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# Power line robotic device for overhead line inspection and maintenance

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**Abstract**

**Purpose** – This paper aims to focus on the design and testing of a robotic device for power line inspection and cleaning. The focus for this design is on simplicity and compactness with a goal to create a device for linemen and other power line workers to keep in their toolbox.

**Design/methodology/approach** – The prototype uses V-grooved wheels to grip the line and can pass obstacles such as splices. It is equipped with a video camera to aid in line inspection and a scrub brush to clean debris from the line. The operator controls the device remotely from a laptop through a wireless connection. The novel way in which this device moves down the power line allows compactness while still being able to overcome in-line obstacles up to a certain size.

**Findings** – The device has been tested on a test bed in the lab. The device is able to move down a line and expand to overcome in-line obstacles as it travels. Testing proved the mechanical feasibility and revealed new requirements for a future prototype.

**Practical implications** – The device can be used for power line asset management by power companies; line inspection can lead to preventative repairs, leading to less downtime.

**Social implications** – It stands to reduce costs related to maintenance and mitigates down time and emergency repairs.

**Originality/value** – Innovative features include its size, mobility and control methods. Overall, the impact of this work extends to the utility maintenance sector and beyond.

**Keywords** Teleoperation, Overhead, Field robotics, Power line inspection

**Paper type** Research paper

## 1. Introduction

Small, semi-autonomous robots benefit distribution line maintenance and inspection processes. Using remotely operated robotic devices alleviates the complexities of line work by allowing technicians to inspect the lines and perform maintenance from a safe distance (Toussaint *et al.*, 2009). The need for easily installable devices for short time periods is demanding because of power line workers needing to use effective tools for the maintenance of the power line components, including splices and dampers (Aracil *et al.*, 2002). Within the field of power line inspection, different methods have been used to carry out the line inspection. Although there has been research into the efficacy of manned helicopters and unmanned aerial vehicles, focus here is on climbing robotic devices (Jaensch *et al.*, 1998; Dong *et al.*, 2012; Luque-Vega *et al.*, 2014). Climbing robots use the existing lines for support, traveling down the line while resting on it or clamped or otherwise connected to it. These types of devices provide superior resolution in their inspection methods because of their proximity to the line and more controlled motion. This also allows usage of a wider variety of sensors and other monitoring devices and a possibility for maintenance and repair actions executed by the robotic device itself. Through the inspection and maintenance of overhead power lines with robotic devices, power companies are able to manage their assets with greater efficiency and in ways impossible without the devices.

Work on such devices started over two decades ago, driven by safety factors, access to remote and difficult areas and increased operational efficiency. The robotic devices can be used to evaluate the line for defects such as corrosion, degradation or mechanical damage (Katrasnik *et al.*, 2010). Specific applications include checking compression splices for mechanical degradation by measuring resistance, detecting corrosion in the steel core of aluminum conductor steel-reinforced cable or using infrared imaging to detect possible defects in power line components (Montambault and Pouliot, 2003; Barbosa and Nallin, 2014). Video and still images collected by line robots of components not visible from the ground can be used to confirm defects detected by other methods. Collecting visual information to evaluate at a safe distance from live lines and archiving the data benefit inspection personnel (Toussaint *et al.*, 2009).

Robotic devices can also implement maintenance tasks while traversing the power lines. For instance, the devices can locate and remove debris such as salt accumulation, vegetation, ice and animal nests. Performing tasks on live overhead lines add complications to the design of inspection robotic devices. Dangerous high voltages and in-line obstacles present the largest challenges to overcome. Most research to date focuses on maneuverability, specifically around obstacles. Several climbing power line robots exist with different features

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and design mechanisms for overcoming obstacles (Aracil *et al.*, 2002; Katrasnik *et al.*, 2010; Allan, 2012; Lorimer and Boje, 2012; Montambault and Pouliot, 2003). Only a few complete systems have been deployed in the field for testing and use on live lines.

The LineScout Technology, developed by Hydro-Québec, stands out as a complete system deployed in the field for use by linemen. It is controlled by a semi-mobile ground station consisting of transceivers set on a tripod and a portable table with a robust, military-type field tablet PC (Montambault and Pouliot, 2006). It is semi-autonomous and designed for transmission line work. The LineScout weighs 100 kg and measures a length of 1.4 m and height of 0.75 m (Pouliot and Montambault, 2008). This device is a mature prototype tested in field conditions and is capable of overcoming a variety of obstacles in an efficient manner.

The Expliner, designed by HiBot in Japan, uses similar methods to the LineScout for traveling down transmission lines and overcoming obstacles (Debenest and Guarnieri, 2010). HiBot designed the robot specifically for bundled transmission lines in Japan (Debenest *et al.*, 2010). Although both the Expliner and LineScout are successful implementations of a transmission line robot, the devices' bulk and ground control system make the tools specialized devices. They are both too large and outside the range of our design requirements. In addition, they use a balancing mechanism to ensure the dynamical stability of robot on the cable that is crucial to accomplish the assigned task. It should be mentioned that this increases the overall weight of the robot that can be seen as a disadvantage when considering the portability factor.

Hydro-Québec created another device, the LineROVer, specifically as a de-icing tool for overhead ground wires and conductors. The device is more compact than the LineScout, weighing 23 kg (Montambault, 2010). Although the device's original purpose was as a de-icer, new uses and applications have been discovered such as payload elevator, safety net stringing and, by adding new sensors, corrosion detection and splice resistance measurement (Montambault and Pouliot, 2003). Similar in size to the LineROVer, the corrosion detection robot tested by Light SESA, a power distributor in Brazil, has proven useful in the field (Barbosa and Nallin, 2014). Both devices use similar mechanisms to travel down the line involving wheels resting on top of the line. Neither device is capable of crossing over towers or overcoming most obstacles (the LineROVer can overcome splices).

