POLIBOT – POwer Lines Inspection RoBOT

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Abstract

Purpose – Several studies have aimed to develop robotic systems which move in transmission lines. Until this moment, all of them have a high weight and cost associated with the equipment and reduced battery autonomy time. In this context, this paper aims to propose the POLIBOT (POwer Lines Inspection roBOT) with low cost and weight, enabling the movement over the lines and an easier installation and remove.

Design/methodology/approach – The designed robot uses the Profiles Manufacturing Methodology (PMM). The construction of the robot mechanical structure uses modularized aluminum parts built through square profiles. Thus, it's possible a drastic reduction in production time as well as cost reduction and weight when comparing this method with other manufacturing processes like foundry, for example. For hardware and software systems, the use of free and open source software causes a significant reduction in cost and project execution time. The benefits of using open source systems are immeasurable, both from academic and industrial applications.

Findings – The POLIBOT platform is one solution to the problem of inspection in power lines. With this robot, more lines are maintained with lower time. In its constructive aspect, the robotic mechanism is designed using principles of bioengineering. The use of this principle was successful, considering that obstacle transposition is performed with stability and low energy consumption.

Research limitations/implications – The suggestion for future researches is to replace the battery for solar energy and construction in polymeric material to avoid high magnetic fields.

Practical implications – The commercial application is evident because manual inspections are inefficient, very expensive and dangerous. Thus, it is growing the number of researches that develop mechatronics systems for this kind of inspection.

Social implications – The impact is the reduction of accidents because the present procedure requires precision of movements, where the pilot and electrical technician are close to high electrical and magnetic fields. In addition, for some tasks, the worker has to walk on the line to reach some important points. Thus, those tasks involve high risk of death.

Originality/value – The PMM methodology represents an innovation to the state of the art because others robotic mechanisms proposed for inspection tasks present total structure mass between 50 and 100 kg and POLIBOT has only 9 kg. Other fact is its price for implementation as this robot used the robot operating system (ROS) framework, what dispense the use of licenses. Other important features are that the robot performs the tasks autonomously, which reduces errors introduced by the operator and its low manufacturing cost as compared with other projects.

Keywords Robot design, Autonomous robots, Field robotics, Overhead transmission lines

Paper type Research paper

1. Introduction

Nowadays, manned helicopters perform power lines inspection. Thermographic cameras are used to measure cables temperature. This procedure requires precision of movements because both the pilot and the electrical technician are close to high electrical and magnetic fields. In addition, for some tasks, the worker has to sit on the line to reach an important point. Thus, those tasks involve high risk of death (Lima II *et al.*, 2014).

Besides the fact that this is very expensive, in some cases, because of weather conditions and other factors that might hinder the over flight, the crew may be subject to risks associated with the task. Land vehicles are commonly used as an alternative to aircrafts, but in general, this type of inspection is often limited because of inaccessibility of the terrain and unfavorable viewing angle.

When using aircrafts, electricians move over the cable using thermographic cameras which measure the temperature. The cost of this type of inspection is extremely high. As a result, the companies responsible for transmission do not continuously monitor the conditions of the cables and conduct line inspections in large time intervals. This mode of inspection is dangerous, with risks to the people who are on the helicopter

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once that it has to fly close to the transmission lines, representing danger of death for the electrician and pilot.

In this scenario, inspection with autonomous robots is a promising solution regarding cost and risk reduction as well as increase in productivity. Several research institutions and electric companies have been working on developing solutions for inspecting lines although three main factors limit implementation in Brazil: heavy mechanical equipment, high cost of the robot and specific installation procedure requirements.

POLIBOT is a light and autonomous operation solution to visual and thermal inspection of transmission lines with 138 kV and 500 A. The mechanism weight is limited to 14 kg, allowing field installation by two operators. As an operation system and development framework, the team selected open source software that reduces dramatically the project final cost because it is not necessary licenses.

2. Background-related projects

Luo *et al.* (2005, 2007) presented a maintenance robot developed at the University of Shangai to travel along the cables of cable-stayed bridges. Even though this technology does not aim to cross obstacles, the modularity of the design, in addition to the maintenance tasks it already performs under real field conditions, makes it a noteworthy example of the potential of any cable robot. Its ability to apply paint and to detect rust on inner strands is of particular interest.

Montambault and Pouliot (2007), Pouliot and Montambault (2009) proposed the LineScout robot, which is a teleoperated robot for inspection and maintenance of lines with 735 kV. It weighs about 120 kg and its mechanical structure uses prismatic joints which add high rigidity and self-locking characteristics requiring less effort from the motors. On the other hand, the weight of prismatic joints is greater than that of articulated joints.

For the control system, LineScout uses a digital interface provided by LabView®. The LabView® interface is easy to deploy because of the existing libraries, graphical interfaces for data capture and control for different types of actuators and sensors. However, the operator performance may introduce errors in the process. The LabView® platform is not a good choice to *POLIBOT* because of the high cost of licenses and dependency on operator ability.

The Expliner is a robot for remote inspection of power lines which uses an access cable to reach the transmission line (Debenest *et al.*, 2008, 2010). Expliner has a velocity of 40 m/min, 30 kg, 30 degrees of cable's inclination and up to 500 kV cable voltage.

This robot does not provide fully autonomous control and the operator must authorize acrobatic movement mode, for example. Its memory records sequences of movements. A notebook, a panel of micro-switches, joysticks, wireless antennas, batteries and circuit mounted within a robust and compact housing composes the portable control unit. The entire set is dustproof and splash proof. Wireless network makes the communication. The Expliner is controlled from a portable control case capable of driving all joints independently, but this would result in cumbersome and time-demanding operation.

The positive points of this vehicle are that it is capable of performing semi-autonomous tasks and its mechanical structure is manufactured in carbon fiber. Consequently, it is lighter as compared to other robots. The negative point is that Expliner has a complicated control algorithm, and so a manual mode to overcome obstacles is needed.

Wang *et al.* (2010) proposed a mobile robot based on novel line-walking mechanism for the inspection of power transmission lines. The novel mechanism enables the centroid of the robot to concentrate on the hip joint to minimize drive torque. When this robot is compared to LineScout and Expliner, it has a complex algorithm for overcoming obstacles.

Bühringer *et al.* (2010) developed a cable-crawler robot with a mass of 58 kg and only six drives. When compared with other types of crawler robots, this robot has a relatively simple controller, mechanical structure and strategies for overcoming obstacles. This is because of the low numbers of actuators and sensors. Consequently, the vehicle has cheap devices and high speed. In contrast, the vehicle is not lightweight and is not capable to overcome suspension clamps, anti-vibration structures and dampers.

