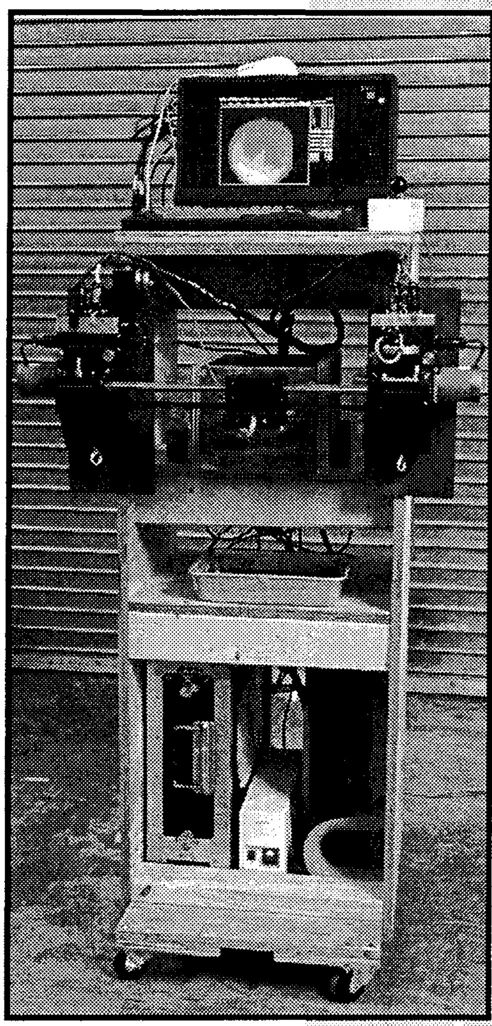
INTERIM REPORT

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



MARGARIT G. LOZEV, Ph.D.
Senior Research Scientist
Virginia Transportation
Research Council

PRADIP N. SHETH, Ph.D.
Associate Professor
University of Virginia

ROBERT A. ROSS
President
Virginia Technologies, Inc.

UGUR CETINKAYA
Graduate Research Assistant
University of Virginia

V·I·R·G·I·N·I·A
VTRC
TRANSPORTATION RESEARCH COUNCIL

VIRGINIA TRANSPORTATION RESEARCH COUNCIL

Standard Title Page - Report on State Project

Report No.	Report Date	No. Pages	Type Report:	Project No.: 5405-010-940
VTRC 98-IR-3	June 1998	20	Period Covered: 1/97-11/97	Contract No.
Title and Subtitle: Interim Report – The Use of Robotics for Nondestructive Evaluation of Steel Highway Bridges and Structreus				Key Words: Nondestructive Evaluation, Robotics, Steel, Bridges
Authors: Margarit G. Lozev, Pradip N. Sheth, Robert A. Ross, Ugur Cetinkaya				
Performing Organization Name and Address: Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903				
Sponsoring Agencies' Name and Address Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219				
Supplementary Notes				
Abstract				

Abstract

This interim report describes the progress during the first year of a project to develop robotics hardware for nondestructive evaluation of steel structures. The project objectives are to (1) develop and test an improved prototype (POLECAT-II) crawling robotics system for the remote nondestructive evaluation (NDE) of high-mast light poles, and (2) to demonstrate the use of robotics systems for nondestructive inspection of highway bridges and structures. The project has produced a new design of a robotic device called POLECAT-IIM which will be further tested and refined. It will be utilized to guide the evolution of a more dexterous device during the remaining 2.5 year project.

INTERIM REPORT

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

Margarit G. Lozev, Ph.D.
Senior Research Scientist

Pradip N. Sheth, Ph.D.
Associate Professor, UVA

Robert A. Ross
President-Virginia Technologies, Inc.

Ugur Cetinkaya
Graduate Research Assistant, UVA

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Transportation and the University of Virginia)

Charlottesville, Virginia

June, 1998

VTRC 98-IR-3

ABSTRACT

This interim report describes the progress during the first year of a project to develop robotics hardware for nondestructive evaluation of steel structures. The project objectives are to (1) develop and test an improved prototype (POLECAT-II) crawling robotics system for the remote nondestructive evaluation (NDE) of high-mast light poles, and (2) to demonstrate the use of robotics systems for nondestructive inspection of highway bridges and structures. The project has produced a new design of a robotic device called POLECAT-IIM which will be further tested and refined. It will be utilized to guide the evolution of a more dexterous device during the remaining 2.5 year project.

INTERIM REPORT
THE USE OF ROBOTICS FOR NONDESTRUCTIVE INSPECTION OF STEEL HIGHWAY BRIDGES AND STRUCTURES

Margarit G. Lozev, Ph.D., Senior Research Scientist
Pradip S. Sheth, Ph.D., Associate Professor
Robert A. Ross, President of Virginia Technologies, Inc.
Ugur Cetinkaya, Graduate Research Assistant

INTRODUCTION

High cost and low productivity have plagued manual nondestructive evaluation (NDE) of highway steel bridge members and structures. Robotics can be used in the inspection of highway systems to improve testing procedures, increase productivity, reduce costs, and remove workers from dangerous areas by reducing the amount of human labor required to perform an inspection. Robotics inspection techniques appear practical for NDE of steel bridge I-beams, box girders and cable stays, as well as steel high-mast light poles and overhead signs. These techniques can also be used to detect cracks in other steel structures and bridges covered with paint or marine growth.

This report is part of a Virginia Transportation Research Council (VTRC) project to develop an autonomous crawling robotics system for remote visual inspection of high-mast light poles and to evaluate its crack detection ability and sensitivity. The project also aims to propose design characteristics for a multipurpose NDE robotics system with additional sensors and attachments that could perform remote NDE of difficult-to-access components, members and inspection areas in highway transportation structures.[1]

The first priority of this study was a simple robotics tool to increase inspection efficiency while reducing hazards to the public and VDOT employees. The researchers acquired an Infometrics TestPro system consisting of a remote control unit, magnetically attached crawling robot, control cables, video and ultrasonic sensors, and host PC with appropriate boards and software modules to implement the multi-sensor NDE tasks for this purpose.

The researchers redesigned the original robot for operation on the tapered magnetic surface of high-mast light poles and to permit circumferential inspection of the pole. The first VTRC prototype crawling robotics system (POLECAT-I) has proven itself to have better crack resolution than previous systems, providing more reliable and efficient inspections at a lower cost. POLECAT-I's design features are described in a separate report.[1]

The mechanical design embodied in the POLECAT-I has evolved through actual working experience. Some deficiencies in the first prototype still have yet to be overcome. The most serious problem is the occasional slipping of the robot's wheels, usually during a climb.

Additional investigation of the magnetic force used in the design is also necessary. Maintaining the necessary normal force between the wheels and the pole surface is of great importance. The current design may not provide as much "footprint" as could be obtained from a softer tread. A point or a line contact may not be as desirable as an area of contact to generate greater traction.

Although the preliminary findings of the first VTRC robotics project are promising, additional research is needed to evaluate the full potential of robotics for NDE of steel bridges, to develop an improved VTRC crawling robot (POLECAT-II) for reliable inspection of high mast light poles, and to develop a snake-like robot (ROBOSNAKE-I) which can overcome vertical obstacles higher than 12 mm and sharp member bends.

