

Robotic Inchworm

For the Inspection of High Power Transmission Lines

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Abstract

The current methods for inspecting high power transmission lines are inefficient and require a great deal of time and resources. However, many everyday activities depend on the power these lines deliver. Because of this, it is important to locate and repair the problems as quickly as possible. The content of this paper describes an autonomous ‘robotic inchworm’ to be used for the inspection of such transmission lines. The designs and proposed prototype are to be completed as the requirements for the graduation of an undergraduate engineering student at Ohio Northern University.

Introduction

In order to provide the energy needed around the globe, electrical wires must be in acceptable conditions and damage from weather or other forms of wear and tear must be avoided. When a problem occurs with one of these wires it is important to locate and repair the damage as quickly as possible. The current methods used to locate these problems are inefficient and require a great deal of time and resources.¹ The purpose of this project was to design and build a ‘robotic inchworm’ device capable of inspecting electrical wires with greater efficiency and decreased costs.

The robotic device created in this project is autonomous. It allows the user to choose specific settings, attach it to a wire, and retrieve data when the inspection is complete. This inchworm-like device attaches and transports itself along the transmission wire, taking still photographs of sections along the route. The frequency of photographs taken depends on the speed of the robot, the area covered in a single frame, and the length of the wire to be inspected. These photographs are stored in sequential order on an external flash memory unit for later retrieval. The use of external memory provides greater flexibility in terms of memory size for various situations and ease of transfer to a PC.

The design team was challenged to create a robotic device that would have low power consumption and a low physical weight. Each of the components must draw minimal energy to maximize the life of the battery for the inspection process and allow the robot to travel along a longer distance of transmission wire. The robot is constructed out of aluminum, a lightweight material that shields the electronics from damage caused by the magnetic fields on the line. It is

powered by a rechargeable battery. The movement of the robot is controlled by a combination of actuators and servos that aid in maneuvering along the line and around various obstacles.

A computer system monitors the available image storage, battery life, and overall status of the system. The device is programmed to avoid situations of insufficient power or storage during the inspection.

To combat environmental concerns, the body of the robot was made from a recyclable material and the power supply is a rechargeable battery with specific recycling instructions. Another important trade-off this team considered was between size and functionality. The design team wanted a robot that would be as small as physically possible yet still be able to traverse the obstacles encountered on the transmission line.

To test this robot both inactive and live-current-conducting wires will be used. Once the device has proven capable of crawling along an inactive wire, testing will be conducted in more realistic environments to ensure the safety of the electronic devices in the presence of magnetic and electronic fields.

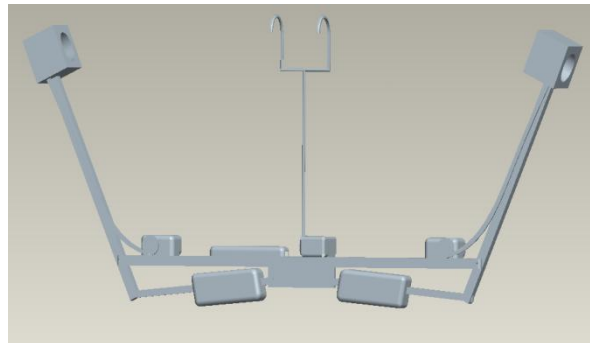


Figure 1: Design of Inchworm in Pro-E

Description

One goal of the project was to make the inchworm as small as possible; still, in order to perform the required tasks, the device must be physically larger than a biological inchworm. By design, in order to travel around an obstacle, the device will have to “reach around” the obstacle and grab the wire on the other side. This means that the device will need an arm that is as large as, or can extend to be as large as, the obstacles it will face. Due to the larger size of the device, larger motors and actuators will be required which, in turn, will require a greater power source. The base function of the device is to attach to a transmission wire and travel along its length, while capturing and storing images in an on-board memory unit. The secondary function of the device is to navigate around obstacles without exceeding the determined size restraints. The device can also protect against interference from the electric and magnetic fields generated by the

transmission wire by adding aluminum shielding to the electrical components on the robotic inchworm. The clamps have been made to withstand powerful wind gusts and constant wind; however a maximum operational wind speed restriction is stated as determined by force calculations and testing for ideal operation of the robotic inchworm.