Mostashfi *et al.* (2014) built a solution similar to Bühringer *et al.* (2010) where the vehicle has 60 kg but the robot is capable to overcome more obstacles, such as suspension clamps and warning balls. The active mechanism has seven rubber-coated rollers, and one of the advantages of the proposed design over the previous studies in the literature is the use of active mechanisms (i.e. motorized rollers and ball screws) along with passive mechanisms (i.e. springs and dampers) simultaneously (Mostashfi *et al.*, 2014). A disadvantage is the heavy weight with high battery consumption and complexity for installation.

Papers presented by Lee *et al.* (2011) describe a system development process to measure line sleeve eccentric degree while the operators stay in a remote area. The developed system minimizes error of line sleeve and maximizes the accuracy while measuring eccentric degree. The system also detects fault line sleeve in a remote area to secure the operator safety. Lee *et al.* (2011) does not show how this robot overcomes obstacles like counterweight, insulator and suspension clamp.

Alkalla *et al.* (2017) created a climbing robot for inspection of petrochemical vessels. The paper's idea is to use propellers and wheels for better adhesion in underwater structure. The new robot, called "EJBot", has a new hybrid actuation system which generates the required adhesion force to support climbing surfaces. One important characteristic is that EJBot is capable to overcome obstacles with up to 40 mm. In the present paper, POLIBOT uses similar strategies for transposition. A disadvantage of this hybrid vehicle type is the complex controller when operating in aerial lines because its dynamics is very faster.

Finally, Miller *et al.* (2017) demonstrated a remotely operated robot. This vehicle is compact and overcomes only splices. The robot has a small two degrees of freedom (DOF) arm for cleaning cables.

The POLIBOT project is highly innovative regarding results achieved as described in literature. It proposes a light structure as well as autonomy for inspection of power lines. Reducing errors is possible as movements do not depend on the operator ability. There is also cost reduction inherent to the actuator size, torque, energy consumption and higher vehicle autonomy.

Moreover, this project uses free and open source software like many distributions of LINUX. With this kind of platform, it is possible to reduce time and cost because expensive licenses for softwares like LabView® are not required. Ubuntu has a big community that develops frameworks for robotics systems, namely, robot operating system (ROS) and Rock.

3. Methodology for design and tests

Figure 1 shows a flowchart for robot design, manufacture and final tests. Each step is explained in the next sections and subsections.

Basically the robot uses two types of joint control. The first one is the kinematic control for the coordination of poses and configurations. Second, the dynamical control uses proportional integral derivative (PID) controllers for each joint independently. Each joint acts as a disturbance for the other ones, while the kinematic control provides set points for each joint. This kind of control strategy follows the Expliner vehicle (Debenest *et al.*, 2008, 2010).

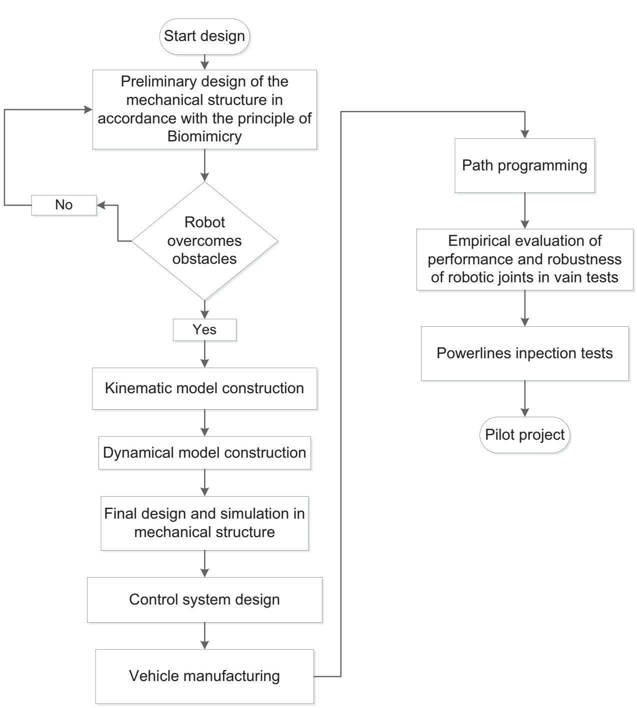
For mechanical design, POLIBOT used Profiles manufacturing methodology (PMM) and bioengineering principles (Bomfim *et al.*, 2015). With these methodologies, POLIBOT robot is lightweight and has low battery consumption when overcoming obstacles.

4. Mechanical concept – mimicry biological

The robot development considers the following guidelines: a robot for transmission lines inspection must be able to transpose some obstacles such as suspender clamps, dampers and anti-vibration devices. In addition, the robot must have the best aerodynamic and electrical characteristics. Among the aerodynamic features, one can cite the lowest possible weight and smooth shapes without sharp corners, which can alleviate disturbances caused by winds. Electrically, robot format must avoid interferences caused by intense electromagnetic fields that can damage electronic components and have influence on the wireless communication system. Finally, the robot structure must not present any edge that could cause sparks because of the high electrical field.

Here bioengineering principles provide a better solution for mechanical structure. In this context, a worm inspired the project. The worm moves by approaching the rear to the front forming a U to overcome an obstacle (Verl *et al.*, 2015) when transposing an obstacle the robot moves under the suspension cable through a set of claws in the same way as a worm. Figure 2 shows a sketch for the mechanical structure.

Figure 1 Flowchart for POLIBOT design, manufacture and tests



5. Kinematic model

The kinematic model for POLIBOT uses a homogeneous transformation matrix (HTM), where 4×4 matrices define robot poses. The matrices have rotation and translation information.

For the kinematic and dynamic analysis, the mechanism was considered a rigid body. In this way, the effects of deflections and thermal deformations were disregarded. This hypothesis can be realized because high precision is not necessary, as the claws have the capacity of self-coupling. The self-coupling capacity is because of the design of the pulley, which has a greater curvature than the cable. In this way, the pulley hugs the cable, allowing self-coupling and low precision in the process.

Figure 3 shows the robot with main dimensions, and Table I shows the weight for each link. Thus, it is possible to calculate the kinematic and dynamical model which enables information about singularities, inverse kinematics and necessary torques in each joint. Considering the support unit as the base of the robot, each arm has two DOF to move the traction units when transposing an obstacle.

5.1 Forward kinematics

For the forward kinematic robot model description, we set two reference coordinate systems:

- System {A}: support reference point – “Support Unit” on the cable.
- System {B}: reference point – “Traction Unit” on the cable.