PURPOSE AND SCOPE

The objectives of the first phase of this project are to (1) develop and evaluate an improved prototype (POLECAT-II) crawling robotics system for the remote NDE of high-mast light poles, and (2) to demonstrate the use of the robotics systems for nondestructive inspection of highway bridges and structures.

METHODOLOGY

The following tasks were performed.

1. Design, fabrication and evaluation of an improved prototype POLECAT-II robotics system.

2. Demonstration field tests.

RESULTS AND DISCUSSION

During the reporting period for this report (January-November, 1997), the following was accomplished:

- POLECAT-I performance and anomalies were critically evaluated to identify the needs for further refinements, improvements, and design changes.

- Based upon this needs analysis, POLECAT-II was conceptualized and designed, and a hardware prototype was constructed. The concept embodied in POLECAT-II is a significant departure from the POLECAT-I design. In early 1997, the researchers submitted an Idea Disclosure Form to protect the potential patentability of the POLECAT-II to VDOT.

- Laboratory and limited field tests were conducted on POLECAT-II to evaluate design performance and to identify any anomalies in the behavior under actual working situations. Some interference between the moving parts and also between the wheel housings and the pole were observed during these tests. This interference occasionally induced the loss of normal contact forces between the wheels and pole, resulting in wheel lifts and the further loss of normal and friction forces.

- As a result of these observations, the POLECAT-II design was refined and modified, primarily to increase the clearances between the moving parts and between the robot wheel housings and the pole surface. The modified design was built. Consistent with the evolution of the POLECAT technology, the modified design prototype was designated POLECAT-IIM, and is now the current prototype. The POLECAT-IIM prototype is currently being tested in the laboratory. Field tests will be done after the laboratory tests are completed and any design changes, if dictated from the laboratory tests, are implemented. The basic design concept embodied in POLECAT-IIM is considered robust and workable from the qualitative observations in the laboratory.

In the original proposal, a distinct separation was envisioned between the POLECAT technology and the future, more dexterous ROBOSNAKE. The ROBOSNAKE technology was directed toward overcoming obstacles of greater heights associated with the more demanding NDE inspection of bridge structures as well as steel poles. The experience with the evolution of the POLECAT technology through the POLECAT-IIM prototype suggests that the design of the ROBOSNAKE may be considered as a further evolution of the POLECAT-IIM concept. Some of the goals for ROBOSNAKE can be achieved by incorporating additional articulations and flexible shafting in the POLECAT-IIM design and by reducing its total weight. ROBOSNAKE is now viewed as an extension of the basic POLECAT technology.

While the original POLECAT-I prototype was successfully deployed in a variety of laboratory and field conditions, some deficiencies in its design were observed[1]. The most serious problem was the occasional slipping of the wheels, usually during a climb. The degree of contact between POLECAT-I and the pole was limited to two tandem pairs of bogie wheels for each of the two drives, and two caster (passive, stabilizing) wheels. It was observed that this contact may not produce sufficient holding force; additional contacts were considered necessary to ensure continuous contact between the wheels and the pole.

POLECAT-I utilized aggressive diamond pattern knurling on the steel wheel treads, hard chrome-plated to minimize wear. The prototype used neodymium magnets, which are the strongest commercially available magnets known. Each wheel consisted of two steel discs with a magnetic disc of smaller diameter sandwiched between them. As is conventional industrial practice, each magnet is magnetized axially, producing a north pole on one of the steel wheel discs and a south pole on the other. Considered to be good design practice, this approach has also been adopted for the wheels of POLECAT-II, with the key objective of increasing the number of contact points. Figure 1 depicts the POLECAT-II prototype resting on a pole scale model in the laboratory. The larger crank at the bottom of the photograph was subsquently replaced by a steer motor in the final prototype of POLECAT-II.

As seen in Figure 1, the number of contact points is significantly increased by increasing the drive wheels from four (2 each on the left and the right sides, respectively) in POLECAT-I to six (3 each on the left and the right sides, respectively) in POLECAT-II. Also significant is the fact that all six wheels are powered by independent motors. The two caster wheels in the front and in the rear are deployed as in POLECAT-I. Each "wheel" in both prototypes is a combination of two discs. Therefore, the number of contact points is double the number of wheels in both prototypes. Further, the six independently powered wheels in POLECAT-II provide greater stability when one pair of wheels is climbing an obstacle such as a lap joint.

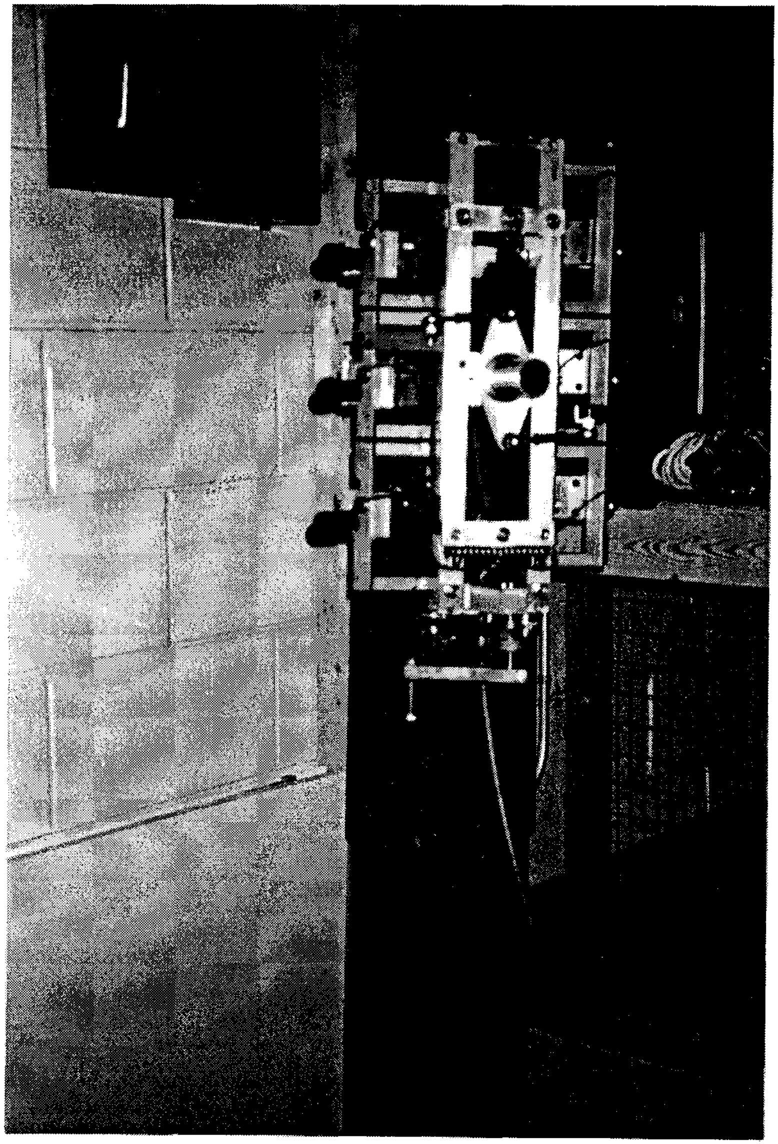
The researchers reduced the weight of the POLECAT-II motors by replacing the heavy (and more expensive) stepper motors with DC servo motors driving through worm gears. Worm gears, with correct lead angles, prevent the wheels from turning when power is off, so no other braking is necessary in this design. The new motors provided similar torque and rotational speeds, at a fraction of the weight. The particular physical and electrical characteristics of these motors were determined to accommodate other planned mechanical modifications and improvements that will be made to the robot.

