PROTOTYPE CRAWLING ROBOTICS SYSTEM FOR REMOTE VISUAL INSPECTION OF HIGH-MAST LIGHT POLES

FINAL REPORT

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ABSTRACT

This report presents the results of a project to develop a crawling robotics system for the remote visual inspection of high-mast light poles in Virginia.

The first priority of this study was to develop a simple robotics application that would reduce hazards to the public and employees of the Virginia Department of Transportation and increase the efficiency of inspections. The prototype crawling robotics system developed (POLECAT-I) consists of a magnetically attached crawler for vertical and horizontal scanning of the outside of poles with a remote visual inspection device.

Laboratory and field tests evaluated the crawler's mechanical performance and video resolution. The robot can inspect flat, cylindrical, and tapered surfaces with a longitudinal taper of 12 mm/m and a minimum outside diameter of 200 mm; change the direction of the inspection from vertical to horizontal and vice versa on these surfaces; and overcome vertical obstacles up to 7 mm high. The system provides better crack resolution than conventional methods. This work holds great potential for significant cost savings with regard to inspections as well as improved safety.

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INTRODUCTION

The use of robotics in the inspection of highway systems can improve testing procedures, increase productivity, reduce costs, and remove workers from dangerous areas by reducing the human labor required to perform the inspection.¹ Robotic inspection techniques appear practical for the nondestructive evaluation (NDE) of steel high-mast light poles, steel overhead signs, bridge steel box girders, and bridge cable stays and for the detection of cracks in steel structures and bridges covered with paint or marine growth.

In Virginia, the study of robotics in transportation construction and inspection has been largely theoretical.²⁻⁴ Because of a lack of funding, highway steel structures and bridges have not been given as high a priority for advanced NDE techniques as nuclear, petroleum, aircraft, and aerospace structures. Significant research and development in NDE is underway at the Virginia Transportation Research Council (VTRC). The goal of this research is to provide new NDE tools to inspectors of steel structures and bridges.

As part of this effort, VTRC is developing a crawling robotics system for the remote visual inspection of high-mast light poles. The Suffolk District of the Virginia Department of Transportation (VDOT) agreed to participate in the project.

PROBLEM STATEMENT

In VDOT's initial inspection of high-mast light poles, inspectors found poles with vertical cracks in the female tube section of the slip joints (see Figure 1). This is the area of primary concern and probably will be defined as a mandatory inspection location in the future.

High-mast light poles are made of tapered steel, which may be one piece or sectional, depending on the height. Most of the poles in Virginia are constructed of weathering steel conforming to the requirements of ASTM A588. A longitudinal taper of 12 mm/m is typical for the poles. A study performed by the Maryland Department of Transportation revealed that moisture running down the outside of the pole is drawn up into the slip joint by capillary action and the weathering steel continues to oxidate instead of developing its normal protective layer (see Figure 2).⁶ The oxide buildup between the two sections produces tensile stress, which causes cracks in the female section.

Currently, poles are inspected by visually examining the slip joints from ground level with binoculars. A 35-mm camera is used to photograph cracks, using a truck-mounted platform attached to a hydraulic boom. However, the crack resolution in the photographs is often inferior, and in many cases, photographs cannot be taken. In short, the current manual NDE inspection techniques have a very low probability for detecting defects.



Figure 1. Crack at slip joint



Figure 2. Concept for robotics system and details of high-mast pole

At present, no corrosion inspection is performed. The base, especially, needs to be inspected for corrosion. In a pole failure in Michigan in which a young boy was killed, the pole corroded from the inside because moisture collected in the debris inside the base of the pole.⁵

A mobile, compact inspection system for the reliable NDE of the slip joints and base of the poles is needed. A crawling robotics system for remote visual inspection could examine the poles with better crack resolution, providing more reliable and efficient inspections at a lower cost.

PURPOSE AND SCOPE

The objectives of this project were (1) to develop the prototype of a crawling robotics system for the remote visual inspection of high-mast light poles, and (2) to evaluate the performance characteristics of the prototype.

Federal Highway Administration (FHWA) personnel suggested extending this study to major overhead signs and steel bridge girders. However, because of the differences in the design characteristics of these structures, one robotics system cannot successfully inspect all of them. Thus, their inspection will be addressed in future projects.

METHODS

Five tasks were conducted to fulfill the objectives of this project.

- 1. The literature on robotics NDE was reviewed, and companies and research institutions that have been active in NDE and robotics were surveyed for pertinent information.
- 2. The concept for the system was developed.
- 3. A robotics system was developed.
- 4. A video inspection device was selected.
- 5. The system was tested in the laboratory.
- 6. The system was tested in the field.

RESULTS AND DISCUSSION

Literature Review

According to the Robotics Institute of America, "a robot is a reprogrammable multifunctional manipulator designed to move material, parts, tools, or other specialized devices though variable programmed monitors for the performance of a variety of tasks."⁷ The robot in this study is an electromechanical system developed for structural safety inspections. Advanced robotics technologies exist in manufacturing, defense, energy, and space-related industries. For instance, remote video and ultrasonic imaging is widely used to inspect hard-to-reach or hazardous environments. These technologies have not been extensively applied to highway-related construction, maintenance, and inspection,^{1, 4} although a number of U.S. organizations and industries are working on highway construction robots,⁴ and a few companies are marketing an inspection system using high-resolution video cameras on robotic arms attached to permanent falsework underneath bridges.⁸ By remote telescanning, details can be visually monitored without an inspector having to climb up to the detail itself. Since 1987, Florida has employed a remote high-resolution computer-controlled TV (CCTV) system to view, document, and record

the interior status of the 46 hollow piers supporting the Sunshine Skyway Bridge across Tampa Bay.² A vehicle named Aerobot, a small, portable, aerial platform that can carry a video camera and hover in a stationary position, has been developed for CALTRANS.⁹ Enhancements to Aerobot include increasing the payload capacity and developing a high-resolution video camera. A possible telerobotics application of dual-arm cam-lock manipulators in bridge inspection has been shown,¹⁰ and the Texas Department of Transportation has discussed specific recommendations for seven robotics applications.¹

Crawling inspection robots are increasingly used for the remote testing and inspection of level pipes, and they can climb pipes with inclinations of up to 30 degrees.¹¹ Vertical runs are more difficult, but magnetically attached wall-crawling robots for inspecting tanks and large-diameter piping already exist.^{12, 13} The crawler, about the size of a shoe box, travels on magnetic wheels and can produce more than 75 kg of vertical pull. Its direction and speed are controlled by a tethered or umbilical cable more than 100 m long. Almost all crawling inspection robots carry a CCTV camera or NDE sensors. No crawlers have been designed specifically for use with tapered surfaces.

