ASEAN Engineering Journal

Full Paper

FABRICATION AND EVALUATION OF A CLAMSHELL LINE INSPECTION ROBOT

Mark James Ferrer, Jeongrok Lee, Marc Heinz Linsangan, Nygel Gian Santillan*, Matthew Sybingco, Alvin Chua, Timothy Scott Chu

Department of Mechanical Engineering, Gokongwei College of Engineering, De La Salle University, Manila, Philippines

Article history
Received
20 August 2023
Received in revised form
13 October 2023
Accepted
15 October 2023

*Corresponding author
nygel_santillan@dlsu.edu.ph

Graphical abstract

Abstract

There are several hazards associated with the task of power line inspection mainly relating to electrocution especially if there is damage to the wire. This hazard is mitigated with the use of power line inspection robots which allow for inspection from a safe distance. However current inspection robot designs are designed for high-tension wires instead of residential power lines making the robots unsuitable for use in residential power line inspection. In this study, an inspection robot for residential power lines is fabricated through 3D printing. A radio control system to control the robot was also built using Arduino Pro Minis and RF24 modules. The robot's performance was tested in several different categories for both quantitative and qualitative results. Tests included measuring the speed of the robot, the amount of rotation or roll, battery life, signal range, and camera quality. In conclusion, the robot met several set parameters with a speed of 3.2455 km/h, a controllable range of 24 meters, a battery life exceeding 1 hour 14 minutes, and an average roll of 5.6 degrees. The camera feed and mirror setup also provided a clear view of both the top and underside of the wire allowing for inspection of wire damages.

Keywords: Clamshell design, Wire-riding robot, Pulse Width Modulation, NRF24L01, 3D printing

1.0 INTRODUCTION

Power lines are an important part of the power grid that allows for the distribution of electricity to various areas. Due to its importance, the maintenance and upkeep of power lines are vital to an effective power grid. Power lines are built for long-term usage, but frequent maintenance and inspection further improve their lifespan and allow for the early detection of faults and defects in the power line. If not maintained frequently, power lines could potentially fail causing damage to the power grid, fires, or injury to nearby humans.

In the field of power line inspection and maintenance, machinery can decrease risks and dangers associated with the field. Electric shock from exposed or damaged lines which can potentially harm the inspector would instead be taken by the power line inspection robot. On average, electric shock has killed 1000 people in the US each year further emphasizing the risks of electric shock in power line inspection [1]. The hazard of falling is significantly reduced through the use of remote-control robots and transmitted video footage allowing the inspection from the ground.

Designs that have general line riding in mind have been presented before. A study in [2] presented a simple line-riding robot that uses two links connected by an "elbow" mechanism. The robot can perform different movements via a clamping wheel design. This allows the robot to move forward and backward or perform aerial maneuvers on the line. More dedicated power line inspection robots with similar design concepts have also been presented in the past.

The current technological situation for power line inspection is detailed in article [3] and focuses on data capturing using drones, cameras, and sensor systems for gathering the necessary data. One example of these technologies is LiDAR (light distancing and ranging). Current equipment for use is either bulky with low maneuverability that requires multiple rounds because of high power usage or are inspection drones that would have similarly high-power usage but can cover larger ranges.

A Tri-arm robot with dual parallelogram architecture (DPA) is another example robot in this category. It was designed and studied in [4] for movement on the transmission lines through its arm movements and its maneuverability on adjacent obstacle-crossing. These robots were built in large sizes and require multiple moving parts for their movement.

Another design presented in [5] shows another Tri-arm design that uses planned arm movement to avoid obstructions in the power line through a series of complex control systems that clamp and unclamp a palm wheel design as well as maneuver three separate arms around an obstruction.

Similarly, a design presented in [6] makes use of only two arms but has a total of three different frames. It has wheel and arm frames that support the wheel structure and move the arms into position, respectively. The third frame is a center frame which is static and joins the two other frames together. The wheel and arm frame move along this center frame. It too uses its arms and a series of movements to move itself around obstacles in the power line.

More simple designs have also been introduced in other studies such as in [7] where a single-motor two-wheel design was used to inspect power lines in Brazil. Instead of having a complex frame with multiple arms, this robot had only a singular frame made of TIG welded aluminum. A flat plate holds all the main components of the robot. Another simple design is presented in [8] which uses two motors and four wheels along with a host of sensors and cameras to perform line inspections. It also has no arms or moving frames much like the design presented in [7] but requires two sets of power lines due to its four-wheeled design.

There are also power line-inspecting robots that do not ride the power line and are more akin to drones. A study in [9] comparing power line riding robots and drone-inspecting robots stated that each design had its benefits. Power line riding robots have less complex control systems and can carry more load and thus equipment compared to drone robots. Drone robots are easier to design because they need far fewer design considerations compared to line-riding robots. Examples of drone robots are found in [10], [11], and [12]. All three of these designs are standard drones with intelligent cameras and data processing capabilities. These drones can either land by themselves, perform line inspection autonomously, or both.

These power line inspection robots are primarily built for high-tension line inspection rather than residential lines, letting larger and heavier robots be made. Drones can be used; however, these are rather expensive, and the technology is still being developed. Moreover, power lines in the Philippines are not properly maintained in many areas. Although the power lines in the country are in a better state than the telephone wires which are sagging, knotted, and tangled, some damage to the power line is not uncommon. The danger of it towards an inspector would also be unknown as the severity can only be checked physically. Even if some current designs are light enough for residential lines to support these robots, obstacle avoidance measures are not included and are unstable and inconsistent. Therefore, existing wire-riding robots are unsuitable for residential power lines in the Philippines.

