Robotic Platform for Monitoring Underground Cable Systems

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Abstract-- **Accurate, real-time information about the aging status of the power distribution cable network can save the power industry millions of dollars lost due to line failures and premature replacement of cables. Hence, a novel, semi-autonomous robotic sensor platform has been developed for monitoring underground, power distribution cable systems. A segmented, legged modular configuration allows the robot to traverse cables with a diameter of four to eight centimeters and negotiate obstacles along its path. The design of platform consists of a multi-processor control board, a 900 MHz wireless communication module, and infrared, dielectrometry, and acoustic sensors. The robot is capable of fully autonomous operation or human tele-operation via a LAN or Internet connection. A prototype platform has been developed and tested with a 14kV distribution cable. Currently, sensor integration is underway.**

Index Terms—**Dielectrometry, distribution power system, mobile sensing, power cables, real-time monitoring, sensor array.**

I. INTRODUCTION

The nationwide power distribution network contains millions of miles of cable, all in various states of aging. Currently, cables are replaced either reactively (when a fault occurs) or periodically. Reactive replacement often results in loss of service, leading to lost customer revenue, whereas periodic replacement is costly because lines that could have several more years of reliable operation are replaced prematurely. A case study showed that up to 2/3 of the cable system that is scheduled for replacement could be kept in service with predictive diagnostics [1]. Real-time knowledge of the aging status of these cables can save the power industry millions of dollars in lost revenue.

Traditionally, cable monitoring is performed with the aid of a fixed distributed sensor network or by a highly specialized technician. These monitoring methods have inherent problems, e.g., high cost and low accuracy. Recent advances in sensing, signal processing, control, communications, optimization theory, and robotics indicate that mobile monitoring is a viable alternative. Remote monitoring of underground power cable systems can also minimize the occupational hazards presented to human technicians.

Several mobile monitoring applications have previously been demonstrated. In 1989, two manipulator systems were developed by Tokyo Electric Power Co. to traverse and monitor fiber-optic overhead ground transmission wires (OPGW) above 66kV power transmission lines [2]. It was shown that the systems were fully capable of performing distribution line construction work a using stereoscopic TV camera system. Several other tele-operated robots have been developed for live-line maintenance in Japan [3], Canada [4], and Spain [5]. An autonomous mobile robot was developed in Japan to inspect the power transmission lines in 1991 [6]. The robot could maneuver around obstructions created by subsidiary equipment and negotiate transmission towers using an arc-shaped arm that acts as a guide rail. A similar concept of inspection robot was also developed in Japan to inspect electric railway power feeder cables [7]. Feeder cables are extremely long and have many irregular points and obstructions. A multi-car structure with joint connections and biological control architecture was adopted; thus allowing the robot to traverse the cable with sufficient speed and negotiate obstacles.

While previous applications have demonstrated mobile monitoring of overhead power cable networks, none have addressed underground power cable monitoring. Hence, a novel, semi-autonomous robotic platform equipped with infrared, dielectrometry, and acoustic sensors, has been developed.

II. ROBOT PLATFORM

Specific challenges associated with this application include space confinement, size and weight restrictions, wireless communication requirements, and adverse environmental conditions.

A. System Overview

A unique segmented configuration allows the robot to traverse cables with a diameter of four to eight centimeters and negotiate obstacles along its path. The design of platform consists of a custom multi-processor control board, a 900 MHz wireless communication module and multiple sensor arrays. Fig. 1 and Fig. 2 show the conceptual design and a picture of the mobile platform.

This work is supported by NSF CAREER Award #0093716. It is also partly supported by the Electrical Energy Industrial Consortium and Advanced Power Technologies (APT) Center at the University of Washington. The APT Center is supported by ALSTOM ESCA, CESI, LG Industrial Systems and Mitsubishi Electric Corp. The research of undergraduate students is sponsored by Mary Gates Foundation, Washington Space Grant, and NSF REU program.