A trade-off in maneuverability for compactness and ease of use lets linemen, and maintenance workers use a similar robotic device in everyday maintenance and inspection. By reducing the size and weight and using non-specialized operating equipment, the power line robotic device can be simplified for daily use by all linemen.

We have created a lightweight, remotely operated overhead distribution line scrubber for power line inspection and cleaning. Design objectives focus on robot mobility with the ability to cross obstacles found on a typical distribution line while using the conductor as support for traveling. Other important design requirements include safety, easy placement and removal from the line, wireless control, visual access to the top of the distribution line, variable speed brush control, easy operation and low cost. We have designed the robot described in this paper specifically as a *compact, low-cost tool* for linemen to keep with them. The main purpose of the robot is maintenance and inspection. The benefits of this robot design are safety, low cost and simplicity in a teleoperated, multi-objective device. Maintenance tasks, including inspection and repairs, are identified as high-value applications in transmission and distribution live-line work (Toussaint *et al.*, 2009).

The simplicity of this robot design makes it accessible to power line maintainers to keep in their toolbox. It will not require specialized operators and can be easily incorporated into maintenance programs. Figure 1 shows illustrations of our first prototype.

Overall, the impact of this work extends to the utility maintenance sector and beyond. The device stands to reduce costs related to maintenance, increase safety for linemen and mitigate down time and emergency repairs. Reliable power with lower maintenance costs can positively affect entire communities. Electrical injuries consist of four main types: electrocution (fatal), electric shock, burns, and falls caused as a result of contact with electrical energy (Electrical Safety – NIOSH Workplace Safety And Health Topic, 2016). According to Worker Deaths by Electrocution, a summary of NIOSH findings, the occupation of linemen had the highest number of fatal injuries out of the top ten job classifications with the most of fatalities (Worker Deaths by Electrocution: A Summary of NIOSH Surveillance and Investigative Findings, 1998). A broader impact of this work is a reduction in these statistics.

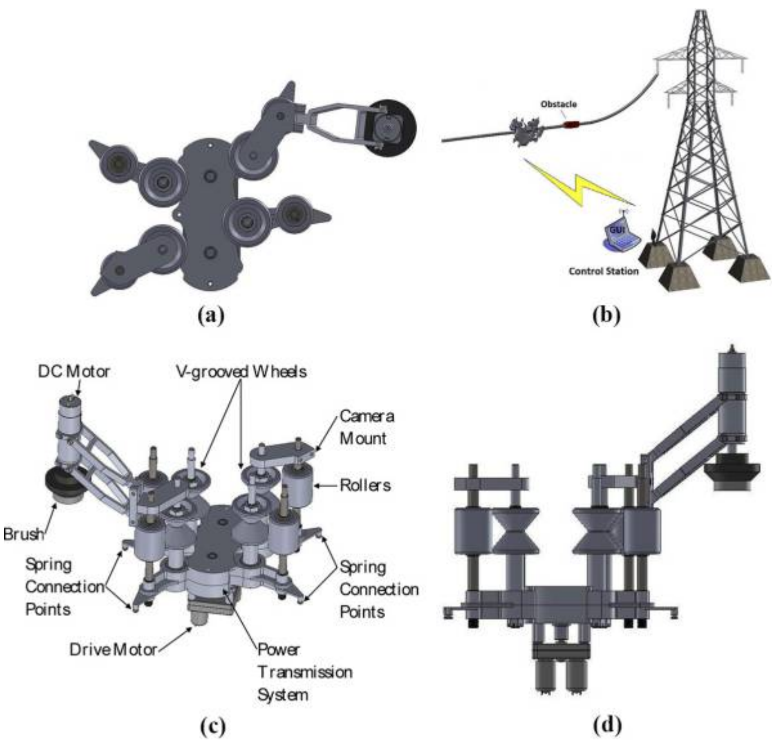
This paper describes the design process for the first prototype of the robot and some of the experimental results. Section II discusses the design objectives. Sections III and IV describe the mechanical and electronic specifications of the robot. Then, in Section V, we discuss the robot testing and associated results. The final section contains our future design plans.

## 2. Design goals

The primary goal is to design and prototype a small-scale robotic device capable of inspecting the power line conditions and also cleaning the cable. Design aspects important to this project include *simplicity, safety, robustness and compactness*. Aside from safety, the most important aspect is simplicity and the ease of use. We intend for this robot to be usable without special training or a specialized skill set outside of skills a typical lineman possesses. This specific robot is not going to substitute the large high-tech robots that already help power industries in maintaining the power lines that are hard to access such as lines passing over lakes, mountains and other difficult-to-access regions. Instead, this device should be easy to use on a daily basis. We are aiming at adding a user-friendly tool to power line workers toolbox that is suitable for short-term usage on the cable. This translates to an easily installable and controllable robot with capability of adding different features ito avoid the hazards arising from direct contact of workers with the power lines.

Other required design features include a vision system for power line inspection, a scrub brush for cleaning the line, wireless control for remote operation, auto-stop safety features

**Figure 1** The wheeled robot for cleaning power lines



**Notes:** (a) Top view (in an open position); (b) placement of the system on the power line; (c) full view; (d) side view

and the ability to maneuver around certain obstacles. The battery life must be acceptable for extended periods of use, and the batteries should be field swappable and rechargeable.

Over time, power lines experience corrosion and mechanical degradation from environmental factors (Aggarwal *et al.*, 2000). A vision system for the robot allows the operator to locate areas of deterioration. The operator needs to be able to record both video and still images to document and assess the condition of the line.

The maintenance aspect of the robot includes a scrub brush to clear debris from the power lines. In coastal regions, salt can build up on the lines and lead to corrosion. Additionally, dust, industrial smoke and polluting winds produce deposits on lines and insulators (Aggarwal *et al.*, 2000). The brush should help remove these types of debris.

Robot mobility and obstacle avoidance present the main design challenges for this robot. Several existing autonomous robots possess obstacle avoidance capabilities (Rowell and Boje, 2012; Toussaint *et al.*, 2009; Li and Yi, 2009). Full autonomy is not a design goal here, and our focus is on overcoming splices up to 60 mm in diameter.

