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Prototype Line Crawler for Power Line Inspection

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Abstract: In South Africa, electricity is supplied through thousands-of-kilometers of overhead power cables, which is owned by Eskom the national energy supplier. Currently monitoring of these overhead power cables are done by means of helicopter inspection flights and foot patrols, which are infrequent and expensive. In this paper, the authors present the design of a prototype power line crawler (inspection robot) for the monitoring of these overhead power lines in South Africa. The designed prototype power line crawler is capable of driving on the wire, balancing on the wire and is capable of maneuvering past certain obstacles found on the overhead power cables. The prototype power line crawler is designed to host a monitoring system that monitors the power line as the inspection robot drives on it. Various experimental tests were performed and are presented in this paper, showing the capability of performing these tasks. This prototype inspection robot ensures a platform for future development in this area.

Key words: Inspection robot, line crawler, power lines, maneuverability, center of gravity, balancing.

1. Introduction

Eskom is the biggest distributor of electricity in South Africa and therefore has thousands of kilometers of transmission lines running across the country, as shown in Fig. 1 [1, 2]. These lines must consistently be patrolled and maintained to ensure optimal use of the lines. A detailed helicopter inspection is done every two years. To prevent the occurrence of catastrophic failures, every transmission line needs to be inspected regularly. Key components need to be checked for potential problems, for example, a line connector has the potential to fail very quickly if damaged [1]. Eskom [2] currently uses foot patrols and helicopters to perform annual checks on the lines, which is extremely expensive.

Elements that make these inspections so costly and timely are the fact that not all of the transmission line towers are so easily accessible, due to rural developments, cities and mountains. Mountains pose a problem for the foot patrols and roads are not always available on mountains. Cities and rural areas pose a problem for the helicopters as there are lots of buildings and other elements that could potentially put the helicopter and its team at risk [1, 3].

It was therefore decided to conceptualize, design and build a prototype inspection robot (line crawler) that is capable of running on the wire and maneuvering past normal transmission line obstacles that might block its path. The inspection robot is designed to ensure that it does not damage any components on the transmission line or the inspection robot itself, whilst maneuvering past these obstacles [1].

The inspection robot is designed with the capability of incorporating a monitoring system that monitors the transmission line as the robot drives on it and is designed to function in such a manner that the fast helicopter inspections and foot patrols can be replaced by it [1-3]. The inspection robot is designed to be able to maneuver past obstacles on the transmission lines whilst monitoring the line for signs of defects, deterioration, bird nests and other related problems. When designing an inspection robot, the construction of the overhead power lines needs to be taken into account [4].

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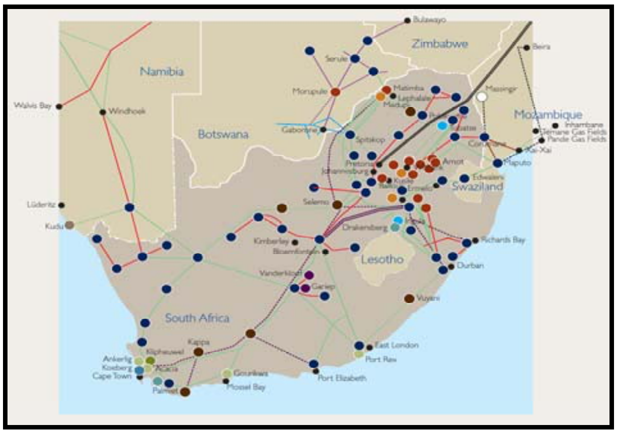

Fig. 1 Transmission grid map of Southern Africa.

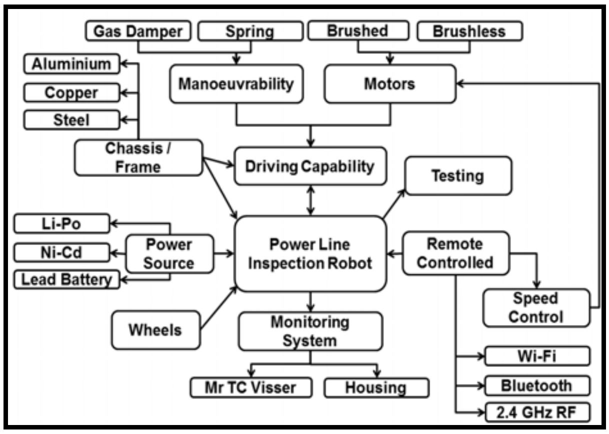

Fig. 2 Conceptual design of the line inspection robot.