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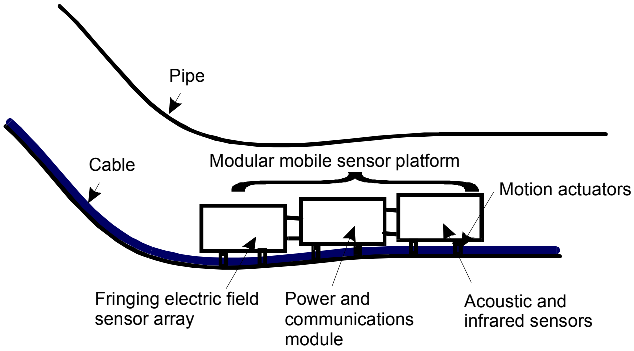


Fig. 1. Conceptual design of miniature robotic platform.

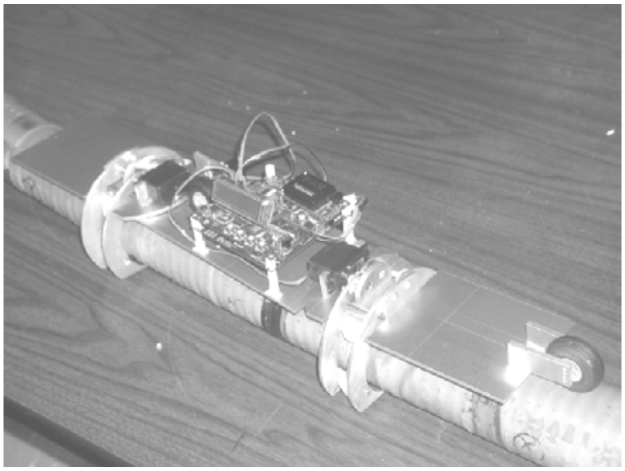


Fig. 2. Robotic platform for monitoring of power cables.

The robotic platform consists of three segments coupled by two freely rotating joints. Each end segment has a pair of servo-controlled legs that can actively hug or release the cable, thus allowing the robot to negotiate line branches and similar obstacles. The middle segment contains a servo-powered drive wheel on a simple suspension system, control electronics, and batteries. The end segments each contain a sensor array. Additional segments may be added as functionality evolves.

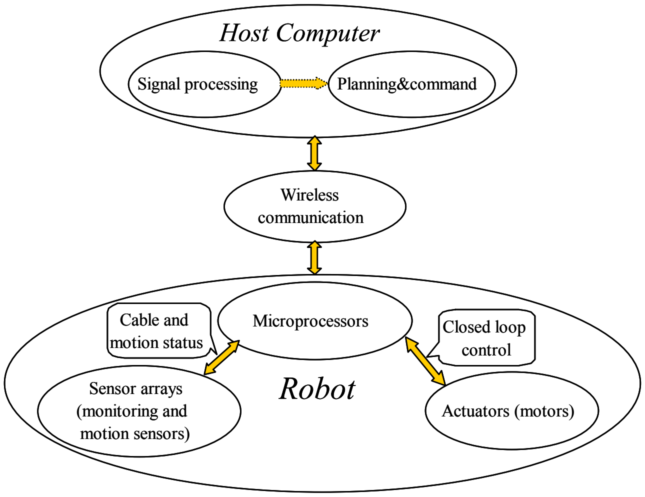


Fig. 3. Information flow of the robotic platform.

The system control architecture is divided into two parts: remote host computer control and on-board robot control.

The host computer communicates with the robot via a radio transmitter module connected to the host computer serial port. The radio communication module is comprised of two AVR AT90s8535 micro-controllers (MCU) operating at 8 MHz. Data is transmitted through a LINX TR-916-SC radio module, with a central frequency of 900 MHz and 33.6 bps baud rate. The robot control board consists of multiple MCU's, which allows for parallel data processing and convenient sensor integration. The primary MCU is an ATmega103 operating at 6 MHz. It controls four AT90S8535's through a serial data bus (SPI) in a master/slave arrangement. Fig. 4 shows the schematic representation of the control board. The master MCU is responsible for data routing between the slave MCU's and supplies a PWM control signal to the main drive motor and leg actuators. A shaft encoder is used for closed-loop motion control and extracting platform location information.

