RIOL - ROBOTIC INSPECTION OVER POWER LINES

Luís Tavares [*] **João Silva Sequeira** [**]

[*] *Institute for Systems and Robotics*
email: ltavares@isr.ist.utl.pt
[**] *Instituto Superior Técnico,*
Institute for Systems and Robotics
IST, Av. Rovisco Pais 1
1049-001 Lisboa, Portugal
email: jseq@isr.ist.utl.pt

Abstract
This paper describes ongoing work on a prototype robot capable of moving on electric power lines executing monitoring tasks. The inspection of the power lines infrastructure, forest fire surveillance and wildlife study are the some of the potential applications.
The robot is composed by a central body with three serial arms. Two of these are used to provide motion, using a statically stable variation of the brachiation movement, whereas the third arm is used to insure stability and assisting in the overtaking of obstacles in the lines. In addition, this third arm helps maintaining the torques required by the other two arms within reasonable values. Two vertical rotation joints allow the robot to perform curves and control its center of mass.
The paper presents basic simulation results and details of the prototype under construction.

Keywords: Robot Kinematics, Robot Dynamics, Power Lines

1. INTRODUCTION

The development of robotics is greatly motivated by its potential for helping humans in dangerous/demanding tasks. The inspection of electric energy distribution lines is one of them, due to the hard accessibility, span and height of the lines, and electrocution danger. Currently, this work is mostly done by human experts either flying over the lines onboard helicopters, or by direct access to the line. Both solutions are expensive and risky. Remote surveillance using static sensors, e.g., video and thermal cameras, or through autonomous (Schempf *et al.*, 1999), or semi-autonomous mobile robots (Bares and Wettergreen, 1999) are also possible alternatives. Static sensing tends to be cost inefficient and the optimal location of the sensors may vary with time. Monitoring the lines from ground is also expensive as lines cross all sorts of terrains and often rend impossible the use of land vehicles to support the inspection.

This paper describes a prototype robot able to navigate over power lines and perform monitoring/surveillance tasks. Several projects aimed at developing an autonomous robotic platform for operating in such environments (see for instance (Rocha and Sequeira, 2004; Li *et al.*, 2004)). Strong electromagnetic fields, weight limits imposed by the line infrastructure, and harsh meteorological conditions, set the design boundaries for this class of robots. Figure 1 shows a kinematics diagram for the basic 2-link serial structure in (Rocha and Sequeira, 2004). The claws at the extremities can grab the line to allow a worm like motion in the absence of obstacles and a statically stable variation of the brachiation movement when overtaking an obstacle. Figure 2 shows the kinematics for a robot described in (Li *et al.*, 2004), with a rolling mechanism to slide over the cables and several prismatic joints.

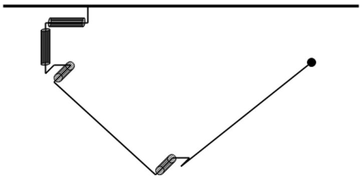


Figure 1. Two link serial robot, (Rocha and Sequeira, 2004)

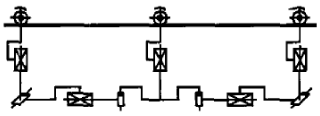


Figure 2. Multi-link robot, (Li *et al.*, 2004)

The RIOL robot prototype described in this paper builds upon the basic structure in (Rocha and Sequeira, 2004). Figure 3 illustrates the kinematics diagram for this proposed version. This upgraded kinematics yields torques within the capability of off-the-shelf motors and an acceptable overall weight. The structure is composed by a central body, two lateral serial arms and a central linear arm. The central arm is used to help maintaining stability when overtaking obstacles.

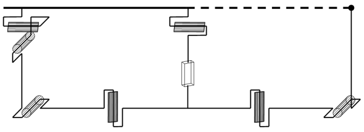


Figure 3. RIOL's kinematic structure

The paper is organized as follows. Section 2 describes key aspects of the environment where the robot operates. Section 3 briefly reviews the conclusions withdrawn from previous work. Section 4 explains the adopted locomotion strategy. Section 5 describes the simulations on the dynamics. Section 6 describes materials, motors and key mechanical components. Section 7 presents the control architecture. Finally, Section 8 contains conclusions and directions for future work.

