NEW APPROACHES FOR SURVEILLANCE TASKS ⋆

José Rocha ∗,1 **João Sequeira** ∗∗,2

∗ *Escola Superior de Tecnologia de Setúbal/Instituto Politécnico de Setúbal, Rua Vale de Chaves, Estefanilha, 2910-761 Setúbal, Portugal*
∗∗ *Instituto Superior Técnico/Institute for Systems and Robotics, Av Rovisco Pais 1, 1049-001 Lisboa, Portugal*

Abstract
This paper describes part of a study on a prototype robot for monitoring/surveillance tasks conducted over the infrastructure provided by electric power lines/electric shield wires. Among the most relevant tasks that can be carried out by this robot are forest patrolling, environmental mapping and wildlife monitoring. The robot uses a statically stable variation of the brachistochrone motion to move along electric shield wires/electric power lines overcoming the standard obstacles. The paper describes the kinematics and basic simulation results on the dynamics and control of the robot.

Keywords: Surveillance Robotics

1. INTRODUCTION

This paper describes a robot for a variety of monitoring tasks. The robot moves along the electric shield wires mounted over electric energy distribution lines. The inspection of the power lines, the surveillance of wide forestry areas, specially those of difficult access, environment parameters monitoring such as humidity, sunlight and pollution, monitoring of animal species such as the endangered ones, are examples of socially and economically relevant tasks that can be accomplished by this robot.

Such tasks are normally executed locally or remotely by experts. Remote surveillance/monitoring can be done in a variety of ways, namely through static sensors, e.g., video cameras installed in important locations or through autonomous, (Schempf *et al.*, 1999), or semi-autonomous mobile robots, (Bares and Wettergreen, 1999). Static sensing tends to be not cost effective as the optimal location of the sensors may be time varying. As a consequence, the adaptation to environment dynamics may be difficult. Local surveillance/monitoring may also be not cost effective Electric power lines cross all sorts of terrains. For land based robots, harsh conditions, often encountered in forest environments, may require specific kinematic designs that tend to difficult fully autonomous approaches. Semi-autonomous robots either aerial or ground based, though in the range of current technological capabilities, require specialized operators and hence tend also to be not cost effective.

The alternative approach proposed in this paper considers already existing infrastructures as the robot locomotion support. Electric power lines

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[1] jrocha@est.ips.pt
[2] jseq@isr.ist.utl.pt

represent a highly structured environment for a robot, providing clear views over wide areas, and are typically spread among vast regions, some of which of difficult orography. Furthermore, the use of robots such as the ones proposed does not affect the normal operation of the lines.

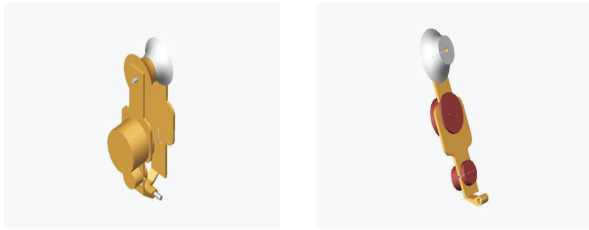
The proposed robot moves with a statically stable variation of the brachistochrone motion (see (Nakanishi *et al.*, 2000) for the dynamically stable version). The static stability is desirable as the robot must carry sensing devices that, most likely, require a stable support platform. A large variety of monitoring instruments can be attached to the robot thus spanning the range of possible applications. The robot can carry multiple environmental sensors, namely infrared and video cameras, global positioning devices and systems for measurement of atmospheric parameters. Multiple communication media can also be considered, namely Earth and satellite radio links, such that it can interface the remote operators using, for instance, web based applications.

This paper is organized as follows. Section 2 details the main kinematics and dynamics aspects of the proposed robot. Section 3 focuses on the control strategies used in the proposed robot. Section 4 presents preliminary simulations results on two different approaches to the control of the robot. The conclusions are presented in Section 5, along with directions on the future work.

2. THE PROPOSED SYSTEM

The proposed locomotion approach resembles the motion of a cabbage worm, which moves by expanding and contracting his own body. The shield wires usually mounted over the electric power lines provide a highly structured locomotion support for which the cabbage worm gait can be adapted.

Figure 2 shows a stick diagram for the basic robot. The kinematics model for this basic structure, a serial kinematic chain with three degrees of freedom, is elementary. The robot has three revolution joints, interconnected trough two rigid links, and two claws, one at each extremity of the kinematic chain. The two claws are identical and both equipped with worm gears. Their specific design enables the tight grabbing of the line, hence providing the fixed point for the statically stable brachiation motion gait, and the sliding along the line. The worm gears guarantee system safeness, avoiding the fall of the robot in case of malfunction in the system controlling the opening/closing of the claw, e.g., an electric power failure. Both claws have pulleys to ease the sliding motion along lines. Figure 1 shows the claw main body with the pulleys. The grabbing mechanism is not displayed.