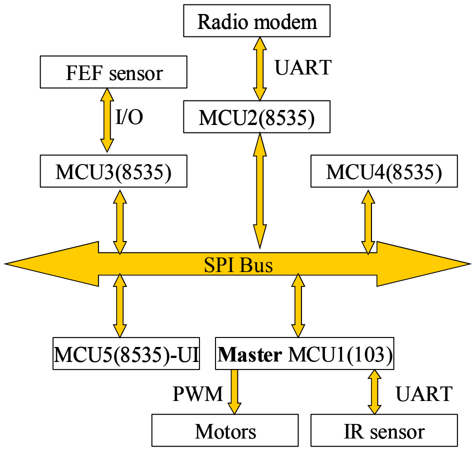


Fig. 4. Control circuit board on the robot.

Ancillary functions include IR based obstacle avoidance and bumper switch collision detection.

B. *Internet remote control*

A complementary PC application was developed in parallel with the platform to control the robot and analyze gathered data. The software was designed with a modular architecture, so that as the project grows, the user can simply replace functional modules rather than integrate new code into a monolithic program. The resulting architecture consists of a suite of modules that interact through software sockets as shown in Fig. 5.

Each module communicates with the main control program via bi-directional asynchronous software socket connections. The main control program issues high-level commands and routes data between the functional modules. For instance, the main control module can issue high level commands to the communication module, which in turn relays the signal to the robot. The data processing and data visualization modules have yet to be implemented.

The current system allows a technician to control a remote, distributed network of power line inspection robots through a LAN or dial-up connection. This goal was realized with a distributed client/server model, detailed in Fig. 6.

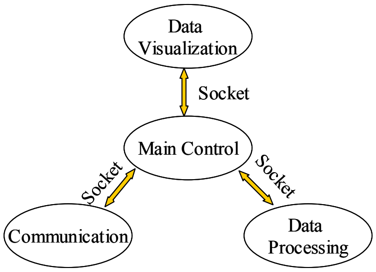


Fig. 5. Modular software architecture for robot control.

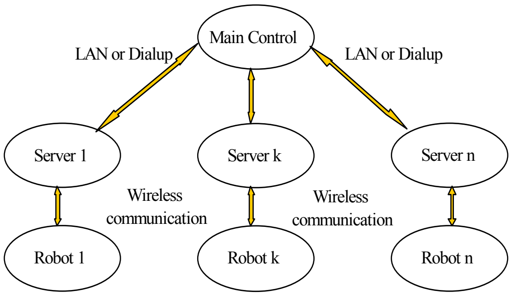
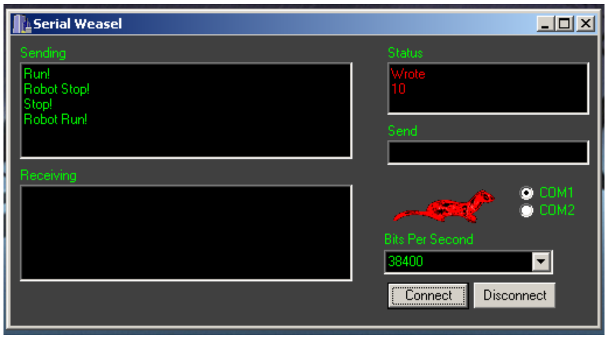


Fig. 6. Client/server model for distributed line crawling robot team.

Multiple instances of remote robot control can be established by creating bi-directional asynchronous socket connections from the central computer to each server, using standard TCP/IP protocol. Every server is assigned a unique port number on the central computer. After connecting to a new server, the user has full remote control of the associated robot and can operate it in one of two modes.

The first mode places the robot into fully autonomous operation, with all data processing done onboard. In this scenario, multiple robots can continuously patrol a network of power lines, reporting detected cable faults back to the central computer. In the second mode of operation the robot is fully controlled by the central computer and does no data processing onboard. Rather, it relays all data back to the central computer for analysis. This mode can be used by technicians to investigate reported errors in greater detail.

User interfaces for server applications and the central computer are seen below in Fig. 7 and Fig. 8 respectively.



