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Abstract

This report presents the results of a project to finalize and apply a crawling robotic system for the remote visual inspection of high-mast light poles.

The first part of the project focused on finalizing the prototype crawler robot hardware and control software from the intial prototypes constructed in earlier projects. Significant mechanical design improvements such as the auxiliary caster wheels and improved camera system were adapted to the final proptotype.

The second part of the project was directed toward acquiring field experience and disseminating the knowledge about this technology. Field tests in Iowa, South Carolina, and Minnesota were carried out. In addition, presentations were made at an American Society of Civil Engineers meeting, at an American Association of State Highway and Transportation Officials meeting, and at the Federal Highway Administration Turner-Fairbank Research Center.

Safety of the inspection personnel, quality and quantity of the inspection data, the ability to produce report-ready permanent inspection records and video imaging files, the productivity and cost-reduction opportunities, and the enhanced ability to carry out more detailed non-destructive evaluation inspections such as ultrasound or eddy current probes make this technology an attractive technology. However, a continued program of development, field experiences, and adaptation of this technology to specific applications is necessary. Both, a generic robotic technolgy and a more specifcally directed automated inspection technology are viable candidates for consideration in applications to highway structures.

FINAL CONTRACT REPORT

USE OF ROBOTICS FOR NONDESTRUCTIVE INSPECTION OF STEEL HIGHWAY BRIDGES AND STRUCTURES

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INTRODUCTION

The use of robotics and other automated devices in the inspection of highway systems can improve tesing procedures, increase productivity, reduce costs, and allow workers to access dangerous areas remotely.

A research program at the Virginia Transportation Research Council (VTRC) over the past several years has produced several prototype robotic systems[1, 2] for non-destructive evaluation (NDE) of highway high-mast light pole structures. In this report, the initial research program is concluded by producing a final prototype robotic crawler and by acquiring field experiences in the use of this robotic crawler for the NDE of highway high-mast light poles.

PURPOSE AND SCOPE

The objectives of this project were (1) to develop a finalized prototype of the crawling robot, called Polecat-PRO, and (2) to acquire field operating experiences in the use of this robot for the NDE of high-mast light poles and in the process disseminate this technology to the potential users.

METHODS AND MATERIALS

Figure 1 shows a high-mast pole, and Figure 2 shows the overall concept of the robotic system used for NDE. Figure 3 is a photograph of the robot inspecting a pole at Troutville Exit location on I-81 South near Roanoke, Virginia. As shown in Figure 2, the robotic system, which is identified as the "crawler," carries a digital camera. The data generated from the inspection include the video images and coordinate locations of the robot on the pole. These data are transmitted to the ground-based computer system for real time viewing and for storing the data on a hard disk for further analyses. The possibilities and opportunities for on-site data analyses on the ground-based computer are virtually unlimited. The crawler, or mobile robot, is tethered to a power source on the ground, which in field applications typically includes a portable generator system. The same tethering cable system includes cables for transmission of video data.

FIGURE 1. High-mast light pole.