## 3. Mechanical design specifications

Our first priority is to come up with a design that can handle all the mechanical and dynamical complexities on the cable, which also leads to a device easy enough to install and use for workers and technicians. To meet the defined objectives with the first prototype, we have designed a V-grooved wheeled mechanism that can move along the cable by a rotatory power provided by two compact DC gearmotors. To overcome the most challenging concern of passing obstacles, two springs are chosen with suitable stiffness to generate enough force that keeps the wheels in contact with the cable and obstacle while passing it.

The design of the device allows the power line technician to install the robot on the distribution line. The robot attaches around the distribution line with the bulk of the hardware hanging below the line. Spindles and wheels clamp around the line with springs, providing the tension needed to tightly hold on to the line. The springs allow the wheels to expand around obstacles encountered on the line. One brush rests on the power line and rotates, scrubbing the line to remove dirt and debris. The hardware includes two motors to control the forward and backward motion of the robot and one motor to control the scrub brush, a video camera and two ultrasonic proximity sensors. Additionally, there exists a control box housing the microprocessors and motor drivers, batteries, wires and wireless antenna. The robot is 43 cm long, 24 cm wide and 33 cm tall. It weighs 9.5 kg without the control system and batteries and 13.7 kg with the control box and batteries.

### 3.1 Material

The chosen material should fulfill requirements of the design such as lightness and appropriate grip to prevent the wheels from slipping, which can lead to the waste of a limited amount of power provided by the batteries. It is worth mentioning that grooving rubber into the wheel surface can enhance the grip.

### 3.2 Motors

Although high-speed movement on the cable is not necessary, the robot might need a high torque to pass the potential obstacles. Therefore, according to the design specifications such as the speed and estimated size of the obstacles, we created a dynamical simulation model of the robot on the cable using Working Model software (Working Model 2D - 2D Kinematics & Dynamics Software - Engineering Simulation, 2013). After considering details such as the maximum robot weight and maximum speed (0.4 m/s), the simulation results showed the maximum required torque to be 2.82 N·m. Other factors should be taken into account, for example, the size and weight of the motors should be as low as possible to maintain a desired weight and a small profile.

To achieve the predefined specifications, two compact DC gearmotors are chosen with less than 7.46 W of power. Each gearmotor consists of a motor and a geared speed reducer to lessen speed while increasing torque. The motors are brush style with an internal permanent magnet. All of these face-mount gearmotors are rated for continuous duty and have sleeve bearings, iron and acetal gears, terminal lugs for electrical connection and four 10-32 threaded mounting studs. They also have a flat side on the shaft to accept set screws for easy equipment connection. The motors operate at 12 V DC and have a full load current rating of 1.4 A. The maximum provided torque by each motor is 2.83 N·m. This is high enough to pass obstacles on the cable by taking the estimated friction of the brush and the effect of the sag into account. The friction coefficient of the brush has been taken into account as studied in Vanegas-Useche *et al.* (2011). Also, the effect of the sag has been considered as the resistance force associated with 25° sag. Gravity is considered in the opposite direction of the robot when it is moving upward on the cable. The gearmotors can be used in either clockwise or counterclockwise rotation that is necessary to move forward and backward. Figure 2 shows the designed motor.

### 3.3 Power transmission system

The power transmission system should be compatible with the design requirements. Because of the low rotational speed and high torque provided by the motor, the roller chain mechanism is a perfect choice for the current design. Driven by the size and weight limitations, the chosen roller chain mechanism is compatible with the design requirements. The whole power transmission system can fit into a small (10.6 × 16.5 cm$^2$) case and weighs less than 0.4 kg. Figure 3 shows the system with the chain rollers highlighted. A shaft extends from each of the four outside rollers and turns the V-grooved wheels. The system is reliable and easy to repair, and the low energy loss is indispensable because of the limited power supplies in the present design. In fact, any friction between the chain rollers and sprocket teeth is virtually eliminated because the rollers rotate on the outside of the bushes, independent of bearing pin articulation inside the bush. As a result, very little energy is wasted and tests have shown the chain to have a high efficiency between 98.4 and 98.9 per cent (Pedersen, 2004).

### 3.4 Wheels

Because of the geometry of the power line cables, proper design of the moving parts of the robot is essential to guarantee the stability of the robot on the cable and at the same time provide enough grip to keep moving even on the slippery surfaces. After considering different designs, we chose the V-grooved design, illustrated in Figure 4(a). This specific shape has some advantages over others; first, its machining is easier than similar designs such as U-grooved wheels, which will decrease the final cost of design. Second, the shape of the groove gives us the demanded statistical and dynamical stability on the cable. In fact, the horizontal forces on two sides of the cable cancel out each other, and the robot weight provides the required normal force to have enough friction on the cable.

The rollers in front of the wheels, as seen in Figure 4(a), provide a low-friction method for expanding the wheels to move around an obstacle. They help the springs open up and provide enough space to pass the obstacles. The maximum size of the obstacles that this robot can pass is shown in Figure 5. The spring connects two arms which have shafts to the rollers and wheels on either side of the cable. The configuration, illustrated in Figure 4(b), provides a higher force associated with the expansion of the springs compared to the case where springs are attached to the shafts at the wheels for the same opening angle. The higher force keeps the wheels

**Figure 2** The motors driving the robot

**Figure 3** The roller chain mechanism

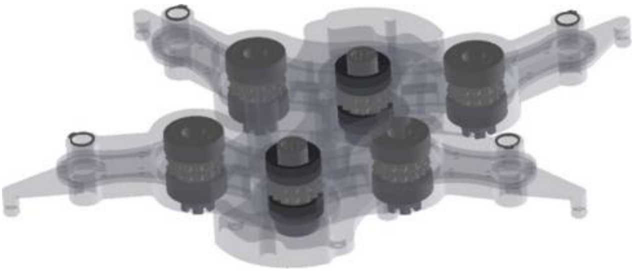
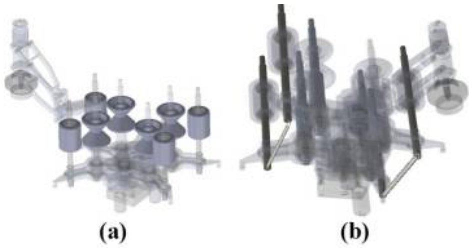