Overhead power line inspections using foot patrols and helicopters are expensive. The inspection robot is designed not to cost more to be operated and be maintained than the current methods used by Eskom to monitor their overhead power lines.

Projects with similar scopes are projects such as the Cable Crawler [5, 6], the CAS robot [7, 8], the Expliner [8], the LineScout robot [8, 9] and the inspection robot for 500 kV EHV power lines [7].

2. Materials and Method

Through researching previous projects with similar scopes, a basic idea has been formed on what the robot needs to do, what needs to be avoided, what the elements are that needs improving, how to base the design of the robot and what tests should be done. Fig. 2 provides the conceptual design of the robot.

To determine if the inspection robot would be feasible, the following tests need to be performed:

- Virtual Test: By using SolidWorks®, a virtual concept can be created. This concept can then be tested as the real robot would have been tested. If the virtual robot is capable of passing the tests, the chances are good the real robot would also succeed that in the real tests. This will also decrease the building time of the robot, as all the dimensions are available to the manufacturer.
- Balancing Test: An important aspect of the robot is that it should be capable of balancing itself on a transmission line cable. Thus a testing rig will be constructed to simulate a transmission line. The robot will be placed on the line and see if it is capable of keeping its balance and if it does, up to what angle will it be balanced before it starts losing its balance.
- Communication Test: As this is just a prototype, the robot will need commands from a user on the ground. The user must be able to communicate these commands to the robot with little to none interference. The distance at which the robot will still be capable of receiving commands should be determined, how well the communication is on an open field in comparison with a crowded city area and how the robot will react if the communication link is broken.
- Manoeuvrability Test: The robot must be capable of manoeuvring past certain obstacles found on a transmission line, as seen in Fig. 3. These obstacles were replicated and installed on the simulated transmission line to determine if the prototype is capable of driving past these components without damaging the components, the line or the robot.
- Power Consumption Test: The battery of the robot should also be monitored. This will give the user a rough estimate of how far the robot will be capable of travelling on the line at certain tempos.

3. Experimental Results

Experimental test results demonstrate the feasibility of a project. The results obtained from the tests mentioned above, as well as some additional test results, are stated below:

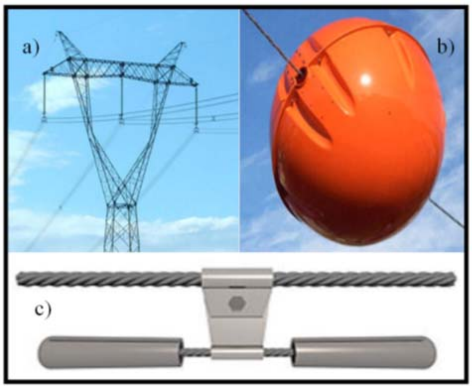

Fig. 3 (a) Tower structure; (b) visibility marker; (c) damper.

3.1 Motor Results

The motors used on the inspection robot were tested with and without a load. Their RPM (revolutions per minute) were determined to define what speed would be ideal to travel along the transmission line. The amount of RPM of the motor can be determined by the amount of volts applied to the motor. The motor has a "kV" rating and this rating is used to indicate the amount of RPM that can be delivered for each volt sent to the motor. The results that could be acquired from a 4 cell Li-Po battery can be seen in Table 1.

Table 1 Revolutions per minute per volt.

Volts (V)	RPM
1	620
3	1,860
5	3,100
7	4,340
9	5,580
11	6,820
13	8,060

Tests were done on the motor whilst there was no load acting in on to the motor. The current was measured to determine the amount of power that will be delivered to the motor. The results were taken before start-up, during start-up and during the running phase, after the current stabilized. The results can be seen in Table 2. The tests were done whilst only the ESC, receiver and the motor was connected.

Table 2 No load testing results on motor.

Motor status	Current (A)
Not active	0.13
Start-up	4.14
Running	0.68

From these results one can see that the starting phase takes a lot of current, as does any motor at start-up. The main result is the current during the running phase. The motor was operated at quarter throttle, this meaning at a voltage value of 3.7 V. This voltage value can be used to determine the RPM at which the motor was turning, the results of the RPM was 2,294 RPM. The total power being dissipated, through the motor and ESC, during the running phase can be calculated using the volts needed to drive the motor and the current being dissipated to make the motor turn. To get the total power, the voltage and current, mentioned above needs to be multiplied with one another. The result for the no load running phase was 2.516 W.