(a) Claw (b) Half Claw

Figure 1. Prototype of the claws placed at each end of the robot

Figure 2 illustrates, with a stick diagram, the kinematics structure for the cabbage worm gait. In the obstacle free motion both ends of the robot are in contact with the line.

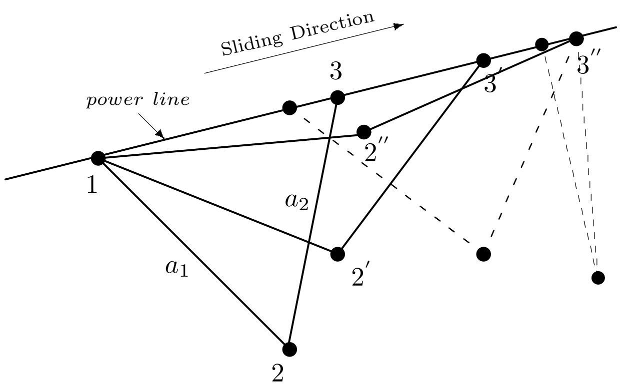


Figure 2. Basic structure, with two links of equal length, sliding along a power line.

In the absence of obstacles, the locomotion gait has two phases, hereafter named expansion and contraction. During the expansion phase (shown as the solid line) point 1 stays fixed, as the corresponding claw tightly grabs the line. whereas point 3 slides along the line, in the direction of progression. Joints 1 and 2 move the links a_1 and a_2 in the same progression direction. This phase stops when the robot is near the totally stretched singularity. Once the extension phase ends the contraction phase begins (shown as the dashed line) with the roles of the points 1 and 3 reversed. Point 1 now slides along the line whereas point 3 stays fixed. The contraction movement finishes when the distance between the two claws approaches zero (another kinematics singularity).

Obstacle transposition requires also a two phase locomotion gait. In the first phase one of the extremities of the robot tightly grabs the line whilst the other extremity moves freely to avoid the obstacle. This gait is identical to standard manipulator motion in free space. The second phase is similar to the first one, with the roles of the fixed and free ends of the robot reversed.

3. DYNAMICS MODELLING AND CONTROL

The dynamic model for the robot can be easily obtained from standard Newton-Euler or Lagrange formulations. Given the kinematics in Figure 2 and the aforementioned locomotion gaits two dynamical models are obtained, respectively for the obstacle free motion and for the obstacle transposition motion. During the obstacle transposition the dynamics model is similar to that of a double pendulum. During the obstacle free motion the reaction force acting on the sliding claw has to be accounted for, thus yielding resulting a constrained double pendulum model. Standard models including viscous forces are considered for the dynamics of the electric motors driving the joints, (Schilling, 1990).

The robot is controlled using a standard inverse dynamics scheme. In the absence of parametric and structural undertainties, this scheme yields a double integrator control system for which PID control can be used.

Due to the unceertainties, the exact linearization performed with this scheme is seldom a realistic approach. The estimation of an exact model for this robot is highly dependent of technological factors, e.g., dimension and weight of the actuators, the specific materials used. In addition, different missions assigned may require different loads, affecting masses and inertias, and hence the dynamics. However, given the simplicity of the kinematic structure, these factors tend to induce mainly parametric errors, for which the PID control may still be a reasonable option. Standard robust control schemes are be used to cope with the uncertainties in the dynamic models.

4. EXPERIMENTAL SIMULATION RESULTS

This section details some aspects of a robot made out of a single basis element such as that shown in Figure 2. Both links are 0.7 m long and have a mass of 2.5 Kg. The length value comes out from a tradeoff between the length needed to overcome standard obstacles in the lines (e.g., unions), the length yielding reasonable torques (longer links yield higher torques and hence heavier motors with high energy requirements) and the maximum weight allowed on the lines. Furthermore, longer links tend to induce modelling errors due to the flexibility of the structure.

The simulation experiments account for disturbances caused by aerodynamic forces, namely wind gusts blowing in the plane of the motion. In general, these are difficult to model exactly and thus they are not included in the model based decoupling/linearizing control law. The inclusion of a robustness term in the control law overcomes most of the problems caused by the lack of information on the disturbances in the dynamics. Robustness terms derived from a standard control formulation have been used in the control of a serial manipulator, (Sciavicco and Siciliano, 1999). This is the strategy considered in this work. Robustness terms implemented by neural networks have been used in the control of biped robots, (Katić and Vukobratović, 2003).