Computer-based fiberoptic video instruments are the newest remote visual inspection technology for NDE, producing video images directly at the worksite.¹⁴ The worksite is illuminated by a fiberoptic light guide-bundle connected to a light source. The remote video image device has a flexible probe with a charge couple device (CCD) at the tip. The CCD accommodates thousands of light-sensitive capacitors on its face and acts like a TV camera. Each chip capacitor is a pixel of information and sends an analog electrical signal proportional to the light energy falling on it to a camera control unit (CCU). The CCU digitizes the image, which can be displayed on a monitor or sent to a computer for enhancement and analysis. A wire assembly carries the electronic information.

Remote image devices produce color images in two ways: real-time simultaneous fourcolor imaging with dedicated pixels, and a red, green and blue (RGB) sequencing color lighting system. In both, the image of the subject is focused on the chip's pixels by the objective lens of the system. The real-time imaging renders color better, which is important for corrosion inspection. The RGB system requires fewer pixels, making it easier to design a smaller tip for the probe, but the image tends to blur when the tip is moved.

Ultrasonic travel-time measurements are commonly used for thickness determination and corrosion detection in piping and pressure vessels. Real-time ultrasonic images can also be used to inspect corrosion damage in highway steel structures.¹⁵

Concept of the System

The concept for the system is shown in Figure 3. An Infometrics TestPro system consisting of a remote control unit, a magnetically attached crawling robot, control cables, video and ultrasonic sensors, and a host PC with appropriate boards and software modules was



Figure 3. Typical splice detail

acquired for the multisensor NDE robotics tasks. The system can be used to perform remote NDE of flat and wide components and members of highway transportation structures. The controller can operate the crawling robot and the sensors from a distance as far as 33 m. The system consists of a state-of-the-art FPS/60 video capture board that can accept external and internal video signals. Data acquisition is Windows-based on-line, with real-time data acquisition with Windows-based off-line data analysis (zoom/pan, palette modifications, etc.)

using Adobe Premiere and Adobe Photoshop software. The compression is motion JPEG compression/decompression in a YUV 4:2:2 format and a ZORAN/FAST chipset format. The image storage is in an AVI format. Full-screen dynamic playback of the image scan is available with a resolution from 640 x 480 to 1,280 x 1,024 pixels. A separate miniature TV monitor can be used for simultaneous viewing of video and ultrasonic images. A split screen for video and ultrasonic simultaneous viewing in the future is feasible.

Modifying the crawler was the first step in adapting the system for specific structures and bridge inspection applications. The Infometrics crawler was redesigned by VTRC in cooperation with the University of Virginia (UVa) to operate on the tapered magnetic surface of high-mast light poles and permit circumferential inspection of the pole.

Design and Fabrication of Crawler

The problem often encountered in designing a crawler for outside tapered surface inspection is determining how the crawler will adapt to varying diameters from one pole to the next or the varying diameter along a single pole. Since no existing crawler can be used directly for climbing steel poles of varying diameters, crawlers have been proposed and the designs of existing crawlers have been modified to accommodate this application. The major factors considered in the design of a crawler were weight, size, and cost. Four types of vehicle structures were considered: a robotic arm, a lead screw structure (worm gears), a small vehicle with omnidirectional wheels, and a crawler with magnetically attached wheels and a flexible axis.

Crawler with Robotic Arm

This crawler uses three sets of robotic arms, each having four links magnetically attached to the pole and positioned around the pole to support the platform (see Figure 4). The flexibility of the robotic arm, caused by its various joints, enables the crawler to adjust to the varying diameter of the pole.

Electromagnets and permanent (rare earth) magnets (made from neodymium or samarium) were considered for attaching the robotic arms to the light poles. It was determined that for movement or sliding purposes, electromagnets were best suited for this system. However, in a preliminary weight analysis of the system, it was determined that electromagnets which could support the weight of the proposed system would weigh too much because of their size.

The movement of the three sets of robotic arms should permit the crawler to scale up or down the pole and stop at the various joints. With the bottom magnet stationary and both elbow joints free to move, the motor in the shoulder joint should cause the top magnet to move up (down) the pole, thus elongating (contracting) the bottom robotic arm and contracting (elongating) the top. Then, with the top magnet stationary and both elbow joints again free to



Figure 4. (a) Proposed crawler using three sets of robotic arms; (b) top view of pole showing position of robotic arms around pole

move, the bottom magnet would scale up (down) the pole, thus causing the bottom robotic arm to contract (elongate) and move the platform up (down). This movement would continue and occur at smaller intervals as the platform approached the desired pole joint. Figure 5 shows the movement of a robotic arm up the pole.

By examining the description of the arm movement with the use of robotic arms with four links, it was determined that the same movement could be attained using robotic arms with two links (see Figure 6). This would decrease the weight of the crawler by almost half.

Various concerns arose in investigating this crawler. As the camera moves around the platform, the camera power cord cannot wind around the pole. The biggest concern was its weight, more than 70 kg. Therefore, the conclusion was drawn that a crawler which uses robotic arms was not the best for this application.

Crawler with Lead Screws

The second proposed crawler uses lead screws (worm gears) positioned around the pole in place of the robotic arms (see Figure 7). The weight of this crawler is significantly less than that of the robotic arm crawler since there are no heavy robotic arms to support and the motors and magnets can be smaller since they, too, are supporting a smaller weight. In this case, an electromagnet connects the platform to the pole and another electromagnet attaches the motor to the pole.



Figure 5. Progressive movements of robotic arms needed to crawl up pole: (a) top magnet moving up pole, bottom magnet stationary; (b) top magnet stationary, bottom magnet moving up pole; (c) crawler further up pole as result of movements



Figure 6. Proposed crawler using three robotic arms with two links



Figure 7. Proposed crawler using lead screws (worm gears) instead of robotic arms

The major concern in this design was ensuring that the platform could adjust to conform to the changing pole diameter. Another concern was determining what type of motor would be most beneficial to the design: a stepper motor or DC servomotor with or without a commutator.

In investigating various motors, electromagnetic AC brake motors were identified as a possibility for this application. When power is being applied to an AC brake motor, the rotor rotates as usual. When power is removed, brakes that enclose the rotor clamp onto the rotor, causing rotation and all resulting motion to stop.

Electromagnetic brake motors, which have great stopping capabilities, can move the platform up or down the pole, and thus can stop the platform at the different joints. When the motors are off, holding torque is large, and, therefore, the motors can support the platform in its desired position as the camera travels around it.

