Autonomous Approach for High Voltage Transmission Line Inspection and Fault Detection

Thamashi Malaviarachchi, Thadeesha Perera, Supun Perera, Pasika Ranaweera
Department of Electrical & Information Engineering
Faculty of Engineering, University of Ruhuna
Sri Lanka
Email: thamashi.u@gmail.com, thadeesha@gmail.com, supunclemont@gmail.com, pasika@eie.ruh.ac.lk

Abstract — **High Voltage Transmission line inspection and maintenance is an extremely dangerous employment due to the reason that such tasks are performed at high altitudes around high magnitude voltages. In countries like Sri Lanka, this employment has caused the demise of experienced technicians over the years. As a solution to this timely matter on power distribution sector, an autonomous approach is introduced to perform the inspection through remote operation. A Remotely Operated Vehicle (ROV) prototype was implemented to test the proposed approach in a single transmission line span. The intended functions of the proposed ROV are positioning, live video transmission and the sag template indication of the transmission line which are being explicated in this paper. The prototype was tested in a high voltage laboratory environment to verify the feasibility of operation. A magnetic energy harvesting circuit was designed and implemented to satisfy.**

Keywords- fault detection; high voltage; magnetic energy harvesting; ROV; transmission line; video streaming

I. INTRODUCTION

Transmission lines are essential to transfer the electricity produced in power plants to cities and homes. Any failure in such lines may bring severe consequences to people's daily lives by affecting transportation, health, security and sanitation. Therefore, the proper maintenance of high-voltage transmission lines is extremely important. However, the transmission lines are laid in high altitudes, and the lines transmit current at higher voltages such as 132 kV and 220 kV according to Sri Lankan standards. Hence, transmission lines inevitably require routine maintenance.

In Sri Lanka, the transmission network is distributed throughout the island, which is approximately 2000 km. The transmission line inspection and maintenance work is currently performed by specialized workers for once every 3 years. Inspection procedure includes checking insulator status, measuring transmission line clearances, etc. The routine inspection and maintenance of high-voltage transmission lines is a dangerous and time-consuming task which should be carried out by experienced specialists who are operating at higher elevations above the ground, and closer to live lines which are carrying thousands of volts.

In other countries, use of robots to accomplish this task is an active research area [1]. But in Sri Lanka, researches haven't been carried out to automate this process till now. So, our focus is directed to implement a low cost, accurate inspection robot incorporated with real time data processing which would be compatible for the transmission lines laid across national grids island wide.

In this paper, the basic concept of the proposed ROV along with its mechanical design and the control system is introduced. The validity of the proposed concept will be confirmed with results of experiments, discussed at the end of this paper.

II. INSPECTION OF TRANSMISSION LINES

High-voltage transmission lines are usually arranged in single or 2 wires, supported by transmission towers. The distance between the towers is usually between 300 m and 500 m, which are laid across forests, mountains or any other isolated places. The suspended transmission lines are often composed of a metallic core and metallic casing. When exposed to the elements, the lines may suffer from corrosion, damages by lightning bolts, or even rupture of the core. In order to inspect the lines, workers must walk on the lines; in many cases suspended 20 m above the ground. The currently used methods require skilled workers, and expose the workers to unnecessary levels of danger and stress. In addition, when the lines are being inspected, the transmission of electricity must be temporarily suspended, which means that other lines may be overcharged in order to compensate for the line that is undergoing maintenance as well as it takes a high cost. Moreover, it takes approximately 3 years to carry out the inspection procedure in the entire transmission network. This is due to the lesser availability of the specialist employees who are willing to take the risks.

Insulators in the transmission lines could be damaged by lightning bolts and surface corrosion. Therefore the insulation level will become lower than the expected level. Mostly in Sri Lanka these insulators are inspected by

Binoculars or by naked eye. This scenario is not accurate and it can result in severe damages inflicted to the transmission network. So, there should be a proper method to inspect insulator status.

Although there are many forms of robots existing for transmission line inspection over the world, they are not suited for line configurations and atmospheric conditions in Sri Lanka [1],[2]. Moreover, measurements taken from such robots are exclusive of parameters such as ground clearance, sag template and insulator condition. Additionally, they are too expensive to purchase and maintain for a developing country.

The proposed Inspection robot will cater the problems under Sri Lankan perspective since it will be designed considering the existing transmission line architecture. The robot will give a close range visual on transmission line while gathering other significant data such as the ground clearance level and the transmission line sag. Allocation of human resources is drastically reduced since the operation requires a single person located in a remote location. The robot is self-powered so that it can traverse along the complete network continuously which will reduce the amount of time spent on inspection and also the cost will be zero since there is no need to power down the lines. Therefore the robot will provide an all-round cost effective efficient solution for the difficulties faced in inspecting and maintaining high voltage transmission lines.