The general objective of this study is the fabrication and testing of a compact and lightweight clamshell wire-riding robot that would serve as a residential power line robot and inspect for any potential damage. The weight of the robot should not exceed 3 kilograms to not have a significant burden on the wire. The robot is to be remotely controlled and will primarily comprise 3D-printed components. The robot should be able to achieve a speed of 3 km/h and a battery life of 1 to 2 hours.

This study also focuses on the performance of the fabricated robot to traverse a 14 mm^2 triplex power line at a distance of 6 meters and its ability to inspect for damages on the wire. This size of wire was chosen as this is the standard for residential power lines in the Philippines [13]. It will explore the ability of the robot to adapt to a variety of wiring conditions namely tangled and damaged wires. The study will also give an analysis of the capabilities of the robot mainly to do with its overall speed, stability, and damage-finding capabilities. Note that this robot will not be able to surmount the issue of crossed wires here in the Philippines. The purpose of the robot is to deal with the inspection of straight wires with consideration to the obstructions posed by the presence of frayed and tangled wires.

With this design, the researchers are aiming to target a critical hole in robot-based line inspection, this being the lack of focus on residential power line inspection. As of writing this study, no current line inspection robots are purpose-built for residential power lines. Much focus has gone into developing power line inspecting robots for high-voltage power lines which are very capable designs; however, if these designs were to be applied to residential power lines, these designs would simply not be reasonable or practical. They are too heavy, too complicated, and too expensive. By creating a design that is focused on residential power lines that is compact, light, practical, and relatively cheap, the researchers aim to fill this gap in robot-based line inspection.

2.0 METHODOLOGY

2.1 Methodological Framework

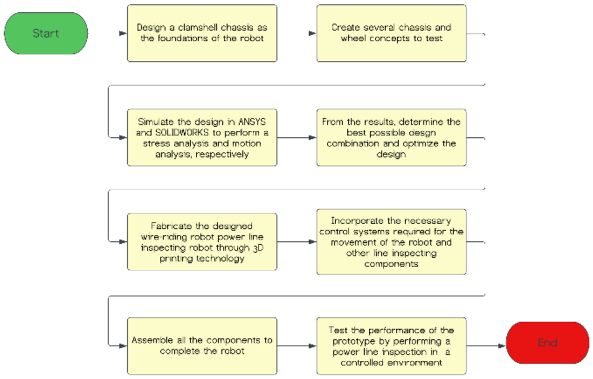

Figure 1. Methodological Framework

Figure 1 shows the methodological framework for this study. It is broken down into eight main sections. The first section involves the design of the robot chassis using the clamshell concept as a basis. Several chassis and wheel designs are then made to explore possible design avenues. All designs are then tested through ANSYS and SOLIDWORKS to analyze the performance and behavior of each design. The best-performing design is then optimized to explore a combination of structural integrity, balance, and reduced printing time. After the components have been printed, the control system can be designed and implemented. Once the control system has been soldered together and tested, the robot itself can then be assembled. The monitoring system can then be fabricated and implemented once the robot is assembled. Now that the robot is effectively complete, testing can commence.

2.2 Design and Clamshell Chassis

Figure 2 shows the initial chassis design for the robot in this study. The chassis is split into two sections, the top and the bottom. Both comprise the outer skeleton of the robot. Both chassis were designed with the printing dimensions of a 3D printer called the Ultimaker S5 in mind. The overall size of the robot when considering both chassis is 220 mm in length, 140 mm in width, and 210 mm in height.

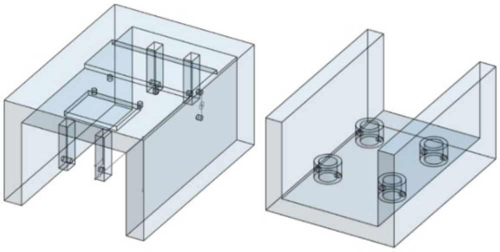

Figure 2. Initial Chassis Design

Another area of concern is the power transfer. For the robot to function, a system is needed for the power of the motor to be transmitted to the robot. Due to the compact nature of the robot, a spur gear arrangement was chosen. The spur gears are also 3D printed as it was easier to design around the robot and print a specified gear for the task rather than trying to find a gear that would fit the robot and design around that.

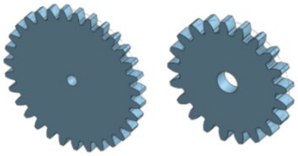

Figure 3. Spur Gear Design

2.3 Chassis, Wheel, and Miscellaneous Component Concepts

Figure 4 shown above illustrates the various chassis designs explored by the researchers. Aside from the initial rectangular chassis shown in Figure 2, three other designs were tested to determine other possible design avenues. The wide rectangular chassis is essentially the same as the initial design but with extra width to make fitting components easier. This design does add weight to the robot and causes unwanted roll. It also takes quite long to print. The hexagonal design is a compromise between the cylindrical and rectangular designs. The flat surfaces make it easier to fit parts to the robot compared to the cylindrical design but because some parts of the chassis are at an angle, this can make the motor hard to fit. The cylindrical chassis is the most compact of all the designs but because of the curved nature of the design, fitting components can be quite difficult. Cutouts need to be made to fit parts which can compromise structural integrity.