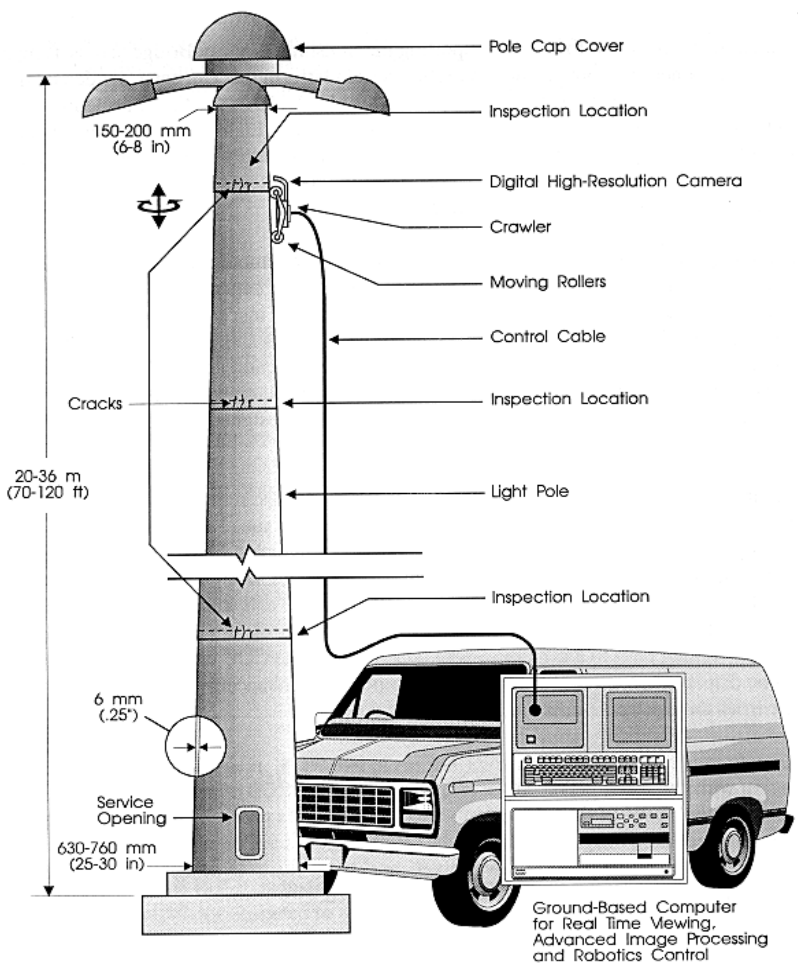

FIGURE 2. Schematic configuration of Polecat inspecting high-mast pole.

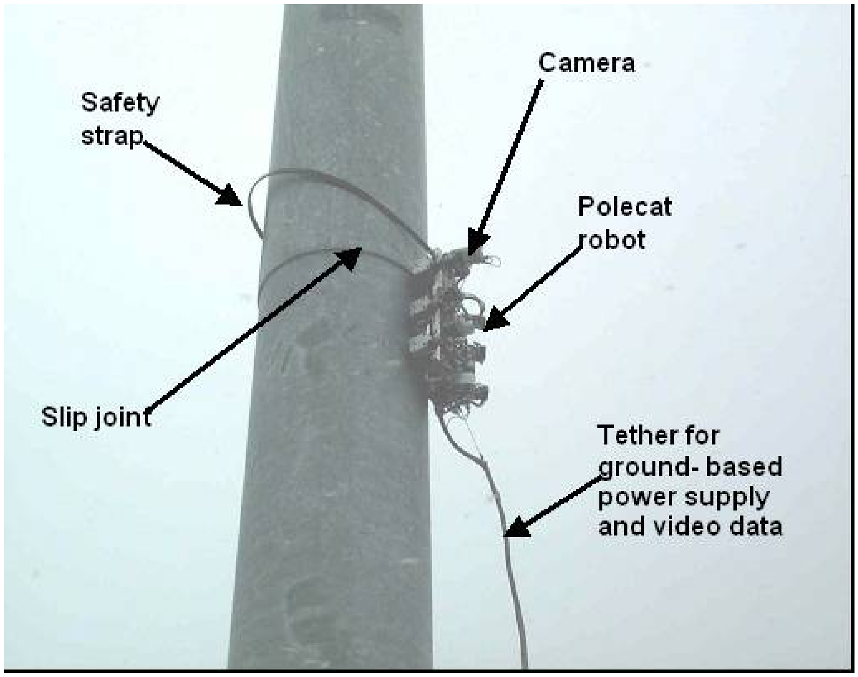

FIGURE 3. Polecat in field inspection. Strap and slip joint can be seen.

High-mast light/camera poles are typically 70 to 120 feet high, but taller poles may also be found in some states. They range in diameter from 6 to 8 inches at the top to 25 to 30 inches at the base. These poles are tapered, and most have circular sections, but poles of polygonal sections are also used. Most of the poles are constructed from weathering, galvanized steel, conforming to the requirements of ASTM A588. These poles are made of tapered steel, which may be one piece or sectional, depending on the height, and their sections are inserted one inside the other. The male section of the tube fits inside the female section, forming a slip joint. Generally, but not always, detectable cracks form on the female section. A highway crew at the ground level or in a “cherry picker” bucket at higher elevations typically identifies these externally visible cracks with binoculars, but this method of inspection can, at best, yield a less than thorough inspection. The detection of subsurface cracks, not externally visible, requires ultrasonic sensors. Polecat can provide video imaging of the entire pole inspection in both digital format and, simultaneously, a continuous VCR tape.

