Robonwire: Design and development of a power line inspection robot

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***Abstract*—This paper presents a design of a low-cost, lightweight powerline inspection robot:*Robonwire*. Though commercial and research robots for inspecting and monitoring powerline are available, the weight of the robot is high and it requires a lot of human effort during set-up and operation. We focus on developing a laboratory scale robot for power line inspection. The robot has three arms and a base frame which houses the electrical and electronic elements to control the locomotion and avoiding obstacles. It uses three powered motors with wheels one for each arm providing the mobility of the robot on the wires. Each arm has two joints. The upper joint connects the arm body to the wheel assembly while the lower one connects the arm body to the base frame. The obstacle avoidance is achieved by lateral rotation of arms in sequence. This paper presents the initial phase of the development in which a robot is built for travelling on wire. The motion planning for obstacle avoidance and simulations for torque requirement analysis of joint motors are also presented.**

Keywords – Powerline inspection robot; Robot; Robonwire

I. INTRODUCTION

Modern power distribution networks are unquestionably critical in the progress of any nation. Because, they represent both significant investment and critical resource to every citizen, they necessitate regular inspection and maintenance [22]. Currently, manned or autonomous helicopters are used to inspect individual sections of the line, a hazardous and generally expensive process for energy providers. The use of helicopters for powerline inspection has a long tradition [12], [22], [7], while currently, growing use of unmanned aerial vehicles can be seen [3], [20]. Thus, it is proposed to develop a low cost, robust, wire scaling robot to conduct the inspections safely and securely under live wire conditions.

A recent development in the field of robotics is the use of robots on wires where robots are used for powerline inspection. These robots are designed to perform tasks while moving on a cable or rope. The ability of these robots to operate autonomously or to be remotely operated makes them an attractive solution for jobs involving inspection and maintenance. The advantages of implementing a robot on wires would be (i) Continuous inspection on live-wire: The robot can be left to operate with minimal interference with occasional maintenance, (ii) Low risk: The robot can be put into tele-operation or autonomous mode and inspect hazardous or high value assets without endangering human lives, and (iii) Higher precision and accuracy: The robot may provide operators with a greater quantity of accurate telemetry than would be achievable with periodic inspections.

As such, several such application-specific wire robots have been designed in recent years [5], [2], [16], [17], [21], with a majority focussing on high voltage transmission line inspection and suspension cable inspection. However, other applications also exist, for example, (i) structural and cable inspection robots: currently being developed to inspect the suspension cables on bridges and other structures [8], [6], (ii) Power transmission inspection [14], [16], (iii) Surveillance: Robotic surveillance along wires would allow for a wider surveillance field than static mounted cameras and sensors [24], and (iv) Research: Robots that are designed to travel along power lines can also be re-purposed to monitor the sizable land areas over which they travel. This data can be used for forestry research, remote observation, or crop monitoring.

The scope of this work is limited to modelling design and development of a robotic platform and the accompanying electronics necessary for its motion on the wire. This is the initial phase of the research which focus on design and development of locomotion mechanism and kinematic analysis. The main contributions of this paper are:

(i) A laboratory prototype robotic platform is designed for powerline inspection with three arms with wheels for traversing on the powerline.
(ii) Kinematic and dynamic analysis of the robot is achieved for torque requirements.
(iii) The design is focussed on avoiding the largest obstacle: aircraft warning ball while the robot will roll over the smaller.
(iv) A laboratory scale working prototype is developed for preliminary testing and experiments.
(v) Arduino based controller is developed for motion control

The paper is organized as follows: The next section II discusses the relevant literature in powerline inspection robot and it discusses a review of existing design solutions from locomotion standpoint. A brief consideration will be given to articles on the modelling the robot locomotion. The section III discusses the physical design and individual sub-components of Robonwire. The section IV presents the sequence of motions of arms for avoiding obstacles along with state machine for avoiding obstacle. A simulation study for calculating torque requirements are presented with kinematic and dynamic analysis of the robot in section V. The paper ends with discussions and conclusions in VI.

II. Relevant work in powerline inspection robots

Recently, a significant effort in making powerline inspection robot is seen by industries: Hydro-Quebec, HiBot Corp., and collaborating Universities. Traditionally, the transmission line is inspected through visual observation, thermal sensor, by climbing up the tower and foot patrol. The high voltage lines are monitored by helicopter assisted inspection. These methods pose high risk to the operators and line-men and also inspecting network of powerlines is a time consuming and monotonous job. A recent survey [9], [10] discusses the different types of faults, types of robots used for inspection.