The PID gains are identical to all controllers and were obtained after a manual tuning process. In addition to the inertia of the links, the inertias of the actuators must also be included in the dynamic description, specially when large reduction gears are used (as in this robot).

Table 1 shows the main data used for the simulations. The PID gains correspond to $K_{P_i}, K_{I_i}, K_{D_i}$ and are identical for all joints. The actuator inertia and gear ratio are represented, respectively, by I_i and r_i. FALTA EXPLICAR O SIGNIFICADO DE ε, ρ e $\mathbf{P}$

$K_{P_i} = 150$	$K_{I_i} = 0.0016$	$K_{D_i} = 20$	$\varepsilon = 0.09$
$a_i = 0.7m$	$m_i = 2.5Kg$	$\rho = [200\ 6]$	$\mathbf{P}$=0.5 $\mathbf{I}$
$I_i = 127g.cm^2$	$r_i = 285$		

Table 1. Robot data

All experiments consider a robot composed of a single basis element (see Figure 2). Complex missions may eventually require robots composed by multiple basis elements.

Obstacle detection can be done with multiple sensors, e.g., electronic whiskers vision or ultrasonic sensors. Two phases are identified for obstacle transposition. After the detection of the obstacle, the robot enters the first phase in which the front tip of the structure breaks the contact with the power line and follows a pre-specified path to acquire a configuration that allows the transposition of the obstacle. During this motion, video sensing tracks the position of the line such that a goal point, ahead of the obstacle, for the robot to grab is identified. Once this point is grabbed the second phase begins. The tip at the back position (the fixed one, in the first phase) breaks the contact with the line and performs a transposition motion similar to that executed by the front tip, also grabbing the line.

Electric power lines/shield wires are layed over the terrain in a multitude of configurations. The basic design in Figure 2 can only execute planar movements. Moving along lines forming an angle at the supporting points (see Figure 3) is a problem that can be tackled by introducing additional rotation joints at both tips. These joints allow the main body to rotate along the vertical axis.

Figure 3. Angle formed by a power line at a supporting structure.

Typical obstacles arising in the lines can be transposed using multiple paths. Figure 4 shows a piecewise linear path with a triangular shape, suitable to transpose most objects.

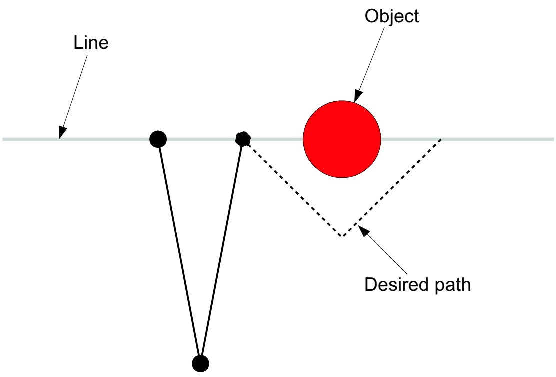


Figure 4. Obstacle transposition using a piecewise linear path

Figures 5 to 7 show simulation results for obstacle transposition using the piecewise linear path. The control scheme considered only the inverse dynamics without robustness terms. Disturbances are caused by wind gusts blowing with a maximum speed of 10 m/s. The initial configuration is (q_1,q_2)=(-0.44π, 0.89π) rad.

Figure 5 shows the trajectory performed by the free end of the robot. Higher proporcional gains improve performance system, but the required torques tend to exhibit fast oscillations. The maximal absolute error between the output path and the reference path is 4.9 cm. The positional error is comprised in $[-0.06, 0.04]$ rad (see Figure 6) even in the presence of disturbances. For $t \geq 21s$ the robot is close to a singularity (fully stretched) and hence both joints become more sensitive to modelling errors.

The torques required (see Figure 7) indicate that avoiding an obstacle is feasible, even though the simplicity of the robot. The torque required by joint 1 is the most demanding and grows along the path (joint 1 corresponds to the fixed tip during this phase). The torques (50 N.m at most) can be easily met with off-shelf electrical motors.

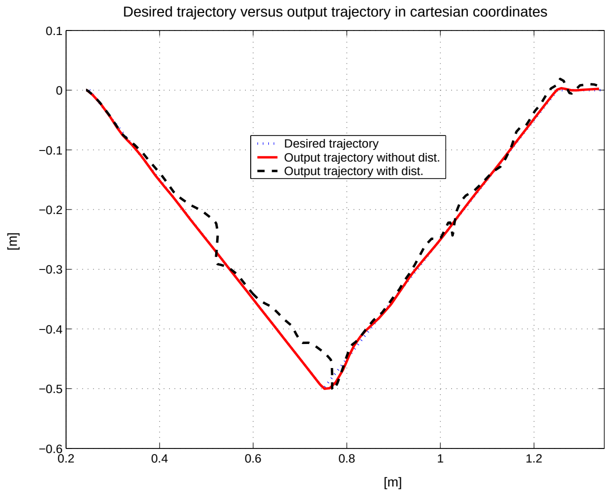


Figure 5. Trajectory of the loose tip of the robot under the piecewise linear path following