Figure 4 is a close-up of the Polecat on a laboratory pole. Polecat is equipped with six powered wheels, three on each side of the robot, and two non-powered caster wheels, one placed at the center front and the other at the center rear of the robot. These caster wheels serve two critical functions: (1) they provide stability and help maintain a constant distance between the frame of the robot and the pole surface, and (2) they provide extra holding force while traversing an obstacle. There are, thus, eight contacts between the robot and the pole, and the holding force between the robot and the pole is created at these contacts by permanent magnets. Each of the eight wheels is designed as two disks sandwiching a magnetic disk. The treads of the disks of the six powered wheels are also provided with aggressive diamond pattern knurling to increase the friction and hard chrome plating to minimize wear. Each magnet is magnetized axially, producing a north pole on one of the two steel disks and a south pole on the other. Neodymium magnets, which are the strongest commercially available magnets, are used. The magnetic force provides a normal force between the wheel disks and the pole, thereby proportionately producing the traction force based on the effective coefficient of friction between the disks and the pole. The resulting traction supports the mobile robot and its payload during the vertical climb of the robot in addition to creating the necessary reactions to support the motor's torque. As another illustration of the strength of the normal force created by the magnetic wheels, if the robot is made to hang upside down from a structure, the normal attractive forces at the eight contacts support the entire weight of the robot and its payload. Of course on the high-mast light poles the robot would not be made to hang upside down, but this situation is used as an illustration for the strength of the holding force if this type of robotic device is ever utilized for situations requiring upside down configuration. Traction is also a critical feature to prevent wheel slippage—rotations of the wheels are sensed by encoders to compute the exact distance traveled by the mobile robot on and around the pole, relating the geometric displacement coordinates to the video images and signature data. The use of the magnetic force restricts the mobile robot to the inspection of poles and structural components with magnetic steel materials only. However, a review of the pole materials used on highways indicates that a majority of poles are made of magnetic steels; this restriction is not considered significant for the intended application.

The maximum speed of Polecat is 5 feet per minute for climbing up or down the pole, and the minimum speed is 0.5 foot per minute for the actual inspection motions. Typically, the robot moves at the faster speed vertically from a slip joint to the next slip joint and then proceeds circumferentially at the slower speed for the inspection of the slip joint. With these speeds, the total data collection time for a pole is about 80 minutes. A crew of two persons, a small van, and a generator can check about six poles per day. In addition to the speed requirements, the mobile robot is expected to encounter steps or bulges on the poles and must negotiate these steps in its path. Based on a review of various available specifications, a maximum step height of 0.4 inch is expected for the high-mast light/camera poles. Polecat is equipped with an articulating suspension, including auxiliary caster wheels, to allow the Polecat to climb over and step down from these obstacles. The articulating suspension also allows Polecat to conform to the tapered poles as it moves from the larger diameter to the smaller diameter sections of the pole and move over multi-sided polygonal poles. Further, a specially designed leveling system keeps the frame of Polecat and the video camera at a constant separation distance from the pole surface as Polecat traverses the pole. This is a key feature for the proper operation of the camera and other sensors. A braking system or "backstop" for locking the reverse motion of Polecat is provided by a worm gear drive system installed between each motor output and the wheel axle.