The rotation of all six drive wheels and the two caster wheels in POLECAT-II is accomplished by a single steer motor actuating two screws, one each on the left and the right sides. The rotation is through 90°. Thus, POLECAT-II is a two-position system—0° for the climb motion and 90° for the circumferential motion. The screw systems on both sides drive nuts, one each for each of the wheels.

An additional design consideration for POLECAT-II was the need to incorporate some flexible suspension for the wheels which would allow each wheel to remain flat on the surface in spite of irregularities. With rigidly mounted wheels, even small irregularities can cause one tread to lift off the surface, thus breaking the flux path of the magnetic field. In POLECAT-II, flexibility is provided by pivoted arms for each of the wheels.

The components and the subassemblies of the POLECAT-II were designed to be modular and easy to assemble. The robot's primary components are listed in Appendix 1. Engineering sketches, with appropriate dimensions for the manufacturing and/or purchasing of these parts (including a list of parts vendors), are retained in the project file and are not included here.

Figure 1. POLECAT-II Laboratory Test



The electrical parts, including the motors, are described in Appendix 1. The electronic modules used to drive the POLECAT-I robot's stepper drive motors cannot be used to operate the DC servo motors in the modified POLECAT-II. DC servo motor drive modules were selected for this purpose. It is essential that the user have control of the robot's speed and direction through a joystick or other similar device. Electronic modules needed to control any electromechanical devices required by the modified POLECAT-II design, such as electromagnets or solenoids, will be selected or designed as appropriate.

The wiring cable harnesses used to provide power to and receive video from the POLE-CAT-I robot were replaced with cabling appropriate for the modified POLECAT-II. An effort was made to reduce their weight by using the minimum wire gauges electrically acceptable for this application. This improvement reduced the drag force on the POLECAT-II while climbing and allowed the harnesses to be more easily transported.

The POLECAT-IIM retains the same parts of POLECAT-II with some part dimensions modified to increase clearances, as indicated earlier.

The POLECAT-II design is presently being captured in a full 3-dimensional mathematical model. This model will allow computer-based quantitative analysis of the POLECAT-II's kinematics and dynamics, in support of additional detailed investigation and refinements of the design. The laboratory and the field tests on POLECAT-IIM will continue in the next reporting period.

Several sites were used to test and demonstrate the robotics systems (Infometrics TestPro and Polecat II) for NDE of highway structures:

- High-mast light poles on I-81 in Roanoke, VA. The improved POLECAT-II robotics system was used for visual examination of the female tube section of the slip joints. POLECAT-II also collected ultrasonic data on corrosion damage during several field tests in Roanoke area. Figure 2 shows the crawler working its way up a tall galvanized pole as it conducts an inspection.

- Bridge on US-17 over the York River near Yorktown, VA. The TestPro system was used for external remote visual inspection of the steel pivot box girders and B- and C-scan ultrasonic inspection of the top flange of the north steel box girder. Cold cracks have been detected in the welds and base metal of the box girders during an ongoing VTRC project. A three-month NDE inspection period for the north box girder was proposed using comprehensive NDE methods and instrumentation. To calibrate the system for ultrasonic inspection of flat surfaces, a 75 mm thick plate was used. Twelve flat bottom holes with diameters ranging from 2-10 mm and depths from 1-20 mm were used. Figure 3 depicts the system's calibration in the laboratory. The calibration results—B scan, C scan and 3-D images—are shown in Figure 4. The Infometrics crawler scanning the top flange of the pivot box girder is shown in Figure 5.