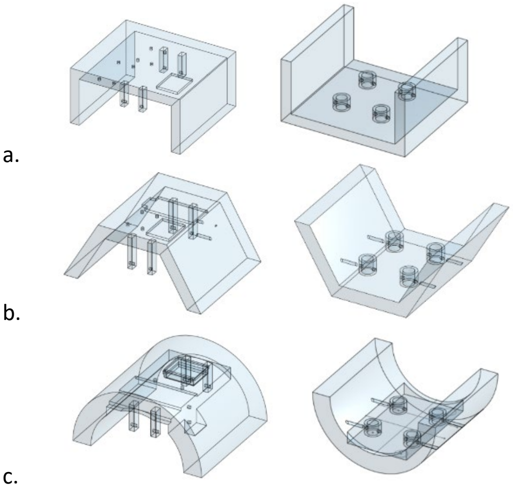

Figure 4. Various Chassis Concepts (a) Wide Rectangular, (b) Hexagonal, (c) Cylindrical

Figure 5 shows the various wheel concepts the researchers explored in the study. The wide-wheel design works for a wide array of wires because of its shape. This makes it more flexible in terms of use because it can accommodate different wire sizes. The downside with this design is that it lacks support from the side walls and that it takes a large amount of space. A U-type design ensures a secure fit between the wheel and the wire. It effectively locks the wire between the two side walls of the wheel and into its groove. Among the wheel types, it does take the most amount of time to print among the different wheel designs. The V-type wheel serves as the gap between the wide wheel and the U-type wheel design. It also has side walls that lock the wire between the wheel, but since it is not curved, it takes less time to print. Because it is not grooved, it does not fit the wire as well as the U-type, which potentially allows for some unwanted side-to-side motion.

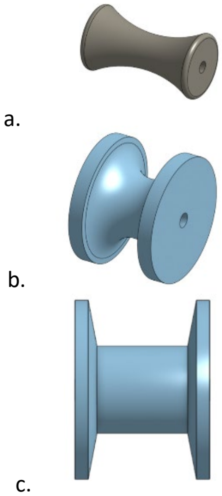

Figure 5. Various Wheel Concepts (a) Wide, (b) U-type Groove, (c) V-type Groove

2.4 Simulation in Ansys And Solidworks

Figure 6 shows the ANSYS and SOLIDWORKS simulations conducted for the study. All designs were initially put through stress simulations to analyze if all the components could handle all the potential loads they could be subjected to. Results show that all parts are more than capable of handling the loads subjected to them. Since all designs were structurally sound, they were then placed into motion analyses. Here, the researchers were able to observe the behavior of each chassis and wheel design. From the observations, it was noted that the initial rectangular design with U-type wheels performed the best out of all the design combinations. Since the design was structurally sound, this gave the researchers the confidence to optimize the design by reducing the amount of material used. Note that detailed results of both the stress simulations and motion analysis are available in another paper entitled “Design and Simulation of a Compact Line Inspection Robot.”

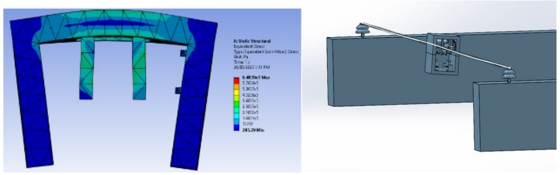

Figure 6. Computer Simulations (a) ANSYS Stress Analysis, (b) SOLIDWORKS Motion Analysis

2.5 Design Optimization

Figure 7 shows the optimized chassis design used in the study. It is 10 mm thinner than the original design and it also incorporates holes for where some of the components can be bolted to. Moreover, it removes unnecessary material from the sides of the chassis using a truss design which ensures the structural integrity of the chassis despite the material loss. Upon testing in SOLIDWORKS and ANSYS, the design has no real discernable difference in performance when compared to the original design. This optimized design, paired with an applicable print setting, saves about 76 grams compared to the original design.

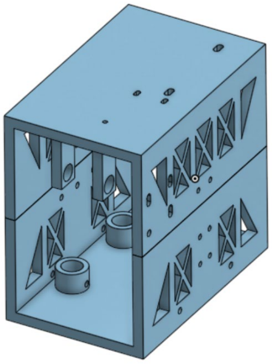

Figure 7. Optimized Chassis Design

2.6 3D Printing Fabrication

The fabrication process requires filaments for the material of the print. These filaments are often light, and durable. PLA plastic offers several advantages, including its lightweight nature, strength, and electrical resistance [14]. It is also lighter than the metals used in previous designs. Ideally, the design should have been made with Acrylonitrile Styrene Acrylate (ASA) plastic. It is generally stronger than PLA plastic, has UV protection, and has a higher glass temperature, allowing it to be used at higher temperatures without warping [15]. Due to the material not being available at the time of the study, PLA was used as a substitute. This research design does not incorporate any of the previous complex mechanisms, keeping the weight low by eliminating the need for heavier metal components. By minimizing weight and size, the robot becomes more versatile and capable of traversing different wire types with varying tension levels. The goal is to use a cheaper, lighter, and less intensive material while maintaining the required strength and functionality.

Figure 8. 3D Printed Parts

After the material and designs that required 3D printing were finalized, the components were then printed out. The entire printing process took just over one day to complete. Figure 8 shows some of the 3D printed parts such as the bottom chassis and two wheels.

