A DYNAMIC DESIGN ON PORTABLE, LIGHT AND FASTER ALUMINUM-BASED CLIMB-SLIDING INSPECTION ROBOT FOR POWER TRANSMISSION LINE

Ahmad Bala Alhassan¹, Xiaodong Zhang¹,², Haiming Shen¹, Jian Guo¹ and Khaled Hamza¹
¹School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an 710049, China
²Shaanxi Key Laboratory of Intelligent Robot, Xi’an Jiaotong University, Xi’an 710049, China
amadkabo@126.com, xdzhang@xjtu.edu.cn, shenhaiming@stu.xjtu.edu.cn, 1303263182@qq.com

Abstract: Efficient and uninterrupted transmission of power from generation stations to consumers is crucial for the development of any country. This paper presents the dynamic design on portable, light and faster aluminum-based robot for safe, cost-effective and reliable inspection of power lines. Unlike the existing robots which are slow and heavy, the proposed two arm aluminum 6061 based robot designed using SOLIDWORKS is fast, portable and inexpensive. The designed concept has been actualized into a real lab-scale robot. To investigate the dynamic behavior of the robot, the mechanical properties of the robot were used to represent the system in a mass-spring-damper configuration. The Lagrange’s equation was used to derive the mathematical equations of the robot. In addition, MATLAB was utilized for the simulation analysis of the robot under different operating conditions. Finally, a bang-bang input was used to drive the robot along the power line in real-time. The simulations and experimental results show that the designed climb-sliding robot has been successfully implemented and can be used for power line inspection.

Keywords – Lagrange equation; MATLAB simulation; Power transmission line inspection; Service robot; SOLIDWORKS; Vibration analysis

1. INTRODUCTION

The demand for an uninterrupted power supply by industries, government institutions, and the general population has been ever-increasing due to global population growth and technological development. Thus, the need for reliable and efficient inspection of the transmission lines has been a major concern by the power transmission companies. Manual inspection of transmission power lines has been extremely difficult due to the fact that, transmission lines are exposed to harsh weather condition and normally passed across the mountainous area, water bodies and thick forest [1-4].

Power transmission line inspection robots (PTLIRs) are designed to replace the costly, time consuming and unsecured traditional manual inspection techniques that employed the use of human operators. The main purpose of any inspection techniques is to assess the running conditions and detect any potential damage to the transmission lines or its supporting components. At present, researchers focus on two unmanned inspection robots, namely, flying robots and climb-sliding robots [2, 5]. The climbing-sliding robot can climb and slide on the overhead transmission line and autonomously avoid obstacles (towers, clamps, aircraft warning balls) and most importantly inspect the lines. On the one hand, the flying robot uses the flying ability to inspect the lines and its mechanism is more complex as compared to the climbing robot, because it has to be at some distance from the transmission line without touching the transmission line. Thus, this affects the quality of the inspection data recorded.

The major advantage of the flying robot is its ability to avoid obstacle quickly and accurately as compared to the climbing robot that involves a lot of slow maneuvers. Though the climbing robots are simple to design as compared to flying robot, they are not readily available in the market. So, they must be built from scratch before employed in the field, whereas the flying robots are already available in the market which only requires little modification to serve the intended purpose [6-7]. The main advantage of a sliding robot is that it gives detailed and more accurate inspection data as compared to the flying robot.

Over the past couple of years, researchers and research institutes have remarkably focused in the field of robotics, particularly the power line inspection robots. An unmanned autonomous helicopter based smart copter for inspecting power line has been presented in [8]. This robot utilizes the visible light camera and an infrared camera for the line inspection. One of the first climb-sliding inspection robot prototypes designed for transmission lines is presented in [9]. However, this robot has a lot of limitations including a stability problem. However, significant progress has been made for the design of such robots with obstacle avoidance mechanism as presented in [10-12].