2. ENVIRONMENT

Electric power lines offer a structured environment that can serve as the locomotion infrastructure for a robot. The main characteristics of the lines, e.g., cable diameter, material, maximum slope, stiffness, are standardized. Also, the type of obstacles that are common on the lines is limited and with well defined characteristics. Still, extreme climatic exposure, weight limits and difficulty in grasping/propelling over a cylindric lax cable with obstacles represent a challenging problem. Figure 4 shows examples of typical obstacles in power lines. These include aircraft markers (a), insulators connection cables (b) and other small objects, e.g., scarecrows. Plots (c) and (d) show examples of situations the robot must detect when inspecting a line. The aircraft marker is the among the biggest obstacles common in the lines and hence it is used as reference to define the physical dimensions of the robot.

(a) Avoidance Marker (b) Connection cable

(c) Damaged insulators (d) Damaged cable

Figure 4. Common obstacles and situations in power lines

Some of the characteristics of the line inspection problem, like the strong electromagnetic fields around the cables, the resistive heat caused by the energy flow and the appearance of ice during the cold seasons are not addressed in this paper. This fact does not constrain the usefulness of the present study. In fact, this corresponds to a feasibility study on the structure and locomotion gait that must be done prior addressing such problems.

3. PREVIOUS WORK

The 2-link structure in Figure 1 was intended to move using a statically stable variation of a brachiation gait. In the absence of obstacles this movement is achieved simply by (i) fixing one of the claws to the cable, (ii) letting the other claw sliding along the line, and (iii) repeat the procedure with the roles of each claw reversed. In the presence of obstacles, the movement is achieved by swinging the frontal arm forward and grasping the line again, followed by similar movement for the back arm, that is, releasing and advancing the rear arm and claw (see Figure 5). The study in (Rocha and Sequeira, 2004) demonstrated the adequacy of this basic structure for motion on a line. As for overtaking obstacles, such as the aircraft markers, the main issue is related to the high torques required for the statically stable variation of the brachiating movement.


(a) Releasing the cable (b) Swinging and grasping

Figure 5. Maneuver to overtake an aircraft marker.

Simulations results using a PID controller and links $0,7m$ long and weighting $2,5Kg$, indicated that the rear claw could bear a $50N.m$ torque. This value is close to the limit for off-the-shelf electrical motors with compatible dimensions/weight.

Although, the simulations shown good performance for this simple structure, and control strategy (for instance the maximum deviation of the grasping claw under wind gusts of up to 10 m/s was about 0.06 m), small increases in the lengths of the links or masses involved rapidly yield unacceptable torques. This led to the evolution of the structure to include an additional arm such that at each time instant the robot is suspended by at least two points, hence reducing the torques required by the joints providing the traction.

4. LOCOMOTION GAIT

The RIOL structure is composed by three arms joined at a central body. Two double link arms provide the base points for traction/propulsion. The third arm is used just to provide support of the whole structure aiming at reducing the torques required when overtaking obstacles in the line. For instance, when surpassing aircraft markers the robot always grasps the line at two points, providing a stable support to the whole body.

The central body is composed by three blocks connected through vertical rotation joints. These allow the RIOL robot to control its mass center and move across lines with different directions. The third arm is essentially a vertical linear joint, capable of holding the robot alone and recoiling completely when avoiding obstacles. Figure 6 shows a full scale CAD model of the RIOL robot. The sphere represents a full size aircraft marker and is shown for comparison.

The total length of the arms is defined from the dimensions of the aircraft markers maximum radius, about $91cm$. The prototype's dimensions are shown in Figure 7. The estimated weight is around $30Kg$.

Figures 8 and 9 illustrate the locomotion gaits, respectively, for sliding along an obstacle free line and for obstacle overtaking.

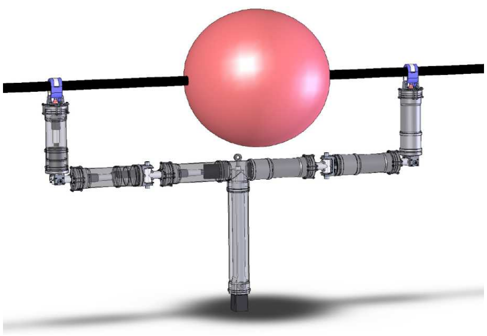


Figure 6. Real scale model of RIOL

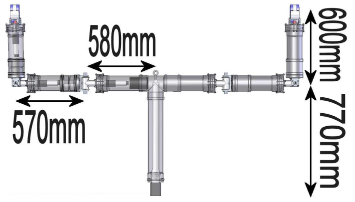
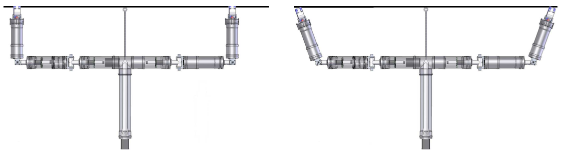


