

# Wireless inspection of structures aided by robots

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## ABSTRACT

The inspection of structures by humans is often hampered by safety and accessibility concerns. One method of reducing human inspection activities is to use remotely located sensors, such as strain gages and accelerometers. Running cables to power the sensors and transmit data can be expensive and inconvenient. This paper describes a development effort in which a robot is used to power and interrogate remotely placed sensors. The sensors are powered by a noncontact inductive system, which eliminates the need for batteries or interconnecting lead wires. The data are sent by a wireless connection back to a central data logger and processor. The power demands of telemetering data are decreased by close proximity of robot. The system utilizes existing microminiature, multichannel, wireless programmable Addressable Sensing Modules (ASM's) to sample data from a wide variety of sensors. Demonstration style robots are built and tested with ASMs in simple tabletop design, and a more robust task specific I-beam crawler robot for structural application.

Keywords: remote interrogation, robot, inductive power, wireless, addressable sensing modules

## 1. INTRODUCTION

Inspection of civil structures is an importance component of public safety. Many instances of unforeseen failure of civil structures have occurred over the past. Bridges have collapsed due to scour (erosion of the sediment supporting the bridge structure due to various influences<sup>1</sup>) and caused deaths in recent times through out the country. In 1987 the Interstate Highway Bridge over Schoharie Creek in New York State collapsed killing 10 people<sup>2</sup>. Scour is difficult to monitor, as the causes of the erosion also often make for dangerous inspection conditions. The ability to monitor scour during flooding conditions using a robotically interrogated remote sensing process increases safety, gives up to date information, and potentially saves lives. A proposed method of scour measurement is the use of peak strain detectors. As the structure's supports deteriorate the peak strain increases<sup>3</sup>. In addition to safety issues, the cost of maintaining, repairing and replacing highway bridges is significant. The Federal Highway Administration is scheduled to spend \$4.5 billion in FY 2001 on highway bridge repair and replacement (<http://www.fhwa.dot.gov/tea21/factsheets/bridge.htm>).

There have been previous efforts using robots to monitor civil structures. "The Robotic Inspector" (ROBIN) was developed at the Intelligent Robotics Lab at Vanderbilt University to inspect man made structures<sup>4</sup>. ROBIN is highly mobile and versatile, but is restricted by limited payload areas and a power cord. Visual/Inspection Technologies Inc. called SPOT that utilizes movable cameras for pipe inspection has developed another robotic system. 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<sup>5</sup>.

This paper focuses on the development of an autonomous robotic sensor inspection system capable of remote powering and data collection from a network of embedded sensing nodes, and providing remote data access. A main aspect of the system is the utilization of multichannel wireless programmable Addressable Sensing Modules (ASM's) to monitor a wide variety of sensors. These inductively powered nodes do not require batteries or interconnecting lead wires, which greatly enhances their reliability and ease of installation. Sensors of peak displacement, peak strain, corrosion, temperature, inclination, as well as continually developing microelectromechanical systems (MEMS), are capable of embedment or attachment on structures, and are compatible with the ASM this system utilizes.

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The purpose of this study is to remotely and autonomously interrogate a group of sensors that are attached to a large structure. There are two main components to this effort: developing the robot and the ASMs. The technical objectives are: dispatch the robot from its base station at regularly scheduled and remotely programmable time intervals, have the robot search for ASM modules along a predetermined path, stop and provide power to the ASM's, perform data collection via a telemetry system, and return to the base station for data downloading, and recharging.

## 2. ADDRESSABLE SENSOR MODULES

A major part of this system is the ASM, which is an inductively powered data acquisition and microtransmitter system, Figure 1. The microtransmitters are created using off-the-shelf surface mount IC's. The requisite bridge signal conditioning, multiplexer, A/D converter, and programmable gain and filter functions are included on one chip. This chip features 3 true differential bridge inputs, 5 pseudo differential inputs, a maximum resolution of 22 bits, and software programmable gain of 1 –128. This device can be configured by programming the microprocessor through the serial port of a PC<sup>6</sup>. A standard configuration includes channel specific gain, filtering, and sample rate parameters. The configurations are easily changed to accommodate the type of sensor attached to the ASM. The ASM is capable of running a wide variety of sensors including strain, temperature, acceleration, pressure, and displacement gages.

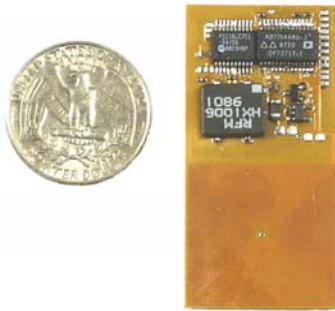


Figure 1 ASM module.