Figure 2. Robotic Inspection of Galvanized Steel Pole in Roanoke, VA

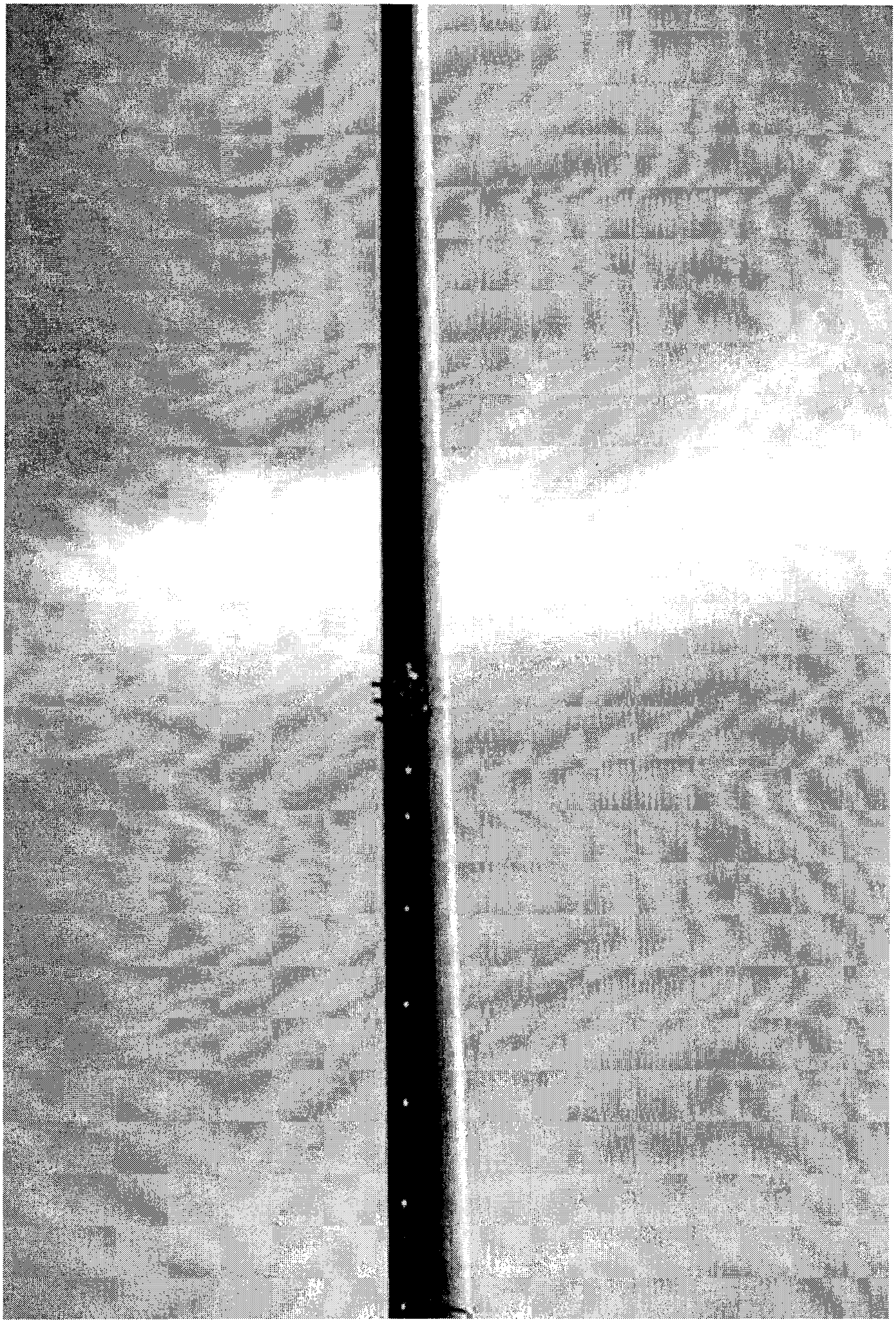


Figure 3. Robotics Calibration Procedure