Figure 7. Physical dimensions for the RIOL robot


(a) Initial position (b) Stretched position

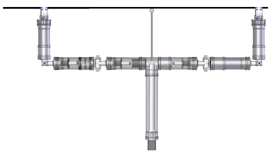
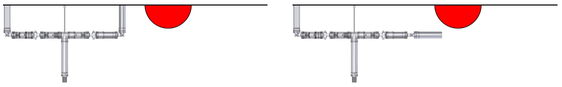

(c) Final position

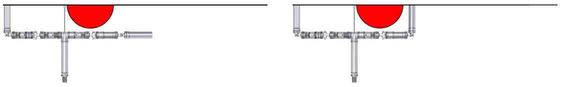
Figure 8. Sliding along an obstacle free cable

In Figure 8 the robot grasps the line with the rear claw and opens both arms. The linear arm can either be retracted or be left grasping the line loosely, that is, simply providing a support point for the weight, such that it can slide along the line. This procedure allows the sliding of the frontal claw along the line requiring a small effort from the rotation joints as most of the weight is supported by the linear arm. When some predefined stretching limit is reached the roles of the lateral arms are reversed. The robot grasps the line with the frontal claw, sliding the rear and central claws forward and returning to the initial configuration.

In Figure 9 the robot starts by lowering its frontal arm, so that it may pass under the obstacle. The central arm and the rear arm then perform the movement described for sliding over the line. Note that the front vertical joint aids maintaining the platforms balance. Once the linear arm is near the obstacle, the frontal arm grabs the cable, allowing it to recoil completely. Sliding continues until the linear arm is clear again to attach to the cable.



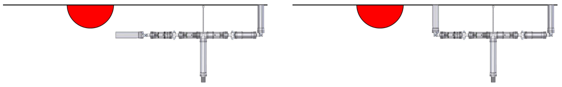
(a) Initial position (b) Lowers the frontal arm



(c) Advances toward the obstacle (d) Raises the frontal arm

(e) Recoils the central arm (f) Passes under the obstacle

(g) Stretches the central arm (h) Lowers the rear arm



(i) Advances (j) Raising the rear arm

Figure 9. Obstacle avoidance gait

The final steps include lowering the rear arm and moving forward until the obstacle is passed and the cable is grabbed again.

5. SIMULATIONS

The dynamics of the RIOL robot depends of the particular locomotion gait. In both the sliding and obstacle avoidance gaits three kinematic configurations can be distinguished: (i) all the three arms are attached to the line, (ii) both lateral arms grasp the line and the central prismatic is recoiled, and (iii) the prismatic and one of the lateral arms are holding the line while the other lateral arm is free. The last two are the more demanding in torques and stability control.

This section addresses the dynamics simulation for these last two configurations. From the perspective of simulating the dynamics, the strategy is to decompose the robot in simpler kinematic structures and assessing each of them. The control architecture in charge of the switching between the different gaits can then generate the adequate reference trajectories for each of the joints.

Figure 10 shows the simplified kinematics when the lateral arms are grabbing the line and Figure 11 when only the central prismatic and one lateral arm grab the line.

The kinematics in Figure 10 shows the robot as a 6 DOF serial manipulator. The design is simplified as in reality the front claw (identified by the dot in the plot) is connected to the cable by two rotation joints, identical to 1 and 2, and a prismatic joint that allows sliding along the cable (Y axis). The rotation joint 1 is not actuated and it is only used to model the rotation around the line axis.

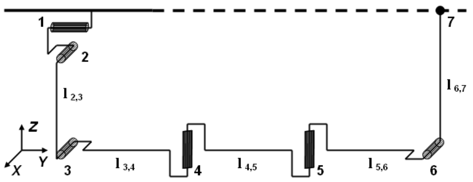


Figure 10. Kinematic configuration when both lateral arms hold the line

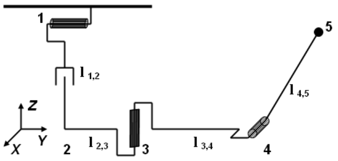


Figure 11. Kinematic configuration when the prismatic and one arm hold the line

The kinematic structure of Figure 11 ignores the influence of the lateral arm in the position of the frontal claw. In this case, RIOL is a 4 DOF serial actuator with a prismatic joint.

Figures 12 and 13 show the Matlab SimMechanics model developed to simulate both configurations.