Figure 2 Initial sketch for POLIBOT

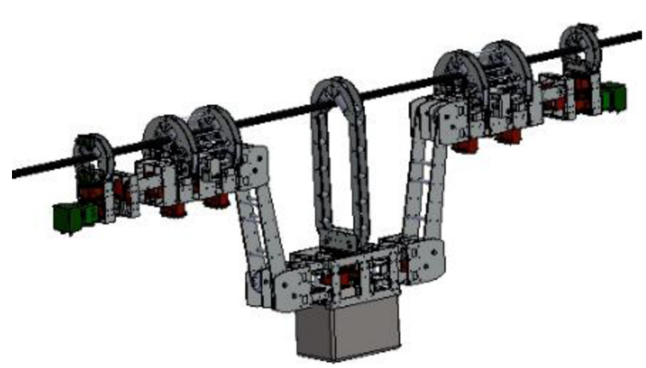


Figure 3 POLIBOT with main dimensions

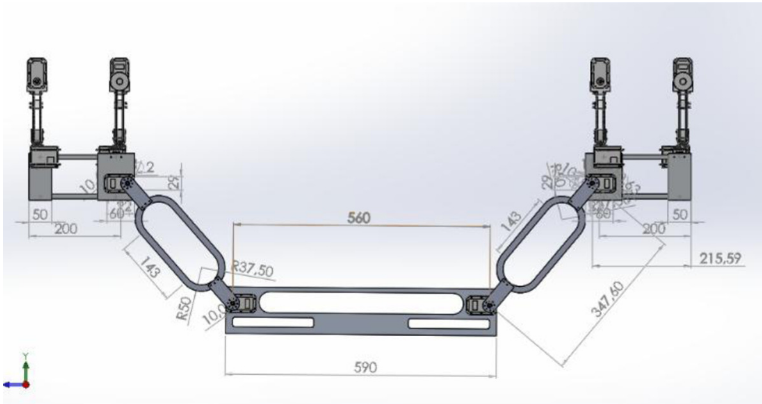


Table I Mass and length properties for POLIBOT

Unit	Mass (kg)	Length (m)
Traction	2.134 (m1)	0.215 (L1)
Arm	0.239 (m2)	0.347 (L2)
Support	4.174 (m3)	0.560 (L3)

Table II DH parameters for POLIBOT

I	a_{i-1}	α_{i-1}	d_i	θ_i
1 $\left({}^{A}_{1}T\right)$	L3/2	0	0	θ_1
2 $\left({}^{1}_{2}T\right)$	L1	0	0	θ_2

For each joint, a coordinate system is defined where Z_n is the direction of rotation of the joint and θ_n is the positive direction of rotation.

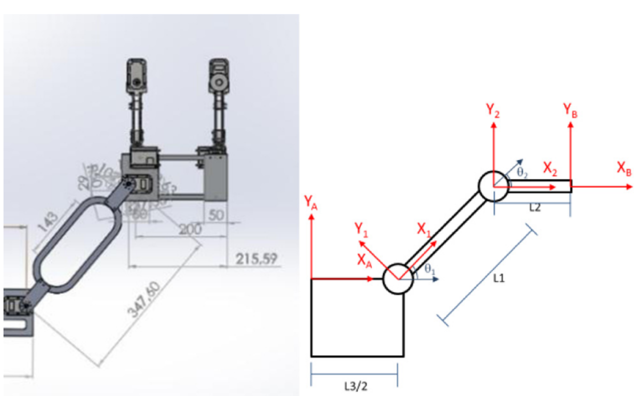
Figure 4 shows the coordinate systems for one arm of the robot as two DOF mechanism.

With these definitions, the forward kinematics model determines the HTM ${}^{A}_{B}T = {}^{A}_{1}T\,{}^{1}_{2}T\,{}^{2}_{B}T$ through Denavith-Hartenberg (DH) parameters as shown in Table II and a constant HTM ${}^{A}_{1}T$ defined by the dimensions of the robot. The coordinate system for this analysis is the support unit as the inertial referential while the robot overcomes obstacles.

Thus:

$$
{}^{A}_{B}T = {}^{1A}T^{1}_{2}T^{2}_{B}T = \begin{bmatrix} c_{12} & -s_{12} & 0 & L_3/2 + L_1c_1 + L_2c_{12} \\ s_{12} & c_{12} & 0 & L_1s_1 + L_2s_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Figure 4 POLIBOT, Right side, as two DOF mechanisms



where $c_{12} = \cos(\theta_1 - \theta_2)$, $s_{12} = \sin(\theta_1 - \theta_2)$, $c_1 = \cos(\theta_1)$, $s_1 = \sin(\theta_1)$, $c_2 = \cos(\theta_2)$ and $s_2 = \sin(\theta_2)$.

5.2 Inverse kinematics

To calculate inverse kinematics, the definition of rotation matrix and translation vector is necessary in equation (1). With this information, it is possible to calculate the value for $cos\theta_2$ (Craig, 1989):

$$
c_2 = \frac{(x - L_3/2)^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2} \tag{1}
$$

and $sin\theta_2$:

$$
s_2 = \sqrt{1 - c_2^2} \tag{2}
$$

The sine value is always positive because POLIBOT has constraints in movements for fourth quadrant.

Finally, computing θ_2 using the arc tangent routine with two arguments:

$$
\theta_2 = Atan2(s_2, c_2) \tag{3}
$$

Because the cable is approximately parallel in relation to the ground, we selected a negative value to θ_2, leading to:

$$
\theta_1 = Atan2(y, x) - Atan2(k_2,\ k_1) \tag{4}
$$

where $k_1 = L_1 + L_2c_2$ and $k_2 = L_2S_2$

With the obstacles geometry and inverse kinematics, it is possible to create routines for overcoming obstacles and avoiding collisions on power lines.

6. Velocities and stall torques

When the arm is outstretched, joints 1 and 2 have infinity velocities. These poses are singularities. Thus, infinity theoretical torque is necessary for joint movement. Because of this, kinematics description avoids such poses.

To calculate a stall torque (ST), knowledge of the mass and length of vehicle links are needed. Table I shows mass and length for each unit. With these data, it is possible to calculate the torque and power for each joint.

To calculate the lever arm on the joint, it is necessary to know the cross product between force and distance. Equation (5) calculates this product:

$$ST = (m_2 L_2 sin\theta + m_1(L_1 + L_2)sin\theta)g \tag{5}$$

where g is gravity acceleration.

The ST in joint one is 12.82 Nm.

7. Dynamical model

Newton–Euler dynamic formulation (NEDF) defines a dynamical model. Thus, it is possible to calculate the torque vector to simulate the resultant movement in each joint.