In addition, three research institutes were on the front line of the power line inspection revolution. The Tokyo power company’s Expliner robot capable of inspecting multiple transmission lines has been proposed in [13-14]. Another advanced robot called Linescout has been designed by Canada hydro-Quebec’s research center [15-16]. Also, the
American electric power institute’s recent developments presented a more portable inspection robot in [17]. This robot is permanently installed on the power line and it sources power from the transmission line. However, it requires modifying the existing power lines by adding extra cables to facilitate the obstacle avoidance mechanism. Thus, this made it a costly approach. Some of the works that focused on the dynamics and simulation of power line inspection robot have been presented in [18-20].

However, the existing PTLIRs are either heavy which made them slow and consumes a lot of energy or have a high running cost, and there are limited mathematical representation and analysis of the robots. In this paper, a portable, light and faster aluminum-based PTLIR is proposed. The designed concept was realized into a lab-scale PTLIR real-time inspection of the power lines. In addition, using the mechanical properties of the robot, the robot was represented as a mass-spring-damper system and therefore modeled using Lagrange’s energy equations.

The mechanical parameters of the robot’s components basically stiffness and damping coefficient were used for the MATLAB simulation analysis of the robot dynamic behavior. The dynamic response of the robot subjected to step input force, frictional force and white noise wind disturbance were analyzed and investigated. These time domain responses provide comprehensive information about the robot dynamic behavior and also for the selection of suitable control strategies for an efficient and effective operation and control of the climb-sliding PTLIR. The designed has been successfully implemented and tested in a lab environment. The real-time experimental results show that the PTLIR can be used for the power line inspection.

This paper is organized as follows. Section II describes the structural design of the robot including software design and mechanical realization. Section III describes the dynamic behavior and parameter estimation of the robot. Section IV discusses the simulation results. In addition, section IV presented the mechanical set-up and experimental verification of the robot. Finally, section VI presented the conclusion and intended future work.

II. STRUCTURAL DESIGN OF THE ROBOT

A. Conceptual design of the climb-sliding PTLIR

The design concept of this study is illustrated in the flowchart of Fig. 1. Unlike the conventional inspection robots that are sliding or flying, the concept of the proposed robot consists of two detachable robots namely climb-sliding robot and flying robot as shown in Fig. 2(a). The main function of the flying robot (FR) is to convey the sliding robot (SR) to the power transmission line (PTL) and take it back to the ground when the inspection is completed. This makes it easier for placing the robot on or off the line and the climb-sliding robot can autonomously inspect the transmission line and avoid obstacles.

![Flowchart of flying-climb-sliding inspection robot](image)

**Fig. 1** Work flow chart of flying-climb-sliding inspection robot.

<table>
<thead>
<tr>
<th>S/ N</th>
<th>Item</th>
<th>Length</th>
<th>Base</th>
<th>Thickness</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>gripper</td>
<td>177mm</td>
<td>150mm</td>
<td>3mm</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>circular pipe</td>
<td>400mm</td>
<td>-</td>
<td>3mm</td>
<td>20mm</td>
</tr>
<tr>
<td>3</td>
<td>Robot trunk</td>
<td>450mm</td>
<td>60mm</td>
<td>3mm</td>
<td>-</td>
</tr>
</tbody>
</table>

In a situation where the obstacle is too big (e.g. tower), the flying robot will be reattached to the climb-sliding robot to avoid the obstacle. The complete robot has a rectangular shape and the dimensions of the individual components are tabulated in Table 1.

However, at this point, we focused on the climb-sliding robot which needs to be designed from scratch. The two-arm climb-sliding robot has two isosceles triangular grippers, two circular pipes arm and a rectangular base which housed the root’s electronics and power supply unit as shown in Fig. 2(b). For motion control, the robot basically consists of six motors; two for the rollers for motion along the line and four for the manipulation of the arms during obstacle avoidance mechanism. Two additional rollers and one safety lock are attached to each gripper for support and smooth motion of the robot especially when the transmission cable sagged or slanted. In addition, a steering engine is installed for navigation and guidance as shown in Fig. 2 (c).