**Figure 4** The wheel and roller system



**Notes:** (a) The V-grooved wheels and rollers; (b) a bottom view showing the springs and shafts to the rollers

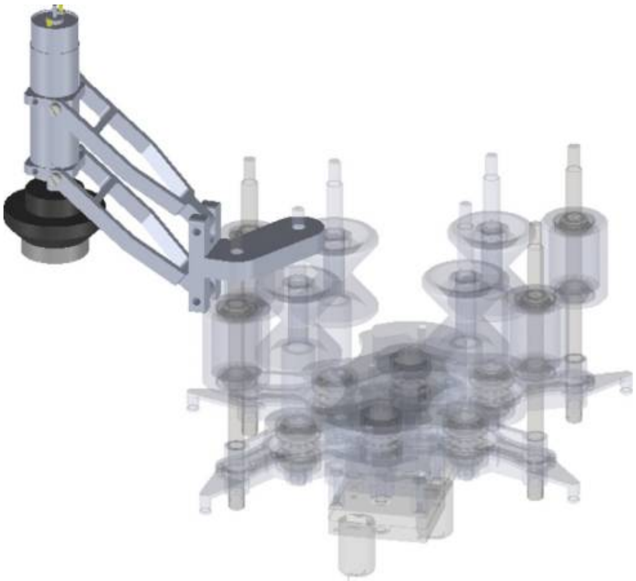
**Figure 5** The maximum diameter of an object the robot can pass is 55.88 mm

in contact with the cable while passing the obstacles and provides enough friction to move steadily along the cable.

### 3.5 Brush

As described earlier, the robot will mainly be used to inspect the cable and clean the parts that are not easily accessible, such as splices, dampers, etc. This requires implementation of a brushing mechanism with the capability to clean up the upper side of the cable and any attached equipment. The designed vertical brush arm and joint mechanism can move up and down while passing differently sized obstacles and, also, the gearmotor provides a high rotational speed. Figure 6 shows the arm and joint mechanism and its configuration on the robot.

**Figure 6** The brush arm assembly



## 4. Electronic control specifications and elements

Our semi-autonomous device, as currently designed, uses a simple set of electronics to control the motors and to provide data collection and a wireless connection to the remote operator. The control system includes proximity sensors; motor battery voltage and current sense; and motor drivers. Ultrasonic sensors detect obstacles on the line, alerting the operator and stopping the robotic device if it gets too close to the obstacle. Batteries power the microprocessors, sensors and motors. Once the batteries drop below a certain threshold, the microprocessor sends a signal to the operator to alert the operator of the low battery status. The batteries can be changed out in the field to extend the use of the robot. The control system keeps the linemen safe and provides easy operation, but is not currently designed to be fully autonomous.

### 4.1 Motor drivers

A microcontroller platform, called Arduino, is utilized to control the motors that drive the robot and rotate the brush. The Arduino is an open-source physical computing platform based on a simple microcontroller board utilizing the ATmega328P microcontroller and a development environment for writing software for the board (Arduino – Introduction, 2014). The Arduino's low cost and expandability coupled with its simplicity makes it a good choice for prototyping.

When the operator inputs a command, the Arduino receives it and sends the appropriate signals to the motor driver card. The motor driver card, an off-the-shelf printed circuit board, features a pair of robust VNH5019 motor drivers capable of controlling bidirectional, high-power DC motors (Pololu Dual VNH5019 Motor Driver Shield User's Guide, 2014). The card controls the direction and speed of the motors and also monitors the motor current and features driver fault detection, aiding in safety controls.

By using pulse width modulation (PWM), the microcontroller controls the amount of voltage supplied to the motor. This allows variable speed settings. The operator can slow down the robot to capture a more detailed video. Additionally, a higher voltage can be supplied to the motors when the robot is overcoming an obstacle. The operator alters the voltage by entering a command in the interface. Potentially, the current drawn from the motors can be monitored and the voltage can be increased or decreased accordingly.

### 4.2 Main on-board computer

The Arduino uses serial communication to receive and transmit data from and to the main single-board computer controlling the robotic device. The single-board computer, a Raspberry Pi (RPi), is the main computing power responsible for the teleoperation connection to the operator, the video camera operations and communication with the Arduino. It acts as a wireless access point and a server, hosting the website through which the operator can control the robot. This high-level device can process and store data for later retrieval and has the capacity to add more peripherals.

#### *4.2.1 Vision system*

The website streams live video with the options of recording the video or taking a snapshot of the image. The videos and snapshots can be downloaded directly from the website at any time. The video camera connects directly to the RPi via a flexible flat cable and the RPi processes the video. The camera attaches to the robot and aims down at the top of the power line. The operator is able to adjust various settings for the camera remotely such as sharpness, brightness and contrast. An image captured by the camera is shown in Figure 7.

### 4.3 Ultrasonic proximity sensors

The Arduino also handles the data from two ultrasonic proximity sensors located on the front and back sides of the robot. The ultrasonic sensors detect objects in the path of the robot and provide data to calculate the distance to the object. The software alerts the operator of an object. If the operator does not respond, the microcontroller stops the motors once it detects that the object's distance is less than 25 cm.

The sensor works by transmitting a 40 kH ultrasonic burst and providing an output pulse that corresponds to the length of time it takes to receive an echo (Ultrasonic Distance Sensor, 2013). It measures distances ranging from 2 to 3 m. Considerations for using this type of sensor include interference, object material, object positioning and air temperature. Using ultrasonic waves eliminates interference from bright sunlight and any electromagnetic interference from the high voltage lines.