III. PROPOSAL FOR AUTOMATION

A. Proposed Model for the ROV

This study is focused on designing a transmission line inspection robot that will operate only in a single span. The prototype requires at least two supporting points and a body to hold all the electronic circuits of the ROV. To keep the stability of the robot when moving on the lines, the centre of mass must be positioned as low as possible, ideally under the transmission line. Therefore, the body is constructed to be light weighted and the supporting points are placed in balanced positions in order to be stable on the transmission line.

Hence, the robot is composed of two supporting points and pulleys that move on the transmission line. Each supporting point is equipped with one motor for motion on the cable and they are connected to the body by a belt and an arm. The body is to be protected from electromagnetic interferences. Therefore a proper enclosure is implemented on the robot. Since the proposed ROV is exposed to open air while in operation, it is constructed to withstand any climatic disturbances occurring during the inspection period. A magnetic energy harvesting method is proposed to recharge the battery of the model.

B. Simulations

The basic design was modeled and simulated using SOLIDWORKS®. For the stability of the robot on the line which is about 20m high, the wheel configuration is important. The simulation was carried out by considering several configurations. Taking into account dynamic effects, the configuration that presented the best results is displayed in Fig 1. The simulation results revealed that the motion of the robot will be stable if the two wheels were placed on opposite sides of the conductor.

The enclosure design proposed for the ROV was also simulated using ViziMag®. Several materials with magnetic shielding properties [3] were simulated. The simulation results revealed that the most suitable material for magnetic shielding is low carbon steel, which reduce the magnetic interference to the structure by a factor of 600, which is more than the expected value. The simulation results are shown in Fig 2.

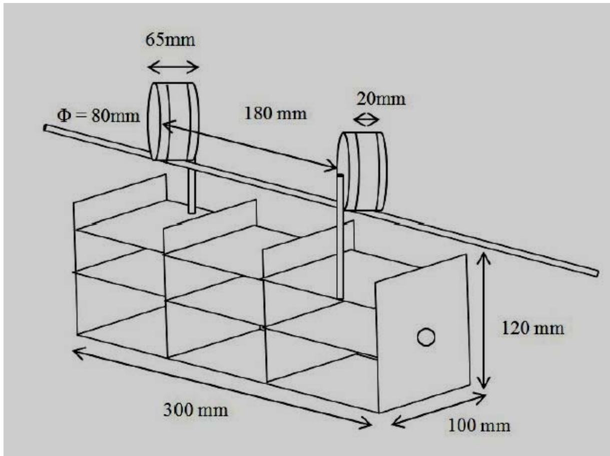

Fig. 1. Overall view of the proposed rov and its components

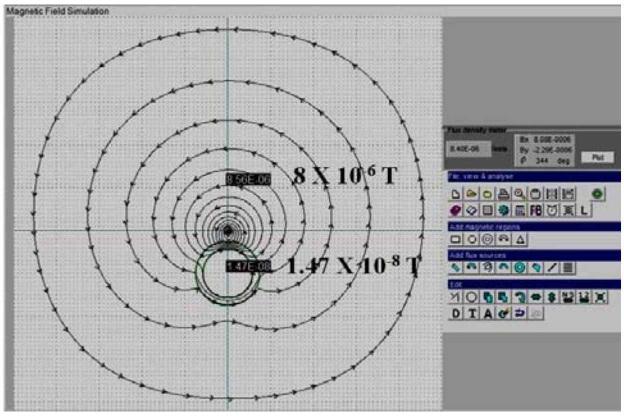

Fig. 2. Simulated magnetic shield for the proposed model

IV. MECHANICAL DESIGN

A. Motion Units

The proposed ROV consists of two motion units, each with one pulley and a shaft. A DC motor is embedded in to the top surface of the body. And the torque is transmitted to the pulley using a timing belt. The pulleys (P1 in Fig 3) are made of Nylon, with two grooves, one for clinging on the transmission line and the other for the belt which connects to the gear motor. The clinging groove diameter is matched to the diameter of the transmission line conductor while the other groove diameter is chosen as 5 mm to be suited for the motors. Each shaft (S1 in Fig 3) is made of iron to get the strength required to hang the robot on the transmission line. And it is insulated with high voltage insulation tape to prevent resulting formation or electric arcs between the lines and the body of the robot.

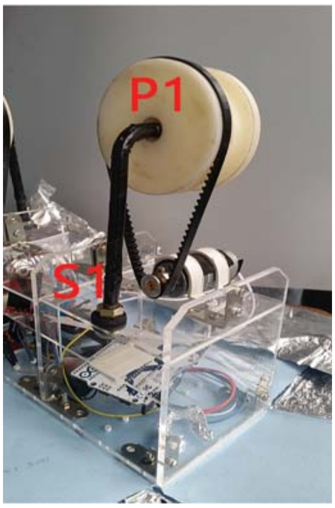

Fig. 3. Arrangement of a single wheel in the ROV prototype

B. *Structure of the prototype*

The structure which contains all the electronic circuits of the ROV is made of Perspex to lighten the total weight. For the driving mechanism, two DC motors operating at 120 rpm and produces a maximum torque of 60 Ncm is connected to the upper plate of the structure along with a 12 V battery. This range of rpm is required with a better gear system to reduce the wheels backward motion on upper part of the sag.