When NEDF is symbolically calculated for any manipulator, they yield a dynamic equation (6) below. This equation is in configuration-space form (Craig, 1989):

$$\tau = M(\Theta)\ddot{\Theta} + \mathrm{B}(\Theta)[\dot{\Theta}\dot{\Theta}] + \mathrm{C}(\Theta)[\dot{\Theta}2] + \mathrm{G}(\Theta) \tag{6}$$

where $M(\Theta)$ is the mass matrix, $\mathrm{B}(\Theta)$ is a matrix of Coriolis coefficients, $\mathrm{C}(\Theta)$ is a matrix of centrifugal coefficients and $\mathrm{G}(\Theta)$ is a vector of gravity terms.

The parameters of equation (6) were calculated in equation (7). From the vector torque in equation (6), it is possible to formulate equations of torque in joints 1 and 2, which are given by nonlinear equations (7) (Craig, 1989):

$$\begin{aligned}\tau_1 &= m_2 l_2^2\left(\ddot{\theta}_1 + \ddot{\theta}_2\right) + m_2 l_1 l_2 c_2\left(2\ddot{\theta}_1 + \ddot{\theta}_2\right)\\ &\quad + (m_1 + m_2) l_1^2 \ddot{\theta}_1 - m_2 l_1 l_2 s_2 \dot{\theta}_2^2 - 2 m_2 l_1 l_2 s_2 \dot{\theta}_1 \dot{\theta}_2\\ &\quad + m_2 l_2 g c_{12} + (m_1 + m_2) l_1 g c_1\\ \tau_2 &= m_2 l_1 l_2 c_2 \ddot{\theta}_1 + m_2 l_1 l_2 s_2 \dot{\theta}_1^2 + m_2 l_2 g c_{12}\\ &\quad + m_2 l_2^2\left(\ddot{\theta}_1 + \ddot{\theta}_2\right)\end{aligned} \tag{7}$$

where $s_x = \sin(\theta_x)$ $c_x = \cos(\theta_x)$, $c_{12} = \cos(\theta_1 + \theta_2)$ and g is the gravity acceleration. All masses and lengths constants were estimated in the CAD software used to design the mechanical structure. Exact simulation results are not needed as PID is tuned using Dynamixel procedure.

With the use of MatLab® software, it was possible to plot a graphic with a torque in function of the joint angle. Acceleration was fixed in 1 rad/s^2, velocity in 1 rad/s and θ_2 in zero degrees, worst case (singularity pose). To calculate the τ_2, θ_1 was fixed in zero degrees. Figures 5 and 6 show the torque variation in joints 1 and 2, respectively.

Figure 5 Torque variation in joint 1 with different poses

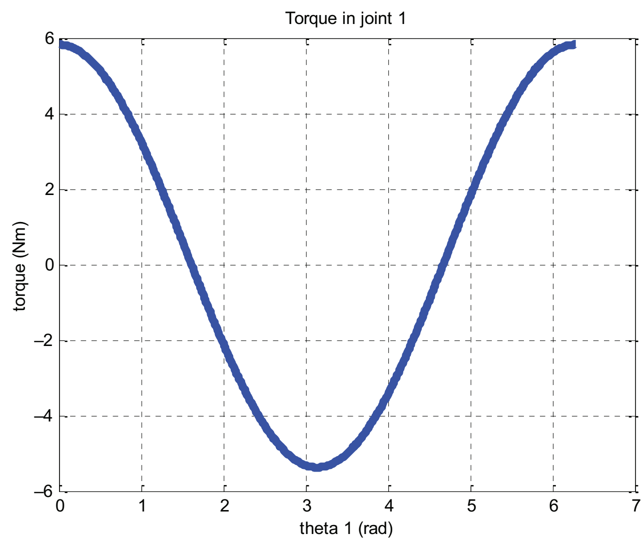
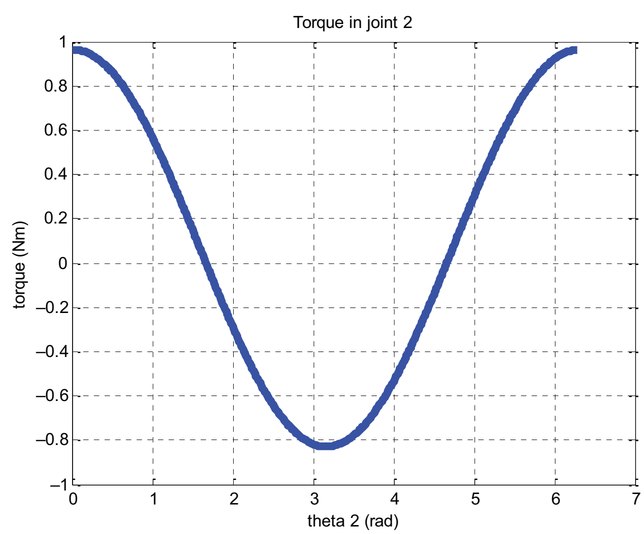


Figure 6 Torque variation in joint 2 with different poses



The maximum torque in joint one is 6.0 Nm and 1.0 Nm for joint two. In this project, the main goal to calculate joint¨s torque or dynamical model is generate information for actuator selection.

8. Control architecture and systems

For execution of the project by a multidisciplinary team, the autonomous robot has seven basic systems: mechanical, traction, external communication, control, central processing, sensing and visualization (Rangel *et al.*, 2009).

8.1 Mechanical system

A viable solution for transposing obstacles is the use of the biological mimicry principle, where displacement performed by the worm inspires obstacles transposition, considering that solutions found by nature are, in most cases, optimized models.

Thus, three types of modules or units define the proposed mechanical concept: arm, traction and support. Figure 7 shows these units. The arm is responsible for moving the traction and support units. The traction unit is responsible for the driving force of the robotic device and its displacement along the power line. Finally, the support unit acts as a reference point for moving the equipment in the transposition of obstacles, functioning as a support, which decreases torque during transposition.

The mechanism's symmetry allows the displacement in either direction of the suspension cable, avoiding the need for decoupling when the direction of inspection is changed.

In its constructive aspect, the robot design uses the PMM (Bomfim *et al.*, 2015). The robot mechanical structure is constructed in a modularized manner through square profiles built in aluminum alloy 2024-T6. Thus, there is a dramatic reduction in production time as well as in cost and weight when compared to other manufacturing processes like foundry, for example, because the construction of molds and other things related to the casting process are not necessary. In its first version, the vehicle was built using laminated object modelling (LOM) methodology (Ramalho Filho and Bracarense, 2007). With this methodology, the robot had 25 kg in its mechanical structure and took five months for its construction. Using PMM, manufacturing time was one month, and its weight was close to 1.8 kg. Figure 8 shows an isometric perspective of the robotic arm. The PMM allowed for the construction of the arm with only 153 g, and the mass of the robot mechanical structure only 1.8 kg. It represents an innovation to the state-of-art because the total structure mass of the other robotic mechanisms proposed for inspection tasks is between 30 and 120 kg.