The ASM is remotely powered by an inductive coil that generates an AC magnetic field when driven with AC current. This coil is carried as part of the robot's payload and integrated with a highly efficient power amplifier that converts battery supplied DC power into the AC power required to drive the inductive coil. Magnetic near field coupling is utilized to transfer power to the target coil that is located on the ASM. In turn, an AC voltage is generated on the target coil that is rectified and filtered to provide the DC power to operate the sensors and telemetry system, Figure 2. AC sensors can be used in conjunction with a specialized AC module. This method of 'non-contact' powering enables the ASM to be fully embedded within a structure or completely encapsulated for increased life span, Figure 3.

## 3. ROBOT DEVELOPMENT

An initial proof-of-concept robot was created with the LEGO Mindstorms<sup>®</sup> programmable robotic invention system. The purpose of this preliminary design was to evaluate the ability of an autonomous robot to remotely power and transmit data transmission from the ASM to a receiver and datalogging PC. A second robot was built for interrogating sensors located along the span of a common I-Beam. This design utilizes a fully programmable microcontroller on a custom built chassis for robotic inspections.

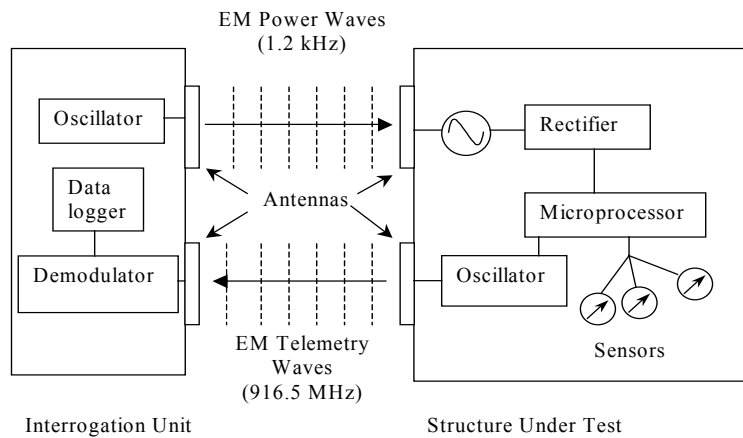


Figure 2 Schematic of ASM wireless inductive power and data transmission system.

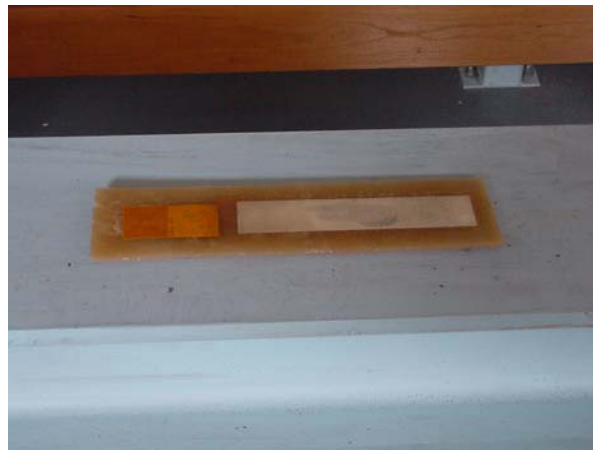


Figure 3 ASM and strain gage rosette encapsulated in composite case.

Preliminary tests for the project were run using a LEGO Mindstorms<sup>®</sup> robotic system, Figure 4. There were several reasons for choosing the Mindstorms' system, including the ease of programming, the wide variety of possible robot configurations, and the ease of integrating the bundled robotic sensors, motors, and microprocessor.

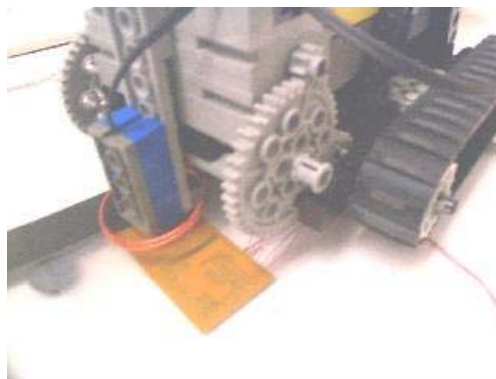


Figure 4 Tabletop robot interrogating ASM.

Preliminary tests of this concept were carried out on a large platform with two temperature measuring thermisters attached to the ASM. In the first test, a track following robot was built that followed a path of black tape to the location of the ASM. Once there, a trigger mechanism told the robot to pause and transmit temperature data. Figure 5 is a schematic diagram of the tabletop robot test.