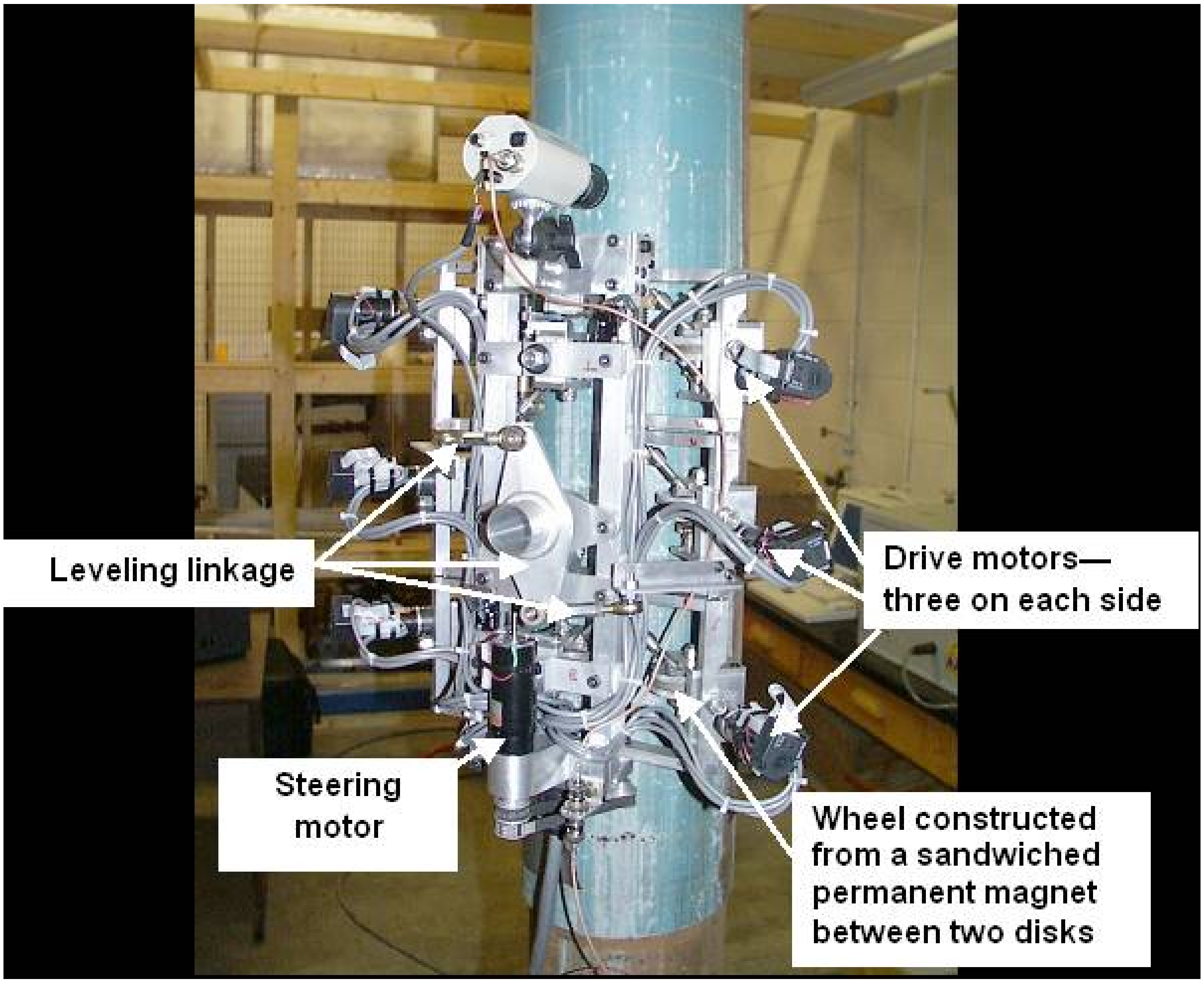

FIGURE 4. Close-up of Polecat on laboratory pole.

Polecat wheels maintain an alignment of 0 degree for vertical motion and 90 degrees for circumferential motion. The “steering” system for the robot is a two-position system achieved by the left and the right lead screws with linearly traveling nuts attached by tiller links to wheel assemblies and the two caster wheels. The wheel assemblies are revolute jointed in the vertical axis to allow “yaw” rotations. A relatively large steer motor powers both screws with a V-belt/pulley system. The spatial linkage created by the nuts, tillers, and wheel assemblies is sized such that the nut travels produce the 90^o rotations of all eight-wheel assemblies concurrently. Limit switches are used to signal the completion of the turn. The turn, of course, occurs while the drive wheels are turned off and vice versa. This process is fully automated in the control system.