8.2 Traction system

Plate 1 shows a POLIBOT traction unit. As the name suggests, this is responsible for linear movement along power lines, allowing its displacement while performing the inspection tasks.

Figure 7 Basic configuration for POLIBOT

Figure 8 Basic structure for POLIBOT arm built in aluminum alloy 2024-T6

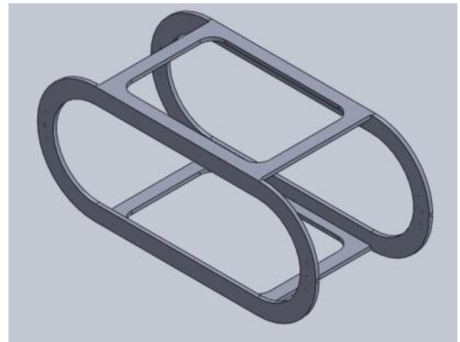
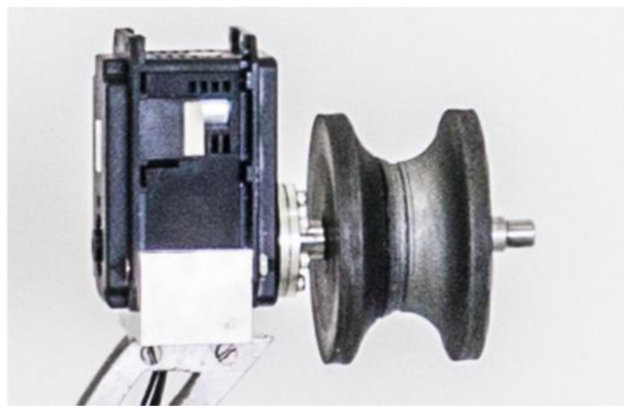


Plate 1 Traction unit for POLIBOT robot



Equally important is the fact that Dynamixel MX-106R is a multi-turn servo motor communicating via RS-485 protocol where each motor has a specific number of ID. So, all of them communicate with the central controller through a unique bus, reducing the cabling. This motor also has an internal processing system that provides configuration possibilities and technical information such as PID tuning, torque, temperature, current, voltage, position, speed and acceleration control.

8.3 External communication system

For the correct operation of the external communication system (ECS), the following items must be met:

- communication with the inspection robot shall be galvanically isolated, ensuring the safety of the operator in the field;
- usual communication with the robot shall be possible at a distance of at least 20 m, corresponding to the average height of the tower;
- communication with the robot shall provide a resource for the sending of an alarm signal for rescue, this particular form of communication being possible at distances exceeding one kilometer; and
- communication with the robot shall provide resources for remote configuration/parameterization of the inspection robot, remote and real-time visualization of the status and

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operation of the robot, as well as providing resources to retrieve data from inspection such as photos, videos and reports.

The proposed solution is to base the ECS on the implementation of a wireless network between the operator and the robot, being the physical means for the implementation of this network based on the use of a module Wi-Fi.

Thus, a script must be implemented in Linux for the automatic configuration of the Wi-Fi network, which should be executed automatically after initialization. With the adoption of this concept for robot communication, the ECS proposes to implement the human machine interface (HMI) of the robot as a Web page running as an application of the robot operating system. Once the Web page is opened in a browser, and the HMI can be accessed through the browser present in a smartphone, tablet, laptop or desktop, taking advantage of the advancement of the connectivity of these handsets, with the adoption of Wi-Fi network features, practically as a standard.

Thus, the hardware cost of the system is reduced in relation to the proprietary module design, and this cost is mainly summarized only to the cost of the Wi-Fi adapter, the 3G modem with GSM/GPRS and the antennas and cables. With the implementation of the Web server in the robot and a page of access, control, configuration, parameterization and supervision, the system will be multiplatform, not having to develop a client application, as it will be the browser of the tablet, notebook or mobile phone itself the operator. This only needs to open the browser and in the URL field enter the robot IP number, establish the connection, receive the HMI page, log on and, if access is allowed, supervise the operation and control some of the robot's features remotely.

The HMI for POLIBOT is shown in Figure 9. For the examples described, it adopted the hypothesis that the robot CPU has a Linux operating system and, on this, the ROS is installed and executed, where the management and control software of the robot and its internal subsystems are developed.

8.4 Central processing

The ROS is open source software similar to an operating system; because of that, ROS is considered a meta-operating system (O'Kane, 2013). Among the similar characteristics are package management, hardware abstraction and low-level control mechanisms to allow the communication among processes, libraries and tools for control devices across a number of computers.

In this project, one of ROS features explored corresponds to the execution of multiple nodes, which are associated with the Web server (rosserver js). This server allows Web developers to create applications for robots through JavaScript programming language. Then many applications for robot management, access and visualization of sensor data were implemented. Thus, the information about the power line temperature is sent in real-time.

8.5 Control system

The simplest independent joint control strategy is to control each joint axis as one input and one output, SISO (single input, single output) system. The coupling effects between the joints because of configuration variation during movements represent output disturbance. A PID controls the Dynamixel MX-106R and has a high robustness to disturbances. In addition, it has high-speed response to set-point variations. The independent joint control strategy proved to be adequate to the robot arm and the traction system.

8.6 Sensing system

In POLIBOT, the detection of obstacles must use combined ultrasonic and laser sensors. The ultrasonic sensors are effective in measuring the distance between robot and obstacle. The laser sensor is responsible to scan the obstacle shape. Consequently, the robot can identify the shape and select the strategy to transpose the obstacle.

Figure 10 shows two ultrasonic sensors on the traction unit. These sensors are positioned as shown because the suspension clamp and jumper are above and below the power lines, respectively. In this way, the sensors can detect both obstacles.

The laser sensor used was Hokuyo with the UTM-30LX model making it possible to identify the type and dimensions of obstacles (Barbosa *et al.*, 2014).