Tests were done on the motor whilst a load was acting in on to the motor. The current was measured to determine the amount of power that the motor was dissipating due to the increased load. The load placed on the motor was more than the load it would face on the transmission line. The results were taken before start-up, during start-up and during the running phase after the current stabilized. The results can be seen in Table 3. The tests were done whilst only the ESC, receiver and the motor was connected.

From these results, one can see that the starting phase takes a lot of current. The main result is the current during the running phase. The motor was operated at quarter throttle, this meaning at a voltage value of 3.7 V.

Taking this voltage value, it can be used to determine the RPM at which the motor was turning, the results of the RPM was 2,294 RPM. The total maximum power being dissipated, through the motor and ESC, during the running phase can be calculated by using the volts needed to drive the motor and the current being dissipated to make the motor turn. To get the total power, the voltage and current, mentioned above needs to be multiplied with one another. The result for the full load running phase was 11.581 W.

Table 3 Load testing results on motor.

Motor status	Current (A)
Not active	0.13
Start-up	6.69
Running	3.13

3.2 Battery Results

The battery can be seen as the heart of the project, as it is the power source to all the crucial elements inside the robot. If the battery is dead, nothing could work, thus knowing how long the battery would last could ensure that the project would stay running as long as possible. Important factors would be the life span of the battery with the components connected to it as well as the time it will take to recharge the battery.

An important factor to keep in mind is that with a Li-Po battery, the voltage value should never drop below 2.5 V or else one risks the chance to damage a cell, causing an unbalanced effect inside the battery and in the end damage the whole battery. ESC cut of the power to the motors as soon as the voltages are too low for further operation, ensuring that the user does not discharge the battery past the 2.5 V level.

To determine how long it will take before the battery is fully discharged. The amount of power needs to be determined. The power needed to run the motors have been calculated in the motor test section. By using the results obtained for the running phase of both no load and full load, the following results can be obtained, as displayed in Table 4.

From this result, it can be seen that at full load, the system can be operated longer than half an hour, but as this is at the maximum load the motors would endure, the life cycle of the battery would increase. From this statement, the result would be anything between 38.34 min and 176.47 min.

Due to the fact that the battery has a rated capacity of 4,000 mAh, the battery can be recharged at a minimum rate of 4 A and a maximum of 10 A. It is important to use a Li-Po compatible charger with balancing capabilities to ensure even and balanced charging or else one runs the risk of damaging the battery.

Table 4 Nano-tech 4 cell 4,000 mAh Li-Po discharge rate.

Load type	Operating time (min)
No load	176.47
Load	38.34

The power capability of the charger will determine the time it would take to recharge the batteries, as will the amount of current used to charge the batteries. If a 50 W charger is used at a capacity of 4 A, the batteries would take an hour to charge to full strength. As the batteries have a capacity rating of 25 A to 50 A, one could charge the batteries at a higher capacity. Thus by charging the batteries at a capacity of 10 A would state that the batteries will be recharged in 20-30 min.

3.3 Chassis Results

The chassis is the key element for the project, without it working properly, the components such as the monitoring system would be of no use. Thus the chassis should be stable, balanced and importantly not be too heavy. If the chassis pass all these criteria, the robot will be capable of functioning perfectly.

The first test will be to see whether the robot could balance itself on the simulated transmission line wire. This determined whether the robot had a lower center of gravity than the transmission line as well as how balanced the electronic layout was inside the chassis. Fig. 4 shows the result for the balancing test.

The results are clear to see that the robot is capable of balancing itself on the transmission line without any problems. The wheels have enough weight to ensure that the robot has a lower center of gravity than the center of gravity of the transmission line. Thus the robot is balancing itself without any problem.

To be sure that the robot would stay balanced through the tests, a tilting test was conducted to see whether the robot could rectify itself if it should get tilted via the wind or an obstacle on the line. A test was done with and without the components to see at what angle it stopped rectifying itself. The results from the test can be seen in Table 5.

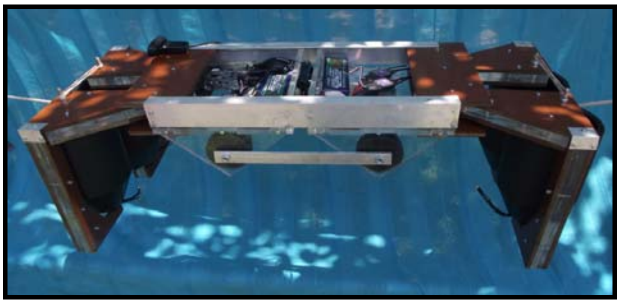

Fig. 4 Inspection robot balancing on transmission line.