2.7 Control System Implementation

The control system was based on existing designs found in [16] and [17], where both the controller and receiver are run through Arduino Pro Minis and communicate via NRF24L01 modules. The Arduinos themselves are the 5V 16 MHz variant of the Pro Mini. These can be powered with a DC power supply of 5-12 V. The Pro Mini can have a maximum current output of 150 mA [18]. The NRF24L01 has an antenna attachment which theoretically boosts the range of the module to 1100 meters. It also runs at a lower voltage of 3-3.6 V and operates at a current of 115 mA [19]. Because the NRF module runs at a lower voltage, a voltage regulator needs to be used. An AMS1117 is used to step the voltage going to the NRF module down to 3.3 V. The controller uses joysticks as a means of controlling the motor speed and direction. These are similar to those seen in gamepad controllers and run on a voltage of 5V [20]. The motor itself is an XD3420 which is a 12 V brushed DC motor with around 0.1 Nm of torque which is theoretically enough to power the robot to the desired 3 km/h speed. It operates with a current range of 2-3.7 A and has a maximum power output of 30 W [21]. The motor speed is controlled via the PWM (Pulse Width Modulation) capabilities of the Arduino which caps the amount of voltage being delivered to the motor depending on the input of the joysticks on the controller. The further forward the joystick is pushed, the greater the speed of the motor. The NRF module on the controller communicates the position of the joystick to the receiver which then directly controls the motor via the Arduino and a L298N motor driver. The L298N motor driver effectively communicates the instructions from the controller in a language the motor can understand. The L298N runs on 12 V and a current of 2 A [22]. Both controller and receiver are powered by Liitokala 18650 Lithium-ion batteries with a rated capacity of 3500 mAH and a 10 A rated output [23]. All components on the controller and receiver were soldered on specifically designed PCB boards which kept the overall size and form factor of the control system rather compact.

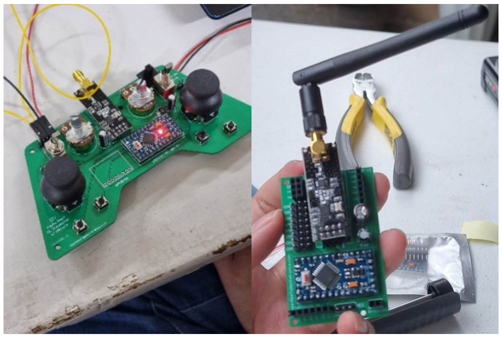
Figure 9. Complete Controller and Receiver Assembly

2.8 Robot Assembly

The robot has a receiver attached to the top chassis. The receiver receives different signals or commands from the controller. The gears were then attached to the motor shaft and to a wheel shaft to move the robot. Seen also in Figure 10 are some of the bolts that hold the latch and hinge of the robot in place. These holes were part of the design, to begin with, and did not need to be drilled in to prevent damage to the chassis.

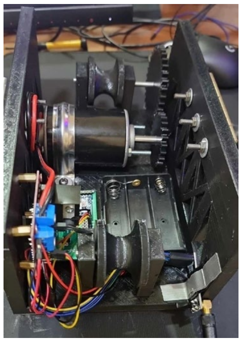
Figure 10. Top Chassis Assembly

The bottom chassis is much simpler in its construction. Four suspensions were hot glued to the bottom of the chassis to only allow 1 dimensional movement. There would be two shafts and wheels placed on two pairs to allow for better control on top of the wire. The two shafts or rods were held in place using bottle caps to prevent the rods and wheels from shifting left and right.


Figure 11. Bottom Chassis Assembly

2.9 Monitoring System Fabrication

A GoPro mount is attached to the top of the Chassis and the camera is connected to a phone via Wi-Fi and Bluetooth, allowing for the monitoring of its camera feed [24]. The robot needs to provide visual information from all sides of the power line simultaneously. To attempt to address this concern, a combination of the camera and a mirror to capture the required angles of inspection is used.

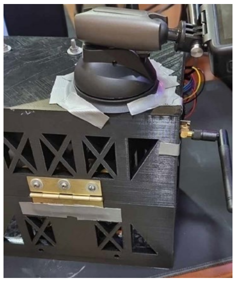
Figure 12. Attachment of Bottom Chassis and Camera Mount

Figure 13 shows the implementation of the mirror on the robot. It is held together on the robot using a bed of wooden sticks for stability and duct tape to keep the mirror in place.


Figure 13. Attachment of Mirror for Full Scope

Figure 14 shows the complete robot assembly. The controller is also seen in the photo on top of the robot. The overall weight of the whole assembly is 2.6 kg which is within the 3 kg target limit.

Figure 14. Complete Robot

2.10 Prototype Testing

After designing and constructing the robot, different tests were done to ensure its viability, and that it will not cause heavy strain on the line itself. The test done for the robot would be done on a simulated setup on a power line. A pseudo power line using 14 mm^2 triplex service drop wires was used. The main aim of the robot is to be able to provide clear visual images of the line. Testing was split into quantitative and qualitative tests. The quantitative tests were regarding the speed, range, battery life, latency, sway, and installation time of the robot to the power line.

The speed test was conducted by marking two points on the power line and measuring the time to reach point B from point A. The velocity can then be calculated. The range test was conducted by moving the controller a horizontal distance away from the robot starting from 6 meters. The controller was moved further until the robot stopped responding. Just under this distance was defined as the maximum range of the system. The battery life of the robot was tested by letting the motor run till the batteries ran flat and documenting the time it took. Latency was measured from the time taken for the robot to respond to commands and the delay between the camera and the live feed. The sway test was done using an application called Phyphox which uses a phone's sensors and gyroscope to measure certain variables. In this instance, the phone was attached to the bottom of the robot. The amount of roll, using one of the features of the app, was then measured in degrees during the robot's movement.

Qualitative tests were also done in the study. The tests were camera feed quality, motor test, chassis durability, wheel durability, and miscellaneous durability. To test the performance of the camera feed, the line had imperfections and damage on it to give the robot an inspection target such as wire damage, exposed wiring, and tangled wires. If the inspector was able to see and assess the damage on the power line from the camera, then the quality of the camera was considered acceptable. Tangled wires were simulated by adding balls of paper with a diameter not exceeding 8 mm. The motor test was a preliminary test done to see if the control system worked. The durability tests inspect any damage to the components after all tests are done.