8.7 Visualization system

The visualization system consists of two cameras. The first camera covers the visible spectrum (VS), and the other one

Figure 9 Human machine interface for POLIBOT

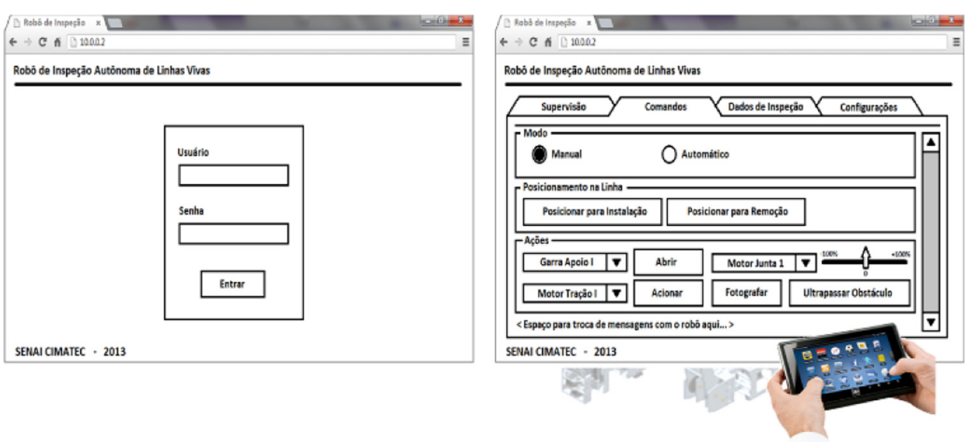
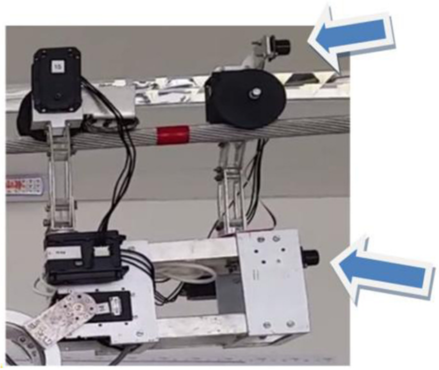


Figure 10 Traction unit with evidence for ultrasonic sensors



covers the infrared (IR) spectrum. The VS camera is responsible to record the operation of the robot and the structures involved (cables, towers, suspension clamps, dampers, etc.). The IR camera captures thermographic images. With these thermographic images, the system can perform specific diagnostic seeking to verify the physical integrity of the components of the lines, in terms of cracks, corrosion and possible damages that may harm the supply of electricity.

9. Systems validation

After the selection, design and construction of the seven basic systems, tests at the laboratory were started. Initial tests demonstrated that the robot morphology was able to overcome obstacles encountered on transmission lines, and the units responded accurately to the commands of position, velocity and acceleration. The second step consisted of testing the various sensors. Plate 2 shows the tests with the laser sensor, which detects the type of obstacles. Results showed the speed and efficiency in sensing and visualization systems.

Plate 3 shows the final version of the mechanism. In this image, robot's mass is 8.92 kg. Considering the other state-of-the-art mobile robots like LineScout, *POLIBOT* is very light.

In the last stage, POLIBOT susceptibility to magnetic interference and electrical field generated by the line potential was analyzed (Plate 4). At this stage, tests on live lines with up to 207 kV showed that robot systems answer is satisfactory. Locomotion, communication and filming tests were carried out gradually increasing the potential of the line from 20 kV to 180 kV, in steps of 20 kV. At all tested values, the communication was not influenced by line voltage. The locomotion and filming achieved satisfactory results.

Plate 2 Obstacle identification with laser and ultrasonic sensors

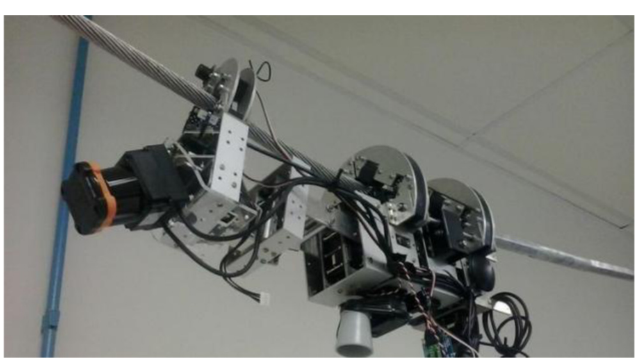
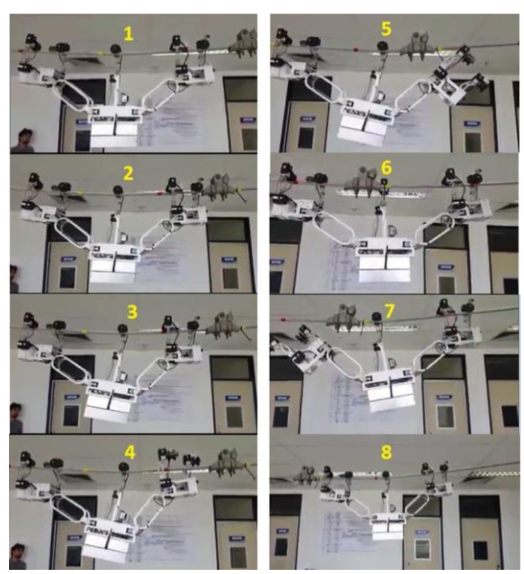


Plate 3 Final structure for POLIBOT with 8.92 kg

Plate 4 Autonomous robot in tests at CEMIG's laboratory

Figure 11 shows the POLIBOT running the transposition of a suspension clamp in a potential of 138 kV. Picture 1 in Figure 11 shows the POLIBOT moving towards the suspender clamp. Picture 2 shows the robot detecting the obstacle. Picture 3 shows the robot going back to take a little distance from the

Figure 11 POLIBOT Performing a transposition in suspension clamp in laboratory tests



clamp. In Picture 4, the ultrasonic sensor is being directed at the obstacle and measuring the distance from it. Picture 5 shows the robot frontal part dropping the cable to make the transposition. The sequence of translation movements is shown in Picture 6 when the intermediate robot module drops the traction units holding to the cable. Picture 7 shows the last module of the robot dropped. Finally, the robot completes the transposition in Picture 8.

The transposition process is done gradually until the robot transposes its three modules over one obstacle. Furthermore, throughout the movement the robot must stay in contact with the power line on at least two points. Thus, the stability of the robot is insured.

When POLIBOT ultrasound sensor spots an obstacle, the laser scan starts the obstacle identification making it possible to get to know each joint angle – this is the space of joints. Thus, the robot is capable of automatically overcoming obstacles like suspender clamps or jumpers.

The PMM methodology facilitates the creation of a robot with 8.92 kg only which represents a paradigm brake because the mechanism built so far has around 120 kg. Such significant reduction in weight allowed for the choice of small motors with 10 Nm of torque and less battery consumption.