The middle plate of the structure is equipped with an Arduino UNO board for RF communication and a motor controller. The bottom plate consists of the main processor, Raspberry pi, Accelerometer for sag measuring and a GPS module for fault location tracking. A fish eye lens camera is also included in the front of the structure to take a video feed of the inspection.

C. *Enclosure of the structure*

To overcome the difficulties appeared in the presence of magnetic and electrical fields of high voltage lines, a well-insulated enclosure box is constructed. This enclosure consists of a magnetic shield, an electrical shield along with a roof to withstand the climatic conditions. According to Ampere's law, a higher magnetic field exists in high voltage transmission lines. To avoid magnetic field interferences, a proper magnetic shielding material should possess a low permeability. Therefore for the construction of the magnetic shields shown in Fig 4, the material is selected as low carbon steel which attributes a permeability of 4000 H/m. As the best shape for the structure, a cylindrical shape is chosen to avoid interferences that might occur in the presence of magnetic fields with higher magnitudes [4].

In order to avoid electro-static forces, the structure is wrapped with aluminum foil paper as shown in Fig 5. A cooling fan is used to prevent the overheating of electronic components inside the prototype. Since the ROV should be light weighted for proper operation of motors in the transmission line, polyvinyl chloride (PVC) is used for implementing the enclosure of it.

Since this robot operates in open air, it should be capable of withstanding climate changes, such as rain, and operate properly. Therefore a cover is made using PVC as illustrated in Fig 6. And also this roof design acts as a vibrant stand when the robot is on ground.

The back panel of the robot consists of a cooling fan, main power switch, data analyzer switch, battery recharging terminal and indicators as shown in Fig 7 below. The cooling fan will blow out the exhaust air inside the structure providing a uniform cooling for core of the structure.

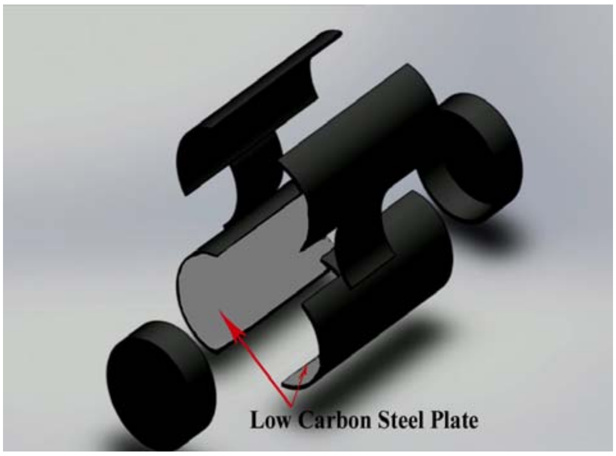

Fig. 4. Magnetic shielding Enclosure of the ROV prototype

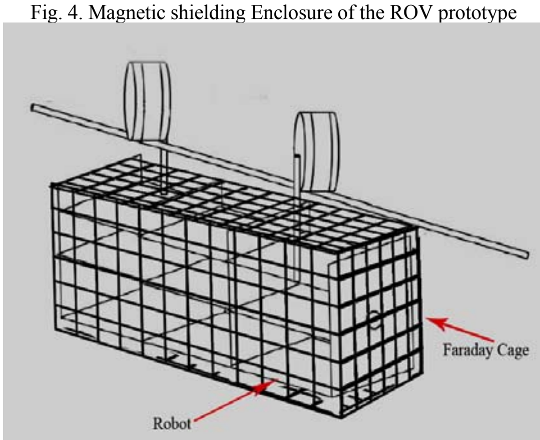

Fig. 5. Electric shielding of the ROV prototype

DOI 10.5013/IJSSST.a.17.32.14 ISSN: 1473-804x online, 1473-8031 print

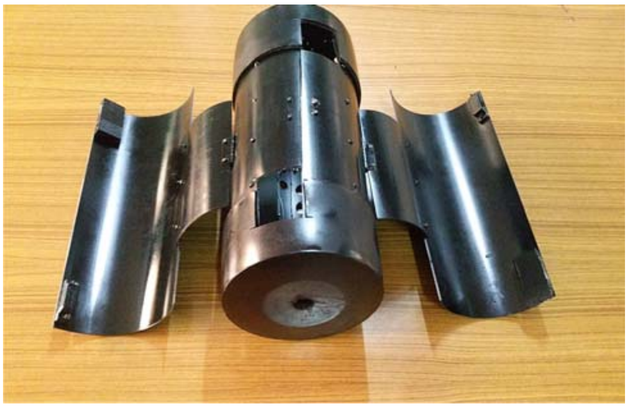

Fig. 6. The complete enclosure of the ROV prototype

Fig. 7. Back panel of the ROV prototype

D. *Magnetic Energy Harvesting Circuit*

A power harvesting method is developed to recharge the battery bank that would provide continual power supply for the operation of the robot [5]. The power supply operating principle is based on the harvesting of the magnetic energy around the power supply lines using an electric current sensor. The circuit design is shown in Fig 8.