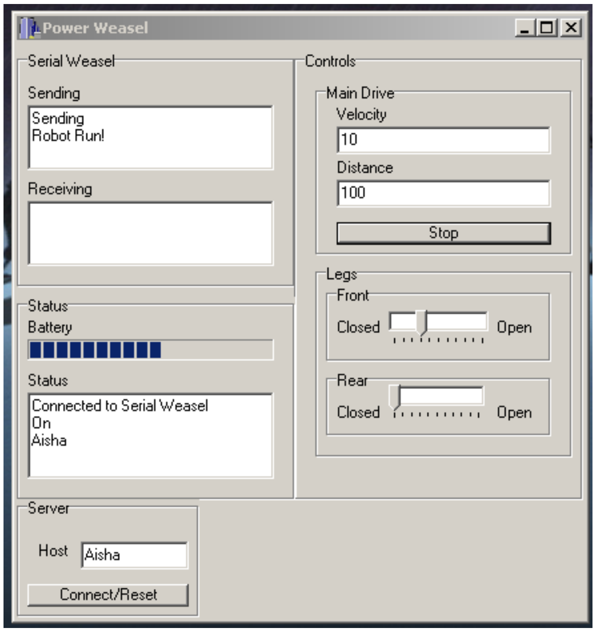
Sending:
Run!
Robot Stop!
Stop!
Robot Run!

Status:
Wrote
10

● COM1
○ COM2

Bits Per Second: 38400

Fig. 7. Server user interface.



Sending:
Sending
Robot Run!

Velocity: 10

Distance: 100

Status:
Connected to Serial Weasel
On
Aisha

Host: Aisha

Fig. 8. Central computer user interface.

III. SENSOR ARRAY

The main sensing principles appropriate for nondestructive, power cable monitoring include acoustics, dielectrometry, thermal imaging, eddy currents, and visual inspection. Of these, the following sensors were chosen for initial system integration: infrared, dielectrometry, and acoustic.

A. Infrared sensors

Thermal analysis plays an important role in the evaluation of insulation status. Polymers commonly used as electrical insulation are thermally sensitive due to the limited strength of the covalent bonds that make up their structures. The lifetime of electrical insulation is reduced when it is subjected to continuous overheating. One experiment showed that reducing the accelerating aging test temperature from 90°C to 75°C increased the cable life by a factor of two for thermoplastic polyethylene, and about 3.7 for crosslinked polyethylene [8]. Generally, overheating occurs due to overload, physical damage, insulation aging factors, or conditions of crossing regions. The hot spots often are accompanied by partial discharges [9]. In addition, unfavorable conditions of surrounding environment, such as street crossing, may make the conductor temperature rise up 20°C [10]. The platform measures cable temperature using a commercial non-contact IR sensor, the "Thermalert MID," produced by Raytek. This particular sensor was chosen for its combination of high accuracy and small size.

Preliminary IR sensing experiments have been encouraging. A mobile platform equipped with the Thermalert MID temperature sensor traveled along a 14 kV distribution cable that had an artificially produced "hot-spot." The platform was configured to travel at 15 cm/s and record 10 temperature data points per second, resulting in a spatial temperature resolution of 66 samples per meter. Temperature data was relayed to a host computer and plotted in Fig. 9.

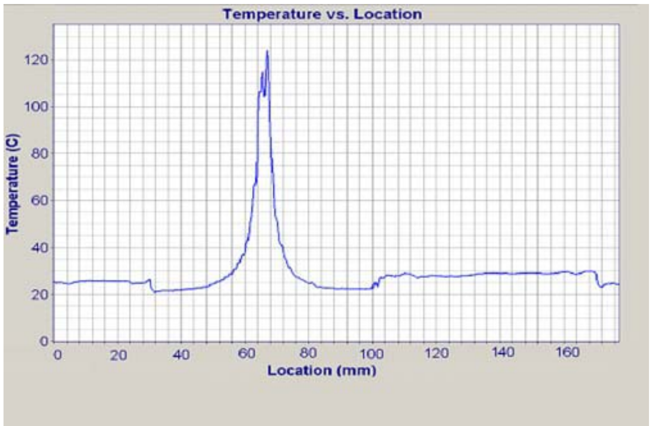


Fig. 9. Preliminary temperature sensing data.

B. Dielectrometry sensors

Fringing electric field dielectrometry sensors are used to gather information about the aging status of power distribution cables by measuring the dielectric properties of insulating materials.

In principle, the sensor applies a spatially periodic electrical potential over the surface of the material under test. The combination of signals produced by varying the spatial period of the electrodes, combined with the variation of electrical excitation frequency, provides significant information about the spatial profiles and dielectric spectroscopy of the material under test. Since changes in the dielectric properties are usually induced by changes in various physical, chemical, or structural properties of materials, the dielectrometry measurements provide effective means for indirect non-destructive evaluation of vital parameters in a variety of industrial and scientific applications.