An example of an obstacle avoidance procedure is illustrated in Fig. 3 (a-i) for an airplane warning ball. Initially, when the robot senses an obstacle, the robot unlocks the safety lock of the front roller and use the adjustment motors to open the robot arm to avoid the obstacle as shown in (a-d). The front adjustment motors will then take the roller back and closes the lock. In a similar passion, the rear roller will now open as in (e-f), and the rear adjustment motor will rotate the arm away from the power cable until the obstacle is avoided as in (g). The arm will then be rotated back to the power cable as shown in (h). Finally, the lock will be closed and the robot can continue its motion as shown in (i).
Fig. 2 Structure of the integrated PTLIR: (a) Flying-climb-sliding (b) climb-sliding only (c) rollers and steering engines positions.

Fig. 3 Typical procedures from (a) to (i) for an airplane warning ball obstacle avoidance along the transmission line.
B. **Design of BLDC motors for the climb-sliding PTLIR**

This section presents the types of motors selected for the motion control of this PTLIR. The robot can be powered by an external power source (24V battery) and the supporting circuitries like the motor driver were housed on the robot base. Furthermore, a highly efficient Robomaster brushless DC motor was chosen for the robot motion and rotation. An RM2006 P36 BLDC was installed for each of the two rollers and an RM3508 P19 BLDC was chosen for each of the four joints for manipulations. These motors were selected due to their proven high dynamic response, high efficiency, wide speed ranges, and low maintenance. Also, the motors were controlled by C620 speed controller as prescribed by the manufacturer. The summary of the motors’ characteristics are given by the manufacturer’s data sheet as shown in Table 2 [21].

<table>
<thead>
<tr>
<th>S/N</th>
<th>Parameter</th>
<th>M3508 P19</th>
<th>M2006 P36</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rotational speed (without payload)</td>
<td>482 rpm</td>
<td>500 rpm</td>
</tr>
<tr>
<td>2</td>
<td>current (without payload)</td>
<td>0.78 A</td>
<td>0.6 A</td>
</tr>
<tr>
<td>3</td>
<td>rated rotational Speed</td>
<td>469 rpm</td>
<td>416 rpm</td>
</tr>
<tr>
<td>4</td>
<td>rated torque (continuous torque)</td>
<td>3 N·m</td>
<td>1 N·m</td>
</tr>
<tr>
<td>5</td>
<td>rated current</td>
<td>10 A</td>
<td>3 A</td>
</tr>
</tbody>
</table>

III. **DYNAMIC MODELLING AND PARAMETER ESTIMATION OF THE CLIMB-SLIDING PTLIR**

The derivation of the mathematical model of an inspection line robot is very complex due to its higher number of degree of freedom and the associated nonlinearities. However, this study proposes a new method to model the robot in a mass-spring-damper configuration based on the fact that, a continuous system theoretically having infinite number of degree of freedom can be approximated into a single degree of freedom mass-spring-damper, if the dominant mode can be isolated. That is to say that with known system parameters (damping coefficient and stiffness), the robot can be model and analyze.

A. **Dynamic modelling**

The vertical components of the robots (arm and gripper) are considered to undergo axial tension when the robot moves along the power line. The proposed schematic diagram of the robot is shown in Fig. 4, where $\delta_1$, $\delta_2$ ($\delta_3$, $\delta_4$, $\delta_5$) are the displacements of rear arm of mass $m_1$, a front arm of mass $m_2$ and robot base of mass $M$ respectively in the $y$-direction. $F_1$ and $f_2$, $f_1$, and $f_2$, $f_3$ are the actuator force, frictional force and wind disturbance respectively. Also, $\gamma_1$ and $\gamma_2$ are the input disturbances when the robot immediately lands (climb) on the power line, $\lambda_1$ and $\lambda_2$ are the distance between the center of the robot to the left and right edges of the robot, respectively.