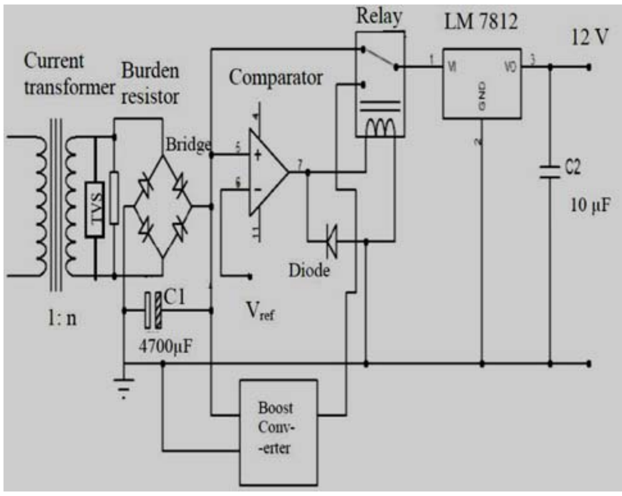

Fig. 8. Magnetic energy harvesting circuit

The regulated output voltage of the prototype circuit developed in relation to Fig 8, is compared using two burden resistor values. And it is tabulated against the controlled input bus current in TABLE I and TABLE II for burden resistors of 470 ohms and 1000 ohms. The variations are plotted in Fig 9 and Fig 10 respectively.

TABLE I. OUTPUT VOLTAGE OF ELECTRIC ENERGY HARVESTING MODULE FOR THE RESISTOR VALUE OF 470 OHMS

Bus current (A)	Input voltage (V)	Rectified voltage (V)	Regulated voltage (V)
5.0	2.64	2.24	0.16
7.5	3.64	3.12	2.32
10.0	4.24	3.72	2.48
12.5	4.68	4.12	3.28
15.0	4.96	4.40	3.92
17.5	5.20	4.96	4.40
20.0	5.60	5.12	4.80
22.5	5.60	5.52	5.04
25.0	6.00	5.76	5.04
27.5	6.40	6.08	5.04
30.0	6.80	6.40	5.04
32.5	7.20	6.64	5.04
35.0	7.20	6.88	5.04
37.5	7.60	7.12	5.04
40.0	7.60	7.36	5.04

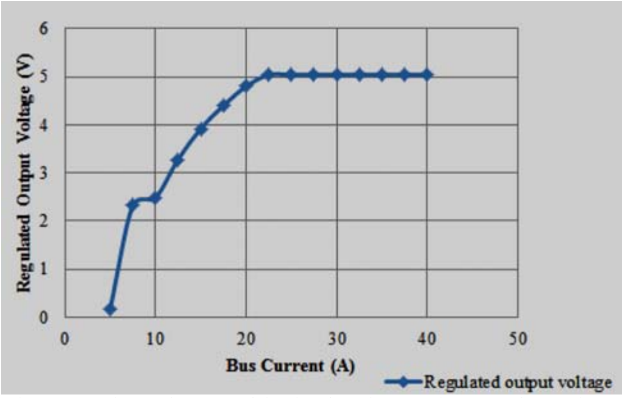

Fig. 9. Experimental output of the developed magnetic energy harvesting circuit for the resistor value of 470 ohms

TABLE II. OUTPUT VOLTAGE OF ELECTRIC ENERGY HARVESTING MODULE FOR THE RESISTOR VALUE OF 1000 OHMS

Bus current (A)	Input voltage (V)	Rectified voltage (V)	Regulated voltage (V)
5.0	4.20	3.28	2.48
7.5	5.00	4.00	3.44
10.0	5.80	4.80	4.08
12.5	6.40	5.44	4.072
15.0	7.00	5.84	5.12
17.5	7.40	6.32	5.12
20.0	8.00	6.88	5.20
22.5	8.60	7.52	5.20
25.0	9.20	8.24	5.20
27.5	9.60	8.48	5.20
30.0	10.00	8.96	5.20
32.5	10.40	9.36	5.20
35.0	10.80	9.76	5.20
37.5	11.20	10.00	5.20
40.0	11.40	10.40	5.20