An AC brake motor seemed well suited for the lead screw crawler design, although for this application, a DC motor is preferred. DC motors are easy to control, have good torque characteristics, and are very reliable. On the other hand, AC motors require a varying frequency instead of a varying voltage, and although they are also reliable, their disadvantages seem to outweigh their advantages.

DC stepper motors are brushless motors that convert digital pulses into fixed incremental movements. They are very accurate, as in this case, for positioning the platform at the joints of the light pole. However, for this design, a DC servomotor is better than a stepper motor because it has more torque (can support more weight). If only a stepper motor is used, the motor may not support the weight of the crawler and cables.

There are two types of DC servomotors: brushless and commutator. Commutator DC servomotors are cheaper, are highly accessible, perform very well, and are very reliable, but they

have a lower motor efficiency and a reduced motor life and are noisy because of the commutator and brushes. Brushless DC servomotors are more reliable since there is no electrical or mechanical connection to the rotor. They also they weigh less on average and are easier to control, but they cost more than commutator DC servomotors. The torque versus speed and torque versus armature current characteristics of the two types of motors are very similar. For these reasons, a brushless DC servomotor was considered better for the crawler.

Crawler with Omnidirectional Wheels

The third proposed crawler uses permanent magnets attached to and distributed along the base of the cart vehicle and two omnidirectional wheels. Figure 8 shows a cart with magnets along its base. In this case, permanent magnets could be used since they have a much stronger holding force than electromagnets of equivalent size and weight.

Possible permanent magnets to be used in this design were neodymium and samarium cobalt. Neodymium is better for this design since it is cheaper and 30 percent stronger than samarium cobalt. Samarium cobalt is typically used for higher heat applications. The distance the magnets would have to be from the surface of the pole to optimize their holding force needed to be determined.

Another design consideration was to make the body of the vehicle long so that a small imperfection or obstruction present on the surface of the pole was not an obstacle for the crawler to climb over and did not cause its course to change. In other words, only one wheel would be trying to surpass the obstacle at a time and, thus, the crawler would have time to readjust its position, if necessary, before the second wheel came in contact with the imperfection.

The omnidirectional wheels contributed a great amount of flexibility to this crawler design. The wheels are composed of free-rolling rollers that are at a 45-degree angle to the



Figure 8. Proposed crawler using permanent magnets distributed along base of vehicle and omnidirectional wheels

center core of the wheel, but they form a circle when looked at from the side. Movement in all directions is controlled by a DC permanent magnet motor in the wheel that alters the speed and/or direction of particular wheels to achieve movement in the desired direction. With these wheels, the crawler could change its direction of motion without having to rotate.

A rough model of this crawler was made using a small motorized car with permanent magnets attached to the base of the vehicle. In this case, no preliminary calculations were made and simple components were used. The motors and magnets were not strong enough to support the vehicle moving upward. If permanent magnets could be incorporated into the rollers of the omnidirectional wheels, there would be no need for the magnets distributed along the base of the cart vehicle.

Crawler with Magnetic Wheels and Flexible Axis (POLECAT-I)

A decision was made that the prototype robot, named POLECAT-I, should be a remote controlled robotic crawler with magnetic wheels and flexible axis, designed to crawl up steel poles only for inspection purposes. The robot could carry instrumentation such as a video camera and an ultrasonic transducer. The crawler would be controlled and powered by an operator at ground level using a cable system connected to the robot. In carrying out an inspection, the crawler would ascend the pole until a slip joint was reached, rotate, and then move horizontally around the pole inspecting the joint. Following the practice of other crawlers used on flat surfaces or huge cylinders such as storage tanks, the crawler would use magnetic wheels to attach to the surface of the pole. The unique aspect of this crawler was the articulation of the chassis and wheels that would allow it to conform to the curved surface of the pole while maintaining the center platform tangent to the surface for all diameters from 150 mm to an essentially flat surface. This is necessary for inspection purposes.

The geometric principle on which the chassis-wheel articulation was based is shown in Figures 9 and 10. Figure 9 shows the concept for the robot from the front when climbing a vertical flat surface, and Figure 10 when climbing a pole. The two outer wheels are hinged to the central frame at points that are equidistant from the center of the main frame to the center of each outside wheel. Figure 10 shows that when the robot is conforming to the cylindrical surface of a pole, the geometry allows the plane of each side wheel to intersect the axis of the pole, which ensures that the wheel surface is tangent to the surface of the pole, maximizing the magnetic attraction between the wheel and the pole. A further consideration was the distance of the points above the surface. In moving from a flat plate (Figure 9) or a large-diameter pole to a small-diameter pole (Figure 10), the outer wheels at their point of contact had to move closer together by sliding sideways as the robot advanced up the pole. This sliding would be minimized if the points were mounted as close as is practical to the surface of the pole. Thus, distance H in Figure 9 should be minimal.

To maintain this geometry, the outer wheels must move in a symmetrical fashion. This was accomplished by the mechanism shown in Figures 11 and 12. Mounted in the central frame is a tube in which the ultrasound transducer could be mounted. Rotating around that tube on ball



Figure 9. Concept for crawler's chassis wheel on flat surface (front view)



Figure 10. Concept for crawler's chassis wheel on cylindrical surface



Figure 11. Concept for crawler's system (top view): L = lever arm; P = transfer plats; M = main frame; D = transfer disk; J = ball joint



Figure 12. Concept for crawler's system (front view): P = transfer plate; L = lever arm; F = transfer disk; T = tube; J = ball joint

bearings is a transfer disc. Extending from each member that supports the outside wheels is a rigidly attached lever arm. Linking the end of each lever arm to the transfer disc is a link, fastened to the transfer plate and lever arms through the ball joints. Thus, the motion of one outside wheel assembly about point P is simultaneously and symmetrically transferred to the opposite outside wheel assembly. This maintains the desired geometry for all cylindrical surfaces within the required range, 1 to 150 mm in diameter. In addition to maintaining correct wheel contact with the pole, the described geometry also maintains the central tube perpendicular to the pole surface, which is important for ultrasonic transmission.

The basic geometric principles as shown for the outside wheels also apply for the fore and aft wheels in the diamond pattern chassis of the robot shown in Figure 13. The outside or lateral wheels are the drive wheels, powered by electric motors (not shown), and the fore and aft wheels are caster wheels mounted on the caster frames that are hinged to the central frame using the same geometric principle as applied to the lateral or outside wheels. Also not shown is an additional transfer disc mounted to rotate around the central tube as before. This disc similarly links the fore and aft caster frames so that the caster wheels maintain contact with the pole when the robot is moving horizontally around the pole as shown in Figure 14. A transfer disc and links cause simultaneous and symmetrical motion of the caster wheel assemblies to maintain proper contact with the pole.