Electrical Components

The electrical components include a camera module to capture still images, two microcontrollers to act as the *brain* of the robot, as well as memory and power devices that interact with these components. These components and brief descriptions of each component are listed as follows:

- Two JPEG Camera modules (C328R)², each including an OmniVision VGA color image sensor and lens, will be used to collect still images of the transmission wire
- Two Atmel ATmega168³ microcontrollers will be used to control the functions of the robot
- One microcontroller will be used in conjunction with H-bridge⁴ devices to control the motors, actuators, clamps and other mechanical parts of the robot
- One microcontroller will be used to communicate with the camera to take, label, and store images via a Universal Asynchronous Receiver/Transmitter (UART) serial connection
- Programming is completed in C and limited to 16KB flash memory per microcontroller
- MicroDrive⁵ memory module will be used for storage of images communicating using UART connection
- Available memory for images will be limited to the size of the external memory card such as an Multimedia Card (MMC) or Secure Digital (SD) card
- Microcontroller will be programmed to monitor battery life and available memory

General Robot Description

The general specifications include the robotic inchworm's height, approximate weight, as well as the approximate sizes of obstacles and wire diameters the robot can traverse. These general specifications are listed below.

- | | |
|---|--|
| • Wire diameter: 0.8'' - 1.4'' | • Range: TBD |
| • Maximum size of obstacle: 8'' x 4'' | • Time to Recharge Battery: TBD |
| • Maximum speed: 6''/second
(not yet tested) | • Time to Manufacture: TBD |
| • Weight: approx. 7-12 lbs | • Camera Module Specifications: ²
Physical size: 20x28mm |
| • Maximum Length (arms extended): 55'' | Power Consumption: 60mA |
| • Length of Extended Arm: 12'' | 3.3V Operation |
| • Overall Height (hanging from wire): 8'' | UART interface up to 115.2Kbps |

Camera Implementation

The camera and microcontroller communicate using the UART serial interface. The C328R camera module compresses the captured raw image data into the JPEG format.² Figure 2 shows the components of the camera module and the UART connection.

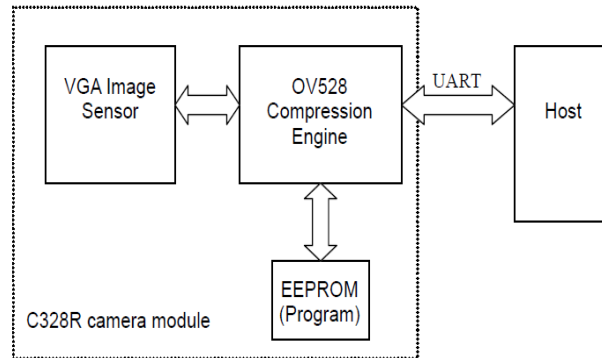


Figure 2: Camera Module Components²

The microcontroller was programmed using C programming language to signal the camera module to photograph the wire at a specified frequency, determined by calculations based on the speed of the robot and the length of wire covered in one image. A sample calculation to determine the number of images needed for a single inspection may include determining the length of wire covered in a single image divided by the total length of wire to be inspected. For continuous motion of the robot, the time needed to process an image must be less than the time it takes the robot to travel the distance covered in an image. However, if this condition is not met, the robot will be able to pause on the wire until the image is completely stored. The images are stored in sequential order on removable flash memory in the form of a Multimedia Card (MMC) or Secure Digital (SD) card. The transfer to PC is simplified with this memory since no direct connection needs to be made with the actual robot itself. The amount of available storage is limited to the size of the memory card chosen by the operator. Memory will be erased after images are transferred to a PC.

Robot Implementation

One of the major challenges the design team had to overcome in constructing the inchworm was making sure it would be able to remain attached to the wire during operation. To accomplish this, a clamping mechanism was used to apply the necessary force to maintain the robot's stability. This was accomplished by using spring loaded hinges and additional extension springs. The amount of force needed to move the inchworm is dependent on the incline of the wire. For example, an incline of 35° requires approximately twenty pounds of force. To find the drive force for this angle, trigonometry was used to find how much force would be needed to lift the weight of the robot up the inclined wire. Using this force, moments were used to solve for the

necessary linear actuator force. The following equation describes how the moments were used to solve for the force.

$$F_m = \frac{l_c F_g \cos \theta}{l_m} \quad \text{eq. [1]}$$

θ - Angle of incline

F_m - Linear actuator force

F_g - Weight

l_c - Distance from pivot to clamp

l_m - Distance to linear actuator connection

The maximum applied force also depends on the amount that can be applied without causing damage to the wires. Due to the wide range of wire sizes, a spring loaded clamping mechanism was used, shown in Figure 3. Figure 4 shows the connector to the arm.

