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Measurement of Power Line Sagging Using Sensor Data of a Power Line Inspection Robot

AYDIN TARIK ZENGİN¹, GOKHAN ERDEMİR², TAHIR CETIN AKINCI³,
AND SERHAT SEKER³

¹Department of Computer Engineering, Istanbul Sabahattin Zaim University, 34303 Istanbul, Turkey

²Department of Electrical and Electronics Engineering, Istanbul Sabahattin Zaim University, 34303 Istanbul, Turkey

³Department of Electrical Engineering, Istanbul Technical University, 34467 Istanbul, Turkey

Corresponding author: Aydin Tarik Zengin (tarik.zengin@izu.edu.tr)

ABSTRACT The operation of energy transmission lines with high efficiency without failure has great importance in today's electricity-dependent world. Problems that may occur in electricity transmission lines are failure cause of many operations not only industrial but also daily life. One of the most important causes of the problems encountered in power lines is the change in the amount of sagging. The change of sagging amount causes line breaks and losing energy efficiency. This problem, which is frequently encountered due to seasonal and climatic changes, is one of the major problems of continuity in the power line. The calculation of sag contains uncertain and variable parameters that can change seasonally, climatically and/or structurally such as weight per unit length of the conductor, the horizontal component of tension, total tension, etc. In this case, it is difficult to calculate a precise and reliable sag amount. The sagging of power lines is generally calculated theoretically or measured on-site by the personnel in charge. In this study, a new approach is presented to measure the sag amount by using sensor data of a power line inspection robot, precisely and reliably. The inspection robot moving on the power line can be remotely controlled and send sensor data. The sagging is measured with an error of less than 2 percent in the laboratory test field by using this technique.

INDEX TERMS Power line inspection, line sag, line inspection robot.

I. INTRODUCTION

Overhead lines are the backbones of every electrical power transmission and distribution system [1]. The lines carried by the poles in the energy transmission lines play the most significant role in the transportation of energy from the power generation facilities to the end-users [2]–[4]. Since there are no dense residential areas and populations around the power plants, energy must be transmitted to long distances. There are various technical procedures in transporting energy from power stations to end-users. These procedures are studied both electrically and mechanically. Mechanical properties include the line properties to increase the mechanical strength of the posts and lines carrying the energy line. Electrical features include pole height, line cross-section, and related parameters. In addition, different analyzes are carried out for conducting economic analyzes so that energy transmission

lines can transmit energy in a sustainable, safe and economical way, and for the poles to be transported to the appropriate geography at the least cost and in the shortest distance [5]–[8]. As is known, the energy produced in power plants should be delivered to users and cities with the shortest distance. Here, procedures such as renting or purchasing the land on which electricity poles will be located are also made at the planning stage. The power pole and transmission line costs must be high, these components fail less, and they are designed and planned to require less maintenance [7]–[10]. Power lines are fixed on poles, and this fixation is made according to certain criteria. The parameters are evaluated according to whether the electric transmission line fixed on the insulators in the selected pole is primarily in the city center or outside the center. These evaluations are listed below:

- The transmission lines should be designed in a way not to harm living life. This design and evaluation should be in a way to reduce both the height of the conductor and the damages of electromagnetic effects [11]–[13].

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- The energy transmission line should be the shortest, safest, and most economical in terms of length and location.
- The route of the energy transmission line should be designed by considering the lease-purchase, risk of life, and economic criteria.
- The route of the energy transmission line must be close to the existing transportation arteries so that it can be reached quickly in case of failure [14]–[16].
- The components on the transmission line should be selected from the longest lasting and highest quality materials to require less maintenance and more failure.
- Energy transmission lines and transmission components should be selected according to the atmospheric conditions of the region. (In particular, very hot, cold, windy, and pulsating regions should be identified, and projects should be prepared according to this determination) [17]–[19].