For safety and in case of a power failure while the robot and its sensors are at high elevations on the pole, a round safety strap is used as seen in Figure 3, which allows Polecat to remain in magnetic contact with the pole; simply pulling on the robot brings it down. The safety strap prevents the robot from falling off the pole – the wheels have permanent magnets in them, but the magnetic force between the wheels and the pole is critically dependent on maintaining a continuous contact. Even a slightest gap caused by the wheel lifting off from the pole will result in the loss of a holding capability. In such an event, which is not generally expected to occur, the safety strap pulls the robot toward the pole, allowing the permanent magnetic wheels to return back to the full contacts. In another failure scenario, if a power failure were to occur then the drive motors cannot propel the robot down and the robot may be brought down by simply pulling on the power cable. In that motion, the safety strap provides an added support to keep the magnetic wheels in contact with the pole.

The electrical system includes a control box on the ground, which is connected to the control software in the laptop computer. Cursor movements on the screen control the Polecat. The controls and data acquisition are simplified by standard WINDOWS®-based mouse-operated controls with a graphical user interface.

Polecat is equipped with a charge coupled device (CCD) color camera with a motorized zoom lens control unit. There are two ways to capture the data from the CCD camera: the PC on the ground can capture the picture as bitmap images, and a VCR can record the streaming video as analog data. Both methods can be used concurrently, and this concurrent capture of analog and selected digital data is the recommended procedure.

As a standard operating procedure for field inspections, the following steps are typically carried out:

- *Step 1: Setup the Polecat inspection system, including the Polecat on the pole, setting up the safety strap on the robot, connections to the control and display laptop computer, connections to the VCR and a larger TV monitor for real time viewing of the inspection video, the generator system, and the connections of the power cables.* The setup can be done in the rear of the van itself, or if the van cannot be brought down closer to the pole, then the setup can be done next to the pole. Figures 5 and 6 show the typical setup.

- *Step 2: Begin the inspection process by moving the Polecat on the pole over a short distance and viewing the inspection data, both in the digital format on the laptop and in the analog format on the TV monitor*. Use a nametag or a business card in front of the camera to adjust, if necessary, the focus of the camera.

- *Step 3: Collect the data.* Without the Polecat, a telescope on the ground is utilized to scan the pole for any externally visible defects. With the Polecat and its on-board digital camera, it is generally not necessary to employ the telescope methods of inspection. However, during this inspection, it was determined that if a telescope can be used to scan the pole and identify some specific location on the pole which might warrant more detailed inspection. The Polecat can actually be directed to go to that location on the pole for a closer inspection. Therefore, the ground-based telescope and the Polecat may be utilized as complementary tools. Figure 7 shows the telescope based inspection setup in conjunction with the Polecat. Figure 8 shows Polecat during the inspection process in Charleston, SC.