### 4.4 Power supply

Different batteries provide power to various components of the robot. Two identical batteries power the motors, one for the motion of the robot and one for the brush. They provide the voltage and current necessary for the motors to move the robot down the line and to drive the brush. The rechargeable batteries are rated at 18 V and weigh 0.9 kg. Additionally, they are standard power-tool batteries which can be swapped out and easily charged. They slide out of the case and plug into a charger. Linemen have the option of using a vehicle charger with the batteries. This allows battery charging in the field. The battery takes approximately 60 min to fully charge.

**Figure 7** An image taken from the camera as the device moves down the line on the test bed

A separate battery is used to power up the microprocessor and microcontroller system. The battery provides a steady supply of power appropriate for electronics. Rated at 10 A-h, the battery can provide power for the electronics for a full day. As currently configured, the electronic controls draw just under 1 A. The microcontroller used to control the motors typically draws 55 mA during operation, measured during testing. The single-board computer typically draws between 700 and 1,000 mA (FAQs – Raspberry Pi, 2014). These calculations include the power needed for the video camera and wireless antenna.

### 4.5 Teleoperation and operator control

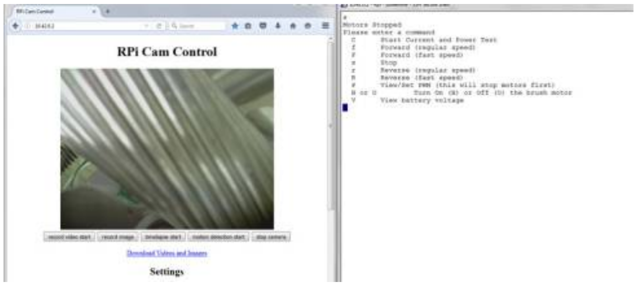
Once the robot is attached to the line, the operator controls the robot from the ground. The device's teleoperation system includes wireless communication between the operator and the robot using a wireless local area network. The operator is able to control the speed and direction of the robot, the speed of the scrub brush and the video transmission. As the robot crawls along the cable, it provides the operator with a view of the line by transmitting a live video feed. By using commercial, off-the-shelf hardware and well-established communication protocols, teleoperations with the robot are low-cost, reliable and robust.

The RPi acts as the main interface between the ground operator and the robotic device. Once the operator powers on the system, the operator can use a laptop, tablet or cell phone to connect to the device's wireless network. Once connected to the wireless network, the operator can use a Web browser to access the video camera and use a terminal to control the motors.

Currently, the operator controls the robot's movements by logging into the RPi via a terminal on a laptop. A screen shot of the control computer can be seen in Figure 8. The command line interface provides a menu with options to move the robot in a forward or reverse direction with two speed settings, stop the device, turn on or off the line brush, check the motor battery voltage, brush battery voltage or set the cruising speed of the device. If the device detects an object within a certain distance, an alert is sent to the operator along with the distance to the obstacle. If the device crosses a certain threshold distance from the obstacle, the microprocessor sends a command to stop the motors. To simplify the teleoperation user interface even more, these commands are being added to the video streaming website to group the control all in one place.

Designing the RPi as a wireless access point and providing a website as the graphical user interface reduce costs

**Figure 8** A screen shot of the control computer showing the web page with the live streaming video and the control terminal



```
#
Motors Stopped
Please enter a command
  C       Start Current and Power Test
  f       Forward (regular speed)
  F       Forward (fast speed)
  s       Stop
  r       Reverse (regular speed)
  R       Reverse (fast speed)
  #       View/Set PWM (this will stop motors first)
  B or b          Turn On (B) or Off (b) the brush motor
  V       View battery voltage
```

associated with auxiliary equipment and operator training. Connecting to a wireless network and loading a web page are common skills requiring minimal training. Another advantage to this set up is with the device used to connect to the robot, which is not limited to proprietary equipment. A common off-the-shelf laptop, tablet or smart phone can connect to the robot without specialized hardware or software.