Along with all these general rules, the length, diameter, and mechanical and electrical properties of the electricity transmission line should be determined separately [20]. Although all these parameters are determined by international standards, each country differs according to its climate conditions, electricity network structure, and the experience of expert personnel. These standards include maximum wind, ice load (varies according to the climatic characteristics of these countries). The electricity transmission line's electrical properties are the recommendations of expert technical personnel [21]–[23]. The components that make up the electric pole have different strength properties; this difference plays an active role in sagging. This situation does not generally comply with the parameters table and should be taken into consideration by expert staff. The design of the pole mechanics in the lines [24] and the project of the energy transmission line is an engineering work that requires long experience. In the energy transmission lines, sagging is observed due to the weight of the transmission line stretched between the insulators and the effects of the climatic conditions [21]–[23]. The distance between these two insulators between the assumed straight line and the point where the conductor stretches the most is called sagging.

The power transmission robot by Yong *et al.* has been used to detect deformations in energy transmission lines [25]. This study can be used especially to detect fire and major deformations. The robot made by Li and Ruan [26] and Cao *et al.* [27] is designed to perform mechanical tasks. In the study conducted by Zhibin *et al.*, a method was proposed to overcome the obstacles encountered by the robot while moving on the power line [28]. In recent years, the overall work has been done to detect obstacles on transmission lines with camera applications [29]–[31]. Some studies focus on determining the static characters of the transmission system [32]. A survey on robotic studies in electric power transmission lines examined all studies in the literature [33]. When the studies here are examined, it is seen that our study differs from the others in design and application. No other study was

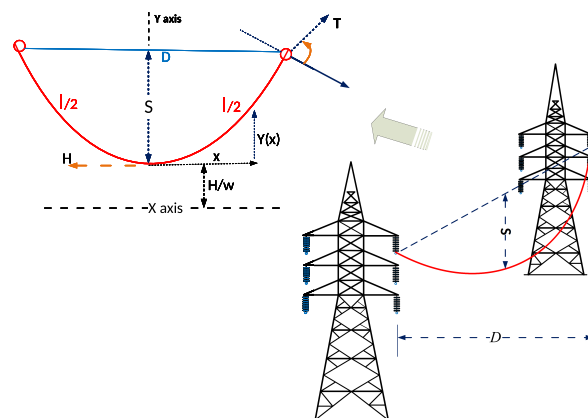


FIGURE 1. Schematic representation of sagging occurring in the electric power transmission line.

found where sagging on power lines was measured using an inspection robot.

In this study, a new approach is presented to measure the sag amount by using a line inspection robot is proposed. In Section II, the classical sag calculation is explained. Then the materials and methods are described in Section III. In Section IV, the experimental results performed in the laboratory test field are presented. Finally, conclusions are presented in Section V.

II. SAG THEORY

Transmission and distribution systems constitute an essential part of electrical power systems. Transmission lines cover the section from power generation plants to distribution stations. Transmission lines with lower voltage levels are also used in the sections after the distribution stations. In this study, a developed robot was made to detect excessive sagging in the transmission lines and to communicate this fault to the technical personnel with its location. Definitions in this study;

- Clearance: It is the horizontal distance between two insulators.
- Sag: The term “sag” can be defined as the distance between the midpoint of the strained transmission line between the two insulators and the assumed direct line between the insulators. In Figure 1, the necessary formulas for the conductor lying on the insulators are given in Equation 1. As shown in Figure 1, the distance between the poles is denoted by D . S is the sagging of the conductor [9].
- Tangent Tension: The actual Tangent Tension direction of any point in a transmission line is calculated by drawing a tangent to the conductor's curve at that point.
- Tension: The Electric Power system shows the horizontal component of the tension in the transmission line of the transmission line, where the horizontal tension is equal at each opening.

In electric power systems, the electrical drain of the transmission line is closely related to the change of the passing load current. However, the transmission line may also

heat with the effect of the magnetic warming skin effect [9], [15]. In sagging calculations, the slope of the line is calculated using a parabolic equation (catenary). In calculations made here, its share is neglected. Since the parabolic approach is used, the error is rather small, except for very long, steep or deep openings. The parameters of the parabolic equation (sagging, tension, weight, and span length) are given in Figure 1 [9], [15].