A. LineScount

The LineScout (Fig. 1) weighs 100 Kg is developed by Hydro-Quebec for live line inspection [13], [15], [16]. It comprises three sections: a wheel frame, a centre frame, and the arm frame. While facing the obstacle, the robot extends the arm frame along the line until it bridged the obstacle, and the raised arms grip the line. Following this, the wheel frame retracts the wheels. The linear actuators shift the center frame forward along the arm frame and then the wheel frame is shifted further until both wheels were clear off the obstacle. The wheel frame remount its wheels on the line. Finally, the clamps are released, and the arm frame retracts and is shifted back. The robot continues along its inspection route.

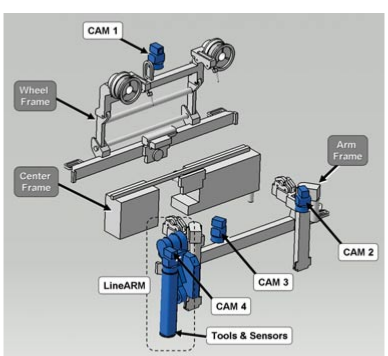


Fig. 1. LineScout Obstacle Avoidance[16]

The design of LineScount utilizes rolling motion, which enables the robot to simply roll over small obstacles instead of being forced to avoid them. Apart from the safety clamps, the LineScout did not need to couple or decouple with the line because motion of the frames are parallel to the powerline. The wheel frame need only be collapsed or raised. The c.g. of the robot is shifted by sliding the arm and wheel frames in the centre frame. This minimize the cantilever effect during obstacle avoidance.

B. Expliner

The Expliner robot (Fig. 2) weighs 84 Kg was developed as a collaboration between the Tokyo Institute of Technology, the Kansai Power Corporation and the HiBot Corporation, from Japan [4]. It has two drive axles with two wheel frames in each. The wheels are driven independently by servo motors. The axles serve as linkages in the robot, and a separate arm carries a counterweight. The Expliner is rolling over smaller obstacles, while for larger obstacles it pivots on the rear set of the wheels by moving the counterweight. This lifts the front wheels off the line. Now, the front axle is rotated so it is parallel to the line. The entire frame is moved forward till the front axle is clear of the obstacle. The process is repeated with the rear axle by pivot on the front axle, and by moving the counterweight forward. When both wheels are clear of the obstacle, the robot continues along. The method the Expliner used to traverse obstacles allowed it, like the LineScount to forgo any coupling mechanism: safety clamps. The robot cannot run on other than dual lines, therefore limiting the operation of the robot.

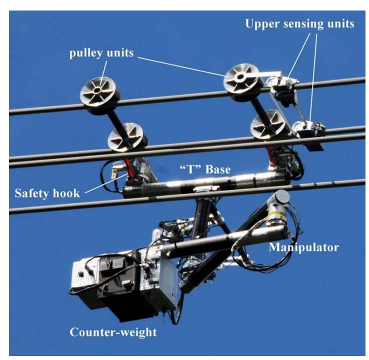


Fig. 2. Expliner Obstacle Avoidance [4]

C. Mobile Robot for Inspection of Power Lines

An older solution [17] to the problem of the line inspection is shown in Fig. 3. The premise of the article is that, for a fully functioning power line inspection robot, the design must be able to traverse the largest obstacle on the line: the towers connected by the lines. Because of the suspended insulator for transmission lines employed in British Columbia, the LineScout was able to easily travel across towers using its existing obstacle avoidance technology. However, when the insulators hold the line to the tower axially, the two combined insulators form an obstacle too large for most robots. This robot has a fold-able frame which, when unfolded, would be large enough to attach to the tower and move around the insulators to the line on the other side. Much like the LineScout, the frame would remain collapsed until such time as it was needed. However, the paper claimed to have highest power to weight ratio with an internal combustion engine.

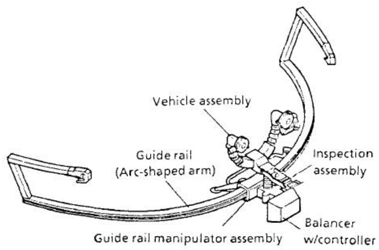


Fig. 3. Mobile robot for power line inspection [17]

This robot effectively solves one of the biggest problems in live line inspection. However, given the objectives of this project, designing and building a frame that large would add a great deal of weight to the robot, and thereby necessitate a more powerful drive system.