In addition, $c_1$, $k_1$ and $c_2$, $k_2$ are the damping coefficient, stiffness of the rear and front triangular gripper of the robot, respectively. $c_3$, $k_3$ and $c_4$, $k_4$ are the damping coefficient, stiffness of the rear and front circular arm of the robot, respectively. Finally, $\beta$ is the angular displacement of the base of the robot and the robot base has a moment of inertia, $J$ for the rotation about the centre of mass given in [22], as expressed in Eq. (1).

$$J = \frac{M(\lambda_1 + \lambda_2)}{12}$$  \hspace{1cm} (1)

Moreover, All Aluminum Alloy (AAA) which is one of the most common power transmission cables is considered in this study and while the robot is made from aluminum 6061, the coupling force between the robot and the power cable is the frictional force. Thus, the climb-sliding robot will experience undesirable vibrations during two operating scenarios;

(i) **Climb operation**: This operation resulted when the robot grasped the power line and thus, the robot will vibrate due to vertical displacements ($\gamma_1$ and $\gamma_2$) caused by the combined mass of the robot ($m_1+m_2+M$) and the gravitational acceleration ($g$).

(ii) **Sliding operation**: After the robot grasped and landed on the line, the robot then slides along the line using two rollers powered by the actuator force ($f_1$ and $f_2$). However, the motion could be affected by two factors; wind disturbance which can be in same or opposite direction of motion of the robot ($\pm f_{w}$) and the kinetic friction ($\mu N$) where $N$ is the normal force and $\mu$ is the friction coefficient.

The Lagrange Equation given in [19] was used for deriving the mathematical equations of the robot as expressed in Eq. (2).

$$\frac{d}{dt} \left( \frac{dT}{dq_i} \right) - \frac{dT}{dq_i} + \frac{dT}{dq_i} = Q_i ; \hspace{1cm} i = 1, 2, 3...n$$  \hspace{1cm} (2)

where $q_i$ is the independent generalized coordinate, $Q_i$ is the total non-conservative generalized forces including external...
forces, frictional forces and damping forces, and $T$ is the kinetic energy of the system with $n$ coordinate points given in Eq. (3).

$$T = \sum_{i=1}^{n} \frac{1}{2} m_i \dot{q}_i^2$$

(3)

and $U$ is the potential energy consisting of energies due to gravity and elastic potential as given in Eq. (4).

$$U = \sum_{i=1}^{n} \left( \frac{1}{2} k_i q_i^2 + m_i g h_i \right)$$

(4)

where $h$ is the height from mass center to a reference point. The total kinetic and potential energies of the robot are given in Eqs. (5) and (6) respectively.

$$T = \frac{1}{2} m_i \dot{q}_i^2 + \frac{1}{2} m_j \dot{q}_j^2 + \frac{1}{2} M \dot{\delta}_5^2 + \frac{1}{2} J \dot{\beta}^2$$

(5)

$$U = \frac{1}{2} (k_1 (\delta_1 - \gamma_1)^2 + k_2 (\delta_2 - \gamma_2)^2 + k_3 (\delta_3 - \delta_1)^2 + k_4 (\delta_4 - \delta_2)^2)$$

(6)

In addition, at equilibrium, $\delta_1 = \delta_3 = \delta_5$, however in the presence of external excitation, $\delta_3$ and $\delta_5$ changes as shown in Eq. (7).

$$\dot{\delta}_3 = \dot{\delta}_4 - \lambda_1 \beta ; \quad \dot{\delta}_5 = \dot{\delta}_4 + \lambda_2 \beta$$

(7)

Thus, for the four coordinates points, i.e $q_1 = \delta_1 , \ q_2 = \delta_3$, $q_3 = \delta_4$ and $q_4 = \beta$, the terms of Eq. (2) can be calculated. Hence, solving for Eq. (2) for all the four coordinates yields the second order dynamic equations for $m_1$, $m_2$, $M$ and $J$ of the complete robot respectively as expressed in Eq. (11) - (14).