In order to gain insight into a magnetic tracking method the robot was fitted with a magnetic "sniffer", which consisted of a very low cost (\$1.50) magnetic reed switch. Inexpensive magnetic tape was placed on a rough floor over a circuitous pathway approximately 30 feet long. The robot was programmed to follow the magnetic strip. Once the sensitivity of the reed switch was optimized, it was possible to follow the stripe without difficulty. These tests demonstrated that an optimized magnetic circuit could be developed which would make magnetic tracking useful in structural monitoring applications, and a combination of optical and magnetic tracking may be ideal for future robotic inspection systems.

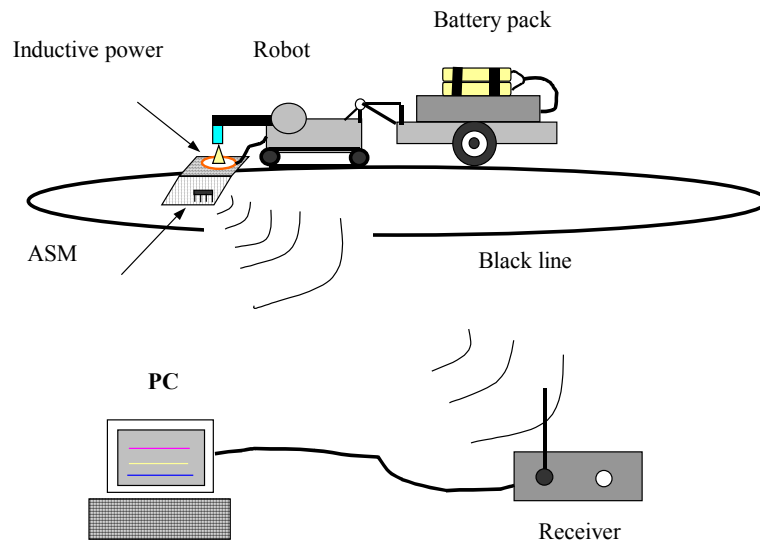


Figure 5 Schematic of tabletop robot test

An initial test was set-up to sequentially monitor the temperature of a soda can as it warmed up to room temperature during the period of a day. The following graph shows the data collected during this trial.

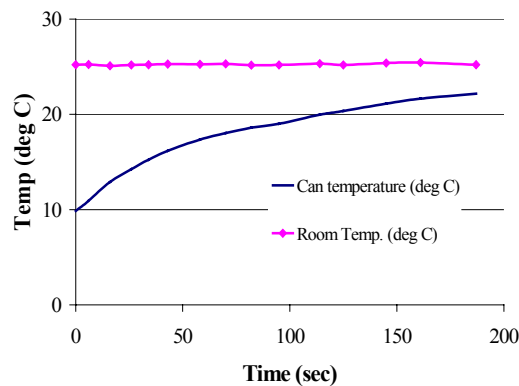


Figure 6 Sample data acquired from the robotic interrogation of an ASM.

The second robot to be built was designed for the specific task of ‘crawling’ on I-beams, Figure 7. A U-Shaped design was chosen for the robot, which is composed of simply three aluminum plates. The drive system consists of a geared 7.2V DC motor, which provided ample torque at all speeds. The motor turns a series of gears, which synchronize the drive wheels. The gears chosen are made of acetyl (Delrin), a self-lubricating and vibration damping material. The gears provide a gear ratio of 1:15, allowing the robot to move at slower speeds. The design also included a base station where the robot can upload data, recharge its batteries, and provide protective storage, Figure 8.