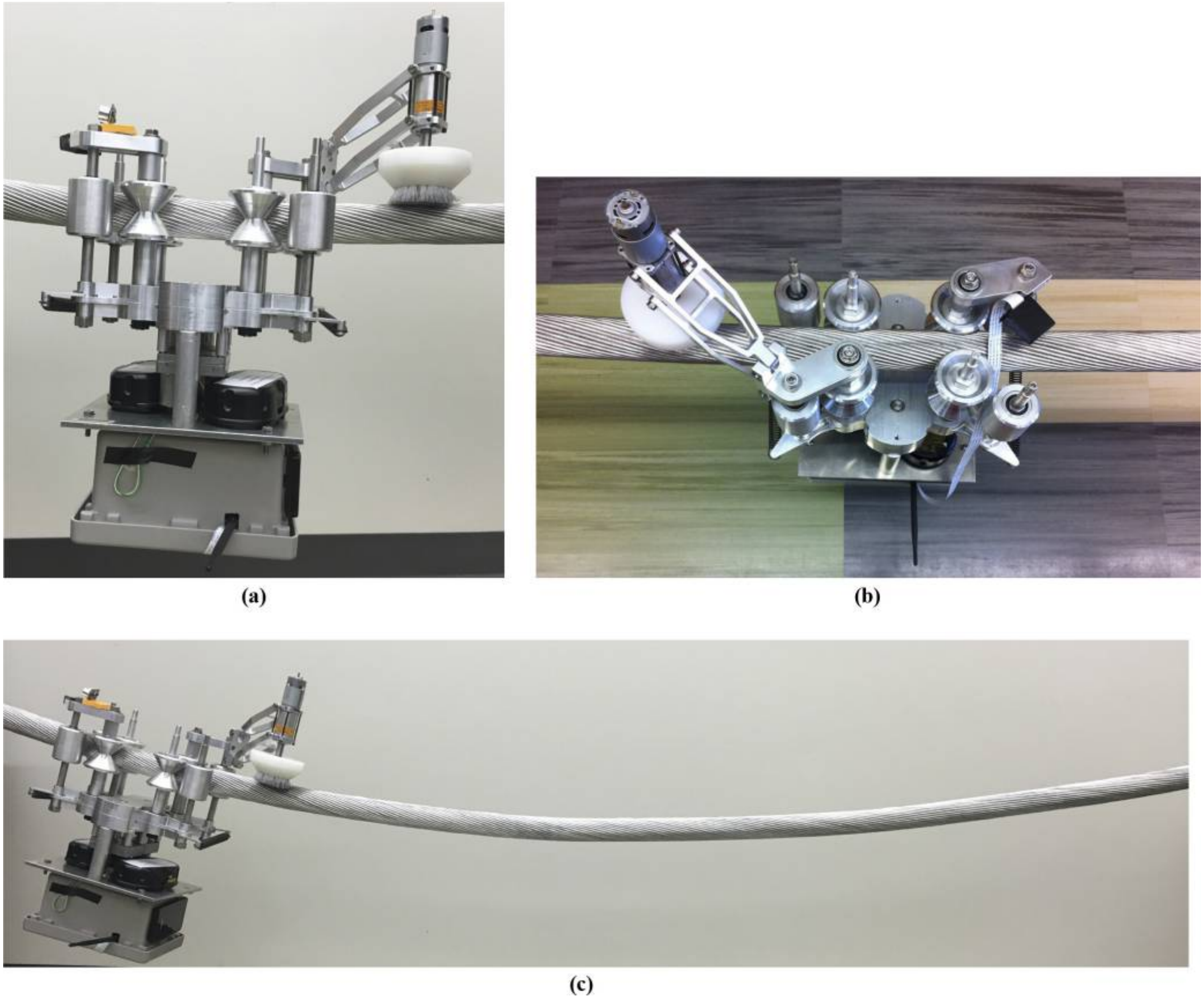
Using existing, standard network protocols from the application layer down to the physical layer assures a robust and reliable data connection (Winfield and Holland, 2000). The connection must be able to handle high data rates to stream video while also providing dependable connectivity to the motor control system. The wireless antenna has a throughput of up to 150 Mbps for both upstream and downstream data transmission when using the 802.11n wireless standard. The antenna is also capable of operating with the 802.11b/g standards, with maximum throughputs of 11 and 54 Mbps, respectively.

## 5. Testing and experimental results

We built a test bed to validate the efficacy of the robotic device in a laboratory setting. The device, shown in Figure 9, is connected to the cable in the test bed. A 4.5 m of cable suspended several feet off the ground acts as the test bed. The cable obtained is specifically used by the local power company. It is an all-aluminum conductor, stranded, with an outer diameter of 46.3 mm. The approximate weight of the cable is 3.53 kg/m, and the approximate rated strength is 19,000 kg. The actual length of the cable navigable by the robot is 3 m. By attaching the cable to two movable bases, the tension and sag in the cable are adjustable, which mimics the sag in actual power lines. All testing conducted thus far has been with varying sag of 10-30° from horizontal. The robot performed well with no slippage even at 30° sag.

Our testing proved the robot's mobility and its ability to overcome wide diameter splices. During testing, we designated different voltages for different operating modes. We set normal

**Figure 9** The robotic device attached to the cable (a), a top view of the robotic device attached to the cable (b) and the robot on the test bed cable (c)


(a)
(b)
(c)

cruise speed by supplying the motors with approximately 12 V. Although each battery is rated at 18 V, measured voltage at the terminals of the battery, when fully charged, ranged between 19.25 and 20.84 V. By using PWM, we set the operating voltage at 62.5 per cent of the full voltage of the battery to achieve a supply voltage of 12.8 V. At this voltage, the robot travels at the speed of 6 cm/s.

### 5.1 Power test

First, to test the power consumption, speed and mobility of the robot, we set the controller to record the current and motor battery voltage. We then performed tests at different speeds with the cable sag set to 15°, 25° and 30° from horizontal.

Figure 10 shows a plot of the power the robot consumes as it starts at one end of the cable, crawls to the other end and stops (forward direction) and a plot of the power as the robot travels in reverse, returning to its starting position (reverse direction), at the three different settings. The data show that the power increases as the robot travels along the cable. This increase in power is attributed to the extra work required to travel up the slope in the cable.

### 5.2 Wireless network range test

The device uses IEEE802.11b/g/n wireless communication to connect with the control operator on the ground. It acts as a server, allowing the operator to communicate with it using any wireless device and by providing the right credentials. Tests conducted outdoors showed a greater than expected range for communication, with motor control achieved at a distance of 193 m from the robotic device.

The test was conducted outdoors in a remote location, which reduced any interference from other 2.4 GHz 802.11 signals. One additional wireless network on the 2.4 GHz band was detected during testing; however, it was a very weak signal and on a separate channel with no overlap.