$$m_1 \ddot{\delta}_1(t) + (k_1 + k_3) \ddot{\delta}_1(t) + (c_1 + c_3) \ddot{\delta}_1(t) - k_1 \gamma_1(t)$$

$$-c_1 \dot{\gamma}_1(t) - k_1 \dot{\delta}_1(t) - c_3 \dot{\delta}_1(t) + \lambda_1 k_2 \beta(t)$$

$$+ \lambda_2 c_3 \dot{\beta}(t) = f_1 - f_{w1} \pm f_{w2} + m_2 g$$

(11)

$$m_2 \ddot{\delta}_2(t) + (k_2 + k_4) \ddot{\delta}_2(t) + (c_2 + c_4) \ddot{\delta}_2(t) - k_2 \gamma_2(t)$$

$$-c_2 \dot{\gamma}_2(t) - k_2 \dot{\delta}_2(t) - c_4 \dot{\delta}_2(t) - \lambda_1 k_4 \beta(t)$$

$$- \lambda_2 c_4 \dot{\beta}(t) = f_2 - f_{w1} \pm f_{w2} + m_2 g$$

(12)

$$M \ddot{\delta}_5(t) + (k_3 + k_4) \ddot{\delta}_5(t) + (c_3 + c_4) \ddot{\delta}_5(t) - k_3 \delta_5(t)$$

$$-c_3 \dot{\delta}_5(t) - k_3 \dot{\delta}_5(t) - c_4 \dot{\delta}_5(t) - \lambda_1 k_4 \beta(t)$$

$$- \lambda_2 c_4 \dot{\beta}(t) = f_1 - f_{w1} \pm f_{w2} + f_{r1} + f_{r2}$$

$$\pm f_{w1} + M g$$

$$J \dot{\beta}(t) + (\lambda_1 c_4 + \lambda_2 c_2) \dot{\beta}(t) + (\lambda_1 k_4 + \lambda_2 k_2) \dot{\beta}(t)$$

$$- (\lambda_1 c_2 k_4 \dot{\delta}_2(t) + \lambda_2 c_4 k_2 \dot{\delta}_2(t) + \lambda_1 k_4 \dot{\delta}_2(t)$$

$$+ \lambda_2 c_2 \dot{\delta}_2(t) = - \lambda_1 (f_1 - f_{w1}) + \lambda_2 (f_2 - f_{w2})$$

(13)

$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$y(t) = Cx(t)$$

(15)

B. Parameter Estimation

The required parameters for the analysis are the damping coefficient ($c$) and stiffness ($k$). However, if one parameter is identified, the other can be analytically calculated using mathematical relations and the most common method for mechanical modal identification is the impact hammer test. The test uses a specialized hammer to impact a known force at different points on the structure and the corresponding vibratory responses are recorded using an accelerometer. Frequency response function (FRF) is normally used to analyze the recorded data for the parameters identification. This experiment was conducted on a similar aluminum material and a damping ratio of 0.35% was obtained as comprehensively presented in [24].

In addition, the Young modulus which describes the characteristics of the constituent element has a constant value and its value for aluminum 6061 is 68.9GPa [25]. The coefficient of friction for aluminum rolling on the aluminum metal of 0.34 was adopted in this work as determined in [26]. Also, the expression of stiffness for a solid shape under tension or compression and the damping coefficient is respectively given in [22] as expressed in Eqs. (17)-(18).

\[ k = \frac{AE}{L} \]  
(17)

\[ c = 2\zeta \sqrt{km} \]  
(18)

where \( A \) is the cross-sectional area, \( E \) is the Young’s Modulus, \( L \) is the length of the element, \( \zeta \) is the damping ratio and \( m \) is the mass of the element. With the known area of the robot components, the parameters used in this study were estimated as illustrated in Table 3.