Movement of the robot is provided by the magnetic drive wheels, which are powered by electric motors connected by drive belts or other means to the wheels. The caster wheels are magnetic, provide fore and aft stability, and have a smooth contoured tire surface for easy caster action in turning. The drive wheels are heavily knurled to provide a good grip on the steel pole for traction.

Both the drive wheels and caster wheels are articulated to the main frame in a manner that allows each to assume the ideal configuration to fit any diameter of pole within the required range. Because the drive wheels and caster wheels are independently articulated to the main frame according to the geometric principles described, when placed at an angle on the cylindrical pole, the entire assembly conforms to the configuration required to maintain the wheels in proper contact with the surface of the pole and maintain the central tube perpendicular to the surface of the pole. For this reason, the robot can turn from the vertical to the horizontal while maintaining the correct orientation of the wheels and the central tube. Similarly, the robot would assume the correct configuration when placed on a sphere. The basic diamond pattern wheel layout with casters fore and aft and drive wheels positioned laterally allows for a highly maneuverable robot. Turning is accomplished by causing one drive wheel to turn faster than the other. Further, if one drive wheel is made to go in one direction and the other in the opposite direction, the robot will rotate about its own center. Control of this motion is easily achieved using a joystick that simultaneously controls speed and direction, a method commonly used in electrically powered wheelchairs.

Preliminary testing of the prototype under laboratory and field conditions presented two problems that were addressed by modifications to the basic design. One problem occurred during the rotation from the climbing position to the horizontal position for crawling around the



Figure 13. Concept for diamond pattern chassis and wheels (top view): F = caster frame; C = caster wheels; W – outside wheel; M = main frame



Figure 14. Concept for crawler moving horizontally around pole (cross section, side view): C = caster wheels; F = caster frame; G = joint; L = lever arm; T = tube; W = outside wheels; M = main frame; D2 = additional transfer disk

pole. This maneuver causes the drive wheels to move closer together, as shown in Figures 9 and 10. In climbing a gently tapered pole, this is accommodated by a very slight lateral motion of the wheels, but in rotating on a small-diameter pole, the required sliding is considerable. If the sliding does not occur, the main frame, and in particular the central tube, will be forced away from the surface of the pole. To prevent this, a tension spring was added from the lever arm of the wheel assembly to the main frame for both the left and right drive wheels. This tends to spread the wheels during rotation and effectively solved the problem.

A second problem was the limitation in climbing over obstacles such as lap joints in the pole. This was overcome by replacing each outside or lateral drive wheel with a tandem pair of wheels, powered with the same motor and mounted in bogy fashion to pivot on the axle of the original drive wheel, as shown in Figure 15. Figure 15 shows the wheels mounted tandem fashion on the bogy frame that pivots on the axle for the original single-wheel design. The geometry connecting the pivot of the bogy frame to the main frame is identical with that already described for the single wheel. In addition to providing greatly increased ability for climbing over obstacles, the traction is doubled, since four traction wheels are used instead of the original two.



Figure 15. Concept for tandem bogey wheels (cross section, side view): C = caster wheels; C = caster frame; G = joint; O = tandem wheels; T = tube; B = bogey frame; J = ball joint; M = main frame

The basic geometric principles already described were also applied in a different design for a pole-climbing robot. This is shown in Figure 16, which shows a plan view of the robot on a flat surface. The central frame is rectangular with the central tube as shown. Hinged along each



Figure 16. Concept for crawler in climbing position (plan view): K = subframe; W2 = drive wheels; L = hinge line; M2 = main frame; T = tube

side on hinge line L are lateral subframes that are made to move in a simultaneous and symmetrical fashion using a similar transfer disc and linkage as previously described. In this example, six drive wheels are attached, two on the central frame and two on each of the subframes, each having its own motor. Each drive wheel and its motor are mounted to its respective frame on an axis perpendicular to the wheel axle and perpendicular to the surface on which the wheels rest. Thus, on a flat horizontal surface, the axis of each drive wheel and motor assembly would be vertical. The purpose for this axis of rotation is to allow the operator to rotate all wheels simultaneously through 90 degrees to the position shown in Figure 17. In this mode, the robot can be driven horizontally around the pole to inspect for cracks, etc. Adjustments in direction can be made by a speed differential between wheels. Similarly, as shown in Figure 16, when climbing up the pole, adjustments in direction can be made by a speed differential between the left and right pair of motors.

There are several advantages of this chassis configuration. In Figures 16 and 17, six traction wheels are used instead of the previous two or four. If required, further traction wheels can be added along the side frames or the central frame. Further, since the orientation of the robot does not change, the control and power cables are more easily managed, simply trailing down from the lower end of the robot as shown in Figure 16. A further advantage is the long wheel base that is possible. This provides greater stability on the pole. It also provides a larger platform for mounting the inspection instruments and/or battery pack if a radio controlled system is preferred. The final drawings for the crawler are shown in Figures 18 through 22.

During fabrication, and in the beginning stages of assembly, the wheels were placed in a diamond configuration with the two drive wheels on the same horizontal line and the two caster wheels on the same vertical line. The drive wheels were connected to the motors by belts. The caster wheels, which are free rolling wheels attached to a swiveled frame, helped the crawler move more easily along the pole and also helped keep the ultrasonic sensor perpendicular to the pole. All wheels were composed of neodynium (rare earth) magnets (Dowling Miner Magnetics Co.), with an outer diameter of 38 mm, a thickness of 9.5 mm, and a magnetic pull of 116 N. Steel tires (washers) were placed on both sides of the magnet. The disc magnets were magnetized through their thickness and had a magnetic flux pattern as shown in Figure 23. The pattern has this form because the circular faces of the disc magnet have opposite magnetic poles. The disc magnets need an outer diameter large enough to ensure that the crawler can crawl over vertical obstructions 7 mm high, although eventually the crawler should be able to overcome obstacles as high as 14 mm. A justification diagram of wheel diameter versus obstacle height is shown in Figure 24. The supporting calculation is as follows:

 M_O (moments about point O) = 0

$$F(R - H0 - WX = 0, \text{ and } X = (2RH - H^2)^{1/2}.$$



Figure 17. Concept for crawler in inspection position (plan view): K = subframe; W2 = drive wheels; L = hinge line; M2 = main frame; T = tube



Figure 18. Crawler on flat surface (front view)



Figure 19. Crawler on flat surface (cross section, side view)



Figure 20. Crawler on flat surface (top view)



Figure 21 Crawler on cylindrical surface (front view)



Figure 22. Crawler on cylindrical surface (cross section, side view)



Figure 23. Magnetic flux pattern for disc magnet (side view of magnet)



Figure 24. Justification diagram of wheel diameter versus obstacle height

Thus

$$F(R - H) - W(2RH - H^2)^{1/2} = 0$$
 and $F = W(2RH - H^2)^{1/2}/(R - H)$.