Two trees were used to hang the power line to simulate the poles that the wires would be attached to. This simplified the setup and reduced the need for tall poles. Data was collected during both these tests for future reference and potential areas of improvement.

Figure 15. Test Setup

3.0 RESULTS AND DISCUSSION

3.1 Quantitative Results of Real-World Testing

The quantitative results of this research cover data gathered that can be quantified through numbers. This section also compares the gathered results to the desired and theoretical results.

3.1.1 Speed Test

Table 1 shows the results of the speed tests. The time it took the robot to move 3.5 m is presented. Three runs are used to ensure consistency and to determine if there are any inconsistencies with the performance of the robot. A stopwatch measured the time taken for the robot to complete each run. As can be seen, the times were fairly similar for each run, hovering around 3.8 seconds to 4 seconds. This results in an average time of 3.88 s. The overall consistency of the timed runs indicates an equally consistent velocity of the robot which was more or less the same throughout the three runs, meaning also that the robot was moving at a consistent and predictable pace.

Table 1. Speed Test Run Times

Test Number	Time to completion
Test 1	3.87 s
Test 2	3.97 s
Test 3	3.81 s
Average	3.88 s

Knowing the time it took for the robot to cross the set distance allows for the approximation of the speed of the robot. The average time taken for the robot to reach 3.5m was 3.8833s. Using the relation between velocity, time, and distance, the speed was calculated to be 3.2445 km/h. This was marginally quicker than the desired 3 km/h but was still deemed acceptable when compared to studies in [5], [25]. The minor excess of speed was not of major concern since the speed of the robot itself could be varied via the joystick controls. Pushing less forward on the joystick would gradually decrease the speed from the maximum.

Table 2. Average Speed vs Desired Speed

Test	Average Speed	Desired Speed
Speed Test	3 km/h	3.2445 km/h

3.1.2 Signal Test

RC Signal testing was done on a street. The robot was placed on the sidewalk. The researcher sent inputs while moving away from the robot. The researcher stopped the test once the robot no longer responded to controller inputs. Both sides were monitored via a group call. The distance between the controller and the robot was measured using measuring tape. The measured distance between the controller and the robot before it lost signal was 53 meters which was greater than the desired 6 meters. This allows for the ground user to be situated further away from the robot while still maintaining control. This can be useful in situations where a damaged wire is deemed dangerous to stay in relative proximity for extended periods due to the risks it may impose. Here, the inspector can stay far away from the danger while still performing the inspection through the robot.

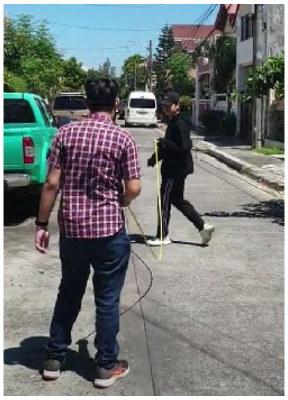

Figure 16. Distance measurement

A video signal test was also conducted on the GoPro camera on the robot. The same methodology was used as that of the controller and the robot. After measuring the distance between the camera and the phone, the distance found was 24 meters. The main limiting factor to the range was the GoPro camera as the working range for this was lower than that of the control system. However, both ranges satisfy the desired signal range of 6 meters.

Figure 17. GoPro viewpoint of signal testing

3.1.3 Battery Life

The battery life of the robot was tested by running the motor at full power until the motor stopped running. The motor ran at maximum power for 5 minutes to simulate a full-speed simulation with short periodic 2-minute breaks to simulate small pauses in the inspection process. The batteries of the robot were drained after 1 hour and 14 minutes which is within the desired 1-to-2-hour battery life target. Although meeting the target battery life, when determining the theoretical battery life of the robot, the actual battery life was short by 4 minutes. This can be down to a multitude of factors such as the possible amp draw reducing the overall capacity of the batteries or the rated capacity of the batteries not meeting the actual capacities of the batteries.

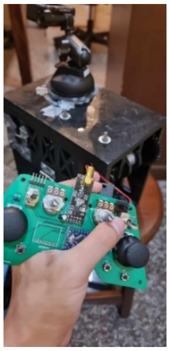

Figure 18. Battery Life Test

3.1.4 Latency

Latency can be a critical factor in the overall manageability of the robot. Having high latency can make the robot hard to control due to the movements being delayed when compared to the input. The latency found for the RC system was negligible. The RC response from the motor showed controls would still react quickly at far distances. The GoPro would send the video of the movement of the robot through the phone, and the camera feed showed a 1-second delay which was still deemed to be acceptable as it did not hinder the actual inspection process itself.

3.1.5 Sway Test

A graph from the sway test is shown in Figure 19. It shows the amount of rotation the robot experiences at a given time. The higher the spike, the greater the roll. For the robot, it is preferred to limit rolling or swaying as this can make the inspection process more difficult. If the robot sways violently from left to right, the camera output will be blurry and unusable. The swaying may also cause unnecessary strain on an already potentially damaged power line. The test was initially run at half speed but was ramped up around the 40-second mark to full speed resulting in greater amounts of rotation. Despite this, the results of the test showed that the average change in rotation was 5.6 degrees which was significantly less than the 10 degrees deemed acceptable in [26] for another power line inspecting robot. This indicates that the robot itself is equally as stable, if not more stable than current power line inspection robot designs.