D. Cable Crawler

The robotic solution Fig. 4 built by ETH Zurich [2] is significantly larger than the above three designs. The cable crawler travels on a single cable at the top of the mast of electrical tower. The goal of this design was to achieve complete freedom along the line by reducing the number of actuators. The robot has large horizontal rollers in both its front and rear drive units. These drive units held the rollers to the lines using spring loaded clamps that enabled the drive units to widen when passing over the mast head. An additional drive segment was mounted in the middle and used to drive the robot over the masthead itself. The robot had sensor payloads on either side encapsulated in clear PVC spheres.

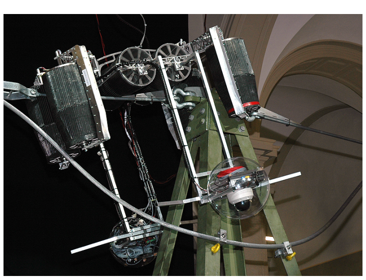


Fig. 4. Cable Crawler [2]

The cable crawler is capable of continuous motion through the line; no obstacle avoidance was necessary because the guide wire upon which the robot moved did not have any obstacles. The smaller ones could be rolled over. In addition, this setup required merely three motors. Nevertheless, there were some drawbacks. The design limited the accessibility of the robot to just the guide wire. Even with the reduced amount of actuators, the design would still expend more power due to its size.

E. Transmission Line Sleeve Inspection Robot

This robot is developed by by Korea Electric Power Research Institute [11]. In contrast to the above robots, it is designed to measure electromagnetic emissions on the line. The robot consists of two parts: drives and the sensor payload. The sensor payload mount connects to two drives, which are concave caterpillar treads that hug the line. An outer groove of flexible spines helps to keep the robot on the line. This robot is not suitable for long distance line movement. There are no mechanisms to avoid large obstacles. In addition, the robot is very small, and may not be capable of carrying a suitable sensor payload. For its purpose, the robot is well suites. However, it may be difficult to apply the robot to full scale line work.

F. Bipedal Line Walking Robot

A team of Kunshan Institute of Industry Research and University of Hamburg developed an elegant bipedal walking robot for powerline inspection [21]. The robot is shown in Fig. 5 composed of three segments: two legs, a waist and a body. The waist of the robot is comprised of a revolute joint mounted on the two prismatic joints of each leg. This allows the waist to translate along each leg. At the end of each leg is a revolute joint that allows the robot to position its feet on the line. The robot has two locomotion gaits: a *flipper* stride in which the robot lifts its legs in a striding motion and a *crawling* stride in which the feet are shuffled along the line.

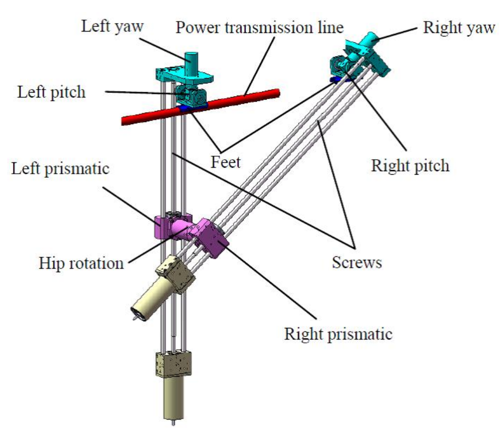


Fig. 5. Biped Line Walking Robot - CAD representation [21]

The waist actuators are close to the center of mass, thereby minimizing torque on the waist actuators and creating lower power consumption. Coupled with the fact that the obstacle avoidance methodology of this robot is a few motions similar to its flipper gait make this design very compelling. However, smooth control of this robot necessitates a fifth order polynomial incorporating joint position, velocity and acceleration.

G. Robotic Inspection Over Power Lines (RIOL)

The RIOL is developed by Institute for Systems and Robotics - Lisbon [18], [19] uses gait locomotion. The robot has five degrees of freedom articulated multi-body with a single prismatic arm in the middle. The robot moves along the line by looping two of its claws around the line, the rear initially clamped securely and the front loosely. Both links are then extended, thus shifting the front claw along the line. Once this is complete, the front claw clamps securely and the rear one relaxes. The two links retract, and the rear claw is pulled forward.