Using this formula, with W115.7 N, R = 25.4 mm, and H = 12.7 mm, as in this case, F = 200.4 N.

The force applied by the motor must be equal to force F plus the force due to gravity, since the crawler is being suspended vertically from the pole.

 $F_{gravity}$ = weight of crawler plus cables = 177.9 N $F_{applied}$ = total force applied by motor = $F + F_{gravity}$ = 378.3 N T_{load} = Load torque = $(F_{applied})(R - H)$ = 4804 N-mm T_{motor} = Motor torque = $T_{load}/20$ = 240 N-mm

As long as the torque supplied by the motor is greater than T_{motor} , which is the required motor torque, the conclusion can be made that a 51-mm-diameter magnet is large enough to overcome a 13-mm obstacle.

The wheels were attached to the main frame of the crawler by arms, which were connected to pivot points on the main frame.

The crawler had to use the same motors (Superior Electric M062-LE09 DC stepper motors) and gearheads, with a 20 to 1 reduction ratio, as the Infometrics crawler to ensure that it would be fully compatible with the software and controller programmed by Infometrics. The

crawler is steered by independently controlling the speeds of the motors. Either a joystick or a computer can be used to control the speeds and, thus, the crawler's direction of travel, whether forward, backward, or while turning. The crawler could climb and inspect the pole at a maximum speed of 4 mm/s because of the requirements for reliable ultrasonic inspection using the original system. The power the motors need to supply was determined from the crawler's torque and speed. Since the speed is relatively slow, it was expected that the motor power would be small and, therefore, satisfied by these motors. To perform the calculations, a weight of 18 kg for the crawler plus cables and a 51-mm wheel diameter were used. Assuming no losses in the gear train, the following calculations showed that the motors must be capable of supplying approximately 7 W, which is small, and can be supplied by most stepper motors.

F = 177.9N T = Fr = (177.9N)(25.4 mm)(1 m/1000 mm) = 4.52 Nm $\alpha = v/r = (38.1 \text{ mm/s})/(25.4 \text{ mm}) = 1.5 \text{ rad/s}$ $P = T_{\alpha} = (4.52 \text{ Nm})(1.5 \text{ rad/s}) = 6.78W$

Figure 25 shows the crawler after final assembly.

The significant features of the crawler were as follows:

- Tandem pair of bogie wheels with neodymium magnets for each drive wheel to allow more opportunities for contact when climbing over obstacles. The key design issue for this tandem pair is the ability to maintain continuous contact with the pole surface without tilting off and losing contact.
- Two caster wheels for improving rolling motions, enhancing steerability and maneuverability.
- Wheels designed for maximum "grabbing" action by using aggressive diamond pattern knurling on the steel treads, hard chrome plated to minimize wear.

Video Inspection Device

Two options for a video inspection device were considered for the crawler: (1) a computer-controlled high-resolution video camera with an independent light source, and (2) a video-imagescope system designed to illuminate large structures and produce clear images of defects at long distance. The most adequate video camera for the crawler was determined to be the Pulnix TM-7CN. This is a miniature black and white CCD camera weighing 169 g. The camera resolution is 768 horizontal and 494 vertical lines. Besides its miniature size, light weight, and high resolution, the camera has a high performance, high stability, a long life, a rugged design, and a bottom-mounted tripod attachment. The camera was attached to a metal





Figure 25. Crawler in final states of assembly: (top) bottom view; (bottom) side view

strip that extends from the tube for a future ultrasonic sensor and sits above the front caster wheel frame. It remains approximately 100 mm from the pole surface at all times.

Eventually, the addition of the ultrasonic sensor will allow not only surface inspections of the pole but also internal inspections and corrosion measurements. The ultrasonic sensor will be placed inside a tube connected to the center of the main frame. After additional tests on subsections of poles with known defects, if the video camera and ultrasonic sensor cannot detect all of the defects present, supplementary sensors, such as a microwave sensor and/or an eddy current sensor, may have to be added.

Laboratory Evaluation

The performance characteristics of the crawler and the video image device were tested on a flat surface, on three poles with constant diameters, and on two scale models of a tapered pole. To determine the ability of the crawler to travel vertically (climbing position) and horizontally (inspection position), climb over obstacles, and rotate, a series of tests was performed in VTRC's NDE lab.

The outer diameters of the three poles with a constant diameter were 165 (small), 216 (medium), and 324 mm (large). Each pole was 7 mm thick. The medium and large poles had one rectangular obstacle approximately 203 mm in the vertical direction, 216 to 229 mm in the horizontal direction, and approximately 11 mm high. The first model of the tapered steel pole was 7 mm thick, with a diameter of 150 mm at the top of the female section and 200 mm at the slip joint. It had one 7-mm obstacle formed by the overlapping female and male tube sections. The second model was fabricated with implanted reference defects: three visible surface breaking cracks. Crack widths varied from 0.01 to 0.1 mm. The length was approximately 10 mm, and the depth was approximately 1.5 mm. The drawings for the second model with the locations of the centerline, toe, and transverse cracks are shown in Figures 26 and 27.

Slipping Force

Tests were performed to measure the slipping force, which is the amount of downward force that would have to be applied to the crawler to arrest its continual motion by causing the wheels to slip. These tests were performed using both the Infometrics crawler (B-scan assembly with two drive units) and the VTRC crawler by attaching an anchored spring scale to the back of the crawler and having it travel up the vertical surface until it could no longer move forward because its wheels were spinning.

First, the weight the crawler could carry was determined with the crawler traveling directly up the pole. These tests established whether the crawler could support the weight of its cables in different situations. Table 1 shows the maximum weight that will prohibit the crawlers from moving further along the vertical surface.



Figure 26. Pole scale model details



Figure 27. Flaw locations in pole scale model

Surface	Infometrics (N)	VTRC (N)
Flat	123.2 ± 2.7	141.0 ± 12.9
324-mm diameter (large)	77.0 ± 11.1	125.9 ± 9.3
216-mm diameter (medium)	59.2 ± 15.6	132.1 ± 11.1
165-mm diameter (small)		123.2 ± 11.1

Table 1. Slipping force as crawlers travel directly up pole

The slipping force of the Infometrics crawler on the small pole could not be determined since its movement was already restricted on the pole because of its size and structure. The crawler slips during C-scan on flat vertical surfaces, too. The cause for slipping is still not clear.