Another part of the work done on electrical power systems is installing electrical poles and mechanical parts in the field. This project is based on the geographical location of the production facilities and distribution facilities. Geographical conditions of the land may create elevation differences in poles; in this case, it may increase sagging in conductors [20], [23]. The connection point of the two ends of the electricity transmission line to the pole is called the level range. The opening at the connection points with different elevation heights is called the oblique opening. Equation 1 and Equation 2 are used for catenary calculations [9], [23].

$$y(x) = \frac{H}{w} \left[\cosh\left(\frac{wx}{H}\right) - 1 \right] \quad (1)$$

$$y \cong \frac{wx^2}{2H} \quad (2)$$

where H is the horizontal component of tension (N), w is the weight per unit length of conductor (N/m), x is the horizontal distance from the lowest point (m), $y(x)$ is the vertical distance from the lowest point at x (m).

The common equation used for the sagging calculation is the Parabolic approach, as given in Equation 3. In Equation 4, sagging is given as a function of line and span length. Calculations assume that the transmission line is under ideal flexibility conditions [9], [34]–[36].

$$S = \frac{wD^2}{8H} \quad (3)$$

$$S = \sqrt{\frac{3S(L - D)}{8}} \quad (4)$$

where S is sag (m), D is span length (m), L is line length (m), H is the horizontal component of tension (N), T is total tension (N), w is the weight per unit length of conductor (N/m).

There are many studies in the literature on sagging calculation and measurement [23], [37], [38]. However, although there are no studies in the literature that detect sagging with robots in the transmission line, there are some studies that solve sagging and other mechanical problems by robotic methods [5], [39]–[41]. There is also a study in the literature on a device that stands on the transmission line and measures sagging [42]. Precision measurement of the sag is related to sensor quality. The limitation of this study is that the sensitivity of the sensors operating under high voltage environment over time decreases. Therefore, sensor errors must be compensated. Briefly, many uncertain and variable parameters are used in the calculation of sagging. Under these circumstances, it is difficult to measure the sagging ratio instantly and precisely. In this study, a new approach is presented to measure the sag amount by using a line inspection

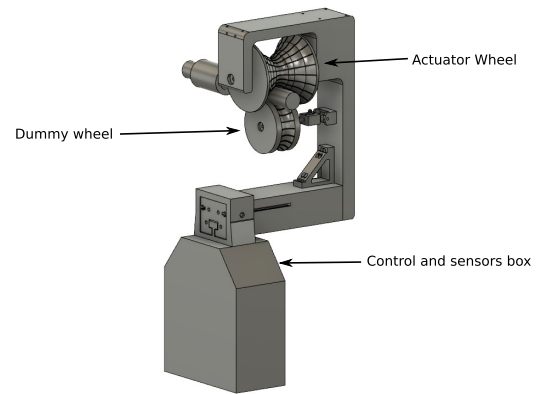


FIGURE 2. 3D model of ROSETLineBot.



FIGURE 3. RoSeTLineBot moving on the power line in the lab test field.

robot during a line maintenance operation. In the following section, introduced methods will be explained in detail.

III. MATERIALS AND METHODS

Materials and methods will be given in two chapters. First, the line inspection robot and its control interface will be shown. Then the data retrieval process will be explained.

A. ROSETLineBot: THE POWER LINE INSPECTION ROBOT

A robot named RoSeTLineBot to inspect overhead lines was previously developed by the authors [43]. In that study, the mechanical structure of the robot was given in detail. A 3D model of the system and several photos of the robot from different perspectives are shown in Figure 2 and Figure 3, respectively. In the previous research, the control