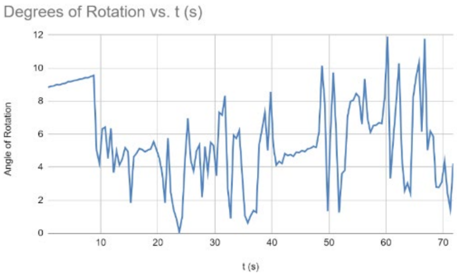

Figure 19. Sway Test Results

3.1.6 Time of Installation

Figure 20 shows the installation of the robot on the power line. This test is meant to demonstrate how easy it is to put the robot into position on the power line. A heavy robot will be very difficult to get into position due to the increased risk of the robot slipping out of someone's hands. To install the robot on the power line, the latch on the outside of the robot was unhooked. The chassis was then opened to get the wheel grooves in line with the wheels. Once in place, the latch was then locked to ensure that the robot would not suddenly open during operation. The total time it took to put the robot on the power line was under 15 seconds. The clamshell style design and light weight made it rather easy and simple to fit the robot on the power line and the whole process could be done by one individual.

Figure 20. Installation of the Robot

3.2 Qualitative Results of Real-World Testing

The qualitative results of this research cover data gathered that cannot be quantified through numbers. This section also compares the gathered results to the desired and theoretical results.

3.2.1 Quality of Camera Feed

To ensure the best battery life during testing, the lowest resolution (720P) setting was used for the GoPro. This resolution setting can be increased up to 4K to further increase the camera quality of the system, however at the cost of battery life during operation. In addition, a mirror was also used to view the underside of the wire which the camera has no viewpoint of without the mirror. Regardless, the testing of the camera feed was able to showcase a sufficient view for observation of the triplex wire used in the experimental setup. It was also noted that the speed at which the robot traveled had no real effect on the quality of the camera feed. Further tests with artificial damage on the wire also showcase the camera's ability to broadcast the damage visually back to the robot operator.

Figure 21. A GoPro view of the wire in 720P

Another round of testing was conducted to assess the robot's ability to detect damage to the wire. Several parts of the wire were intentionally damaged, and the camera was able to identify the defects. Highlighted in the images are the imperfections in the power line, and the debris lodged in the middle of the power line are also observed. The effectiveness of the mirror in identifying potential damages to the underside of the power line is also demonstrated. The mirror allowed for the damage out of sight from the camera to be seen via the reflection. This proved the effectiveness of the mirror setup in covering the blind spots associated with the camera. Moreover, the camera system was deemed to be sufficient in identifying damages in the wire.

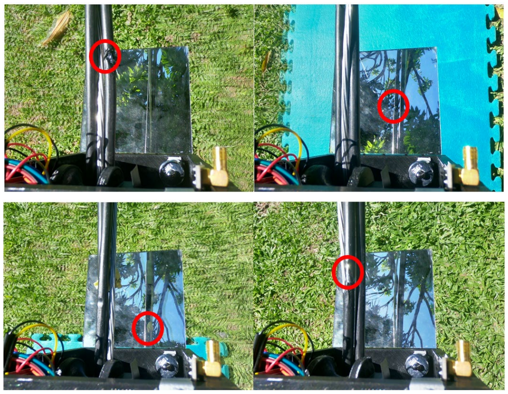

Figure 22. Damage Seen Through Camera

3.2.2 Motor Test

A motor test was done to check for the connection between the Arduino of the robot with the controller. During testing, when the motor was tested on its own, it ran smoothly without unnecessary noise. However, due to inaccuracies with the gear attachment (such as the drilled holes being misaligned to the center), there was an increase in the noise levels due to the gear interactions. This noise, however, was not at a level strong enough to cause discomfort.

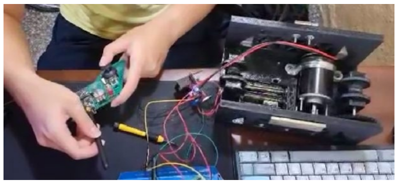

Figure 23. Motor Test

3.2.3 Chassis, Wheel, and Miscellaneous Durability

After the completion of all the tests, the robot was inspected for any significant damage to its structure that would impede its overall performance. There was an observed issue related to the adhesive connection, such as between the wheel and axel of the driven wheel, as it started to loosen, affecting its performance when driven by the motor. However, this issue was determined to be due to improper application of the adhesive during the assembly process. The overall structural integrity of all the parts was determined to be optimal even after the tests were completed.

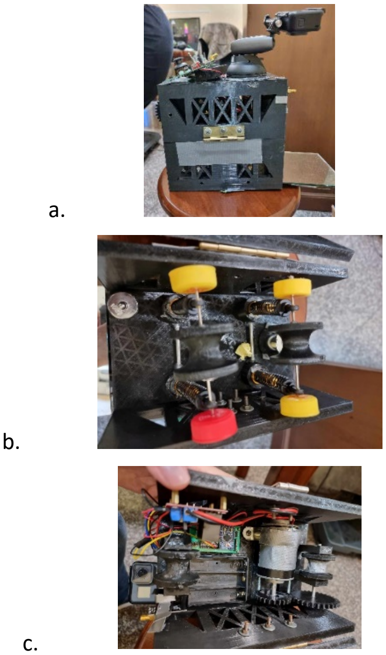

Figure 24. After Test Condition (a) Chassis, (b) Wheels and Axles, (c) Electronic Components

4.0 ADVANTAGES AND DISADVANTAGES

4.1 General Advantages

There are several advantages to the presented design over existing power line inspection robots. As stated earlier, this design is lighter, more compact, and simpler than existing designs. This makes it applicable for residential power line use which cannot be said about similar power line inspection robots. The robot is also shown to perform amicably in the line inspection tests. This is without the use of complicated camera and control systems which simplifies the building process and reduces overall costs.