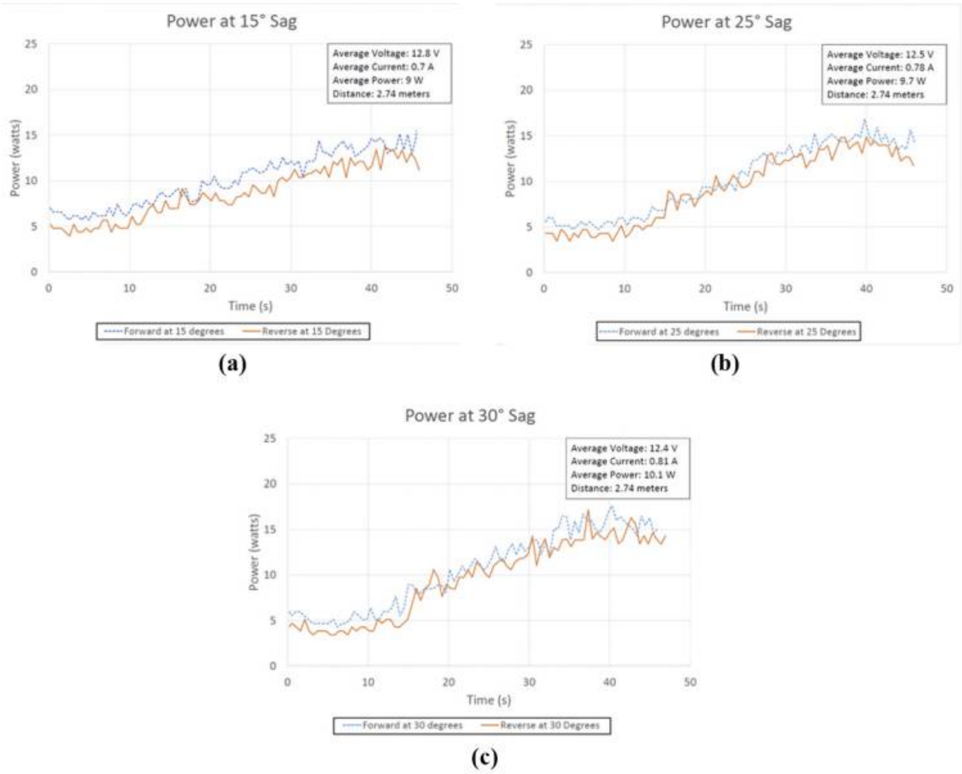
Two different devices were used to connect to the robot control system, an off-the-shelf laptop with an Intel Centrino® Advanced-N 6,205 wireless antenna and a smartphone/iPhone 4 with a Broadcom BCM4329 antenna. The devices were kept within a line of sight with the control box, with some vegetation in the surrounding area but not obstructing the line of sight. For initial range tests, the control box and connecting ground control devices were kept stationary. The weather was clear, with a temperature of 15.5° C.

Full control with streaming video was achieved on the laptop at a maximum distance of 110 m with a measured signal strength of −56 dBm. At this distance, the smartphone could connect to the wireless network and load the control web page but experienced packet loss when attempting to stream the video. At a distance of 193 m, both the laptop and smartphone could load the control website but not stream video.

## 6. Future work

Through designing, testing and operating the robot, we have determined several important changes and new features we plan to add to the robot in the future.

**Figure 10** Power measured as the device traversed the test bed in both the forward and reverse directions with the test bed cable set to (a) 15°, (b) 25° and (c) 30° sag



(a) (b) (c)

**Notes:** In these tests, a forward direction indicates the camera in the front and the brush in the back

The design challenges of obstacle avoidance and crossing jumper cables increase the complexity of a power line robot. Currently, an ultrasonic sensor has been installed in the front of the robot to detect objects, display the distance to the operator and, if necessary, autonomously bring the motors to a stop. In the event that the operator were to lose communication with the robot, this closed loop system would prevent the robot from colliding with obstacles on the cable. A future design goal includes using active control to change the force on the cable by the robot wheels to allow the passing of obstacles of different sizes and to control the speed as the robot approaches and overcomes the different sized obstacles. More autonomous travel is possible with slightly different mechanical features and additional sensors. Closed loop autonomy is possible to control the speed of the robot, which increases or decreases tension on the line and sensors to detect obstacles, and to determine if the obstacle is passable. If the robot determines that it cannot pass the obstacle, it should stop without the need for input from the operator.

Currently, the camera is fixed without the capabilities of pan, tilt and zoom. These features would greatly enhance the data collection capabilities of the robot. We plan on selecting and installing a pan, tilt and zoom camera in the future. An additional feature we would like to add to the vision system is a global positioning system chip, which would allow the operator to tag images and videos with the coordinates of where the image was captured. These features increase the value of the visual data collected and improve maintenance time.

Additional future work includes component shielding and weatherization, robust network security, sourcing lighter material with insulating properties and possibly installing extra sensors for inspection.

## 7. Conclusion

The robotic device developed and described in this paper proves the mechanical feasibility of the design. The V-grooved wheel design provides the grip needed to propel the robot along the cable. The roller and spring mechanisms allow the wheels to expand around in-line obstacles. The device is relatively compact and simple to operate, two main design requirements set at the beginning of the project. The control software offers a simple interface without the need for proprietary control stations. Several experiments in the lab setting have been conducted and results are reported in the paper demonstrating the feasibility of the robot design and satisfaction of the design requirements. Successful tests at varying degrees of sag from horizontal showed that the wheel design works, even at 30° sag from horizontal. Future work includes adding autonomous motion, updating the vision system and field testing.

## References

Aggarwal, R.K., Johns, A.T., Jayasinghe, J.A.S.B. and Su, W. (2000), "An overview of the condition monitoring of overhead lines", *Electric Power Systems Research*, Vol. 53 No. 1, pp. 15-22.

Allan, J.F. (2012), "Robotics for distribution power lines: overview of the last decade", *Applied Robotics for the Power Industry (CARPI), 2nd International Conference on*, *Zurich*, pp. 96-101.

Aracil, R., Ferre, M., Hernando, M. and Sebastian, J.M. (2002), "Telerobotic system for live-power line maintenance: ROBTET", *Control Engineering Practice*, Vol. 10 No. 11, pp. 1271-1281.

Arduino - introduction (2014), available at: http://arduino.cc/en/Guide/Introduction

Barbosa, C.F. and Nallin, F.E. (2014), "Corrosion detection robot for energized power lines", *Applied Robotics for the Power Industry (CARPI), 2014 3rd International Conference on*, *Foz do Iguassu*, pp. 1-6, doi: 10.1109/CARPI.2014.7030059.

Debenest, P. and Guarnieri, M. (2010), "Expliner - from prototype towards a practical robot for inspection of high-voltage lines", *Applied Robotics for the Power Industry (CARPI), 2010 1st International Conference on*, *Montreal, Quebec*, pp. 1-6.