Second, the VTRC crawler was tested traveling at an angle of 10 to 20 degrees and 20 to 40 degrees with respect to the horizontal. The slipping force could not be measured for the Infometrics crawler (B-scan assembly) because it did not rotate very easily on the small and medium poles. Therefore, it was not possible to test the crawler at an angle with respect to the horizontal. In addition, on occasion, the crawler did not turn with the spring scale anchored and attached to its base since the scale fit directly between the two units. These restrictions were due to the geometry of the Infometrics crawler. Table 2 shows the maximum downward force that will impede the VTRC crawler from moving further along the pole when traveling at a small and large angle with respect to the horizontal.

Table 2.	Slipping force of	of VTRC crawle	er when trave	ling at angle	(with respec	t to horizontal)	on pole
I UNIC MI	Suppling force (mg at angle	(min respec	e co normonitar,	on poio

Surface	Movement	Slipping Force (N)	******
Flat	Small angle (10-20)	125.9 ± 17.8	
	Large angle (20-40)	155.7 ± 0.0	
324-mm diameter (large)	Small angle (10-20)	77.0 ± 11.6	
	Large angle (20-40)	96.5 ± 12.9	
216-mm diameter (medium)	Small angle (10-20)	64.5 ± 22.2	
	Large angle (20-40)	22.2 ± 0.0	
165-mm diameter (small)	Small angle (10-20)	92.1 ± 5.3	
	Large angle (20-40)		

The slipping force of the VTRC crawler traveling at a large angle on the small pole could not be determined because the crawler did not achieve an angle of 20 to 40 degrees on this size pole without much difficulty. When the crawler was moving on the medium pole at a large angle, a force of 22 N downward was needed to inhibit it from further motion. The only explanation for the small force measured was that at the large angle, the wheels were no longer flush against the pole surface, and, thus, there was a loss of magnetic adhesion that caused the slipping force to be significantly less than the other values determined. More force was required to prevent a crawler's movement on a given pole at a large angle (20 to 40 degrees) with respect



Figure 28. Force vectors

to the horizontal than at a small angle (10 to 20 degrees). This is evident if one considers the force vectors as shown in Figure 28.

These tests showed that the VTRC crawler can support more weight than the Infometrics crawler, which is largely attributable to the fact that the wheels of the latter were never in full contact with the pole surface at any time during travel. Since the Infometrics crawler could carry the weight of the power cables, it was assumed that the VTRC crawler could, too, since it could support more weight than the Infometrics crawler. The power cables weigh approximately 9 kg, which may cause a few problems in certain circumstances, especially when traveling at a small angle with respect to the horizontal. Tests were performed with the cables suspended, and the crawler supported their weight as it traveled along the pole.

Overcoming Obstacles

A series of tests were performed to determine the ability of the Infometrics crawler to overcome obstacles of varying heights on a steel flat plate 7 mm thick. The first test used the articulated crossbar to connect two motor units (B-scan assembly) and overcome a vertical obstacle 3 mm high, 311 mm long, and 99 mm wide. The obstacle affected only the crawler's right wheel. Initially, the crawler had some difficulty climbing over this obstacle; its motion was halted by the obstacle. Many attempts had to be made before the crawler's front wheel climbed over the obstacle, and it was much harder to get the back wheels to overcome the obstacle in moving upward. The speed of the crawler had to be decreased to overcome the obstacle during the first attempt. With a speed approximately 50 percent or less of the crawler's maximum speed

of 4 mm/s, both the front and back wheels climbed over the obstacle during the first attempt, moving up and down the flat plates.

The second test also used two units connected with the articulated crossbar and overcoming the obstacle 3 mm high. This time, the obstacle was horizontal; therefore, both wheels had to overcome it. The crawler, moving at a slow speed, 50 percent or less of its maximum, overcame this obstacle during the first attempt, when moving both up and down the plates.

The next test involved the articulated crossbar and a 5-mm horizontal obstacle, which was 527 mm long and 51 mm wide. Moving at its maximum speed, the crawler did not climb over this obstacle. But, at a slower speed, it overcame the obstacle on the first attempt, moving both forward and backward.

For the next test, the size of the obstacle was doubled, to 10 mm high. Even with the crawler moving at its slowest speed, it did not overcome this obstacle. The articulated crossbar was removed to give the crawler a little more flexibility, but it still did not climb over this obstacle; the obstacle was too high for one unit to overcome on its own without a crossbar attached between the two units for added support.

The last test to determine what size obstacle the crawler could overcome involved an obstacle 8 mm high (a combination of the 3- and 5-mm obstacles). Without the articulated crossbar, the slow-moving crawler did not overcome the obstacle. On the other hand, with the articulated crossbar, it climbed over the obstacle after a few attempts. The first time the front wheels climbed over the obstacle, the left wheel lost contact with the surface. As movement continued, though, contact was re-established. During the second traversal over the obstacle, the crawler maintained contact with the surface. Both wheels independently bumped the obstacle first and then overcame it. In traversing down the plate, the crawler had no problem overcoming the multiple-layered obstacle (the crawler overcame the 3-mm obstacle, then the 5-mm obstacle, and then, from the highest point, the 8-mm obstacle to regain contact with the flat plate). When using the stiff crossbar, the crawler overcame this 8-mm obstacle. It bumped the obstacle twice before successfully climbing over it.

Thus, it was determined that the Infometrics crawler, when moving at a slow speed and using either the articulated or stiff crossbar, could overcome obstacles with a maximum height of 8 mm when attached to a flat steel plate 7 mm thick.

Tests were performed on the various pole diameters to assess the VTRC crawler's ability to climb over obstacles. Initially, the front caster wheel often detached from the pole as it hit the obstacle edge but reattached on the obstacle surface. The front wheel also disconnected from the pole as it overcame the top obstacle edge (in climbing off the obstacle). This was not a major concern since the top obstacle edge will not be present on poles in the field. The obstacles on the constant-diameter poles were rectangular; thus, there were two obstacle edges, although in the field, the obstacle is formed from a male pole section fitting inside a female section, and thus there is only one obstacle edge. One reason the crawler could have had trouble overcoming the obstacles is that there was a screw in the top caster wheel that was occasionally preventing one of the wheels from turning and rolling along the pole surface.