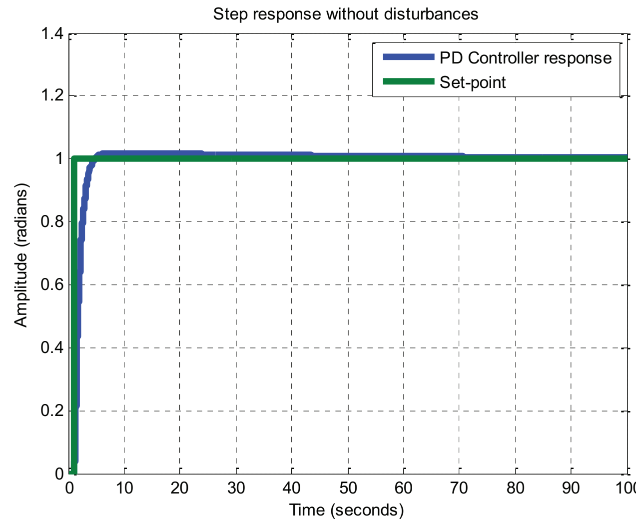
Table III makes a comparative study between POLIBOT robot and eight different robots shown in Table II. From the table, it is possible to conclude that CEMIG has the lightest with 8.92 kg because the PMM methodology was used for its construction. In addition, this robot has low battery consumption and autonomous operation.

10. Experimental evaluation of performance and robustness

PID controller is used as Dynamixel motors have only embedded PID classical controller. The motors provide communication with Matlab® through a serial bus for command, gain set and actual position acquisition. A second motor was used to generate a disturbance torque.

The first step is to obtain PID controller where the integrative gain is equal to zero. The main idea is making the robot control more stable without poles in the controller. Figure 12 shows the closed-loop system response to an input step without disturbance rejection (controller without integrative part). In the figure, it can be seen approximately two per cent of overshoot for a step of one radian in set point for joint 1. This joint has the biggest torque (6 Nm), as shown in Figures 5 and 6.

Figure 12 Closed-loop response without disturbance rejection (PID controller)



In Figures 12, 13, 14, 15, 16, 17 and 18, the green line is the trajectory set point and blue line is the joint response. For experimental analysis, the amplitude step is 1 radian.

Figure 13 shows an inversion of set point where the value is between 1 and −1 radian. By the figure, it is possible to analyze that the PID controller is robust and has low overshoot and settling time of approximately 3 s.

When disturbances are applied in joint one, the PID controller is not capable to reject disturbances. The disturbances are applied in 10, 20, 30 and 40 s; each disturbance is a step of 1 Nm (10 and 30 s) and −1 Nm (20 and 40 s). Figure 14 shows the joint response. The figure shows that the robot has a high error in trajectory, and it is necessary for an integrative gain for disturbance rejection.

In Figures 15, 16 and 17 an integrative gain is used. From the figures, it is possible to analyze that the integrator made the plant less stable as the overshoot increased by 21 per cent, but the controller started to reject disturbances.

Figure 18 shows the system response for an input step and an angle of $\theta_1 = 0^{\circ}$. From the figure, it can be seen that the controller rejects perturbations and that the overshoot is 25 per cent. It can be concluded that the PID controller presented good performance for different poses.

Table III Comparison between POLIBOT and others robots

Robot	Weight (kg)	Autonomous	Software licenses	Battery consumption
POLIBOT	8.92	Yes	No	Low
LineScout	120	No	Yes	High
Expliner	30	Yes	No	Medium
Luo *et al.* (2005)	45	No	Yes	Medium
Luo *et al.* (2007)	45	No	Yes	Medium
Wang *et al.* (2010)	–	No	No	
Lee *et al.* (2011)	–	No	No	
Bühringer *et al.* (2010)	58	No	No	High
Mostashfi *et al.* (2014)	60	No	No	High

Figure 13 Closed-loop response without disturbance rejection (PID controller)

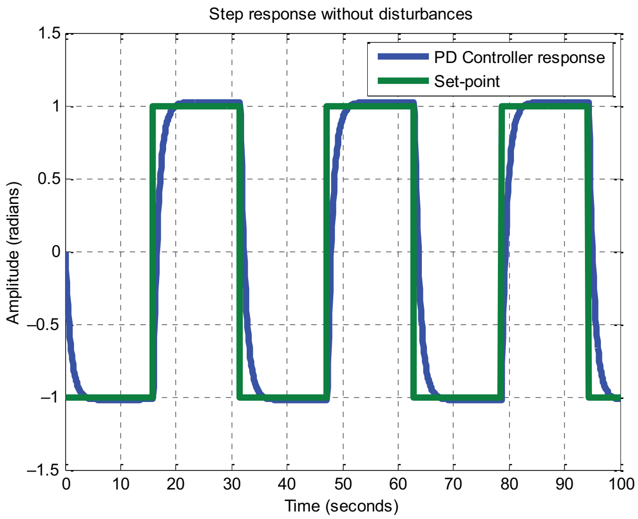
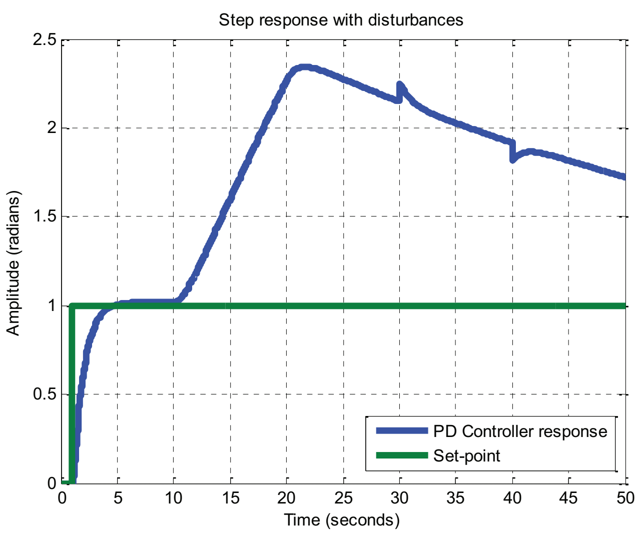


Figure 14 Closed-loop response with disturbances and without disturbance rejection (PD controller)



The PID controller provided a satisfactory control with disturbance rejection. Thus, Dynamixel MX-106R embedded controller was satisfactory for joint-level control. In the task level or high-level controller, the inverse kinematics was generated from transformation matrices, where the framework calculates the joint angles to overcome obstacles using equations (3) and (4) and signals send by sensors, ultrasonic and laser. After the laser scanner sensor sends information about the morphology of the obstacle, the kinematics routines are generated. The purpose of these routines is to position the traction unit in configurations that do not collide with the line obstacles. As a result, kinematic control operated satisfactorily and no collisions occurred during the obstacle transposition task.