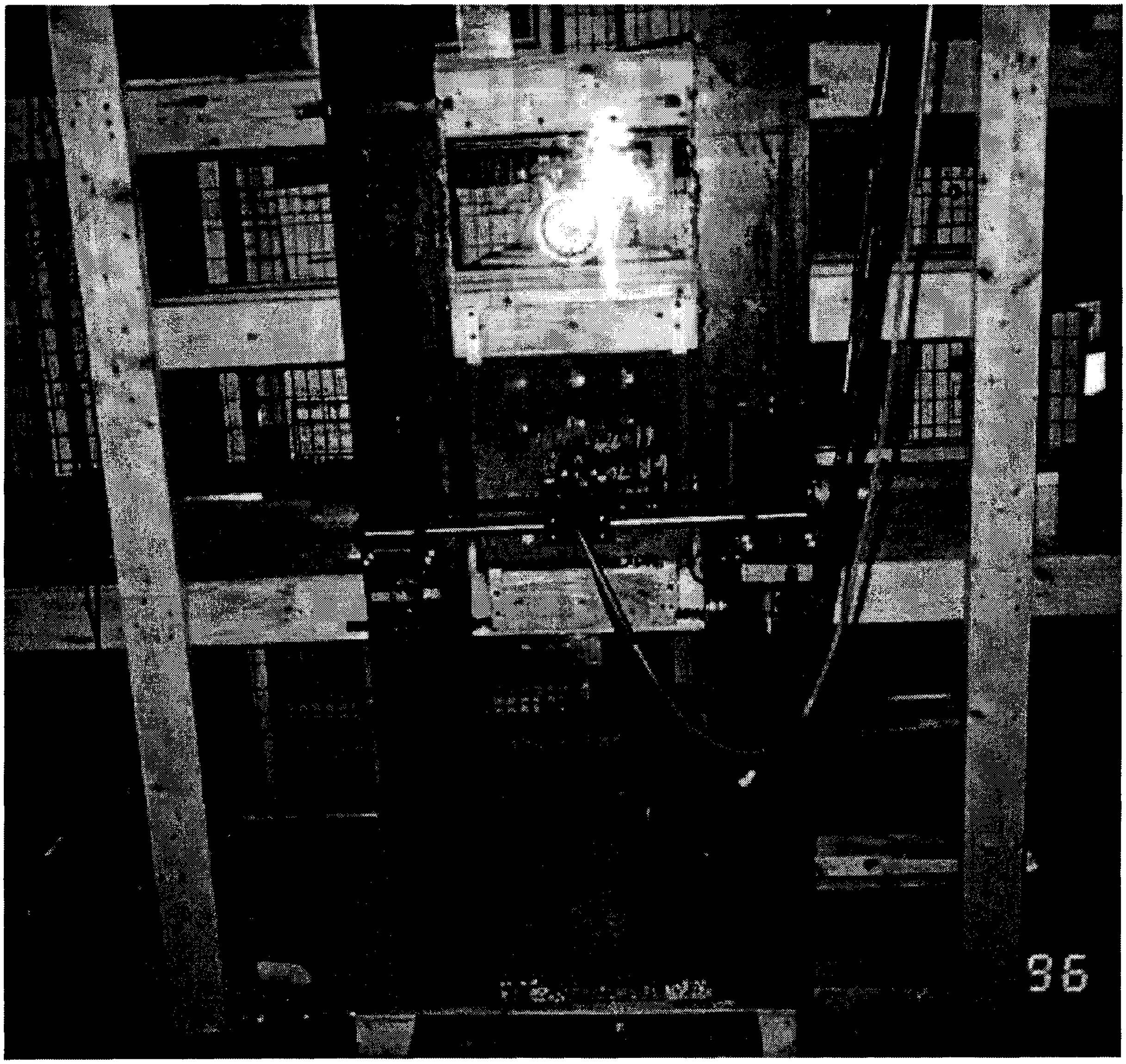


Figure 4. B-Scan, C-scan and 3-D calibration results

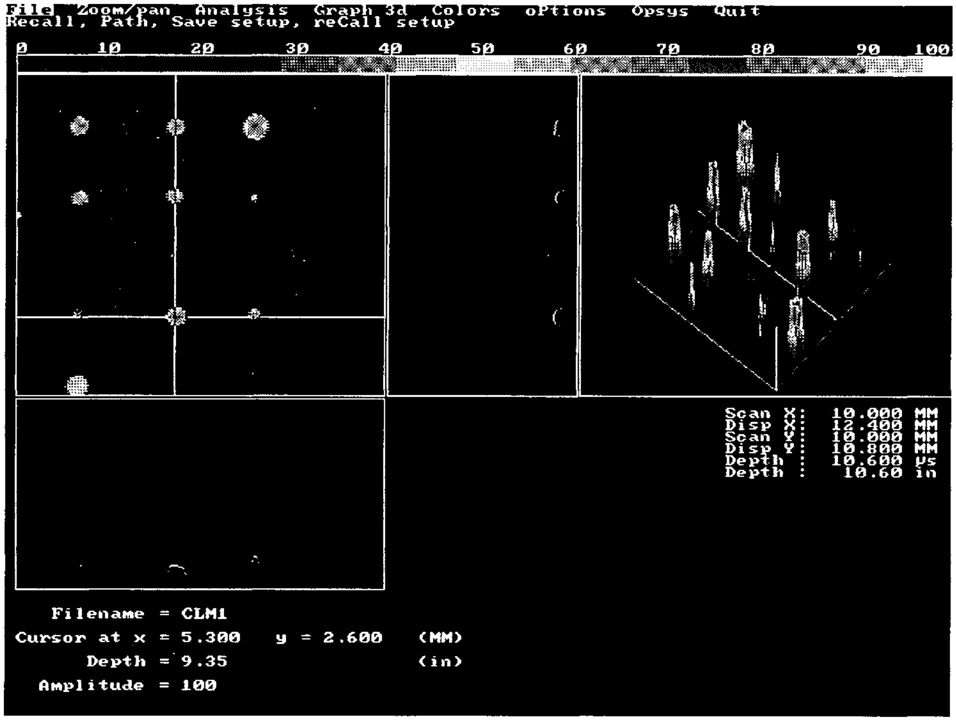
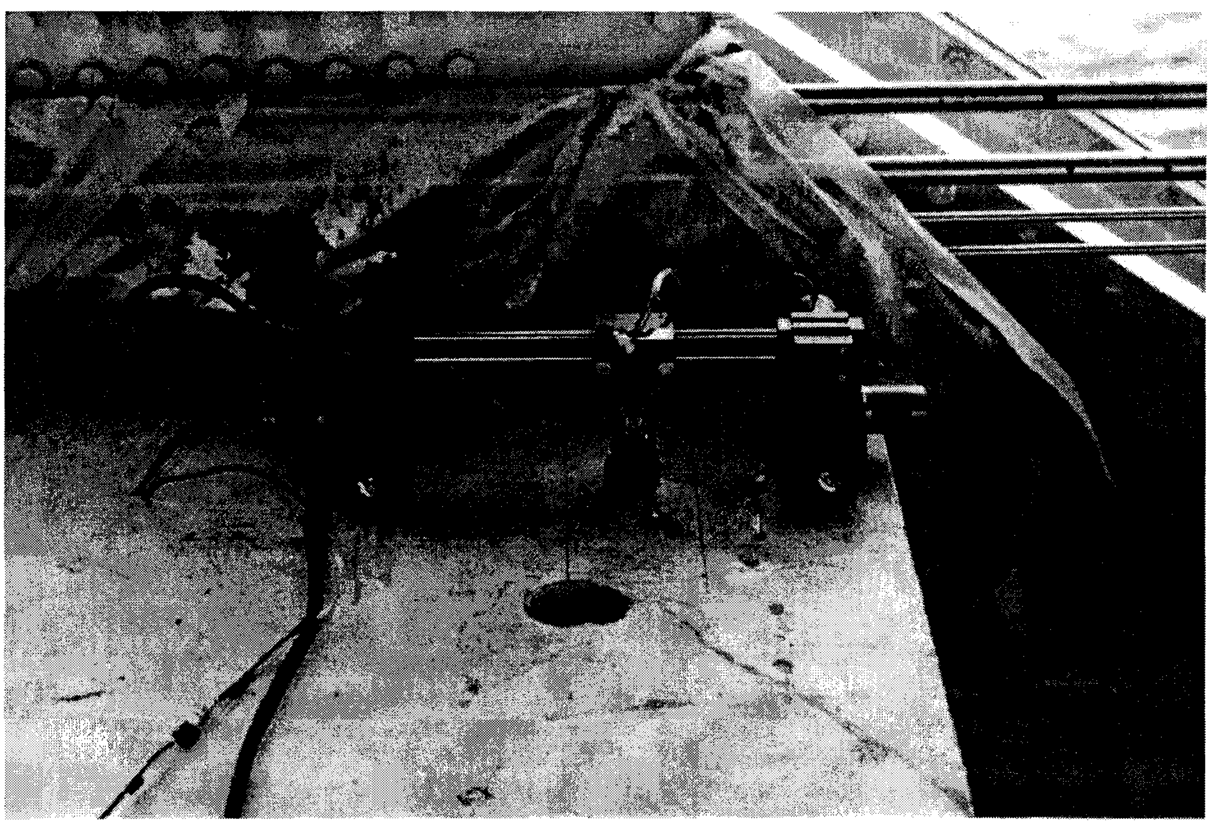