Figure 7 Beam Crawling Robot installed on laboratory I-Beam

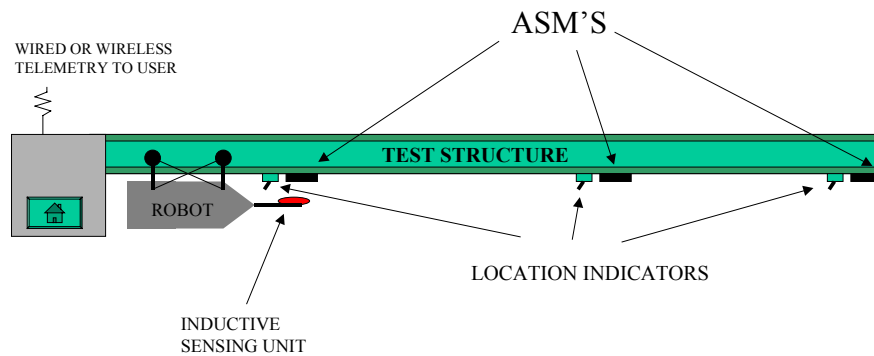


Figure 8 Schematic of beam crawling robot inspection system with docking station

The robot is controlled using a Z-World Jackrabbit BL1800 programmable microcontroller. This device has a 30 MHz processor, multiple analog and digital I/O's, high output I/O's, and various serial ports and timers. Also integrated into the circuit is 128K SRAM and 256K flash EPROM<sup>7</sup>. The Jackrabbit is programmed through the use of custom bundled software and a C programming based compiler. It is interfaced through the use of a PC serial port. This design attempts to maximize power efficiency. In the proof-of concept design, the data were transmitted to a stand-alone receiver connected to a PC. The power required to run the telemetry system located on the ASM increases dramatically when transmitting data over long distances. With the current design, the robot carries a telemetry receiver connected to the Jackrabbit's memory. The data transmitted by the ASM's is stored onboard the robot. This greatly reduces the power required for data transmission because the ASM will be within a few centimeters of the robot. Efficient power usage increases the range of the robot, and lowers the requirements on the coefficient of coupling between the external powering coil on the robot and the ASM node. This allows for greater distances between the coils.

The Jackrabbit allows for robust control design, easily modified programs, and an efficient means for minimizing power consumption. By having customized operations and system parameters, a full spectrum of robot functions can be controlled, including the robot's navigation, powering up of the sensor interrogator, and storage of the data. Inputs to the

microcontroller include various touch sensors that are triggered when the robot finds an embedded sensor, reaches the end of a beam, and when the robot has returned to the docking station. The robot utilizes sequential logic to progress through the stages of data collection, thereby minimizing power consumption and streamlining the robot's operations. Figure 9 is a schematic of the control logic of the robot.

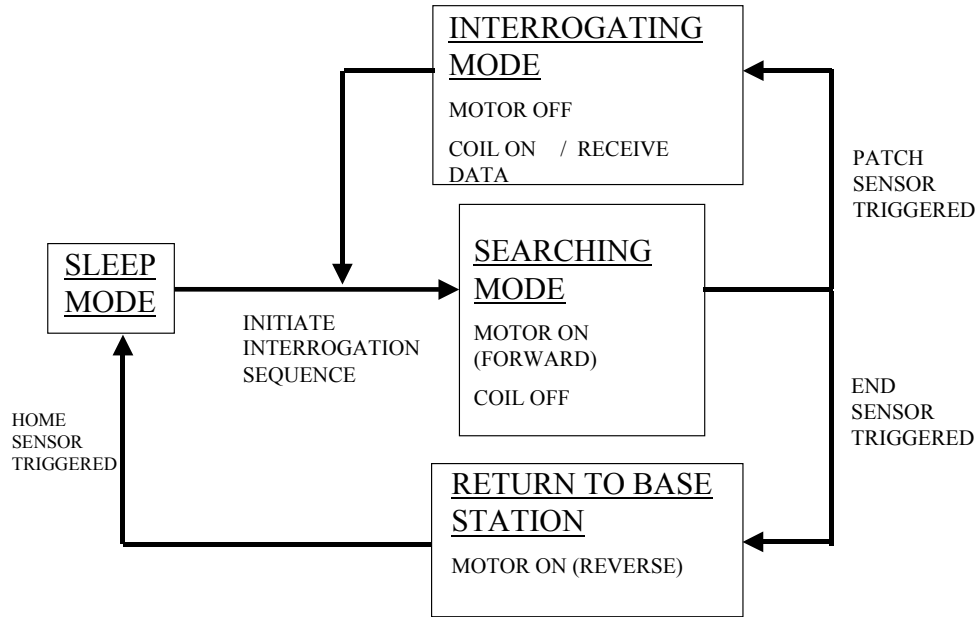


Figure 9 Flowchart of the beam crawling robot control software

A low power SAW based RF (RF Monolithics (RFM), Dallas TX) receiver that resided on the interrogator board collected data from the embedded ASM's. We then used a short-range transmitter (SRT) and receiver on the robot to communicate in the 916.5 MHz band to the base station. This RF communications device is very small (<0.5 in. sq.) and consumes very little power (<15 mW) in receive mode. Only the receiver was utilized when interrogating the sensor nodes, the transmitter was utilized in the downloading of data to the base station as described in the next technical objective. Data were stored in flash memory by the interrogator and included the time of interrogation, sensor data, ASM node number, and device status. Data were written to the sensor node (through the power link) and included the date and time of interrogation.