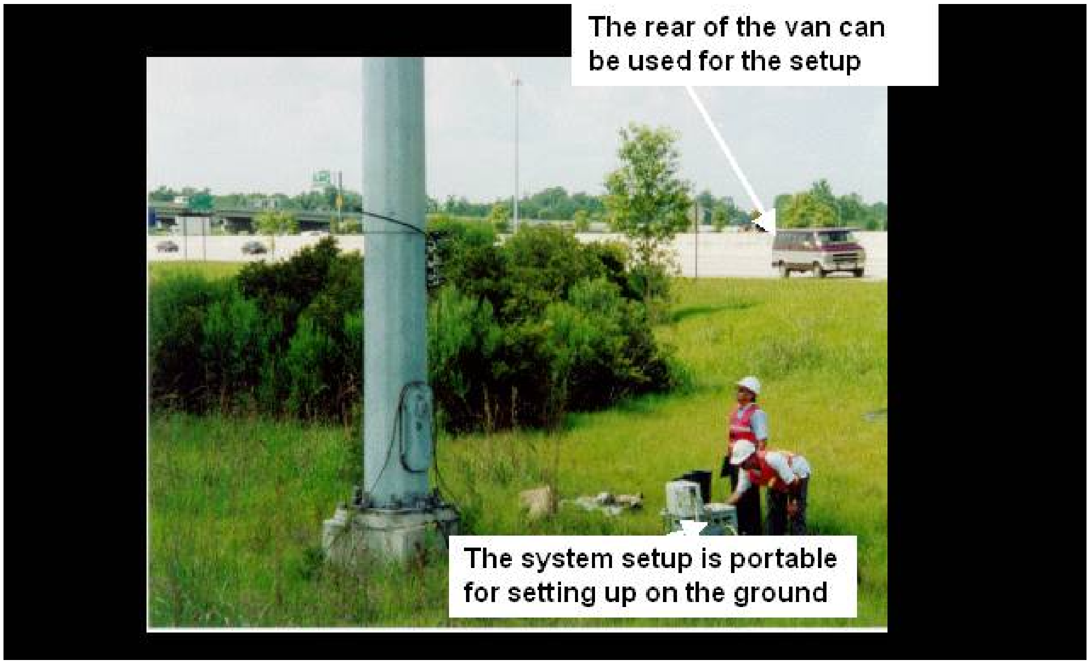

FIGURE 5. Polecat inspection setup on ground in field.

FIGURE 6. Mounting of safety strap is part of setup procedure.

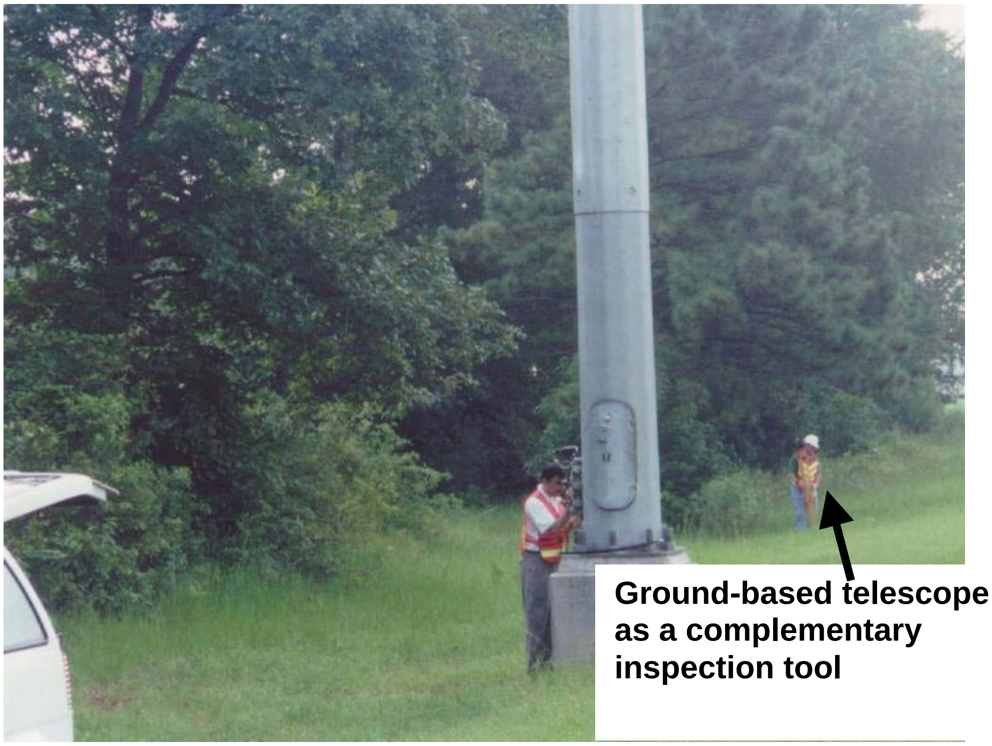

FIGURE 7. Ground-based telescope, as used in conventional inspection, may be used to complement Polecat inspection.

FIGURE 8. View of Polecat during inspection process.

- *Step 4: Two kinds of visual data are collected: an analog video of the entire pole as traversed by Polecat is recorded on a VCR tape; and at selected locations, digital files from the camera are captured on the laptop computer's hard disk.* These digital files can be used for preparing reports. The digital files are in the JPEG format, or alternately a bitmap of the picture can be stored. The individual files can be as large as about 500 KB. Therefore, typically, only a few key locations are saved in the digital files. The entire inspection video on the VCR tape is also available and this video can be utilized in the office to digitize as many locations as are desired. During the inspection both the laptop screen and a large video monitor are utilized to view the camera output in real time.