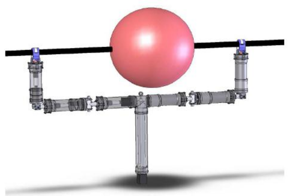


Fig. 6. RIOL Robot - CAD representation [18]

To avoid obstacles, the robot uses a stable form of the brachiation gait [19], a motion commonly employed by gibbons and other primates of interchanging swinging arms for locomotion. The stable method is to have the prismatic arm of the robot clamp the line and then lower front arm. The robot then moves forward, shifting the front arm clear of the obstacle. Once this is complete, the middle arm disengages and the robot moves it clear of the obstacle. Once on the other side, the robot reattaches the middle arm, and then disengages the rear arm. It moves the rear arm clear of the obstacle, and then reattaches it and disengages the middle arm. By always having an intermediary connection to the line, the robot is able to swing its forward arm securely past the obstacle.

H. Inspection robot for high-voltage transmission-line

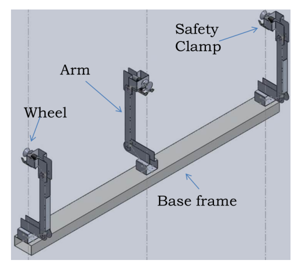
Central South University of Technology, China is developing a mobile robot for powerline inspection [23]. It has two arms with two revolute joints each and a wheel drives mounted their ends. The arms are connected to the base by a prismatic joint, which allows each arm to be extended to a certain extent. It is claimed that the experimental and simulated results are identical and this may be due to friction was not considered in dynamic model.

I. Comments & summary of existing robots

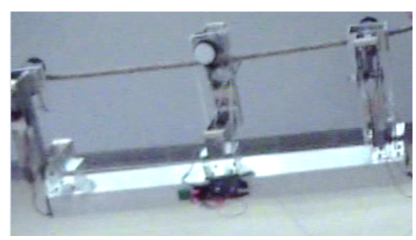
The design of powerline inspection robot is relatively young research area. It is interesting to note that the operational environment is well defined, especially the powerline structure, and obstacles. The primary challenge is the design of a mechanism which can provide continuous motion on the wire and obstacle negotiation. The two widely used designs are: gait motion or rolling motion. Another challenge is power to weight to ratio. The weights of most of the robots are not available, and the two major commercial robots: Linescout and Expliner are too heavy to handle. In view of the above limitations, we develop a laboratory scaled *Robonwire* for powerline inspection robot.

III. Design and Development of Robot on wire (RobonWire)

The *Robonwire* (Robot on wire) is a powerline inspection robot with wheels and arms mechanisms for locomotion, and obstacle avoidance, because the rolling motion has been proven to be faster and more secure. The obstacle avoidance is achieved through retracting and engaging the arms sequentially. Currently, the development is in its initial phase with the focus characterising the locomotion and obstacle avoidance.



(a) Robonwire - CAD Model



(b) Robonwire - Prototype

Fig. 7. Robonwire - Robon on wire

The Robonwire prototype is shown in Fig. 7 consists of a base frame on which three arms are mounted. The base frame houses the control equipment, and power pack. Each arm is a two-link structure and their joints are driven by a high-torque worm gear assembly. The choice was made for a worm assembly because of the gearbox's inherent self-locking nature and the worm gear has high-torque ratio. In addition, the gearbox could be driven by a standard, low power DC motor, instead of a high powered servo-motor. The drive motors are direct drive planetary gear DC motors with built in encoders for localization. In addition, each wheel has a safety clamp for stability and security. The clamp closes when the robot is rolling along the wire and makes sure that it does not slip off the line. The gap between each arm is the maximum obstacle size the robot can accommodate; the arm length is also half of this distance. The biggest obstacles generally found on transmission lines are aircraft markers. These are spherical in shape and measure about 0.75m in diameter [13]. Therefore, while the robot has to accommodate for the diameter of the sphere laterally, it only has to account for the radius height-wise). The Robonwire prototype reduces the number of moving parts like prismatic joint in Linescout and more number of linkages in bipedal mechanism or Expliner. The robot uses simple base frame mounted with three arms with two links. The robot is controlled through Arduino Mega 2560 [1].