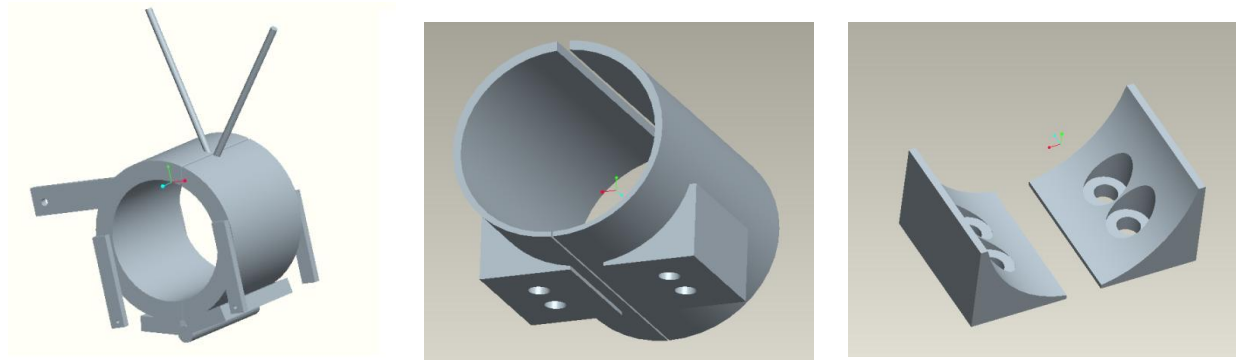


Figure 3: Clamping Mechanism

The operator needs to be properly trained and the safety precautions must be followed to attach the inchworm to the wire in the event that the incline is too steep for the robot to climb. In cases where the inchworm is unable to avoid an obstacle, the operator may be required to climb each tower to move the inchworm around obstacles. If there are obstacles between the towers that are not traversable, the inchworm must inspect each individual section of wire on both sides of the obstacle, approaching from both directions. The required maintenance for the inchworm consists of oiling bearings and other moving parts and replacing springs and battery packs once they are worn.

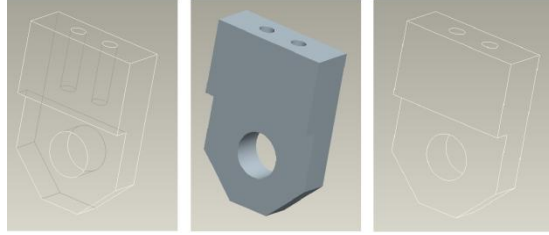


Figure 4: Bearing to Clamp connector

Validation Plan

Before completion of the inchworm prototype, several forms of testing took place. The first test used finite element analysis software. Stress analysis was completed on the high stress components such as the clamping mechanisms. The maximum wind velocity for safe operation was also calculated as part of the validation stage.

The first step in calculating the maximum wind velocity for safe operation was to find the surface area of the inchworm from a view perpendicular to the long side of the base. This view creates the largest area and will experience the largest wind force. The inchworm was estimated to have a surface area of 0.537 ft². Using a strain gauge it was found that approximately fifteen pounds of force caused the inchworm to swing about 15°. The inchworm is estimated to be capable of safe operation at a max of 15°, so this was chosen as the maximum swing angle. A drag coefficient of 1.05 was used for the entire inchworm⁶. This is the coefficient for a cube which is the shape of many of the pieces on the inchworm. The drag force equation was used to calculate the maximum wind velocity for safe operation and is shown below⁶.

$$F_D = \frac{C_D A \rho V^2}{2} \quad \text{eq. [2]}$$

F_D - Drag Force

A - Surface Area

C_D - Drag Coefficient

P - Density of Air at 70°F

V - Wind Velocity (ft/s)

Using the previous equation, the calculated maximum velocity is approximately 18 mph. This velocity is a conservative estimation as the actual maximum velocity may be higher. Various steps could be taken to reduce the drag caused by the wind which includes modifying the shape of the base and arms, increasing clamp strength, and adding material to the clamps to prevent slipping.

Many conceptual and virtual tests were performed before the parts were purchased or assembled and testing of the prototype will continue through the life of the project. Since the prototype is still under construction at this time, no physical testing has currently been completed. However, a validation plan has been outlined to test this robot.