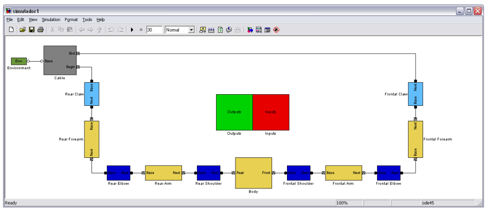


Figure 12. SimMechanics mass-joint model to simulate both lateral arms grabbing the line

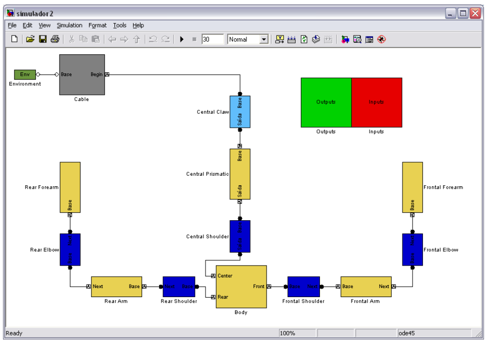


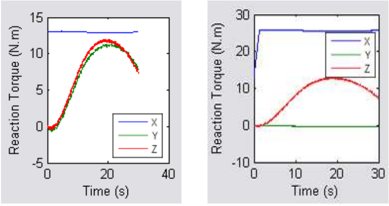
Figure 13. SimMechanics mass-joint model to simulate one lateral arm and the prismatic grabbing the line

Table 1 contains the length and weight of RIOL components considered in the simulations.

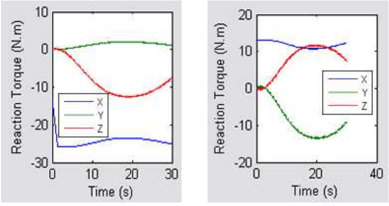
Component	Length	Weight
Cable	$10m$	$220Kg$
Forearm	$0,6m$	$5Kg$
Arm	$0,57m$	$5Kg$
Body	$1,16m$	$10Kg$

Table 1. Physical parameters

Simulation results obtained for each configuration are shown in Figure 14 and Figure 15, respectively, for arms opening angles of 10° each, lateral wind applying $4.6N$ on each component, and random gusts of $0.46N$ (values computed after the typical wind parameters in Portugal and the aerodynamic characteristics of the prototype).

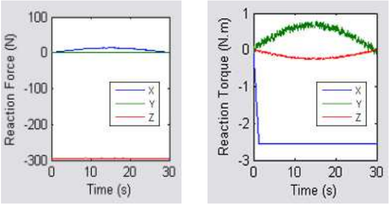


(a) Rear Claw (b) Rear Elbow



(c) Frontal Elbow (d) Frontal Claw

Figure 14. Dynamic results for both arms attached to the line with wind and 20° angle



(a) Prismatic (b) Front Elbow

Figure 15. Dynamic results under windy conditions for one lateral and the prismatic arms grabbing the line

The results confirm the decrease in the torques required by elbows, indicating that the rotation motors must withstand $30Nm$ whereas the prismatic actuator must sustain forces up to $300N$. The influence of the wind is reduced due to the position of the mass center and the linear arm which provides the required stability when only one lateral arm is grasping the line.

6. MECHANICAL STRUCTURE UNDER DEVELOPMENT

The robot prototype is currently under development, with the most of the mechanical components already built. Figure 16 shows a full-size mockup of the prototype.

Standard off-the-shelf DC motors, able to deliver up to $30Nm$ are used to actuate the platforms elbows and shoulders. These motors are controlled using also off-the-shelf controllers, connected through a CAN bus. The structure of the links is made of rigid, $0,4MPa$, PVC tube, with $3mm$ wall thickness, due to its light weight, low cost, easy carving, and high electrical resistance. Figures 17 and 18 show a rotation joint and a motor support with their respective stress distribution models obtained for the double of the maximum required torques. Figure 19 shows the CAD model of the claw used to grab the line, currently under construction. This image does not show the braking mechanism required to create a rigid connection with the line. Figure 20 shows the complete assembly of a rotation joint.

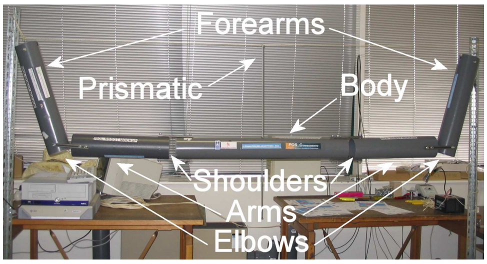
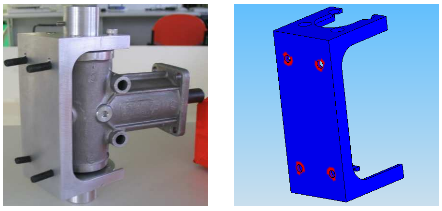
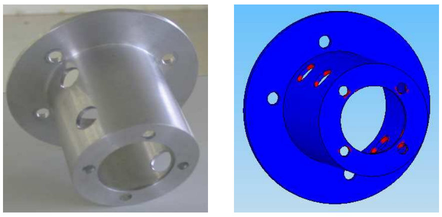