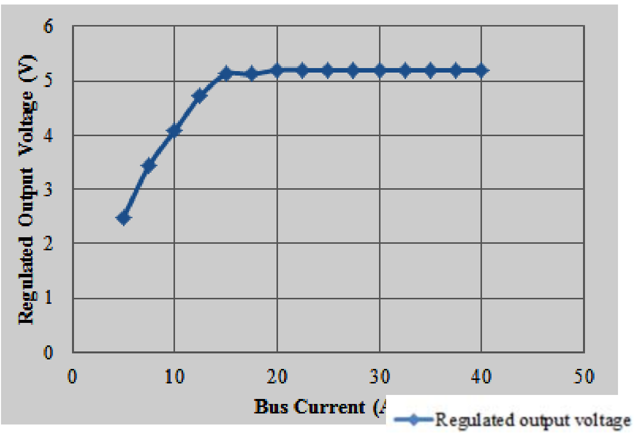

Fig. 10. Experimental output of the developed magnetic energy harvesting circuit for the resistor value of 1000 ohms

Though the 1000 ohms resistor starts harvesting energy earlier than 470 ohms resistor, the 470 ohms resistor was chosen as the optimal burden resistor value, due to the quality of eliminating generated high voltages in the input side of the circuit and thereby protects the secondary side of the current transformer.

When the bus current of the transmission line is in the range of 5.0-40.0 A, a stable 5 V DC voltage source is supplied to the monitoring module.

The simulated power harvesting circuit design plotted using PROTEUS® simulator considering the actual transmission line parameters (Lynx conductor 360 A) is shown in Fig 11. According to this simulation, a stable 12 V DC voltage is observed at the output.

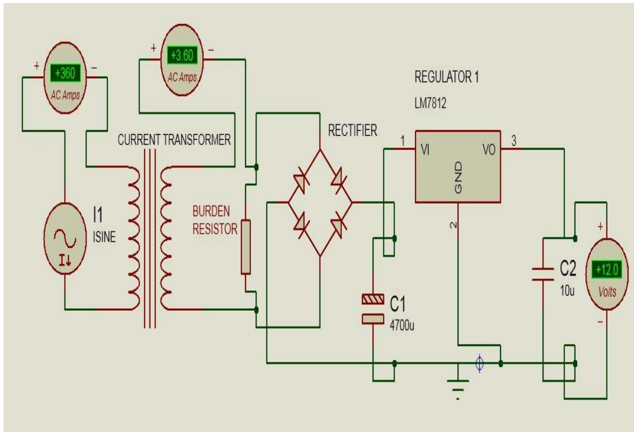

Fig. 11. Simulated magnetic energy harvesting circuit using PROTEUS®

V. CONTROL SYSTEM

The ROV can be controlled remotely, which means the user is always in charge of the operation and all the processed data is transmitted using wireless communication.

A. *Portable Control Unit*

A Radio Frequency (RF) transmitter kit with 433 MHz is used to remotely operate the movements of the ROV. These input RF signals are directed to the Raspberry Pi and then control the motors using motor controllers. The LCD screen displays the current movement of the ROV which helps the user to get the required visual of insulators and conductors.

The remote controller unit is shown below in Fig. 12.

DOI 10.5013/IJSSST.a.17.32.14 ISSN: 1473-804x online, 1473-8031 print

Fig. 12. Portable Control Unit of the robot

B. *Wireless Communication*

There are two main wireless access methods used in the robot. Considering the distance range of the controls, an RF communication and 2.4 GHz wireless LAN is deployed to establish remote connection to the robot.

The separate RF system is used such that to provide a long range and reliable communication which is required for controls of the robot. Therefore a 433MHz RF channel is acquired to send the forward and backward motion signals through SPI protocol where half duplex communication is obtained at the arduino units installed at the user remote and the receiver end of the robot.

The main access method to main processing unit of the ROV is established through a 2.4 GHz Wireless Local Area Network (WLAN) connection. Since Raspberry pi 2 B unit is installed as the main processing unit, the WLAN is accessed using a Wi-Fi Universal Serial Bus (USB) adapter at the ROV end. The operations of the ROV requires internet access since some tools used for implementation (plotly and google maps) uses online data streaming. This feet is achieved by sharing an active network connection at user end to the WLAN. This enables feature of accessing ROV data over internet to authorized remote users.

The main access protocol to Raspberry pi unit is SSH. SSH connection is used to run the python application software initially.

The real time video feed is streamed using Real Time Streaming Protocol (RTSP) and encoded with the VLC encoder. The users can access this stream by connecting to the media network via VLC plug-in at port no. 8554, which was defined for this implementation. The Raspberry pi is configured to work as a server (Apache Tomcat), so that GPS data is hosted as HTML data to the user end. Therefore to acquire GPS data, HTTP connection is established between the user end and the ROV end. The internet connection is used to plot data obtained from sensors online. The data is also pushed to Plotly API through HTML GET POST requests. Distance measuring data is obtained by Raspberry pi through GPIO pins whereas the Sag data is obtained from I2C protocol.

C. *Main Web Interface*

The main web interface of this system contains the real time video feed, GPS plot, sag template and the ground clearance plot which are obtained by the acquired sensor data from the robot as shown in the Fig 13. The interface is developed using html5 and PHP.