The first test will consist of using a 10' wire suspended 3' above the ground with no power running through it. This will test the functions of the inchworm for the range of wire sizes. Obstacles will be added to the wires to represent situations the inchworm might face once in service. The obstacles range in size and geometry to guarantee the inchworm meets the design requirements. Once the inchworm maneuvers around obstacles, the next test will determine the duration of life and possible travel distance of the inchworm. The range both with and without obstacles can be found from this test. The results of this test also show how much memory is needed for inspection over the life of the battery.

Once confirmed that the inchworm works properly, a working environment test will be performed. To accomplish this, the inchworm will be placed on a transmission wire with electricity running through it. This test uses a sample of transmission wire connected to a power source similar to those used in safety demonstrations by local power companies. This test will be conducted at a site controlled by the project's sponsor. Obstacles will be added to this wire, like those encountered on actual lines to test the maneuverability of the robot.

Final testing will involve the ability of the robot to function in various weather conditions such as high winds or rain. Changes to the robot's design and functionality may result as a conclusion of these tests.

Design Process

One of the final courses that an engineering student at Ohio Northern University must complete is a year-long, design oriented class used to introduce the student to the engineering design process. In this course, students are guided by the five step approach to problem solving.⁷ This approach includes defining the problem, gathering information, generating alternatives, evaluating those alternatives, and communicating the results. Over the course of this senior design project, each step was put into practice.

The first step, defining the problem, was started during Fall Quarter when students were introduced to their projects by the group advisors who would be guiding the students throughout the process. In the case of the Robotic Inchworm, a need for such a device to inspect unreachable electrical wiring was defined. Continuing with the problem definition, the next decision was to determine what type of wire inspection would be the focus of this design.

Residential and commercial applications were considered; however, overhead transmission lines became the focus of the design⁸.

The second step in the process included gathering information about the problem and familiarizing the group with the current alternatives and technologies already being utilized. Research was done to learn more about how power lines are inspected and maintained. Consulting the patent database provided the students with technologies similar to the application of the robotic inchworm including a device for oil pipeline inspectors⁹ and a camera module used for inspection on space shuttles.¹⁰

Generating and evaluating the alternatives went hand-in-hand during the next phase of design. Approximately twenty designs were initially brainstormed. Some of these designs were very similar to each other while others were vastly different. Each design had its own strengths and weaknesses. Designs were evaluated through several methods, comparing the advantages and disadvantages of each. Through this process, the best three designs were chosen. The final design was chosen after evaluating the top three designs on criteria such as time limitations, budget, and experience of the team members on the necessary technologies involved.

The Winter Quarter was spent constructing the working prototype. This was the phase of the design process where a majority of struggles were encountered. Up to this point, all work and calculations were theoretical; however, this was the time to see if everything would successfully function together. Also in this stage of the design, team members had to work with theories and topics they had no previous work experience with such as programming serial communications or autonomously controlling the motors of the robot. During this quarter, many individual components were tested and demonstrated to the faculty advisors. Construction and validation testing of the robotic inchworm continues into Spring Quarter and the rest of the academic year.

Over the course of the year, the design was tested and updated to reach the goals of the project. These results will be communicated at many stages of the process and over several channels including the ASEE North Central Section Conference, presentations to the students and faculty at Ohio Northern University each quarter, and in the form of a final written report. Progress meetings and reports have also been delivered to the advisors on a weekly basis.

As with any design process, many obstacles may arise. Several problems have occurred throughout the design process of the robotic inchworm thus far. The first and most troublesome obstacle was coming up with a final design. It was difficult to develop a design which would cover all the design specifications; specifically having the ability to avoid obstacles. Another problem encountered during the design process was communication between group members. Each member had different ideas and it was difficult to develop techniques to share and compare each member's specific thought. Properly budgeting time was also an issue this group has faced.

There was a schedule that needed to be met in order to complete the design project successfully and it was difficult to follow this schedule while still trying to commit to a final design.

Conclusion

This paper outlines the potential implementation for an autonomous robotic inchworm which could be used for inspection of high power transmission wires. The purpose of this project is to create a device that will be more efficient and less expensive than other methods of electrical wire inspection. Different factors considered in this design process included size, weight, power consumption, reliability, speed, maintainability, cost, ease to build, ability to maneuver obstacles, and the specific size of obstacles to be maneuvered. The conclusion of this project will result in a working prototype of the robotic inchworm specified in this paper. This design project is being completed as a requirement for graduation for an undergraduate engineering student at Ohio Northern University.

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