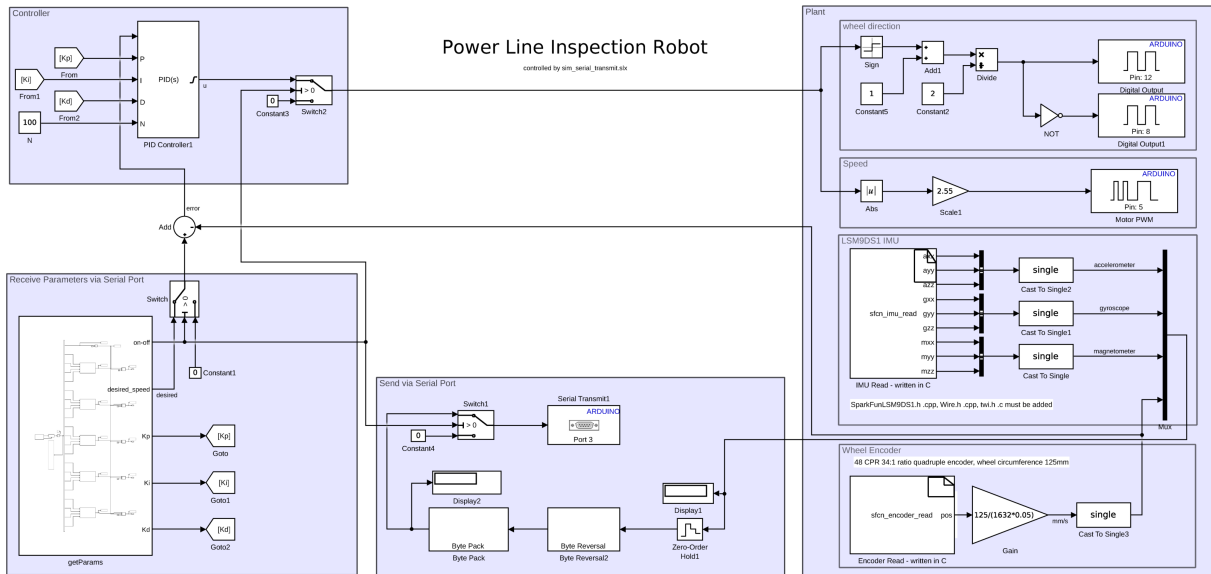


FIGURE 4. Robot controller design in Simulink.

system was developed at a basic level to demonstrate the operation of the system.

In this study, the algorithm was redesigned entirely on Matlab/Simulink to improve the control system’s accuracy and controllability. The embedded software running on the robot is completely designed with Simulink, as shown in Figure 4. Some blocks are coded in C language manually. The model compiled using the MATLAB Coder tool is embedded in the microcontroller, and the system can be controlled remotely. Remote access was achieved through Xbee modules connected to both the robot and the PC.

Plant block defines the robot as a Hardware in the Loop (HIL) system. *Wheel Direction* and *Speed* subblocks determine which direction and speed the robot will move with respect to the control signal created by the *Controller* block. *Receive Parameters via Serial Port* block received control parameters of PID controller, which also applied the on-off signal for the entire system. All the necessary parameters were received in the hex format and recreated by the *getParams* block. Similarly, data to be sent to the remote PC were serialized and converted to hex bytes by the *Send via Serial Port* block. *IMU Read* and *Encoder Read* subblocks acquired sensor data and were written in C language.

A control interface has been developed in Simulink as well, to collect data from the system remotely, and send the necessary parameters and commands from PC to robot. The control interface is shown in Figure 5. Interface sent the control parameters through Xbee connected to the PC USB port and received the measured data through the same channel. Live data was being saved to Matlab workspace in real-time. *Transmit* block prepares the data pack consisting of control system parameters and on-off signal. *Receive* block parses the byte-array, which sent by the robot, and saves it to Matlab Workspace for further analysis.