Figure 5. Ultrasonic robotics inspection of top flange of pivot box girder



- With very small modifications, the TestPro system was used for ultrasonic test of one pin in the Memorial Bridge, Radford, VA. Figure 6 depicts this inspection. A robotic arm attached to the crawler (Figure 7) was used during the ultrasonic robotics inspection of a pin in Structure 1042, Rte. 460, Tazwell, VA. Figure 7 also illustrates how the crawler can perform even in very tightly cramped areas. The results from these and other ultrasonic robotic inspections of steel bridge pins will be discussed in a separate VTRC report.

Figure 6. Robotic ultrasonic inspection of pin in Memorial bridge, Radford, VA

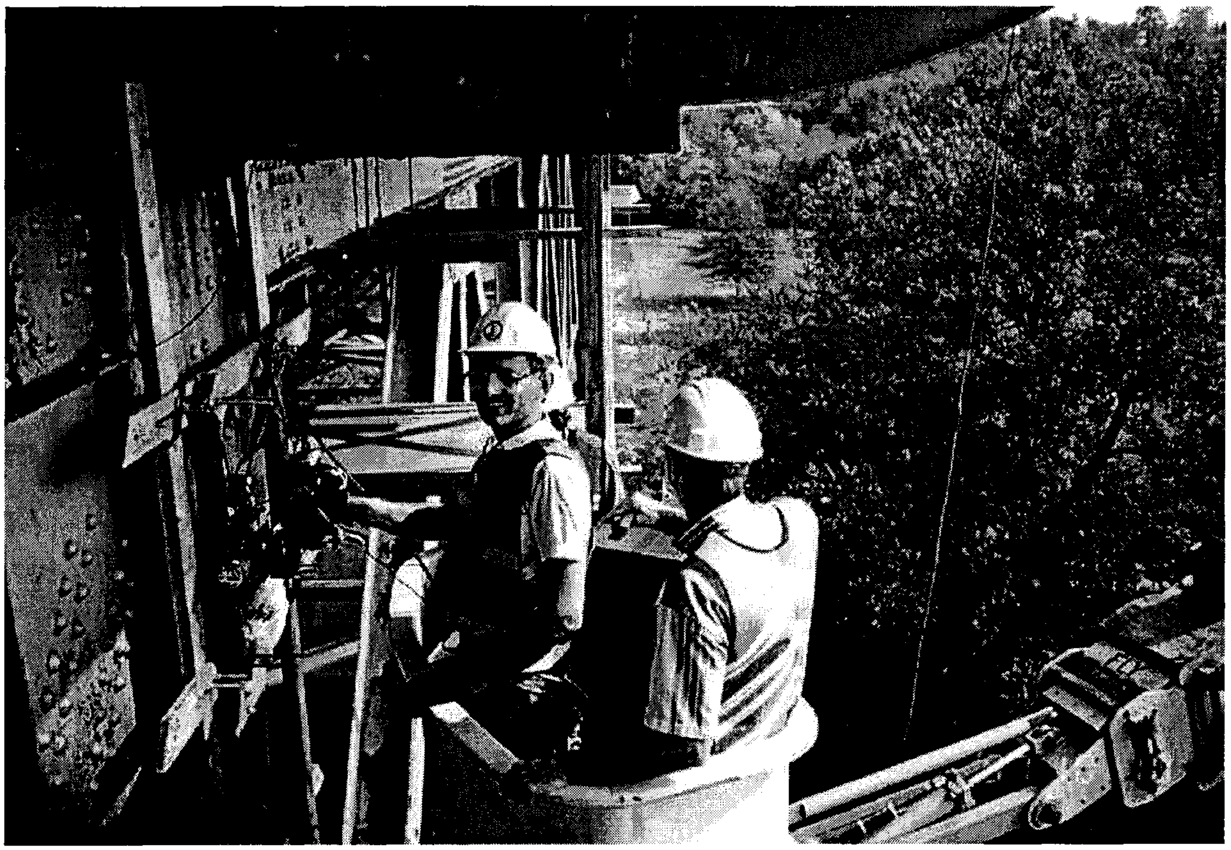
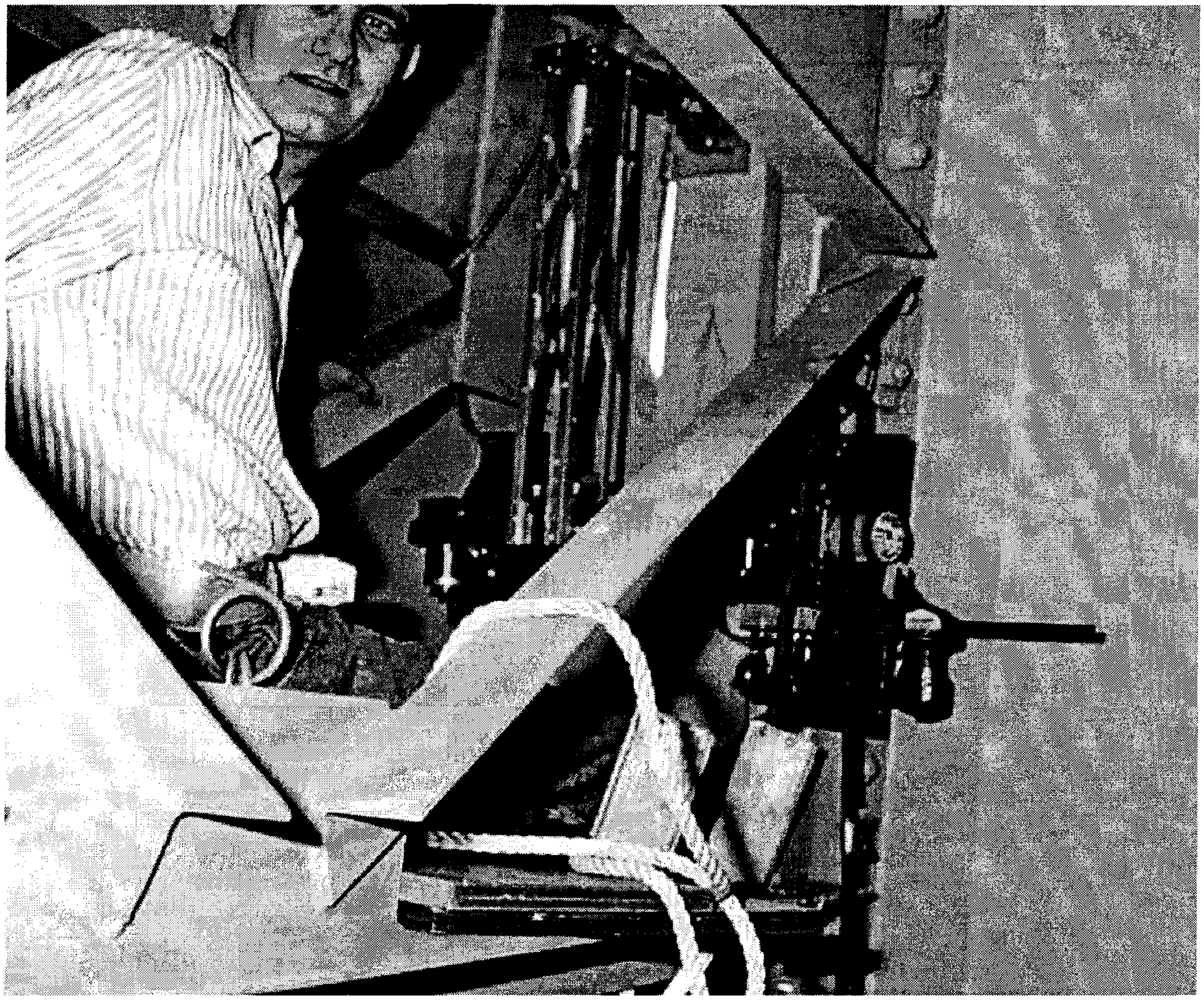
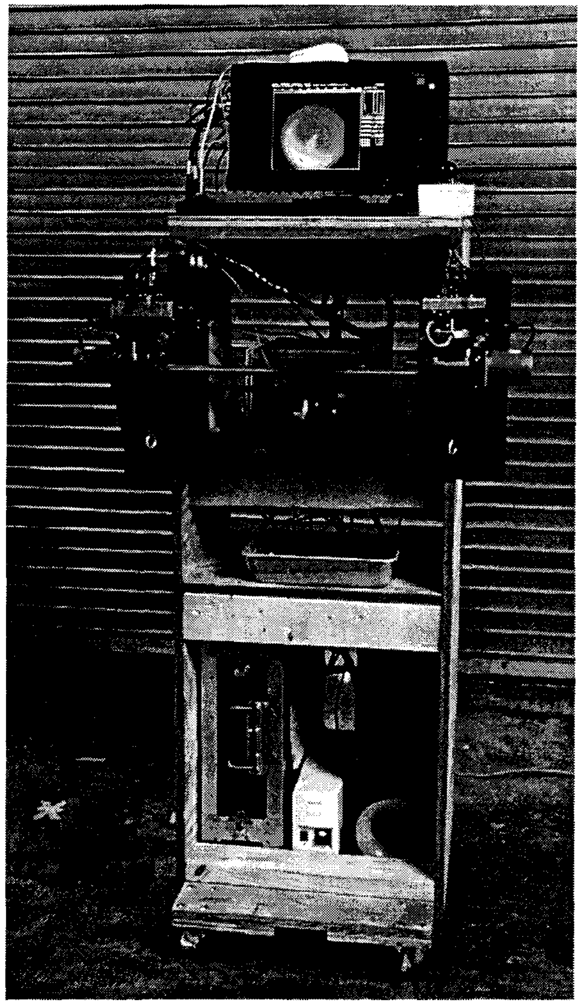


Figure 7. Robotics arm attached to crawler for ultrasonic pin inspection in Tazwell



- Two, one-day ultrasonic robotics pin inspection and demonstrations with a VDOT audience were conducted—one with the Materials Division and one with VDOT bridge engineers and bridge inspectors. The demonstration rack with robotics system, steel plates and the calibration pin is shown in Figure 8. Another demonstration with an FHWA personnel and audience was also conducted recently.

Figure 8. Robotics demonstration rack for ultrasonic pin inspection



CONCLUSIONS

The first year of this 3.5 year project has produced a new design, called POLECAT-IIM. This design will be further tested, refined, and utilized to guide the evolution of a more dexterous device during the remaining 2.5 years of the project, The remaining tasks during the next reporting period (December, 1997 - November, 1998) will include:

- POLECAT-IIM testing and refinements
- Completion of POLECAT-IIM computer model
- Experimentation with higher speed motors to improve inspection throughput
- Evolution of design concept for increased articulation and flexibility for a ROBOSNAKE, perhaps termed POLECAT-III

ACKNOWLEDGMENTS

Thanks are due to P.A. Fuchs and G. A. Washer of FHWA, and G. R. Allen and M. M. Sprinkel of VTRC for carefully reviewing the work and suggesting improvements. C. Apucen, R. Combs and E. Deasy provided assistance with graphics and photographs. M. Edwards edited this report.

REFERENCES

1. Lozev, M.G., McLaurin, C.A., Inigo, R.M., and Butts, M.L. 1997. Developing and testing a prototype crawling robotics system for the remote visual inspection of high-mast light poles in Virginia. FHWA/VTRC 98-R2. Charlottesville: Virginia Transportation Research Council.