A printed circuit board was designed and fabricated which implemented these functions described above and was compatible with the SBC. This also incorporated the circuitry that was designed and breadboarded. This controller board incorporated flash reprogrammability of the program code and therefore allowed for firmware to be easily upgraded, which was an important feature early in the firmware development phase. It also allowed for firmware to be upgraded in the field, as required. All firmware was developed using a C programming compiler (Z World Engineering, Davis, CA) and was tested and debugged using a PC based emulator. After the firmware development phase was completed, the data communications system was tested for bit-error rate over the operating temperature range. The bit error rate for both the SRT and LRT were measured over a twelve hour time frame and bit error rates were found to be less than 0.5 parts per million. This was deemed to be acceptable for these applications.

The reason for specifying a short-range wireless radio and data logger on the robotic interrogator was to minimize the power required by the ASM node. If data needed to be transmitted from the ASM node all the way back to the base station, the power of the RF transmitter would be prohibitive, especially on large structures. Minimizing the power of the ASM allows the coefficient of coupling between the external powering coil and the ASM node to be lower, which allows for greater distances between the coils.

The robots' batteries were recharged using inductive coupling. The recharging of the battery (recharging voltage-current profile) was controlled by the microprocessor, and feedback between the robot and the base station was accomplished

through use of the low power RF transceivers. The robot batteries may be recharged upon every return to the base station, which will insure that the robot's batteries will never come close to being fully discharged.

The base station or docking stations in development utilize a networked computer that allows for the data to be immediately available via the internet once it is up-loaded. The base station also allows for the robot to be reprogrammed. This can be done to change the frequency of the robot's inspection, to pay special attention to certain "problem" areas of the structure, to avoid interrogating malfunctioning nodes, as well as modifying many other parameters of the robot's operation.

In a series of demonstration tests, the robot was commanded to crawl out on the beam and collect data. Figure 10 is a set of typical strain data collected by the beam crawling robot.

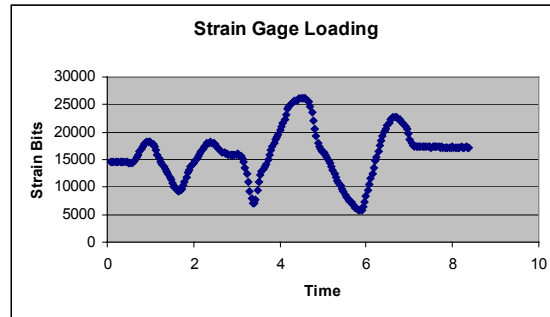


Figure 10 Typical strain data measured by the beam crawling robot

In the process of moving this system out into the field for bridge girder inspection, several issues related to mobility arise. Key issues include the presence of diaphragms, Figure 11, and variable-thickness webs. Figure 12 is a conceptual design of robot suspension that can accommodate diaphragms and variable thickness webs.



Figure 11 I-189 Spear St. overpass bridge with diaphragms

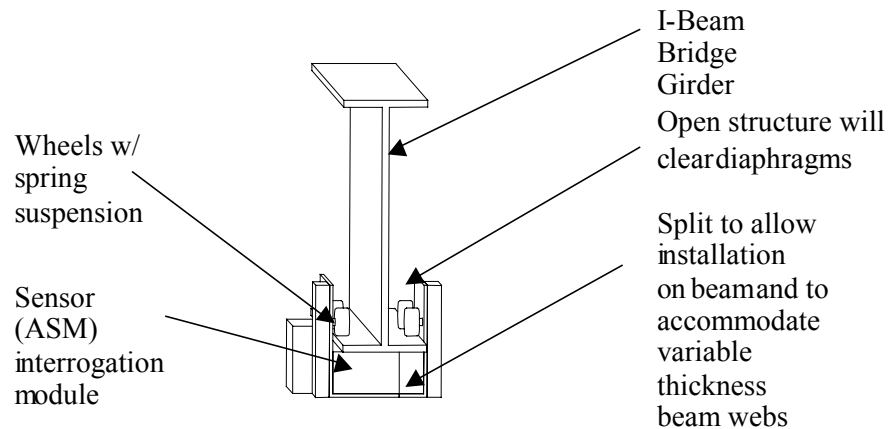


Figure 12 Conceptual design of robot suspension that can accommodate diaphragms and variable thickness webs

#### 4. CONCLUSIONS

Two different wireless robotic structural inspection systems were tested in the laboratory. The next steps include field-testing of similar systems.

#### ACKNOWLEDGMENTS

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