The use of 3D printing is also somewhat of a new concept in this field of robots. Due to the lightweight nature of the 3D printed plastic, this makes the robot easier to transport or position into place especially when compared to large, mostly metal line inspection robots. Because the plastics 3D printing uses are also non-conductive, it reduces the need for non-conductive materials to be added to the robot. The use of 3D printed parts also makes the robot more cost-efficient compared to robots made using metal or other such materials. 3D printing parts makes it relatively easy to make new parts. Assembling the robot itself is also rather simple because there are only a few parts necessary to build the robot. The chassis, wheels, and gears are ready for assembly as soon as they are 3D printed. Other parts simply need to be bolted or glued into position. No welding, metal rolling, or other forms of metal fabrication are needed to build the robot which also saves time and labor.

4.2 Conceptual and Prototype Disadvantages

Despite the robot itself performing quite well in the tests performed and proving it can function as a line inspection robot for residential power lines, it does present some drawbacks. The drawbacks themselves can be split into two categories. Drawbacks related to the actual concept and functionality of the robot and drawbacks related to the prototype specifically.

The actual concept and design of the robot make it a bit difficult to reach some of the components. For example, because the robot is so compact, it can be difficult to remove or replace the batteries located inside the robot. It is not impossible, but it does take more effort to do so. The robot also does not use any major obstruction avoidance mechanisms such as those seen in other designs. Instead, it makes use of a simple suspension setup to ride through imperfections in the power line. If the power line is entangled to a large degree, the robot will not be able to surpass the lumps of wire. The robot is also an open design which makes it susceptible to water or debris-related damage.

When referring to the prototype itself, the researchers would like to note that some of the adhesives were starting to lose adhesion with the mounting points, although, this may have been due to the age of the adhesives. The prototype robot was also slightly taller than expected due to possible variances and inaccuracies during the 3D printing process. This affected some of the mounting points on the chassis. As a result, the bottom wheels were not in as much contact with the wire as expected. This may have caused some extra instability with the robot that would not have been there if the wheels were fully in contact.

5.0 CONCLUSION

5.1 Overall Conclusion

In this paper, a compact and lightweight wire-riding robot weighing only 2.6 kg was successfully designed, fabricated, and tested. The 3D-printed components were made from PLA plastic. The robot was equipped with a wireless remote-control system controllable from a 53-meter distance using joysticks allowing for variable speed control and a GoPro for video transmission that has a transmission distance of 24 meters. This means the effective inspection range of the robot is limited by the camera system to 24 meters. The testing of the robot in a simulated environment revealed that it has met the desired requirements such as 3 km/h speed, stability providing a roll of less than 10 degrees, battery life of greater than 1 hour, as well as the ability to inspect the wire using the camera system.

5.2 Future Work

Furthermore, possible improvements in the robot that can be conducted in the future include the addition of different motor types or sizes, waterproofing of the robot, the use of ASA plastic in 3D printing, and a more cost-effective visual inspection system.

The motor used in the study was a brushed DC motor which, on its own, has no speed control. The Arduino Pro Mini has PWM capabilities that vary the voltage supplied to the motor depending on the joystick position. This system, although effective, is rather primitive. The use of a brushless DC motor with an electronic speed controller may be a more viable option in the future as this system is more commonly used today in various forms of RC motor control.

Waterproofing the robot could also be a possible avenue that can be explored. Since the robot is still in its conceptual phase, it was left as an open design to better analyze the behavior of the internal components. A future step could be to find a way to either waterproof the internal components or waterproof the chassis.

As stated earlier, the use of ASA plastic would have been the preferred printing material if available due to its durability and UV protection making it more suitable for outside use. A future study could explore the potential performance benefits of ASA plastic over PLA plastic in terms of the overall structural rigidity of the robot.

The GoPro-based inspection system can also be an area that can be improved in future studies. Yes, the GoPro system did function as intended; however, it is more expensive than the robot itself. For reference, the inspection system should at least be 720p and 30 fps in quality. It should also have a remote viewing feature with a range of no less than 20 meters. To achieve this, a cheaper GoPro alternative could be used, or a bespoke monitoring system that meets the requirements could also be fabricated. Possibly looking into an alternative to the mirror arrangement for viewing blind spots could also be a potential research avenue.

Acknowledgment

The researchers of this study would like to extend their sincerest thanks and gratitude to the Department of Mechanical Engineering of De La Salle University – Manila, Philippines for their support and for providing the resources needed to complete this research.

References

[1] D. J. Friedman. 2014. Electrical Safety Hazards and Safe Electrical Inspection Procedures for Electrical Inspectors & Home Inspectors. [Online] Available: https://inspectapedia.com/electric/Electrical_Inspector_Safety.php. Accessed October 2022.

[2] N. Morozovsky and T. Bewley. 2013. SkySweeper: A low DOF, dynamic high wire robot. *IEEE International Conference on Intelligent Robots and Systems*. Tokyo: IEEE. 2339–2344. doi: 10.1109/IROS.2013.6696684.

[3] POWER Magazine. 2020. The past, present, and future of Powerline Inspection Automation. [Online]. Available: https://www.powermag.com/the-past-present-and-future-of-powerline-inspection-automation/. Accessed October 2022.

[4] D. Yang, Z. Feng, X. Ren, and N. Lu. 2014. A novel power line inspection robot with dual-parallelogram architecture and its vibration suppression control. *Advanced Robotics*. 28(12): 807–819. doi: 10.1080/01691864.2014.884936.

