributes of experience and intuition into the monitoring process.

6. Conclusions

Equipped with an array of deployable sensors, a MOORAD based robot's uses are myriad. A few examples of their implementation include monitoring of vibrations and strains in load critical structures, such as bridges. Vibration excitation can be measured in nearly any magnetic structure, such as wind excitation of a transmission tower. Waterproof MOORAD based robots can crawl under ships to inspect the hull and fittings. Addition of a specialized arm could allow a robot to climb a light pole and change light bulbs, such as those in large stadium arenas. As long as the structure is constructed of a ferromagnetic material, a MOORAD robot can be used to monitor, inspect, patrol, and possibly even service any type of structure. Also, having the ability to reconfigure a nodal sensor network robotically allows for extreme flexibility of the nature of the data collected, not only during the initial installation but throughout the monitoring process.

As illustrated here, MOORAD based robots such as MagGIE can be used to aid in the health monitoring and security of many structures and systems. The small size and efficiency of these robots permits access to areas and components which previously have been impossible to monitor. The flexibility that a robotically reconfigurable sensing network can offer will provide significant benefits to many applications and fields encompassing academic, commercial, industrial, and military arenas. From a single unit system contained in a small suitcase to inspect HVAC ductwork to a swarm of robots monitoring thousands of parameters of a colossal infrastructure, these robotic systems will find uses and applications on many levels across a variety of disciplines. Because the robot design can be applied to a wide variety of geometric configurations, the need for customized application-specific robots is eliminated. This in turn reduces costs and increases the flexibility of such a system, further increasing possible benefits.

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