Table 5 Tilting angle rectifying test results.

Angle (degree)	Without components	With components
10	Balanced	Balanced
20	Balanced	Balanced
30	Balanced	Balanced
40	Balanced	Balanced
45	Balanced	Unbalanced
50	Unbalanced	Unbalanced

With the results shown in the Table 5, one can clearly see that the components do have an impact on the stability of the robot. The layout of components is near optimal as the difference in angle between the chassis with components and the chassis without is only in the region of 10 degrees. This states that if the wind should tilt the robot, it can be tilted up to about 40 degrees without losing its balance.

The weight of the robot is crucial, as it can not make the wire droop by more than two meters whilst it is running on it. If the earth wire on the transmission line should droop more than two meters, it could cause an arc between the phase lines and the earth wire and thus causing a short on the line [1]. Thus the robot needs to be as light as possible, nothing more than the average weight of an adult male [1]. People are used to inspect the transmission lines inside an isolated structure. The structure helps the person to crawl along the wire to inspect for any problems that could occur on the transmission line.

The robot was placed on a scale to determine its weight. The robot weighed in at 24 kg with all the components inside of the chassis. This states that the robot is indeed lighter than the average male adult and should not pose any risk of causing a short circuit on the transmission line.

As the robot will be travelling along a transmission line, it will encounter certain obstacles found on the line. These obstacles need to be crossed without the robot losing its balance. The robot needs to be able to cross the tower structure, as this is the obstacle that it will have to cross the most on its journey. Fig. 5 shows how the robot crosses the transmission line tower.

From this figure, it can be seen that the robot has no trouble crossing the tower and continuing its journey along the transmission line. The long vertical wheels the aid crossing phase as it keeps gripping onto the wire and thus keep the robot stabilized through the whole process.

The dampers found on the transmission line the robot poses no threat to damaging it, as the robot has a big surface that will pass over it. The high visibility markers were not tested due to the fact that the robot still had some balancing issues while driving on the simulated transmission line, but in theory it would be capable of maneuvering past it as the markers are round. The wheels have been designed to accommodate for the markers shape, it will aid the robot in maintaining its stability over the obstacle.

3.4 Communication Results

To ensure that the robot can be in communication with the user in certain areas where the user can not follow the robot, such as in mountain or certain rural areas, it would be ideal that the robot can be controlled over a certain distance and how it will react to the interference caused by the transmission line itself. This would aid the user and lower the risk of harming the environment or to have the risk of an injury during the monitoring process.

The robot’s communication distance was tested, as well as what happens if the communication was not possible. First the distance test was performed. The results from this test can be seen in Table 6, where indoor represents a building crowded environment and outdoor represents open spaces. The test was done to

Fig. 5 Robot balancing on transmission line.

Table 6 Communication distance test.

Distance (m)	Indoor	Outdoor
500	Received	Received
700	Received	Received
900	Received	Received
1,000	Fail	Received
1,200	Fail	Received
1,500	Fail	Received
1,800	Fail	Fail

see if the receiver registered the command at that specific distance. From the results one can see that the remote control is much more efficient in open areas than in crowded areas with large buildings that can block the signal.

The next test was to see what would happen if the robot did not receive any form of communication from the user. This was tested by running the motors at quarter throttle for a few minutes and then switching of the controller. This simulated the loss of signal between the robot and the user. As soon as the signal was broken, the robot stopped spinning the motors. This is caused due to a fail-safe programmed into the receiver. The receiver registers the input commands from the user and sent it to the ESC.

The ESC processes these commands and controls the motor to these values given. As soon as the signal gets lost, the receiver will stop receiving commands, thus causing it to send a zero value to the speed controllers, causing the motors to stop. The robot's communication module was tested near a transmission line to determine if the line would distort or interfere with the communication signal between the robot and the user. To test this possibility a quad-copter was used to fly above a transmission line for a while. The quad-copter used to test this theory is shown in Fig. 6a.

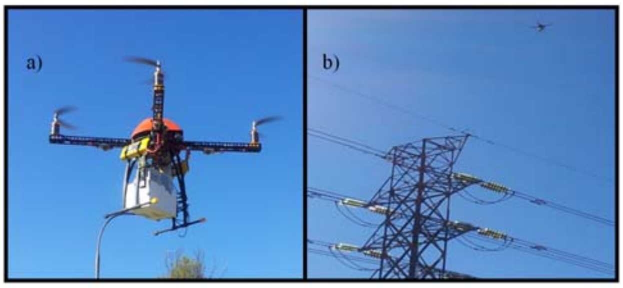

Fig. 6 (a) Quad-copter used for communication test; (b) quad-copter flying over transmission line.