Another important application of the interdigital sensor is the detection the water uptake, since water is best detectable by low frequency dielectrometry techniques for a highly polar material. The spatial moisture distribution has been measured successfully with a three-wavelength interdigital sensor [11].

C. Acoustic sensors

Acoustic sensing is used in this application to detect partial discharges in the power distribution cable. Acoustic sensing is preferable as it is non-destructive and immune to electrical interference, thus allowing it to operate on energized cables.

Partial discharge measurement is an important diagnostic tool, especially for medium and high voltage cables, where local intensity of electric stress can reach breakdown values. While acoustic sensing has been very successful for switchgear and transformers [12], cable applications have been more challenging because acoustic signals are attenuated during propagation, thus requiring close proximity for detection. However, once the sensor can be delivered to a reasonable proximity of the discharge location (about 20 meters), acoustic sensing becomes possible. In this application, high precision, broad bandwidth microphones will be used.

D. Signal processing

One of the most significant challenges in multi-sensor systems is processing large amounts of data, which requires considerable computational resources. This is problematic due to size constraints and harsh operating environment found in underground networks. The two options for data processing are local signal processing, in which all data is processed on-board, and remote signal processing, in which all data is relayed to the host computer for analysis. This system is designed to incorporate both methods.

IV. CONCLUSIONS

With recent advances in the miniaturization of sensor and signal processing hardware, a remote mobile inspection platform presents a viable alternative to conventional underground power distribution cable monitoring techniques.

A novel mobile robot equipped with infrared, dielectrometry and acoustic sensors, has been developed to patrol four to eight centimeter diameter power distribution cables, and gather real time information on the cables aging status. Remote inspection has been realized through a client/server software package that allows a technician to control multiple robots over a LAN.

Future efforts will include signal acquisition, data fusion and signal processing based on multi-sensors information.

V. ACKNOWLEDGMENTS

Special thanks to undergraduate students Dinh Bowman, Rejo Jose, Hans Isern, and Jeff Chen for designing, assembling and operating experimental setups. Research involvement of several undergraduate students has been supported by the Mary Gates Foundation and Electric Energy Industrial Consortium. The authors also appreciate technical assistance of the University of Washington Power Plant employees, especially Mark Kirschenbaum.

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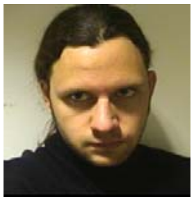
VII. BIOGRAPHIES

Bing Jiang received the B.S. degree from Tianjin University, China in 1995. He is now a graduate student at the Department of Electrical Engineering, University of Washington, USA. He is an author of eight journal and conference papers. His interests include robotics, power, and sensors. He is a student member of the IEEE.



Paul G. Stuart is currently a senior Electrical Engineering major at the University of Washington. His work experience includes a recent seven months internship at NASA JPL in Pasadena California, working on Safe Landing software for future Mars missions. He is currently working in the UW EE SEAL laboratory as a Mary Gates undergraduate researcher. His interests include robotics and machine vision.

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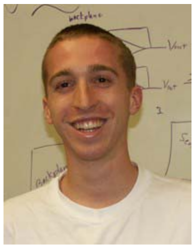

Daniel Villa is currently a senior in Electrical Engineering at the University of Washington. His work experience includes a six-month internship at NASA JSC. He is a member of the student team that won the national Lunar Robot competition in 2002. His interests include robotics and controls.

Alexander Mamishev received B.S. degree from the Kiev Polytechnic Institute in 1992, M.S. from Texas A&M University in 1994, and Ph.D. from MIT in 1999, all in electrical engineering. Currently he is an Assistant Professor and Director of SEAL (Sensors, Energy, and Automation Laboratory) in the Department of EE, University of Washington, Seattle, WA. Prof. Mamishev is an author of more than 40 technical publications. His research interests include sensor design and integration, dielectrometry, electrical insulation diagnostics, and power quality. He serves as a reviewer for the IEEE Transactions on Power Delivery and IEEE Transactions on Dielectrics and Electrical Insulation. He is a recent recipient of the NSF CAREER Award and the Outstanding IEEE Student Branch Counselor Award.