- *Step 5: Use either the complementary telescope information, or the real time images on the laptop computer screen and the TV monitor, or both, to investigate specific locations of interest on the pole by sending the Polecat to those locations through mouse/cursor controls on the laptop computer.* The images sent by Polecat can be viewed in real time on the Laptop computer screen and the TV monitor and if a site location appears of interest, then the camera can be further zoomed on that site for a closer view.

RESULTS

A new prototype of Polecat was designed and built. Key improvements over the previous versions of prototypes include:

- *Incorporation of an auxiliary caster wheel for much-improved stability.* There are now two caster wheels.

- *Reduction in the overall weight, the total weight of the robot is now about 25 pounds.*

- *Improved camera system with color capabilities.*

- *Standardized design of the safety strap.*

- *A standard procedure for calibrated assembly of the robot.* The robot is assembled on a circular pole of the smallest anticipated diameter, rather than on a flat surface. The flat surface represents the "largest" possible diameter of a pole, and the critical configuration occurs at the smallest possible diameter. This has also resulted in significantly improved stability of the robot.

As a part of disseminating the Polecat technology, a number of avenues were pursued, including the following:

- Presentations were made at the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center. A website at the center, http://www.tfhrc.gov/hnr20/nde/lightsign.htm, contains a photograph of the Polecat on a pole, which was a part of the center's survey of states on the technologies used for the NDE of high-mast light poles.

- Working with Collins Engineers from Chicago and their regional office in South Carolina, two inspection trips were made—one to I-35 south of Ames, Iowa, for the Iowa Department of Transportation (DOT) in August 2000. In addition to the digital capture of the pole images, a continuous video was captured on a VCR tape and the tape was provided to the Iowa DOT as a record of the inspection. The second inspection program in collaboration with Collins Engineers was carried out in Charleston, South Carolina, and Columbia, South Carolina, during June 25, 26, and 27, 2001. Five poles were inspected, and VCR tapes of the data were provided to Collins Engineers in addition to a written report.

- Presentations were made to the ASCE Conference in Philadelphia in May 2000 and to the AASHTO Bridge Meeting in Charleston, South Carolina, with a field demo for the AASHTO attendees.

- A field inspection for the Minnesota DOT was attempted in June 2003 and then again in July 2003. In June 2003, the power supply at the base of the pole instead of the standard generator was used, and the resulting power surge destroyed the controller for the Polecat. This was fixed, and the second attempt was made in July 2003 when it was discovered that the bolts and obstacles on the Minnesota poles were higher than the 0.4-inch step height for which the robot is designed. Therefore, the use of the Polecat for the Minnesota poles would have required a redesign of the suspension of the robot, and this inspection was not carried out. However, the trips to the Minnesota DOT led to a new concept of a ring-mounted inspection system, which is presently being developed and field tested.

- The development of the Polecat technology has yielded two Master of Science theses.[3, 4] These theses represent the accumulated technological developments for the Polecat technology and can be useful references for future developments of this technology. A provisional patent was also acquired by the University of Virginia Patent Foundation in September 2003.

DISCUSSION

All participants in this inspection program provided a number of very useful suggestions and observations. These suggestions and observations from the field inspection activities are discussed here to provide a practical focus on this technology.

- The safety strap that was brought to the field in Charleston, South Carolina, was a little too short for the 16-sided polygonal section poles—all five poles were polygonal as opposed to round sectioned. The strap is actually a simple component. We were able to expedite the acquisition of a new strap by obtaining a steel strap from a nearby Lowe's Building Supply store—this is the strap to tie lumber at the store. An auto repair shop was able to quickly grind the ends of the strap and drill some holes. The new strap was installed and ready to be used in about 45 minutes. This is mentioned here to emphasize that Polecat is designed largely to use standard, modular components for ease of use and repair in the field.

- Polecat is able to inspect both the round and the polygonal sectioned poles. The designs of the caster wheels and the auxiliary caster system were particularly valuable in this regard. The minimum number of sides possible for Polecat should be investigated.

- The inspection process can be further aided by mounting multiple cameras, perhaps a ring of cameras to allow a full circumferential view in a single motion.

- Recording of audio in conjunction with the video will provide a better documentation of the inspection data by capturing the inspection comments on the tape.