Adding the second drive wheels helped the crawler climb over obstacles better since, in this case, the back wheel pushes the front wheel over the obstacle. After the bogie wheels were added, another problem was observed. Because of the large weight of the motors and gearheads sitting away from the main frame of the crawler and from the pole, the weight tended to pull the crawler away from the pole surface. This pulling away could eventually cause the crawler to detach from the pole and fall to the ground. To remedy this problem, magnetic idle wheels were placed on either side of the ultrasonic sensor tube in an attempt to keep the center of the crawler connected to the pole at all times. The idle wheels were smaller in diameter than the caster wheels and drive wheels and had a magnetic pull of only 53 N when steel washers were placed on both sides.

The next addition to the wheel structure was a spring-loaded skid, a plastic support that slid over the pole surface instead of rolling located approximately 414 mm from the center of the crawler's main frame. This wheel attached to the tail of the cord holder, a provision that was added to the new crawler to ensure that the power cords did not interfere with the traveling of the crawler, and was supposed to add a little more support to the crawler as it climbed over obstacles. If the skid had enabled the crawler to overcome obstacles better, it would have been replaced by a magnetic wheel. During preliminary tests, though, this wheel did not improve the crawler's climbing capabilities and was actually in contact with the pole only when the crawler was climbing over an obstacle. Therefore, it was removed.

As the crawler maneuvered around the pole, specifically while it was turning clockwise or counterclockwise, at times, its central region still pulled away from the pole surface, possibly because of the idle wheels. The proposed remedies were to add stronger magnets to the wheels in the hope that the stronger magnetic force would make the central crawler region remain attached to the pole or to add light springs to force the drive wheels to spread apart after a rotation, which in turn would push the center region toward the pole. The light springs corrected the problem.

The back caster wheel also had difficulty overcoming obstacles, especially the bottom obstacle edge, when climbing up the pole. This problem was due to the fact that the obstacles on the constant diameter poles were too short. Once the front caster wheel climbed off the top obstacle edge, the back caster wheel was already too close to the bottom obstacle edge to overcome it. For the back caster wheel to not get stuck at the obstacle edge, the crawler had to travel at full speed, although at times it still was unsuccessful. Consideration was given to moving the back caster wheel from the main frame to the cord holder, which would allow a longer time between the time that the front caster wheel would be coming off of the top obstacle edge and the time the back caster wheel would have to overcome the bottom obstacle edge. This idea was quickly dismissed since the problem of the rectangular obstacles being too short would not exist in the field. The same problems, with the front caster wheel separating from the pole surface and the back caster wheel having difficulty overcoming obstacles, did not exist in traveling down the pole since the force of gravity assisted the crawler in overcoming obstacle edges.

On the flat surface, the top caster wheel climbed obstacles during almost every attempt, and the back caster wheel overcame the obstacle edge as long as only one caster wheel was traveling over an obstacle edge at a given time. On the flat surface, both drive wheels did not climb over an obstacle edge simultaneously, and the front caster wheel holder touched the motor casing when angled upward (in climbing over an obstacle).

With the large pole on its side to lessen the force of gravity on the crawler, the crawler had no problem climbing an obstacle 7 mm high and would probably not have a problem climbing a 14- to 25-mm obstacle with the pole in this orientation. Two attempts were made before the crawler overcame the obstacle head on (with both drive wheels reaching the obstacle at the same time), although no problems occurred after these two attempts.

During the first observations made on the vertical tapered pole, the crawler had very few problems climbing over the 7-mm obstacle, although during the subsequent observations, the crawler had some difficulty climbing over the obstacle edge. These attempts were made at both slow and fast speeds, with both wheels approaching the obstacle at the same time and with only one wheel approaching it at a time.

Toward the end of the testing process, a stop was added to the front caster wheel to limit how far the wheels could pull away from the pole surface. By limiting this distance, it was easier for the caster wheel to regain contact with the pole once it was lost.

The difficulty in overcoming the obstacles during the end of the lab testing process was due to the wear on the surface of the wheels. New wheels with a rougher surface and hard chrome coating on the contact surface were fabricated to improve traction and aid the crawler in climbing over obstacles. After the wheels were replaced, the crawler overcame the 7-mm obstacles with both drive wheels approaching the obstacle simultaneously, instead of one drive wheel at a time.

Rotations

Tests were performed to determine how well the VTRC crawler could manipulate turns, or rotations, from the climbing position (vertical travel) to the inspection position (horizontal travel), and vice versa.

During initial rotation tests, the crawler did not rotate counterclockwise on the pole because of slipping in the gearhead attached to the right motor. This problem was corrected by replacing the motor and gearhead with an additional pair. The cause of this problem was the use of stepper motors and the original controller design. When the crawler was turning, the idle wheels and one drive wheel had very little contact with the pole surface; thus, the magnetic force at which the crawler was attached to the pole decreased. The idle wheels and drive wheels do have full contact with the pole when the crawler is traveling vertically or horizontally. Specifically, while the crawler is turning, the drive wheel closest to the centerline of the pole was in full contact with the pole, but the other wheel was on edge, plus the idle wheels did not help secure the crawler to the pole. Since the idle wheels were not helping to hold the crawler close to the pole, and were forcing the crawler into incorrect positions on the pole, such as the drive wheels on an edge, they were eventually removed.

Many problems arose in trying to maneuver from the climbing position to the inspection position, especially on the smaller diameter poles. In traveling up and down the pole, the drive wheels were positioned such that the central plug was close to the pole surface. As the crawler began to turn, the drive wheels moved closer together and did not always spread apart again as the crawler reached the position to begin horizontal travel (around the pole). With the wheels not spread apart, the central region of the crawler pulled away from the pole as the crawler completed its rotation, which could have caused the crawler to fall. The same behavior occurred as the crawler turned from the horizontal to the vertical position.

When the large pole was laid on its side to reduce the force of gravity on the crawler, there was perfect magnetic contact as the crawler rotated 90 degrees on the top of the pole. The conclusion was made that the turning of the crawler and the force of gravity must have been making the center contact pull away from the pole when the pole was upright. In addition, screws were scraping against the stops on the drive wheels as the crawler rotated between 70 and 90 degrees, where 90 degrees signified that the crawler was positioned to travel around the pole.

On the tapered pole, the crawler had to move at a very slow speed while rotating to minimize the slipping of the wheels. This slipping was eliminated by adding drive wheels with a rougher surface. In addition, the caster wheels occasionally would not swivel correctly during transitions or in movement after a transition. This problem was corrected by further rounding of the edges of the caster wheels.