A. Arm design

The arm of the robot is shown in Fig. 8. It is designed as a modular unit. The arms are designed to mount the wheels on the line without any coupling or claw mechanisms. The arm is a two degree of freedom, 3-bar linkage which helps to position the wheel on the line. The arm is eccentric at the base so that during obstacle avoidance, the arm may be shifted directly under the body (for a largest obstacle like aircraft warning ball) of the robot, to maintain the center of gravity.

Each arm has three parts: a base bracket, the arm body and the wheel mount. The base bracket is mounted onto the base frame. It is connected to the arm body through a joint (Lower-Joint). The base bracket houses the lower joint actuator. The arm body is the main part of the arm and carries the wheel mount at its top through a joint (Upper-Joint). The wheel mount is designed similar to the base bracket and it houses the drive mechanism of the wheel. In addition and as with the base bracket, it also holds the upper joint actuator. For all the joints, a potentiometer feedback system is employed for position control of the arm. In addition to the drive, the wheel mount also houses the safety clamp. This ensures the robot stays on the line during adverse conditions. It also enables the robot to rigidly grip the line while dismounting and reattaching manoeuvres.

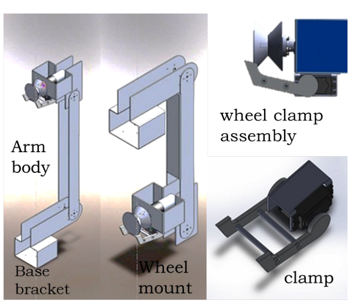


Fig. 8. CAD model of Arm, clamp, and wheel-clamp assembly

Each arm has its own control unit for joint actuators, drive motor and safety clamp servo. Any one controller may be used as a master controller and provide commands to the remaining arms. Since this design is a general purpose robotic platform, the master controller may be modified to accept commands from another, higher level processor. Moreover, the joints are actuated only when the larger obstacles have to be avoided. Otherwise, only the motors for wheels will be powered for locomotion.

B. Safety Clamp Design

The robot has one safety clamp shown in Fig. 8 for each arm. The safety clamp is responsible for securing the robot to the line. The clamp is composed of two hooks mounted to a servo and its accompanying bracket. The position of the servo determines the strength of the clamping. For gripping the line during obstacle avoidance, the position of the servo may be heightened. Under normal circumstances for rolling down the line, it may position lower. For the obstacle avoidance, the clamp is essential to prevent the robot from tilting too far off the line and thereby losing grip. From a modelling standpoint, the clamps are enabled during the transition of the robot to overcome obstacles and therefore allow for an assumption to be made: during transition, the robot arms are rigidly attached to the line. As visible in the subsequent sections, this assumption allows for a collapsed, extremely simplified dynamic model that only takes into account of a single arm at a time.

C. Wheel design

The wheel design is shown in Fig. 9. Initially, the design was focused on creating an inner surface that remained tangent to the line itself. Therefore, the wheel would have been constructed from vulcanized rubber of some nature. However, this proved inefficient, as sufficient traction became an increasingly evident problem. In addition, the fabrication method was not feasible. Thus, a machined solution was required.

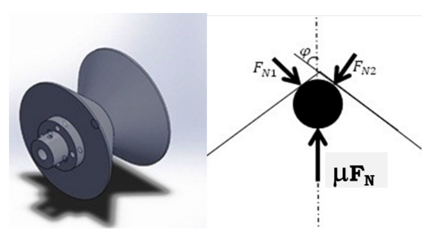


Fig. 9. Wheel design - CAD model

The new wheel design is conical with an inner lining of rubber added to provide the necessary traction. The traction force on the wheel is proportional to the cosine of the cone angle (ϕ) from the normal with coefficient of friction μ. The reaction forces $(F_{N1} + F_{N2})$ is proportional to the normal force (F_N) [16]:

$$F_{N1} + F_{N2} = \mu \frac{F_N}{\cos(\phi)} \tag{1}$$

Therefore, the acuteness of the angle is optimized to accommodate more cable diameters and the traction force. As a compromise, the angle $\phi = 45$ degrees was set for a maximum usable cable diameter of up to 25 mm.

IV. Obstacle Avoidance Methodology

The CAD representation of obstacle avoidance and the state machine to execute the obstacle avoidance are shown respectively in Fig. 10 and in Fig. 11. The obstacle avoidance methodology is shown with transitions of robot's arms around the obstacle. The robot is designed to detach the arm closest to the obstacle. The arm folds underneath the robot to maintain the centre of gravity of the robot. The robot will use the remaining two wheels to move the entire assembly until the front arm is clear of the obstacle. Once this is complete, the robot remounts its forward wheel to the line. This is done for the remaining arms until all three are clear of the obstacle.