<table>
<thead>
<tr>
<th>( \lambda_1 )</th>
<th>( \lambda_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20 m</td>
<td>0.25 m</td>
</tr>
<tr>
<td>( m_1 = m_2 = ) 0.50 kg</td>
<td>( M = 2.0 ) kg</td>
</tr>
<tr>
<td>( k_1 = k_4 = 4.68E09 ) N/m</td>
<td>( c_1 = c_2 = 478.90 ) Ns/m</td>
</tr>
<tr>
<td>( k_3 = k_4 = 5.41E07 ) N/m</td>
<td>( c_3 = c_4 = 36.41 ) Ns/m</td>
</tr>
</tbody>
</table>

**IV. DYNAMIC SIMULATIONS AND RESULT**

In this section, MATLAB simulation results of the derived dynamic equations are presented and analyzed. The objective of these analyses is to study the dynamic behavior of the proposed robot during climbing and sliding operations under the influence of friction and external wind disturbance. As stated earlier, the study focused on the robot base vertical displacement (\( \delta_4 \)) and the corresponding angular displacement (\( \beta \)) which describes the dynamic vibrations of the robot during power line inspections. The desired response is to have a smooth motion of the robot without vibrations. However, numerical values of the parameters of the robot are required for the simulations and thus, parameters of Table 3 were used for the simulation of Eq. (16).

To analyze the response of the system during climbing operation, i.e. when the robot just landed on the power line, a pulse input signal is used to represent the contact force that causes the robot to vibrate. Fig. 5(a) shows the response of the robot displacement, it can be seen that with a reference pulse signal representing a sudden 10mm vertical displacement of the power line for two seconds cause the robot to vibrate to a maximum value of 20mm before settling within zero. Fig. 5(b) shows the response of the angular displacement when the center of mass is assumed to be at the center of the robot. At this point, \( \lambda_1 = \lambda_2 = 225 \) mm, which technically means that the robot is well balanced and there would be no angular displacement, 2.8E-21 in this case. In reality, the equilibrium state and thus, the center of mass of the robot can either be slanted to left or right which increases the displacement. Hence, Fig. 6(a) shows the response of the angular displacement for the tabulated parameters (\( \lambda_1 = 200 \) mm and \( \lambda_2 = 250 \) mm) shows an increased displacement reaching a maximum value of 1.534E-5 rad and settled at zero. The displacements are faster at two points; the time of impact and immediately when the impact is removed before finally settled at zero.

In addition, to investigate the behavior of the robot, a step input is used as the driving force of the sliding motors and a dynamic friction is added to the contact between the rollers and the power line cable for more realistic analysis. Fig. 6(b) and Fig. 7(a) show the response of the linear displacement and angular displacement of the robot using the sliding motors, respectively. By assuming a frictionless surface in a situation where rain lubricated the transmission cable, the friction coefficient is set to zero and the response shows an increased linear and angular vertical displacements of the robot. This is due to the fact that, the sliding motors move faster and hence, generates more vibrations in the absence of friction.

Moreover, a random white noise representing a wind disturbance shown in Fig. 7(b) is added to the system in two directions. The responses of the positive wind in the direction of motion and that of the negative wind opposing the motion of the robot are respectively shown in Fig. 8(a) and Fig. 8(b). The result shows that in each case wind disturbance increases the vibration of the robots.

In summary, the maximum absolute linear and angular displacements for all the presented cases are illustrated in Fig. 9(a) and Fig. 9(b), respectively. It can be observed that with the 10mm reference vertical displacement, an 11% increase of the displacement was recorded when the robot climbs the power line as compared to normal sliding movement. However, increasing the aggressiveness of the grasping (climbing) from 10mm will increase the corresponding vertical vibrations. Moreover, 5% and 12% increase in displacement was recorded for frictionless and wind disturbances respectively as compared to the normal sliding operation of magnitude 0.018m as shown in Fig. 9(a). Likewise, the angular displacement of magnitude 1.22E-5 rad increases by 2% for frictionless motion, 25% for climbing and 85% for wind disturbances as shown in Fig 9(b). In this case, we can observe that the angular displacement is very small and hence, it is clear that the angular vibration of the robot is insignificant.