Figure 15 Closed-loop response with disturbance rejection (PID controller)

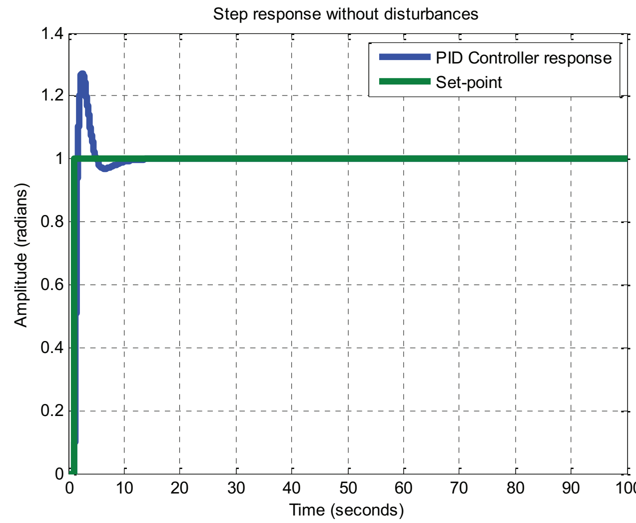
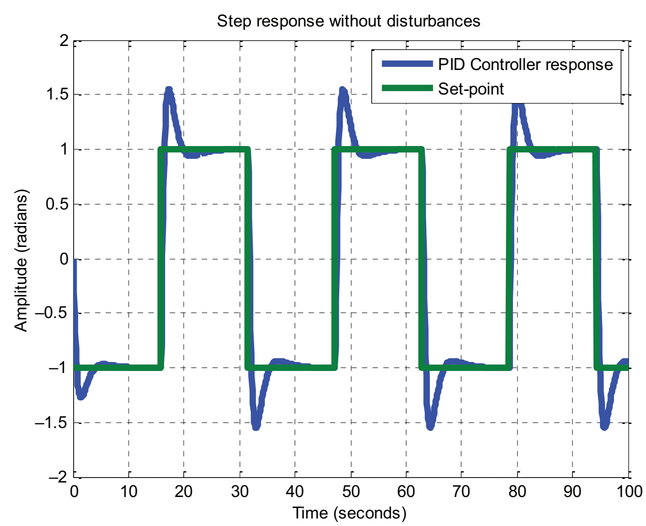


Figure 16 Closed-loop response with disturbance rejection (PID controller)



11. Conclusion and future works

Currently, there are about 100,000 km of transmission lines in operation in Brazil. Manual inspection is costly and inefficient. Therefore, power lines inspection by autonomous robots is a tangible solution for maintenance on transmission lines.

POLIBOT is an answer to the problem of power lines maintenance considering that it inspects more lines in less time. In its constructive aspect, the use of bioengineering principles when designing the robotic mechanism was a major success, considering that the robot transposition performance is stable and has low energy consumption.

Another main feature is the robot's weight (approximately 8.92 kg), which easily allowed for the installation of the robot

Figure 17 Rejection of disturbance at plant in 90 degrees angle (PID controller)

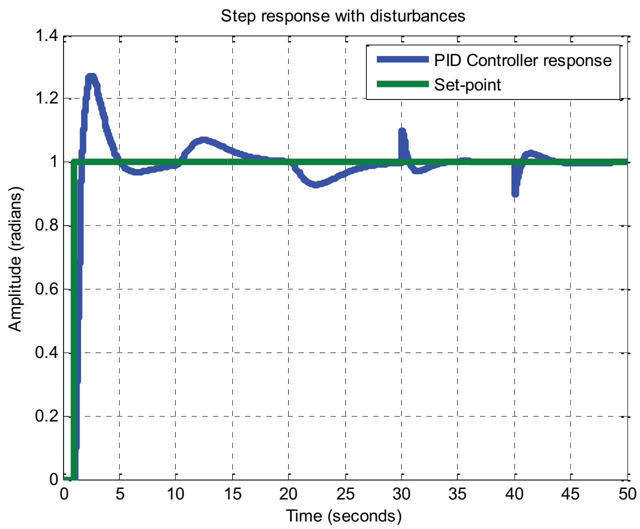
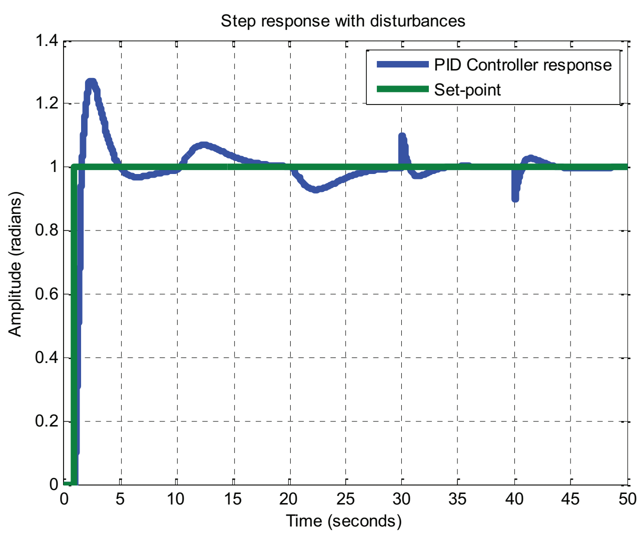


Figure 18 Rejection of disturbance at plant when the joint angle is zero degree (PID controller)



on transmission lines by two operators using the standard procedure. Thus, the PMM methodology is satisfactory.

About hardware and software systems, the use of free and open source software significantly reduces cost and project execution time. The benefits of using open source systems are immeasurable, both from academic and industrial applications. In addition to cost and time reduction, the ease of maintenance and deployment of new tasks in the robotic mechanism must be emphasized.

With a PID controller, the response has low overshoot (2 per cent) but cannot reject disturbances. When the integrative part is introduced, the controller rejected disturbances but the system is less stable (overshoot of 23 per cent). This occurs because the integrator adds a zero in the origin of the controller. This performance is acceptable for the tuning procedure, as the ROS operation system will use ramp as set point.

When compared with others works like LineScout (Montambault and Pouliot, 2007; Pouliot and Montambault, 2009) and Expliner (Debenest *et al.*, 2008, 2010), POLIBOT has lightweight and independent PID control in joints. Thus, it was possible to reject disturbances, and POLIBOT had low overshoot in autonomous mode and was possible keep the vehicle stable in high voltage lines. In LineScout, the rejection of disturbances depends of operator`s ability.

Finally, a future project suggestion is the use of carbon fiber or other materials to reduce weight and consequently torques in joints. Other future work will be use of other control strategies like model predictive control (MPC) and adaptive control.

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