Debenest, P., Guarnieri, M., Takita, K., Fukushima, E.F., Hirose, S., Tamura, K., Kimura, A., Kubokawa, H., Iwama, N., Shiga, F., Morimura, Y. and Ichioka, Y. (2010), "Field and service robotics: results of the 7th international conference", in Howard, A., Iagnemma, K. and Kelly, A. (Eds), *Expliner – Toward a Practical Robot for Inspection of High-Voltage Lines*, Springer, Berlin Heidelberg, pp. 45-55, ISBN: 978-3-642-13408-1, doi:10.1007/978-3-642-13408-1_5, available at: http://dx.doi.org/10.1007/978-3-642-13408-1_5

Dong, G., Chen, X. and Wang, B. (2012), "Inspecting transmission lines with an unmanned fixed-wings aircraft", *Applied Robotics for the Power Industry (CARPI), 2nd International Conference on*, *Zurich*, pp. 173-174, doi:10.1109/CARPI.2012.6473355.

Electrical Safety – NIOSH Workplace Safety And Health Topic (2016), CDC, available at: www.cdc.gov/niosh/topics/electrical/

FAQs–Raspberry Pi (2014), available at: www.raspberrypi.org/help/faqs/

Jaensch, G., Hoffmann, H. and Markees, A. (1998), "Locating defects in high voltage transmission lines", *Transmission & Distribution Construction, Operation & Live-Line Maintenance Proceedings, ESMO '98, IEEE 8th International Conference on*, *Orlando, Florida*, pp. 179-186, doi: 10.1109/TDCLLM.1998.668371.

Katrasnik, J., Pernus, F. and Likar, B. (2010), "A survey of mobile robots for distribution power line inspection", *Power Delivery, IEEE Transactions on*, Vol. 25 No. 1, pp. 485-493.

Li, Z. and Yi, R. (2009), "Control algorithm of an autonomous obstacles negotiating inspection robot for power transmission lines", *Information Science and Engineering (ICISE), 1st International Conference on*, *Nanjing*, pp. 3756-3759, doi: 10.1109/ICISE.2009.430.

Lorimer, T. and Boje, E. (2012), "A simple robot manipulator able to negotiate power line hardware", *Applied Robotics for the Power Industry (CARPI), 2nd International Conference on*, *Zurich*, pp. 120-125.

Luque-Vega, L.F., Castillo-Toledo, B. and Loukianov, A. (2014), "Power line inspection via an unmanned aerial system based on the quadrotor helicopter", *MELECON-17th IEEE Mediterranean Electrotechnical Conference*, *Beirut*, pp. 393-397, doi: 10.1109/MELCON.2014.6820566.

Montambault, S. and Pouliot, N. (2003), "The HQ LineROVer: contributing to innovation in transmission line maintenance", *Transmission and Distribution Construction, Operation and Live-Line Maintenance, IEEE 10th International Conference on, Orlando, Florida*, pp. 33-40, doi: 10.1109/TDCLLM.2003.1196466.

Montambault, S. and Pouliot, N. (2006), "The HQ LineROVer: contributing to innovation in transmission line maintenance", *Transmission and Distribution Construction, Operation and Live-Line Maintenance "LineScout Technology: Development of an Inspection Robot Capable of Clearing Obstacles While Operating on a Live Line" ESMO, IEEE 11th International Conference on, Albuquerque*, doi:10.1109/TDCLLM.2006.340744.

Montambault, S. (2010), "LineROVer remotely operated vehicle for work on live overhead lines", available at: www.hydroquebec.com/innovation/en/pdf/2010G080-40A-LineRover.pdf

Pedersen, S.L. (2004), "Simulation and analysis of roller chain drive systems", PhD thesis, Technical University of Denmark, Department of Mechanical Engineering, Lyngby.

Pololu Dual VNH5019 Motor Driver Shield User's Guide (2014), Pololu Corporation, available at: www.pololu.com/docs/pdf/0J49/dual_vnh5019_motor_driver_shield.pdf

Pouliot, N. and Montambault, S. (2008), "Geometric design of the Linescout, a teleoperated robot for power line inspection and maintenance", *Robotics and Automation, ICRA: IEEE International Conference on, Pasadena, California*, pp. 3970-3977, doi: 10.1109/ROBOT.2008.4543821.

Rowell, T. and Boje, E. (2012), "Obstacle avoidance for a power line inspection robot", *Applied Robotics for the Power Industry (CARPI), 2nd International Conference on, Zurich*, pp. 114-119.

Toussaint, K., Pouliot, N. and Montambault, S. (2009), "Transmission line maintenance robots capable of crossing obstacles: state-of-the-art review and challenges ahead", *Journal of Field Robotics*, Vol. 26 No. 5, pp. 477-499.

Ultrasonic Distance Sensor (2013), Parallax, available at: www.parallax.com/downloads/ping-ultrasonic-distance-sensor-product-guide

Vanegas-Useche, L.V., Abdel-Wahab, M.M. and Parker, G.A. (2011), "Determination of friction coefficients, brush contact arcs and brush penetrations for gutter brush–road interaction through FEM", *Acta Mechanica*, Vol. 221 No. 1, pp. 119-132, ISSN, doi : 10.1007/s00707-011-0490-2, available at: http://dx.doi.org/10.1007/s00707-011-0490-2

Winfield, A.F.T. and Holland, O.E. (2000), "The application of wireless local area network technology to the control of mobile robots", *Microprocessors and Microsystems*, Vol. 23 No. 10, pp. 597-607, ISSN, pp. 0141-9331, doi: http://dx.doi.org/10.1016/S0141-9331(99)00074-5, available at: www.sciencedirect.com/science/article/pii/S0141933199000745

Worker Deaths by Electrocution: A Summary of NIOSH Surveillance and Investigative Findings (1998), Tech. rep. 98-131, US Department of Health and Human Services National Institute for Occupational Safety, and Health.

Working model 2D – 2D Kinematics & Dynamics Software - Engineering Simulation (2013), available at: www.design-simulation.com/WM2D/Index.php

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