Refer to Fig. 10. When an obstacle is encountered, the robot will release the safety grips from the line. It will then dismount the wheels from the line. Both joints rotate until the wheel is flush with the robot's body and located directly underneath the body (only for the largest obstacle - aircraft warning ball). Once this is complete, the robot uses the drives that are still on the line to move the entire robot, including the folded front arm, clear of the obstacle. Once the forward arm is remounted on the line, the process is repeated for the two remaining arms until all three of the arms are clear of the obstacle.

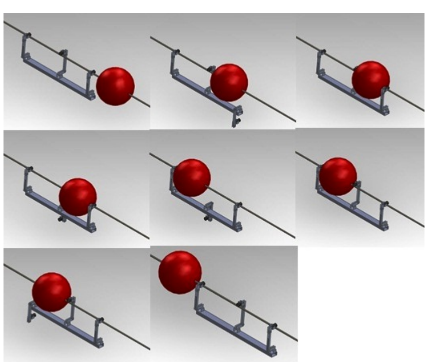


Fig. 10. CAD representations of obstacle avoidance manoeuvres

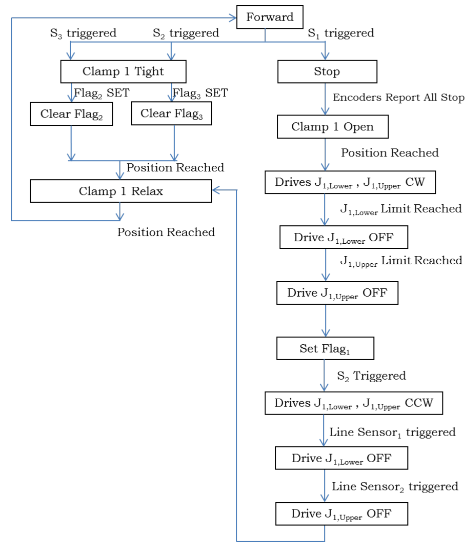


Fig. 11. State Machine for Obstacle Avoidance

The state machine in Fig. 11 shows the sequence of actions required to avoid the obstacle by one arm. To remount the line, the robot will rotate the forward arm counter clockwise while unfolding the wheel mount. Sensors placed on the wheel mount will detect the presence of the line. Once the line is detected by the lateral sensor, the arm body will stop rotating. A second sensor will detect the presence of the line vertically and will stop the upper joint. The flag elements for the other two arms are used to release their safety clamp from a stiff grip. The motion sequence of single arm is represented by $[C + (J_U+, J_L+), FW+, (J_U-, J_L-)]$, where C, J_U, J_L, FW represent respectively clamp, upper joint, lower joint, forward motion, and symbol $+$ represents open and $-$ represents close. The process continues for each arm.

It is proposed that each arm be controlled individually, with the flag bits transmitted over a serial interface. In this way, the state machine described here could be implemented on each microcontroller and the entire operation could be slaved to a higher level controller for tele-operation or feedback. However, the benefits of such a system did not outweigh those of a conventional single controller system. As such, the prototype system will be controlled by an Arduino Mega 2560. The proposed state machine will still provide a programming framework for the project.

V. Modelling & Simulations

A single arm of the Robonwire is essentially a two-link planar manipulator with an eccentric base shown in Fig. 12. The corresponding Denavit-Hartenberg parameters are given in table I. A kinematic model for a single link can be generated based on the assumption that the robot is rigidly attached to the line during obstacle avoidance. As such, the kinematic and dynamic analysis of this robot arm only pertain to the obstacle avoidance phase, in which the robot is either removing or positioning a wheel on the line.