Horizontal and Vertical Travel

Tests were performed to evaluate the crawler's ability to travel horizontally, in the inspection position, and vertically, in the climbing position. The test results refer to the VTRC crawler since the Infometrics crawler could travel up and down the large pole, but motion around the pole was inhibited by the inflexibility of its left and right units.

On the flat surface, the wheels of the crawler were in full contact with the surface, but on curved surfaces, when traveling up or down the pole, they sometimes were not, as was desired to ensure the greatest magnetic force between the wheels and the pole. This loss of magnetic force was accompanied by a small amount of slipping. The only other time slipping was observed in vertical traveling was when the crawler was traveling at maximum speed along the small pole.

At maximum speed, when traveling downward, the crawler slid down the pole, and when traveling upward, the wheels lost contact with the pole.

The drive and caster wheels specifically caused a few problems. In traveling down the large pole, the left front drive wheel flipped backward on occasion, although the back wheel remained in contact with the pole. There was no way to reconnect the front wheel through use of the joystick. Therefore, stops were added to make the drive wheels able to rotate 360 degrees. The caster wheels occasionally got stuck sideways (perpendicular to the direction of movement). To get the caster wheels moving again in the correct direction, the joystick had to be manipulated in such a way to cause the wheels to move forward and rotate simultaneously.

With the large pole laying down to reduce the force of gravity on the crawler, all wheels were in contact with the surface when the crawler was traveling horizontally. There was a metal support on the side of the drive wheel touching the wheel, thus inhibiting movement on occasion. This support was cut back by approximately 3 mm.

In traveling horizontally on the tapered pole, one caster wheel occasionally detached from the pole, although the other wheels remained strongly attached. This problem was corrected by lengthening the ball joint linkages. On a flat surface, after lengthening the ball joint linkages, the ball of the linkage would hit the side of the motor. This was not a major concern for this application. This crawler will be used only to inspect poles and not flat surfaces. Adjustments may be made in the future to prevent this from occurring. On the tapered pole in the lab, as well as in the field, the crawler had no problem traveling vertically and horizontally after the ball joint linkages were lengthened.

Sensors

The sensitivity of the remote visual device to detect reference cracking on the sample's surface was evaluated briefly. The camera's resolution was good for detecting surface breaking flaws on noncorroded surfaces. Figure 29 shows a digital image of the centerline crack (flaw 1). It was not possible to detect the reference cracks covered with a thin layer of rust. There are still no criteria for detecting cracks during the inspection of the poles.

Field Evaluation

Three tests were performed in the field: one on a large-diameter galvanized pole in UVa's football stadium, the second on a galvanized high-mast pole in Salem, Virginia, and the third on a light pole made of weathering steel (ASTM A588) with a brown surface acting as a normal protection layer in VDOT's Suffolk District.

The field evaluation included the performance of the crawler's mechanism during the inspection of tapered surfaces; the ability to change the crawling direction from vertical to



Figure 29. Digital image of flaw 1

horizontal and vice versa; the ability to overcome obstacles in vertical and horizontal directions; the inspection speed; the remote visual device's sensitivity to detect cracks in the slip joint areas (inspection locations); the effect of the pole's surface conditions on the detectability of cracks by visual inspection; and the system's ability to provide fully integrated data acquisition, data storage, and image enhancement.

During the first field test, the crawler did not manipulate rotations very easily. The center contact remained very close to the surface of the pole. Figure 30 and shows the crawler during the second test. Five slip joints were inspected on this pole. The field test was not completed the same day because of windy weather.

Figure 31 shows the surface conditions and the crawler above the third slip joint during the third test. The crawler's speed was 4 mm/s during the climbing and 3 mm/s during the inspection. A surface breaking crack was detected in the female section in the third joint. The zoom of the digital image of the crack is shown in Figure 32. The surface conditions did not influence crack detectability because the crack was 5 mm wide and 75 mm long. During the inspection, real-time full motion pictures were acquired and stored on the hard disk for review and enhancement. The crawler climbed up to 20 m and changed direction from vertical to horizontal and vice versa several times without difficulty. Three slip joints were overcome during this test. Unfortunately, when sitting above the third joint, the crawler occasionally fell to the ground, slipping on the surface without detaching from the pole. The crawler was fixed in the field, and 2 hours later a demonstration to VDOT inspectors was conducted.



Figure 30. (Left) crawler climbing galvanized pole; (right) crawler rotating on pole



Figure 31. Robotics inspection of steel pole in Hampton, Virginia



Figure 32. Digital image of crack detected during robotics visual inspection of pole in VDOT's Suffolk District

In the field, the crawler achieved many of its desired goals, although a few improvements need to be made. The crawler can travel vertically and horizontally and manipulate rotations from one of these positions to the next on tapered poles without difficulty down to 200-mm minimum diameter.

CONCLUSIONS

- The crawling robot can inspect flat, cylindrical, and tapered surfaces with a longitudinal taper of 12 mm/m and a minimum outside diameter of 200 mm; change inspection direction from vertical to horizontal and vice versa on these surfaces; and overcome vertical obstacles up to 7 mm high.
- The system can provide fully integrated real-time image acquisition, storage, and enhancement with a small, lightweight, replaceable video camera with an interline transfer CCD imager (420,000 pixels) that has immediate "plug and play" compatibility with the system's FPS/60 video grabber and MPEG compression algorithm.
- In the future, the system could provide ultrasonic waveform acquisition; storage; simultaneous display of A, B, C, and 3-D-scan images; and analysis of the results using signal qualifier and pattern recognition.
- Some deficiencies must be overcome. The most serious problem is the occasional slipping of the wheels, usually during a climb. Further investigation of the magnetic force is necessary. Maintaining the necessary normal force between the wheels and the pole surface is of great importance. The current design may not provide as good a "footprint" as could be obtained from a softer tread. A point or line contact may not be as desirable as an area of contact to generate greater traction. The cause for slipping is not clear and must be investigated further.

RECOMMENDATIONS

- Conduct additional research to evaluate the full potential of robotics for NDE of steel bridges.
- Develop an improved crawling robot, ROBOCAT-II, for reliable inspection of high-mast light poles.
- Develop a snakelike robot (ROBOSNAKE-I) that can overcome vertical obstacles higher than 7 mm and sharp member bends.

• After development and preliminary lab evaluations, give ROBOCAT-II to VDOT inspectors or contractors to perform 1- to 2-month visual inspections of high-mast light poles. Based on the results of the field intensive inspection, decide whether to add extra NDT sensors (ultrasonic or eddy current or microwave) to the system.

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