The result of the test can be seen in Fig. 6b was the quad-copter is flying over the transmission line and still responding to the commands of the user.

4. Conclusions

Inspecting the transmission lines are a costly affair, thus by building a robot to run on the transmission lines would greatly reduce these costs. The robot will need to be designed in such a manner that it would satisfy all the criteria's stated to certify that the robot could do what is expected from it. It should be capable of overcoming all the obstacles that it would encounter on the transmission line, elements such as the transmission towers, high visibility markers and dampers. After the prototype robot was constructed, it was tested to determine whether it would work or not. The first and most important test was to see whether the robot was able to balance itself on a wire, this was completed successfully.

The next test was to see how far the robot could be tilted without losing its balance. The robot was tested with and without its components to see how it would react. The difference in angle between the two tests was about 5 degrees, as the chassis with components could be tilted up to about 40 degrees without any problem.

The robot passed the tilting test better than was expected. The weight of the robot also plays an important role in the balancing characteristics of the robot. By making the robot heavier at the bottom ensures that the robot has a lower center of gravity than the wire it will be travelling along. By making the robot heavy also poses the risk of creating a short circuiting arc between the earth wire and the phases. Due to the fact that the robot weighs only 24 kg, it would not hold any risk of damaging any element found on the transmission line.

The robot also had to be tested to see whether it was capable of maneuvering past obstacles found on a transmission line. First the robot was tested to see if it was capable of crossing over a transmission line tower, the robot did so successfully. Next it had to cross over a simulated damper mechanism, the robot crossed over it without damaging the unit. Next the robot had to cross over a suspended high visibility marker on the transmission line. The robot had some difficulty in passing this obstacle but was still able to pass it successfully. The difficulty in passing the visibility marker is the fact that the robot has to open its wheels to pass it, causing a slight disturbance in the balance of the robot.

The communication tests were done to see how far the robot would be able to operated, by the user, and what would happen if it would go out of the communication range. So the first test was done to determine the distance that the robot can still receive commands from the user in dens building areas and in wide open areas, as these are the two areas that transmission lines are normally located. The communication distance was a lot farther for the open area than for the crowded area, this is due to the fact that buildings tend to block or reduce the signal power that is being transmitted from the user to the robot.

References

[1] T. Pillay, S. Bisnath, Fundamentals and Practice of overhead Line Maintenance, Crown Publications, British Columbia, 2004, pp. 3-239.

[2] Eskom, Eskom integrated report [Online], 2010, pp. 1-9, http://financialresults.co.za/2010/eskom_ar2010/eskom_abriged-ar2010/index.html.

[3] P.C. Pelser, Routine inspection and maintenance of transmission lines [Online], 2008, pp. 1-6, http://www.nrs.eskom.co.za/LoginsSecure.asp?FileName=asaby9.pdf.

[4] P. Nefzger, J.F. Nolasco, U. Kaintzyk, F Kiessling, Overhead Power Lines—Planning, Designing, Construction, 1st ed., Springer, New York, 2003, pp. 1-6.

[5] J. Berchtold, M. Buchel, C. Dold, W. Fischer, C. Bermes, R. Siegwart, et al., Inspection of high voltage power lines—a new approach [Online], 2006, pp. 1-8, http://publications.asl.ethz.ch/files/buehringer09cablecrawler.pdf.

[6] J. Berchtold, M. Büchel, C. Dold, M. Bütikofer, M. Feuerstein, W. Fischer, et al., Cable-crawler-robot for the inspection of high-voltage power lines that can passively roll over mast tops, Industrial Robot: An International Journal 37 (3) (2010) 256-262.

[7] H.G. Wang, F. Zhang, Y. Jiang, G. Liu, X. Peng, Development of an inspection robot for 500 kV EHV Power, in: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Taipei, 2010, pp. 5107-5112.

[8] K. Toussaint, N. Pouliot, S. Montambault, Transmission line maintenance robots capable of crossing obstacles: State of the art review and challenges ahead, Journal of Field Robotics 26 (5) (2009) 480-482.

[9] N. Pouliot, S. Montambault, Geometric design of the LineScout, a teleoperated robot for power line inspection and maintenance, in: IEEE International Conference on Robotics and Automation (ICRA), Pasadena, 2008, pp. 3970-3977.