The transformation of a two link manipulator with eccen-

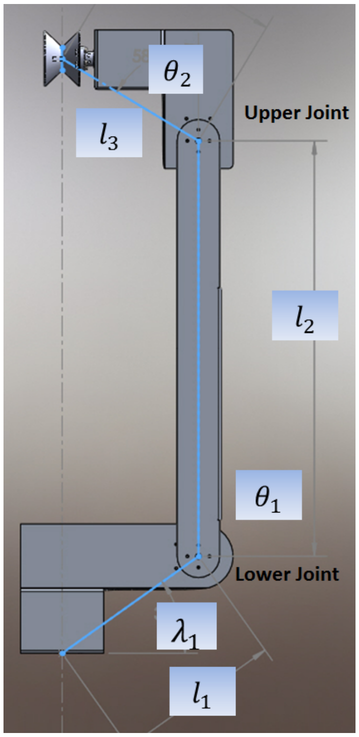


Fig. 12. Kinematics of arm

TABLE I
DH PARAMETERS OF ARM

Link	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	l_1	0	λ_1 + θ_1
2	0	l_2	0	θ_2
3	0	l_3	0	0

tric base is as follows:

$$\begin{pmatrix} \cos(\beta) & -\sin(\lambda_1-\theta_{12}) & 0 & l_2\cos(\lambda_1+\theta_1)+l_3\cos(\beta) \\ \sin(\beta) & \cos(\beta) & 0 & l_2\cos(\lambda_1-\theta_1)+l_3\cos(\beta) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2)$$

where λ_1 is the offset angle between the base of the bracket and the arm joint, θ_1, θ_2 are joint variables, and l_2, l_2, l_3 are the lengths of the base bracket, arm body and wheel mount respectively and $\beta = \lambda_1 + \theta_{12}$, and $\theta_{12} = \theta_1 + \theta_2$.

Thus, the Jacobian J is given by:

$$J = \begin{pmatrix} -l_2\sin(\lambda_1+\theta_1)-l_3\sin(\gamma) & l_3\sin(\gamma) \\ l_2\cos(\lambda_1+\theta_1)+l_3\cos(\gamma 2) & l_3\cos(\gamma) \end{pmatrix} \quad (3)$$

where $\gamma = \lambda_1 - \theta_1 + \theta_2$

Then the joint torques can be computed as:

$$\tau = J^T(\theta_1, \theta_2)F \quad (4)$$

Given the nature of the robot, the forward motion of the robot with the folded arm clear off the obstacle may be modelled as a single prismatic joint, with infinite length. However, for the remount and dismount motions, the above model of a single arm is sufficient.

In order to develop the controller for the system, the equation of motion of the arm is derived using Lagrangian analysis.

Let r_i be the center of mass for link i using the link frame, I_i be the inertial tensor for link i acting at the Centre of Mass (CM), and m_i be the mass of link i acting at the CM. The positions and velocities of the link CMs are:

$$x_2 = l_1\cos\lambda_1 + r_2\cos\theta_1 \quad (5a)$$
$$y_2 = l_1\sin\lambda_1 + r_2\sin\theta_1 \quad (5b)$$
$$x_3 = l_1\cos\lambda_1 + l_2\cos\theta_1 + r_3\cos(\theta_{12}) \quad (5c)$$
$$y_3 = l_1\sin\theta_1 + l_2\sin\theta_1 + r_3\sin(\theta_{12}) \quad (5d)$$

where $\theta_{12} = \theta_1 + \theta_2$

$$\dot{x_2} = -r_2\sin\theta_1\dot{\theta}_1 \quad (6a)$$
$$\dot{y_2} = r_2\cos\theta_1\dot{\theta}_1 \quad (6b)$$
$$\dot{x_3} = -(l_2\sin\theta_1 + r_3\sin(\theta_{12}))\dot{\theta}_1 - r_3\sin(\theta_{12})\dot{\theta}_2 \quad (6c)$$
$$\dot{y_3} = (l_2\cos\theta_1 + r_3\cos(\theta_{12}))\dot{\theta}_1 + r_3\cos(\theta_{12})\dot{\theta}_2 \quad (6d)$$

The kinetic energy of the system is:

$$T = \frac{1}{2}m_2v_2^2 + \frac{1}{2}I_2\omega_2 + \frac{1}{2}m_3v_3^2 + \frac{1}{2}I_3\omega_3 \quad (7)$$

where $v_i^2 = \dot{x}_i^2 + \dot{y}_i^2$.