APPENDIX 1

POLECAT-IIM Parts List, Electrical Specifications and Inspection Modes

Parts list for POLECAT-IIM (1)

PART NUMBER	NAME	MATERIAL	QUANTITY	NOTES
1	END PLATE	AL ALLOY	2	
2	ACME SCREWS	STEEL	2	1 RIGHT HAND 1 LEFT HAND
3	WASHERS FOR SCREWS	AL ALLOY	4	3/8" ID 3/4" OD
4	STEEL SLEEVE	STEEL	4	PRESS TO SHAFT
5	TUBE	AL ALLOY	1	
6	SPACER RING	AL ALLOY	1	
7	TRANSFER DISC	AL ALLOY	1	
8	FRAME TUBES	AL ALLOY	2	
9-A	TUBE CLAMP 1	AL ALLOY	1	
9-B	TUBE CLAMP 2	AL ALLOY	1	
10	STABILIZER FORK	AL ALLOY	2	CONSISTS OF 4 PARTS
11	STABILIZER WHEEL MOUNT	AL ALLOY	2	
12	STABILIZING WHEELS	CRS	4	
13	STUB SHAFT	STEEL	2	
14	ACME NUTS	BRASS	8	
15	COLLAR FOR CONNECTOR	STEEL	8	
16	ACME NUT CONNECTOR	STEEL	8	
17	COTTER PIN	STEEL	8	
18	WHEEL PLATE GEAR SIDE	AL ALLOY	6	
19	DRIVE WHEELS	CRS	6	

Parts list for POLECAT-IIM (2)

PART NUMBER	NAME	MATERIAL	QUANTITY	NOTES
20	WORM UPPER BRACKET	AL ALLOY	6	
21	WORM LOWER BRACKET	AL ALLOY	6	
22	WHEEL PLATE TILLER SIDE	AL ALLOY	6	
23	SPACER WASHER	AL ALLOY	6	
24	MOTOR MOUNT	AL ALLOY	6	
25	WHEEL PLATE GUSSET	AL ALLOY	6	
26	TILLER	CRS	8	
27	WORM & SHAFT	STEEL	6	
28	WHEEL & SHORT SHAFT	CRS	6	
29	TRANSFER ARM	AL ALLOY	2	
30	SWING ARMS	AL ALLOY	12	
31	RETAINING RING	AL ALLOY	1	
32	SCREW SPACERS	AL ALLOY	8	
33	DOUBLE PULLEY	STEEL	1	
34	WHEEL ASSEMBLY PIVOT	AL ALLOY	8	
35	WHEEL YOKE	AL ALLOY	6	
36	WORM GEAR	STEEL	6	
37	SHAFT FOR WORM GEAR	DRILL ROD	6	

Electrical Specifications for POLECAT-II

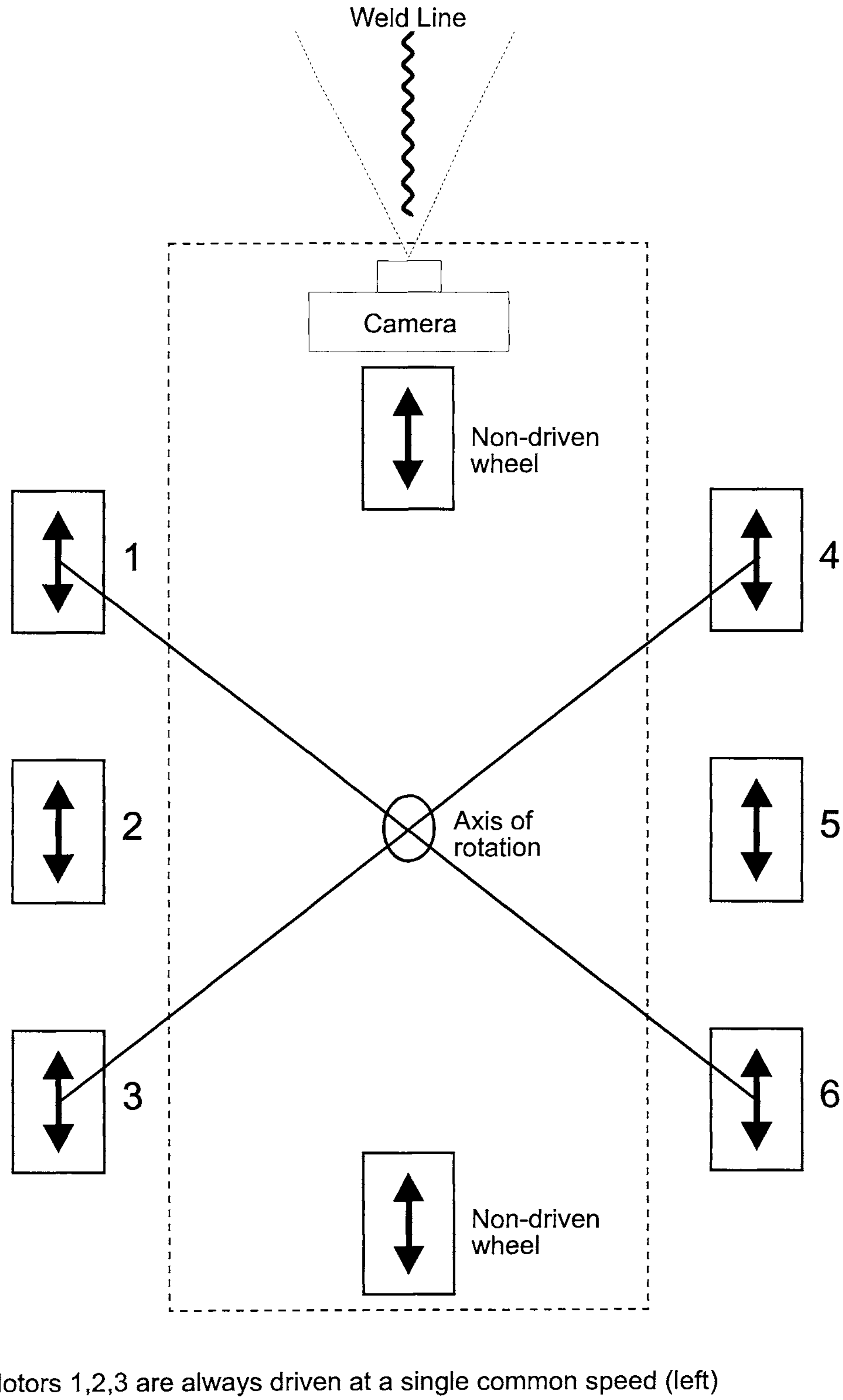
Features of Polecat II Electrical System

* Supports both vertical and circumferential pole inspection modes with simple push button interface
* Electronic logic automatically reconfigures control Push button positions for each inspection mode
* Six direct current permanent magnet motors each provide a minimum of 10 inch-pounds of torque at wheel axles while weighing only 135g
* High resolution CCD camera and optics can simultaneously be used for both pole inspection and vehicle navigation