- The use of color to define cracks should be investigated. Both the analog and the digital video can effectively show the presence of holes, spots, weld plates, weld lines, or any other anomalies on the pole structure. It would be beneficial to further classify these anomalies in relation to vision data.

- Incorporate UT sensors for subsurface crack detection and DT (differential thickness) measurements. The DT inspection is usually done for sign structures and this would be an added benefit from Polecat application.

- The ability to measure the dimensions of a crack, if a crack is detected, would be of significant value. If the depth of a crack can be detected, then that information will add further value to the data.

- The telescope can be used as a complementary tool to the Polecat inspection.

- The weld line (longitudinal along the height of the pole) may also be of interest for inspection purposes, in addition to the male-female slip joints. In addition, the weld line can be used as a reference line in the inspection process.

- There is a need to measure and report the precise spatial coordinates of the robot camera location more detailed than the presently reported distance data.

- The use of a larger size video monitor should be evaluated to see if more clearly visual image could be presented.

- An ability to carry and control a light source in conjunction with the camera would be useful. For example, while inspecting a hole on the pole, a light can be used to mitigate the shadow.

- For situations where the van cannot be brought down to the pole, it would be useful to have a “card table” type setup. Refer to Figure 5 where the setup in the Charleston, South Carolina, inspection is being shown. It would be helpful in that setup if a standard setup for the computer, the video equipment, etc., is developed.

- The setup should include a way to reduce the effects of glare and sun on the visibility of the video monitors.

- The Polecat robot provides a viable technology for sending inspection sensors to remote locations on structures. This specific application of Polecat to highway high-mast light poles may not be a best application of this technology, particularly since there are other alternatives for automating the inspection process for these high-mast poles. Other alternatives in this case include the possibility of utilizing an inspection system mounted on the ring lowering system along with the winch/cable system already available to move the ring lowering system. This alternative, in fact, is under development and has already been field tested. Thus, the Polecat technology would be a viable technology when there are no specific automation solutions available for specific structures. As a clear distinction, the Polecat is a general purpose robotic vehicle that can be used for a number of applications where the structure is magnetic steel while the specific automation systems are designed for applications to a specific class of structures, such as the high-mast light poles.

- The use of wireless technology in collecting and transmitting inspection data would be particularly helpful in reducing the tether load on the Polecat robot. In addition, the use of batteries on the Polecat vehicle should be considered instead of or complementary to the ground-based power supplied by a generator.

- It has also become apparent that a more flexible design that can be adapted to a number of different types of structures and also to various disfferent types of obstacles on the structures would be necessary. A modularly designed robotic system, such that the subsystems and components of the robot can be assembled from standard components to adapt to each specific application is an atractive possibility.

CONCLUSIONS

The robotic technolgy for inspection, as embodied in the Polecat crawler, provides a valuable and versatile tool for the NDE of high-mast light poles. A continuing research and development program of acquiring field experience, improving the robotic system design, and adapting the technology to other structures such as bridges and sign structures would be necessary for successful application developments of this technology to NDE of highway structures.

Another complementary possibility is to carry out focused development of application specific robotic or automation systems for NDE of highway structures. This would contrast with a generic, broadly applicable, modular robotic tool and may well be a simpler and effective way to introduce automation and remote inspection abilities for highway structures. Both of these approaches have merits and should be further evaluated as opprtunities arise.

Further, the application specific automation system can be used to carry a simpler robotic tool, thus providing an opportunity for combining the two approaches.

RECOMMENDATIONS

Based upon the experiences acquired on the robotic system for NDE visual inspection of highway high-mast light poles, it is recommended that the generic robotic systems and also specific tools for specific applications be both considered in future applications as the needs for remote, safe, detailed structural inspections are presented.

ACKNOWLEDGMENTS

The interest and encouragement of Mr. Michael Sprinkel of Virginia Transportation Research Council were invaluable for this project. Mr. Robert Ross of Virginia Technologies, Inc., developed the electronics and controls for this robot, and Mr. Ugur Yusef Cetinkaya carried out the mechanical design developments as a part of his graduate research. The review and editing of an earlier draft of this report by Messrs. John Coleman and Dan Roosevelt significantly improved the quality of this report.

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