[5] Y. G. Wang, H. D. Yu, and J. K. Xu. 2014. Design and simulation on inspection robot for high-voltage transmission lines. *Applied Mechanics and Materials*. 615: 173–180. doi: 10.4028/www.scientific.net/AMM.615.173.

[6] N. Pouliot, P. Latulippe, and S. Montambault. 2009. Reliable and intuitive teleoperation of LineScout: A mobile robot for live transmission line maintenance. *IEEE/RSJ International Conference on Intelligent Robots and Systems. St. Louis: IEEE.* 1703–1710. doi: 10.1109/IROS.2009.5354819.

[7] A. Fonseca, R. Abdo, and J. Alberto. 2012. Robot for inspection of transmission lines. *2nd International Conference on Applied Robotics for the Power Industry. Zurich:* IEEE Computer Society. 83–87. doi: 10.1109/CARPI.2012.6473356.

[8] M. A. Gulzar, M. Sharif, K. Kumar, and M. A. Javed. 2018. High-Voltage Transmission Line Inspection Robot. *2018 International Conference on Engineering and Emerging Technologies (ICEET)*. Lahore: IEEE. doi: 10.1109/ICEET1.2018.8338632.

[9] J. Katrašnik, F. Pernuš, and B. Likar. 2010. A survey of mobile robots for distribution power line inspection. *IEEE Transactions on Power Delivery*. 25(1): 485–493. doi: 10.1109/TPWRD.2009.2035427.

[10] R. Qiu, X. Miao, S. Zhuang, H. Jiang, and J. Chen. 2017. Design and Implementation of An Autonomous Landing Control System of Unmanned Aerial Vehicle for Power Line Inspection. *2017 Chinese Automation Congress (CAC)*. Jinan: IEEE. doi: 10.1109/CAC.2017.8244120

[11] S. Hrabar, T. Merz, and D. Frousheger. 2010. Development of an autonomous helicopter for aerial powerline inspections. *1st International Conference on Applied Robotics for the Power Industry*. Montreal: IEEE. doi: 10.1109/CARPI.2010.5624432.

[12] W. Chang, G. Yang, J. Yu, Z. Liang, L. Cheng, and C. Zhou. 2017. Development of a Power Line Inspection Robot with Hybrid Operation Modes. *International Conference on Intelligent Robots and Systems*. Vancouver: IEEE. doi: 10.1109/IROS.2017.8202263

[13] SOCOTECO-1. 2021. Connection Standards for Residential. [Online] Available: https://socoteco-1.com/consumer-information/electric-service-standards/. Accessed June 2023.

[14] TWI Global. 2020. What Is Pla? (Everything You Need To Know). [Online] Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-pla#Properties. Accessed June 2023.

[15] Fast Radius. 2021. Know your materials: acrylonitrile styrene acrylate (ASA). [Online] Available: https://www.fastradius.com/resources/acrylonitrile-styrene-acrylate-asa/. Accessed July 2023.

[16] D. Nedelkovski. 2019. DIY Arduino RC Transmitter. [Online] Available: https://howtomechatronics.com/projects/diy-arduino-rc-transmitter/. Accessed June 2023.

[17] D. Nedelkovski. 2020. DIY Arduino RC Receiver for RC Models and Arduino Projects. [Online] Available: https://howtomechatronics.com/projects/diy-arduino-rc-receiver/. Accessed June 2023.

[18] Makerlab. 2020. Pro Mini 328-5V 16MHz based on Arduino®. [Online] Available: https://www.makerlab-electronics.com/products/arduino-pro-mini-328-5v-16mhz. Accessed October 2023.

[19] e-Gizmo. 2019. HW-237 NRF24l01+PA+LNA 2.4GHz Long Distance RF Wireless Module with Antenna. [Online] Available: https://www.e-gizmo.net/gizmoshop/index.php?route=product/product&product_id=1615. Accessed October 2023.

[20] e-Gizmo. 2019. Thumb Joystick 2 Axis. [Online] Available: https://www.e-gizmo.net/gizmoshop/index.php?route=product/product&search=joystick&product_id=1453&search=joystick. Accessed October 2023.

[21] Handson Technology. 2019. 3420 Dual Ball Bearing Long Life DC Motor. [Online] Available: https://handsontec.com/dataspecs/motor_fan/XD3420-Motor.pdf. Accessed June 2023.

[22] e-Gizmo. 2019. L298N Double H-Bridge DC Stepper Motor Driver. [Online] Available: https://www.e-gizmo.net/gizmoshop/index.php?route=product/product&search=l298&product_id=1307&search=l298. Accessed October 2023.

[23] LiitoKala. 2019. Lii-35A. [Online] Available: http://www.liito-kala.com/page92?product_id=13. Accessed June 2023.

[24] GoPro. 2022. HERO11 Black. [Online] Available: https://gopro.com/en/us/shop/cameras/hero11-black/CHDHX-111-master.html. Accessed September 2022.

[25] P. Debenest and M. Guarnieri. 2010. Expliner - From prototype towards a practical robot for inspection of high-voltage lines. *1st International Conference on Applied Robotics for the Power Industry*. Montreal: IEEE. doi: 10.1109/CARPI.2010.5624434.

[26] A. Tarık Zengin, G. Erdemir, T. Cetin Akinci, F. Anil Selcuk, M. Nizamettin Erduran, and S. Serhat Seker. 2019. ROSETLineBot: One-Wheel-Drive Low-Cost Power Line Inspection Robot Design and Control. *Journal of Electrical Systems*. 15(4): 626–634. doi: https://doi.org/10.48550/arXiv.1911.08173