POLECAT-II Inspection Modes

Figures 9-11 illustrate the inspection modes of the POLECAT-II system

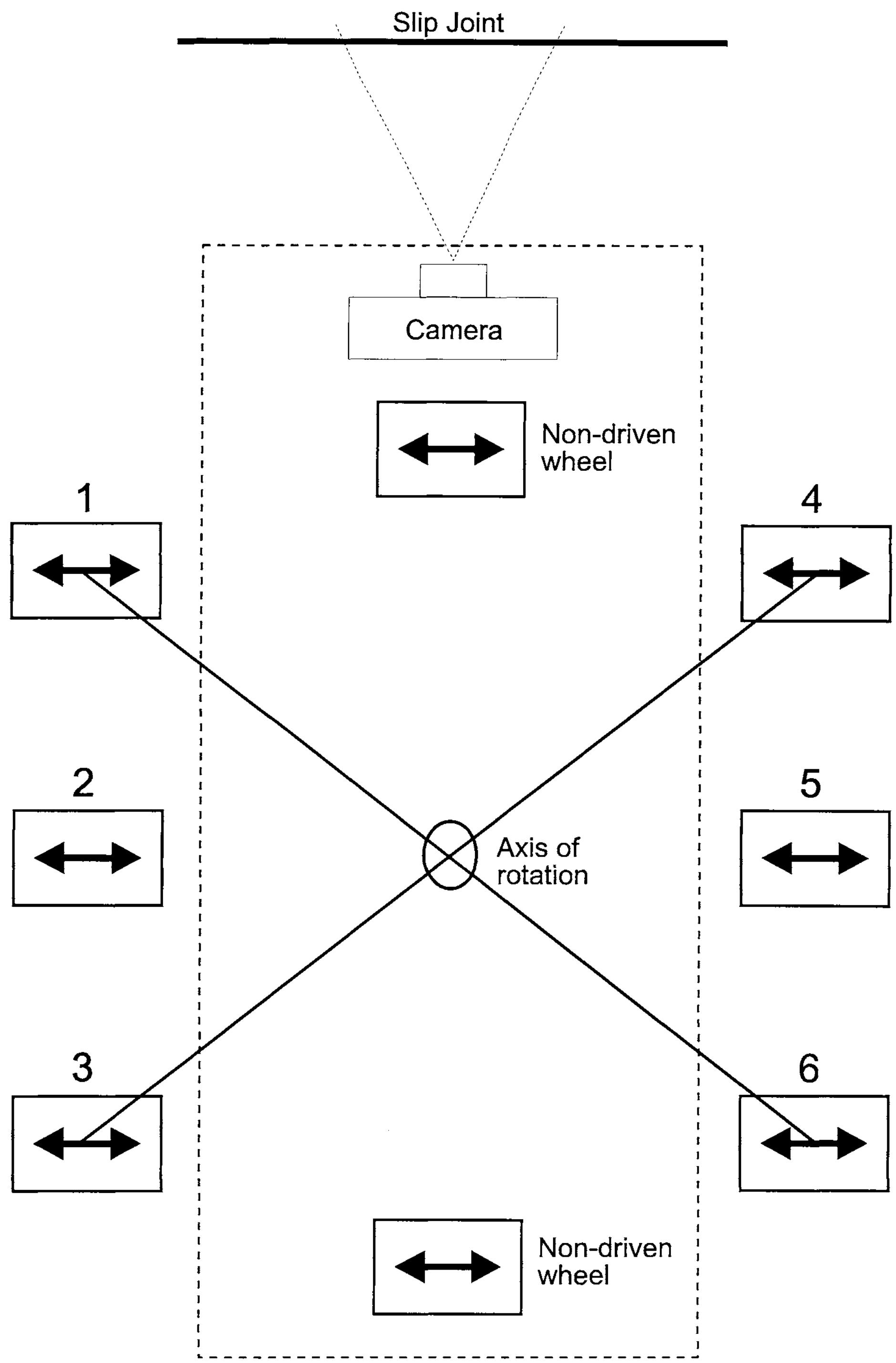
Figure 9. POLECAT-II Vertical Pole Inspection



Notes:

1) Motors 1,2,3 are always driven at a single common speed (left)
2) Motors 4,5,6 are always driven at a single common speed (right)
3) Verticle cross hair on camera lens is used to longitudinally navigate pole using weld line as reference

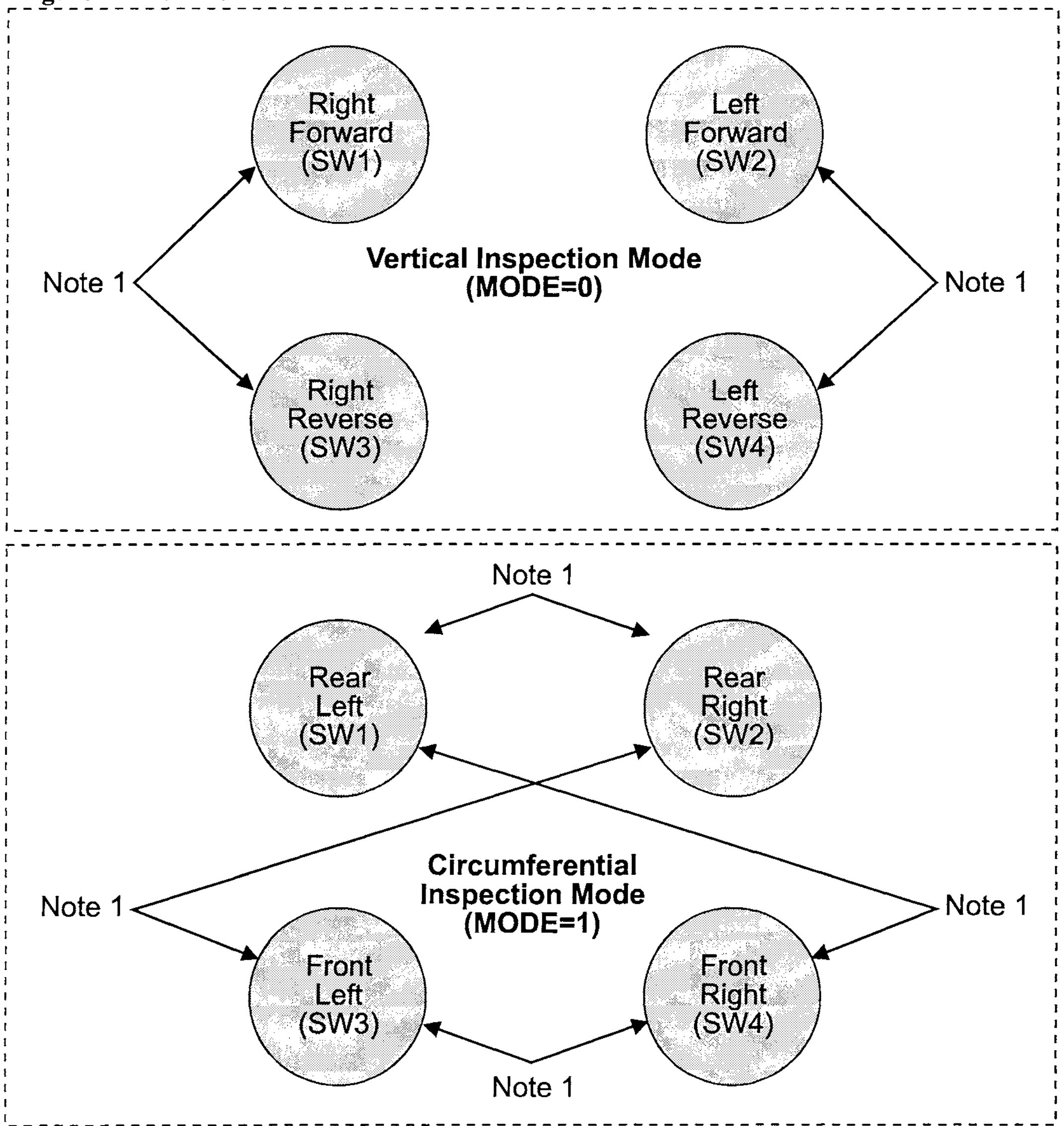
Figure 10. Circumferential Pole Inspection



Notes:

1) Motors 2,3,6 are always driven at a single common speed (rear)
2) Motors 1,4,5 are always driven at a single common speed (front)
3) Horizontal cross hair on camera lens is used to circumnavigate pole using slip joint as reference

Figure 11. POLECAT-II Push Button Control



Notes:

1) Robot does not move when these positions are depressed simultaneously
2) Robot does not move when any three switches are depressed simultaneously