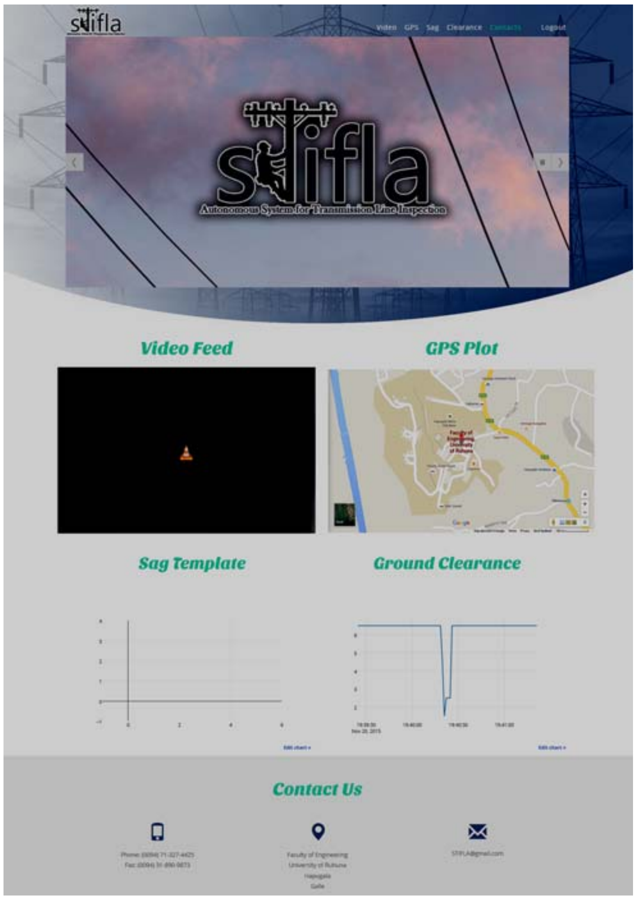

Fig. 13. GUI for inspecting line condition

First a user has to login with the username and the password which is issued by the system administrator to get access to the interface. The authentication page is shown in the Fig 14.

Fig. 14. Authentication page of Web Interface

DOI 10.5013/IJSSST.a.17.32.14

ISSN: 1473-804x online, 1473-8031 print

Authorization is only depend on the administration except the user cannot register by himself in the the interface. If the user is not authorized, the following message appears on the web interface as shown below in Fig 15.

Fig. 15. Unauthorized user login of Web Interface

VI. Data Analysis

The use case view of the user interface is shown in Fig.16 below. And the class diagram and the software flow chart of the data analyzing design are shown below in Fig.17 and Fig.18 respectively.