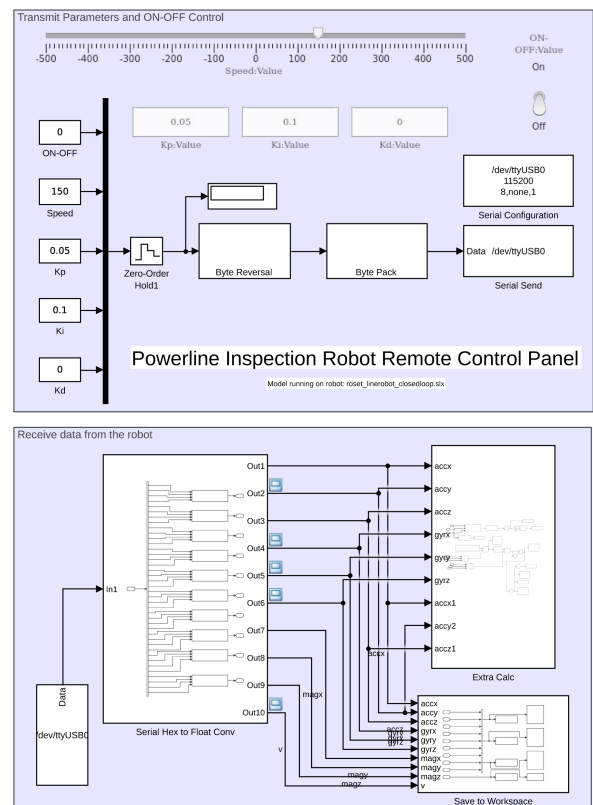


FIGURE 5. Robot control interface in Simulink.

B. DATA RETRIEVAL AND PROCESSING

While driving on the line, wireless data was continuously received from the robot. Both IMU and encoder data connected to the rotor were continuously sent to the control interface. The block diagram of the system is given in Figure 6. ATmega2560 was used as the main controller unit (MCU)

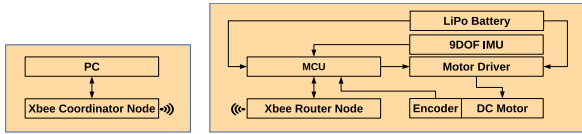


FIGURE 6. Block diagram of system.

in this system. Both the controller and motor were powered by a 3S LiPo battery of 11.1V. XBee modules were set up as Coordinator and Router for the PC side and robot, respectively. Acceleration data were processed to obtain speed and position, respectively. Since the movement on line created a substantial amount of vibration, and the acceleration sensor had a serious sensor-shift, pure measurement was not enough to calculate the displacement. Therefore, we proposed a method to filter the noise and detrend the sensor-shift. Equation 5 and Equation 6 show how the data is processed, where $\omega[n]$ was the cosine-tapered window, $a(\tau)$ was the measured acceleration, $v(\tau)_{dt}$ was the detrended value of velocity and $x(t)$ was the calculated displacement.

$$v(t) = v_0 + \int_0^t [\omega[n]a(\tau)] d\tau \tag{5}$$

$$x(t) = \omega[n] \left[x_0 + \int_0^t [\omega[n]v(\tau)_{dt} d\tau] \right] \tag{6}$$

IV. CASE STUDY

The experimental study was performed in the lab test field in which specifications are shown in Figure 7. Data was collected by driving ROSETLineBot along the test line, which was connected between two walls 13.7 [m] apart. The actual sag was 40.3 [cm] at the midpoint of the power line.

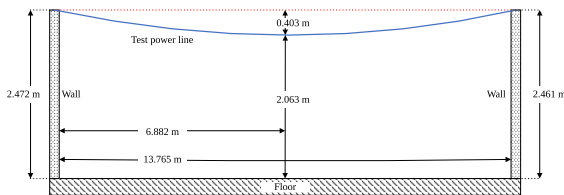


FIGURE 7. Dimensions of the lab test field.

The power line sag measured by the ROSETLineBot presented in this study is shown in Figure 8. The motion of the robot was measured with accelerometer and position change was calculated by two consecutive cumulative trapezoidal numerical integration. After each integration, data were detrended to compensate for the sensor shift and filtered with a cosine-tapered window with a 0.9 taper ratio. Measured sag was between 39.3 [cm] and 40.5 [cm]. According to the test result, the proposed system measured the actual sag amount of less than 2% error.