Since the arm is constrained in $x-y$ plane, $I_i = I_{i_z}$, $\omega_2 = \dot{\theta}_2$, and $\omega_3 = \dot{\theta}_1 + \dot{\theta}_2$.

$$T = \frac{1}{2}m_2(\dot{x}_2^2+\dot{y}_2^2) + \frac{1}{2}I_{2_z}\dot{\theta}_1^2 + \frac{1}{2}m_3(\dot{x}_3^2+\dot{y}_3^2) + \frac{1}{2}I_{3_z}(\dot{\theta}_1+\dot{\theta}_2)^2 \quad (8)$$

Kinetic energy:

$$T(\theta,\dot{\theta}) = \frac{1}{2}I_{3_z}(\dot{\theta}_1+\dot{\theta}_2)^2 + \frac{1}{2}m_2(r_2^2\dot{x}_1)^2 + \frac{1}{2}I_{2_z}\dot{\theta}_1^2 + \frac{1}{2}m_3(l_2\dot{\theta}_1^2 + 2l_2c_2(\dot{\theta}_1^2+\dot{\theta}_1\dot{\theta}_2) + r_3^2(\dot{\theta}_1+\dot{\theta}_2))^2) \quad (9)$$

Potential energy:

$$P = \sum m_i g h_i = m_1 g r_1\sin(\lambda_1) + m_2 g(l_1 + r_2 s_1)) + m_3 g(l_1 + l_2 s_1) + r_3 s_{1,2}) \quad (10)$$

Using the above two equations in Lagrangian equation of motion:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} + \frac{\partial L}{\partial q_i} = 0 \quad (11)$$

where $L = T - P$ is Lagrangian,

$$\ddot{\theta}_1(m_2r_2^2 + m_3l_2 + 2l_2m_3c_2 + m_3r_3^2 + I_{3_z}) + \dot{\theta}_1\dot{\theta}_2(-l_2m_3s_2) + \ddot{\theta}_2(m_3r_3^2 + I_{3_z}) - m_2gr_2c_1 - m_3g(l_2c_1 + r_3c_1) = 0$$
$$\ddot{\theta}_2(I_{2_z} + m_3r_3^2 + I_{3_z}) + \dot{\theta}_1\dot{\theta}_2m_3l_2s_2 + \ddot{\theta}_1(m_3l_2c_2 + m_3r_3^2 + I_{3_z}) - m_3gr_3c_2 = 0 \quad (12)$$

where $c_2 = \cos\theta_2, c_1 = \cos\theta_1, s_1 = \sin\theta_1, s_2 = \sin\theta_2$

The torque requirements are simulated using the data from SolidWorks®. It is found that the torque requirement of the upper joint is lesser than the lower motor. Intuitively, this is correct and hence the design is validated. This helps in selection of motors as

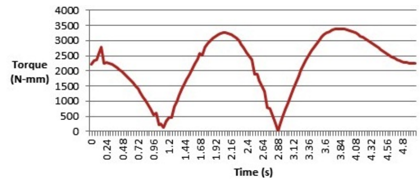


Fig. 13. Torque of upper actuator joint for 180 degree motion

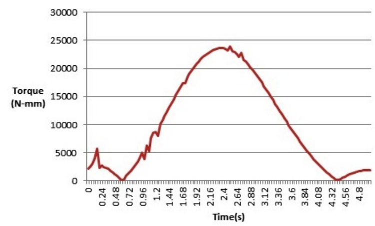


Fig. 14. Torque of lower actuator joint for 180 degree motion

described in Sec. III. The calculated moment of inertia (gm-sqmm) of arm from the CAD model is:

$$\begin{bmatrix} I_{xz} & I_{xx} & I_{xy} \\ I_{yz} & I_{yx} & I_{yy} \\ I_{zz} & I_{zx} & I_{zy} \end{bmatrix} = \begin{bmatrix} 0 & 0.218e6 & -0.25e6 \\ 0 & -0.25e6 & 19.23e6 \\ 19.19e6 & 0 & 0 \end{bmatrix}$$

VI. DISCUSSIONS & CONCLUSIONS

This paper presents initial design of prototype of a powerline inspection robot: *Robonwire*. The aim of the robot design is to make it low-cost & lightweight. In this phase, a robot is built for travelling on wire. A detailed design for motion and sequence of control for obstacle avoidance is presented. The design modelling and analysis of single arm has been completed. Torque requirements for robot joints are simulated with CAD data. It conforms to the design requirement that the lower joint needs higher torque than the upper joint. The prototype robot is able to travel on the wire. Currently, sensor based obstacle avoidance and shifting of robot's centre of mass during obstacle avoidance are under study. Sensor integration, navigation, and telematics are planned for future developments. It is believed that this design will be a more effective solution to the problems that line working robots to maintain and inspect widespread transmission lines. In addition, optimization of design, motion sequence and sensors and actuators are planned in future to make this robot platform robust and cost-effective.

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