Finally, these values may change when the input perturbations changes, however, the nature or pattern of the responses will remain the same. Thus, these time domain analyses provide an insight into the dynamic behavior of the robot under certain conditions and demonstrated that the robot has fast time response and good vibration settling time and hence, would be suitable for power line inspections.

![Fig. 5 Climbing operation: (a) Linear displacement; (b) Angular displacement for \( \lambda_1 = \lambda_2 = 225 \) mm.](image-url)
V. EXPERIMENTAL SET-UP AND RESULTS

The experimental study was conducted in order to verify the effectiveness of the designed robot. The designed PTLIR has been realized into a real lab scale robot as shown in Fig. 10. The 0.5m by 0.6m robot is light and portable as it only weighs 7.5Kg including the electronics circuits. As stated earlier, one of the most commonly used transmission cable; the all aluminium alloy (AAA) conductor was employed in this study due to its strength to noise mass ratio, high resistance to corrosion and good sag characteristics [27]. However, the structure was tested in a lab environment; thus, the cable length was limited to 3m and supported by 0.8m high fixed towers. A tri-axis ADXL335 accelerometer was chosen and installed on the robot base for the induced vibration measurements of the structure due to its cost-effectiveness and low power consumption (0.35mA) [28]. Unlike the simulation analysis that covers the vertical vibration of the robot, this accelerometer allowed us to analyze the vibration in 3-axis. In addition, the simulation results highlighted the response of the robot without control. However, for safety concerns, the robot cannot be tested without motor controller. Thus, a C620 speed controller was installed to the driving motors as prescribed by the motor manufacture as previously described in section II (B). Arduino Uno microcontroller was used as the data acquisition system and the real-time vibratory response of the structure was recorded and analyzed using MATLAB as shown on the monitoring PC.

To demonstrate the effectiveness of the designed PTLIR, the two axes (x and y) responses during start-up (on) and braking (off) conditions were analyzed. Fig. 11(a) shows the reference bang-bang voltage signal used to drive the robot along the power cable. The bang-bang signal drives the robot forward (+24V) and backward (-24V) for 5 seconds each for
6 minutes such that its dynamic behavior on the transmission line can be adequately studied in real-time. The vibrations in x, y and z-axes are shown in Fig. 11(b), Fig. 12(a) and Fig. 12(b), respectively. Furthermore, the test was under the influence of external disturbance and inherent electronic noises, the maximum vibration of x, y and z-axes is 0.169m/s², 0.105m/s² and 0.37m/s², respectively. This shows that the vertical vibration in the z-axis is higher than the horizontal vibrations in x and y directions as previously assumed during modeling. However, based on the general vibration severity graph [29], 0.169m/s² is an extremely smooth vibration and thus, the experiment demonstrated that the robot can slide along the power cable without much vibration as desired.

VI. CONCLUSIONS
The existing power line inspection robots were large and heavy which made them slow and consumes a lot of energy. This work is part of the project under the state key lab of intelligent robotics of Xi’an Jiaotong University, China to design an integrated fast and portable fly-climb-sliding robot for an efficient power line inspection. The climb-sliding structure was initially designed using SOLIDWORKS and later realized into an aluminum 6061 based lab-scale power line inspection robot. Furthermore, using the mechanical
properties of the structure, the system was represented into an equivalent mass-spring-damper configuration. The Lagrangian energy equation was used to derive the dynamic equations of the robot. MATLAB simulation was used to study the dynamic responses of the robot under different perturbations including pulse input force, friction force and white noise wind disturbance. The simulation and real-time experimental results of the robot sliding along the transmission line demonstrated that the robot has a good time response with small induced vibration. These results provide comprehensive information about the dynamic behavior of the robot and confirmed that the robot is cost effective and suitable for an autonomous power transmission line inspection. Thus, our future work comprises of designing an intelligent control for the obstacle avoidance mechanism and an installation of sensing and imaging equipment on the robot for real-time inspection of the transmission line and its components.

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