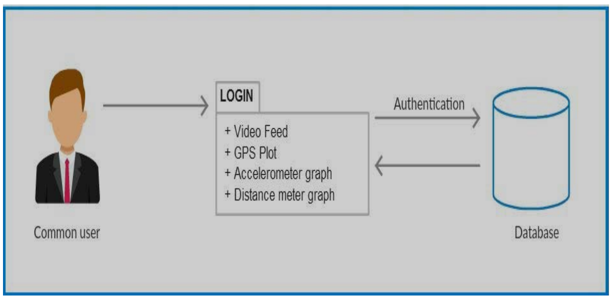

Fig.16. Use case view

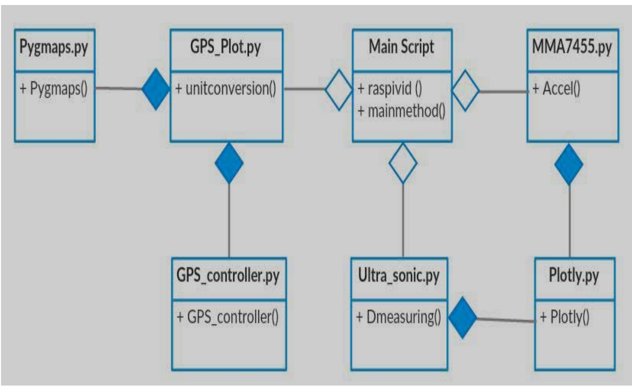

Fig.17. Class diagram of the design

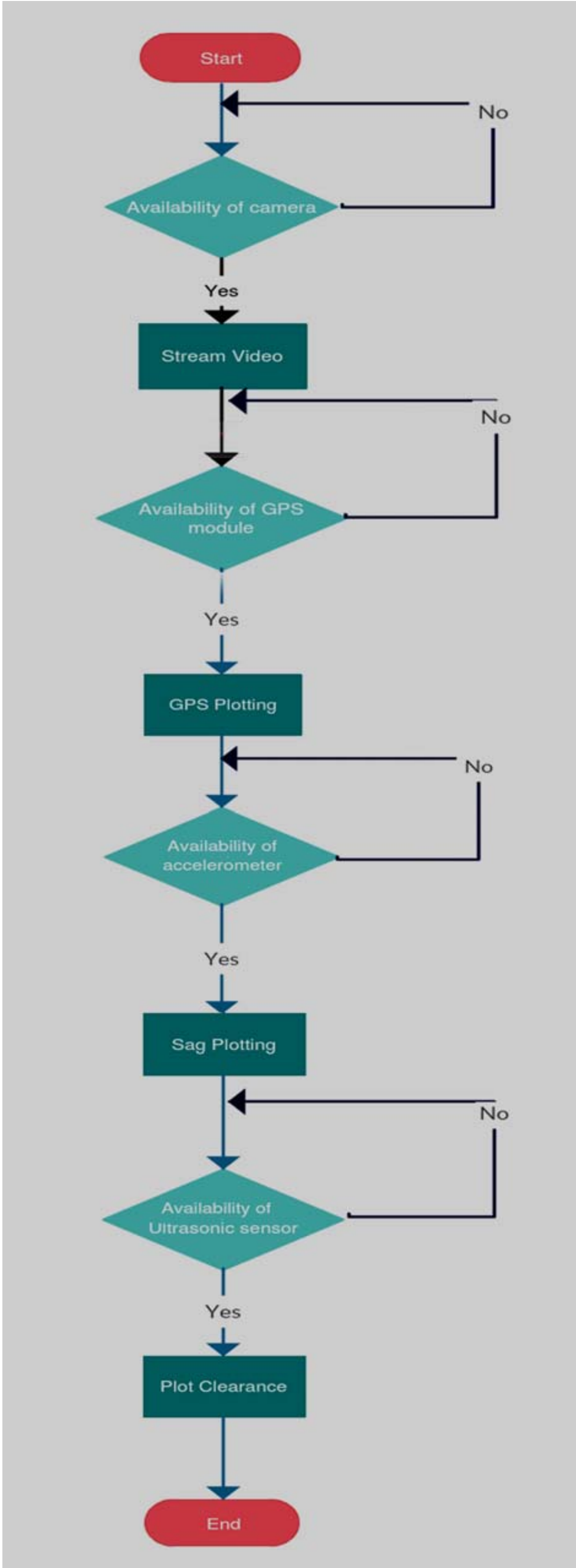

Fig.18. Flow chart of the software design

The operational software design consists of Raspberry pi terminal command for real time video feed, python controllers for GPS, Accelerometer and Distance Measurement.

For real-time video feed raspivid option on Raspberry pi OS is used to obtain the video from the attached pi cam and by using VLC plugin the video is streamed through the WLAN connection. This buffers a high quality video in raspberry pi RAM and allows users to access the content on the network. Because of the quality of the video this method is preferred over JPEG streaming.

When acquiring GPS data, firstly a class is written to allocate device memory and setting up connection with GPS module, then with the obtained GPS data is handled to produce a relatable outcome which is interpreted on Google Maps using pygmaps library. GPS-plot class is used to feed the GPS co-ordinates using a HTML page. The produced HTML page is then hosted at the Raspberry pi and linked to the end user interface.

Ultra Sonic distance measuring is used to determine the ground clearance level. Ultra sonic distance data is acquired from GPIO pins from the Raspberry pi and fed to an online plotting API, Plotly. Ultra-sonic class uses plotly libraries to connect to plotly API, forwarding the real time data to Plotly server. User credentials and a streaming token is used to produce the plotly queries and generate the streaming URL. This URL is embedded at the End User Interface to view the online plotting details.

Above procedure is repeated for the acquired accelerometer data. 'Accelo' class is written to obtain the raw data from the sensor and calibrate the sensor for its proper operation while connecting to Plotly API. Streaming is done as described above.

The Final script assembles all the classes and implements them together simultaneously. It also runs the required background services such as 'gpsd' and 'tomcat' server. This gives a centralized control for the user to deploy the services of the robot.

VII. FIELD TESTING

A. Results of Experiments

1) Outdoor Testing

The ROV prototype was tested in a testing environment for its proper operation.

- Speed: 5.655 m/min, the robot can complete a 300 m long single span inspection within 53.05 minutes.
- Operation on inclined lines: The robot was able to climb cables with an inclination of up to 30 degrees. Since the wheels were made of Nylon, it was able to operate without the interference from slippage of the wheels. But at the top of the sag, slippage of wheels occurred. This issue can be corrected by enhancing the friction through including trails on the wheel surface.
- Data analyzing: All the data including sag template, GPS location, video feed and ground clearance was successfully fed into the GUI.
- The video feed was obtained from the VLC plug-in very clearly and accurately.

2) Electromagnetic Shield Testing:

The prototype was tested for proper operation of its electromagnetic shield with a 220 V: 100 kV step up transformer, which was available in the high voltage laboratory where the tests were conducted as illustrated in Fig 19. The robot was mounted on a Lynx conductor using insulation rods and a measuring capacitor of 100 pF is used as they are well-suited for the reduction of high alternating voltages to values easily measurable with instruments.

A spark was observed when the voltage reached 56.2 kV between a non-insulated nut on the top of the structure and the conductor. This restriction could be addressed by insulating all the nuts and metallic pieces with epoxy resin [6].