V. DISCUSSION

In their study, Wale and Sandeep detect the transmission line’s malfunctions with the cameras on the robot and

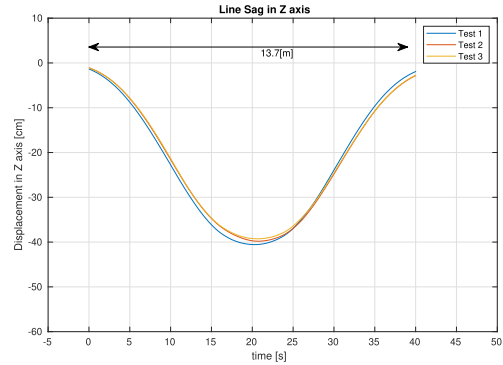


FIGURE 8. Line sag measurement by the RoSeTLineBot.

transmit them to the service center with the GPS module [44]. In the study conducted by Debenest *et al.*, A robot that can move on energy transmission lines was designed, and the robot was controlled remotely to move on hard-to-reach areas [45]. In their study, Golightly and Jones have made an application that can move on energy transmission lines and shoot with the camera [46]. In other studies, robots capable of moving on energy transmission lines that have the ability to transmit images taken by a video camera have been designed [47]–[51]. Although the robots designed in all these studies differ mechanically, they pioneer today’s work and generally transmit video recordings to service centers while moving on the transmission line. The most important difference of this study compared to other studies is that it sends all data collected from the sensors to the central computer in real-time while the robot is moving on the transmission line and can detect sagging and other possible faults such as obstacle, icing, etc. on the line. In this sense, with this feature, this study differs from other studies in the literature.

VI. CONCLUSION

The calculation of sag contains uncertain and variable parameters that can change seasonally, climatically, and/or structurally, such as by weight per unit length of the conductor, the horizontal component of tension, total tension, etc. Hence, assumptions must be made in calculation parameters because of many of them depending on environmental and structural factors. The proposed technique offers a lower error ratio than the classical calculation method. The main reason for this is that the proposed technique does not use uncertain and changeable parameters, but actual measurement. The robot collects actual data and then calculate sag value, during a line inspection process, simultaneously. According to the test result, the actual sag value has been calculated less than a 2% error by using the proposed technique. The test result confirmed that the proposed technique could measure precisely and reliably. Robot’s transition from one line to another is planned as future work. To achieve this, new mechanical design studies have started. Also, in the next study, additional sensors will be placed, and sound analysis will be made for corona discharge measurement on the line.

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AYDIN TARIK ZENGİN received the B.S. degree in electrical and electronics engineering from Ege University, Turkey, in 2007, and the M.E. and Ph.D. degrees from the Department of Computer Science and Electrical Engineering, Kumamoto University, Japan, in 2010 and 2013, respectively. He is currently an Assistant Professor with Istanbul Sabahattin Zaim University. His research interests include autonomous systems and control theory.



GOKHAN ERDEMİR received the B.Sc., M.Sc., and Ph.D. degrees from Marmara University, Turkey. He was a Research Scholar with the Department of Electrical and Computer, Michigan State University, East Lansing, MI, USA. He joined the Health Management and Research Center, University of Michigan, Ann Arbor, as a Project-Based Researcher. He is currently an Assistant Professor with the Department of Electrical and Electronics Engineering, Istanbul Sabahattin Zaim University. His research interests include robotics, mobile robotics, control systems, and intelligent algorithms.



TAHIR CETİN AKINCI received the B.S. degree in electrical engineering, and the M.Sc. and Ph.D. degrees from Marmara University, Istanbul, Turkey. He was an Associate Professor with the Electrical Engineering Department, Istanbul Technical University (ITU), Istanbul. His research interests include artificial neural networks, deep learning, machine learning, image processing, signal processing, and data analysis.



SERHAT SEKER graduated from the Electrical Engineering Department, Istanbul Technical University (ITU). He received the master's degree from the Nuclear Energy Institute, ITU, and the Ph.D. degree from the Electrical Engineering Division, Science and Technology Institute, ITU. He studied the Ph.D. thesis with the Energy Research Centre of the Netherlands (ECN) and worked on signal analysis techniques. He was an Assistant Professor and an Associate Professor with ITU, in 1995 and 1996, respectively. He worked in industrial signal processing with the Maintenance and Reliability Centre, Nuclear Engineering Department, The University of Tennessee, Knoxville, TN, USA, in 1997. He was the Vice Dean with the Electrical and Electronic Engineering Faculty, from 2001 to 2004, and the Department Head of the Electrical Engineering, from 2004 to 2007. He was also the Dean of the Faculty of Electrical and Electronics, from 2013 to 2020.

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