Figure 16. RIOL mockup



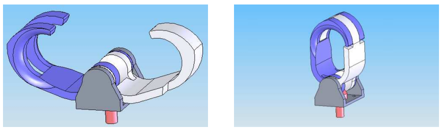
(a) Picture (b) Stress distribution

Figure 17. Rotation joint



(a) Picture (b) Stress distribution

Figure 18. Motor support



(a) Open claw (b) Closed claw

Figure 19. CAD claw design

The red in the stress distribution models identify areas where the factor of safety is below 1. Power is currently supplied by an external source, but LiPo batteries with $4300mA$ will provide onboard power for test missions.

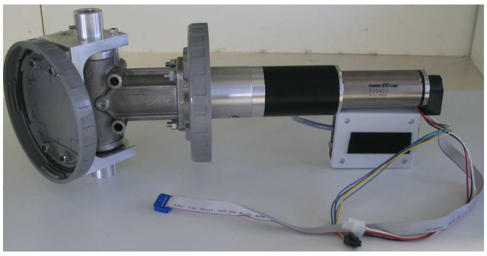


Figure 20. Complete assembly of a rotation joint

7. CONTROL ARCHITECTURE

The control architecture of RIOL is composed by (i) the actuator controllers, and (ii) a finite state machine (FSM) that controls the locomotion gait and generates the reference paths for each joint. The first controls the motors, enabling the following of position profiles. Figure 21 shows the standard block diagram for the off-the-shelf PID-based controller.

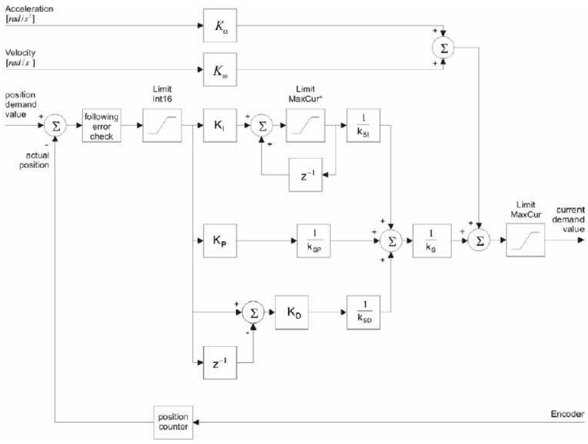


Figure 21. Off-the-shelf actuator controller

Two distinct methods are being developed to sense the environment. Sonars on the claws and horizontal body will detect forthcoming obstacles and measure the distance to the cable. In addition, a lightweight stereo vision system is being developed to extract the position and distance between the robot claws and the line. The actual algorithm is capable of processing 480 × 320 images in near real-time, enabling the extraction of 3D positions.

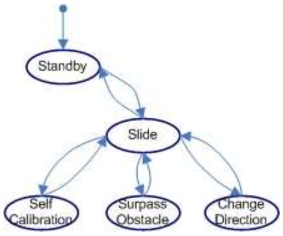


Figure 22. Locomotion gait automaton

The FSM (see Figure 22 for a simplified version) manages the navigation over the power lines, namely controls the switching between the different locomotion gaits, and coordinates the maneuvering required by each gait by generating adequate position profiles for each joint. The standby state occurs at the beginning and when RIOL is expecting a new mission. Slide, Surpass obstacle and Change direction are maneuver states. The first corresponds to move along the cable, the second executes the standard set of actions that overcome obstacles and the third performs the maneuver to pass between lines with different directions. Self calibration occurs when inconsistent positions are returned by the stereo vision and the odometers.

8. CONCLUSIONS

The paper describes the main project options for the RIOL robot. The kinematic structure for the RIOL robot presented in the paper is able to overtake the standard obstacles and most of the non regular ones arising in standard power lines.

The preliminary simulation results seem to indicate that off-the-shelf actuators can be used in the real prototype and also that the RIOL robot will be able to move successfully over power lines with slopes up to 10°. The locomotion gaits considered are able to maintain the static stability of the robot.

Ongoing work includes flexibility tests for the whole robot, design of the claws braking mechanism and assembly of a full size prototype.

ACKNOWLEDGMENTS

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