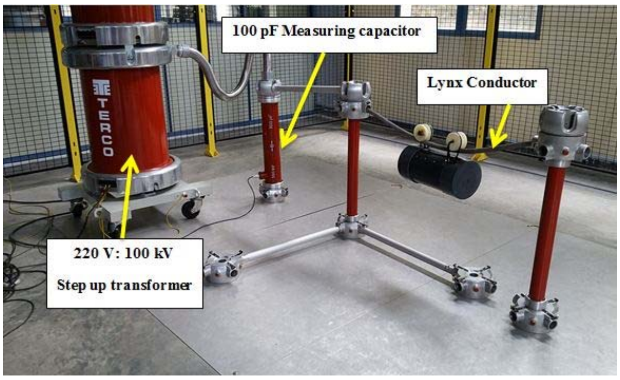

Fig.19. Testing apparatus for electromagnetic shield operation

VIII. CONCLUSIONS

A prototype of high voltage transmission line inspection robot was developed with higher reliability and higher accuracy with minimal cost using available resources. This prototype can be operated up to 56 kV at any weather condition on Lynx conductor, which is the mostly used conductor type in Sri Lanka. This system is capable of transmitting a live video feed, sag template, ground clearance map and the GPS location of the robot positioning. The magnetic field energy harvesting unit is capable of recharging the battery used in the ROV and provides a low cost solution than renewable energy sources. The implemented prototype proves the feasibility of adopting autonomous systems in transmission line inspection and fault detection.

The proposed design is supposed to be operated in a single span. But for the industrial applications, span to span operation is a compulsory requirement. Therefore, an

DOI 10.5013/IJSSST.a.17.32.14 ISSN: 1473-804x online, 1473-8031 print

enhanced structure should be designed which consists of three wheels to successfully operate on multiple spans.

The ground clearance is expected to be in a standard range of 15-20 m. Hence a sensor with more than 20 m is required. Currently the prototype operates with an ultra-sonic sensor which has a maximum range of 5 m. Therefore to achieve the required range with actual transmission lines, high precision LIDAR system [7] can be implemented.

Another major aspect of this design is to inspect insulator and transmission line conductor conditions. Currently the prototype is equipped with a single camera with a fish eye lens in front. More cameras can be installed at the back and top of the ROV structure to improve the perspective. The communication ranges can be further extended with the use of RF modules and installing long range antennas at both ends. For industrial applications a better magnetic shield can be implemented as mentioned in [8].

REFERENCES

[1] Paulo Debenest, Michele Guarnieri, Kensuke Takita1, Edwardo F. Fukushima,Shigeo Hirose, Kiyoshi Tamura, Akihiro Kimura, Hiroshi Kubokawa, Narumi Iwama4 and Fuminori Shiga, Expliner Robot for Inspection of Transmission Lines,2008 IEEE International Conference on Robotics and Automation Pasadena, CA, USA, May 19-23, 2008.

[2] Xiaohui Xiao, Gongping Wu, and Sanping Li, Dynamic Coupling Simulation of a Power Transmission Line Inspection Robot with its Flexible Moving Path when Overcoming Obstacles, Proceedings of the 3rd Annual IEEE Conference on Automation Science and Engineering Scottsdale, AZ, USA, Sept 22-25, 2007.

[3] Magnetic Shielding Materials : Magnetic Properties [Online], Available :http://www.amuneal.com/magnetic-shielding/theory-design/magneticshielding-materials.

[4] Peter Sergeant, Mauro Zucca, Luc Dupr, and Paolo Emilio Roccato: Magnetic Shielding of a Cylindrical Shield in Nonlinear Hysteretic Material, IEEE Transactions on Magnetics, VOL. 42, NO. 10, October 2006.

[5] W.M.M.S.C. Perera, U.L.J.T. Perera, T.U. Malaviarachchi and P.S. Ranaweera: ”Developing a Power Generation Technique for High Voltage Environments through Electromagnetic Energy Harvesting”, Third Annual Research Symposium (ARS 2016) of Faculty of Engineering, University of Ruhuna, Sri Lanka, E/14, 14 January 2016.

[6] Imai.T, Sawa F. , Ozaki T., Shimizu T. , Kido R., Kozako M., Tanaka T., Evaluation of insulation properties of epoxy resin with nano-scale silica particles, in proc. of 2005 International Symposium on Electrical Insulating Materials, 2005 (ISEIM 2005), 239 - 242 Vol. 1, 5-9 June 2005.

[7] How LIDAR works homepage on LIDAR-UK. [Online]. Available: http://www.lidar-uk.com/how-lidar-works/.

[8] Devender; Ramasamy, S.R., ”A review of EMI shielding and suppression materials,” in Electromagnetic Interference and Compatibility ’97. Proceedings of the International Conference on , vol., no., pp.459-466, 3-5 Dec 1997, doi: 10.1109/ICEMIC.1997.669850.