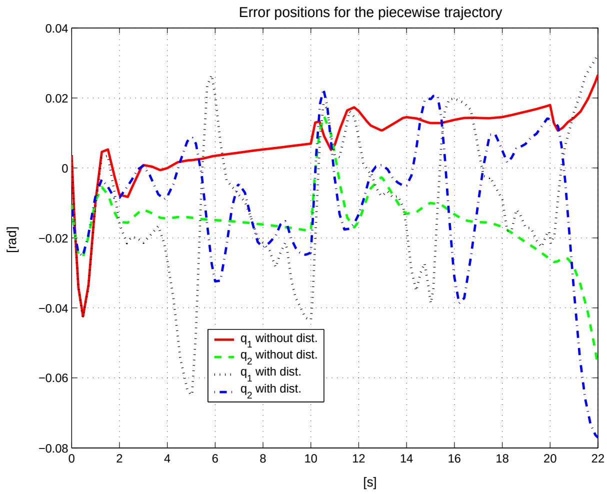


Figure 6. Position errors for the loose tip of the robot under the piecewise linear path following

The joint velocities, shown in Figure 8. The sudden change at $t = 10$ s is due to the beginning of the second segment piecewise trajectory. With low PID gains the system shows a poor response under aerodynamic disturbances. Higher gains improve the performance of the robot. However, these tend to demand higher torques which may be difficult to obtain from the currently available actuators. As a consequence, for this basic robot the controller gains result from a tradeoff between the performance requests and practical feasibility of the robot.

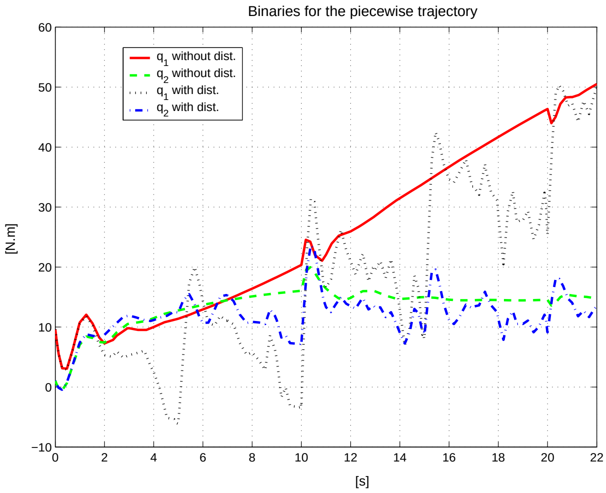


Figure 7. Joint torques for the piecewise linear path following

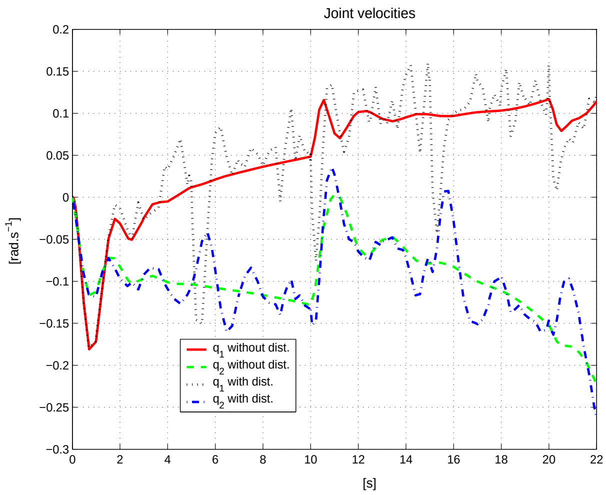


Figure 8. Joint velocities for piecewise linear path following

Figures 9 to 12 show the results when using robust control with and without disturbances. As before, the disturbances considered are due to aerodynamics forces (wind gusts), blowing in the motion plane with a maximum speed 10 m/s. The initial configuration is also $(q_1,q_2)=(-0.4429\pi, 0.8857\pi)$ rad.

The comparison between Figures 5 and 9 shows that robust control generates a smoother trajectory with smaller errors. The maximum absolute error between the trajectory and the reference path is 4.36 cm. Robust control also yields smoother torques.

Position error for joint 2 is also reduced (compare Figure 10 with Figure 6). Near $t \geq 21s$, the robot is close to a singularity (fully stretched) leading to the increase of the error. The joint velocities under disturbances, shown in Figure 12, also show an improvement when compared with Figure 8.

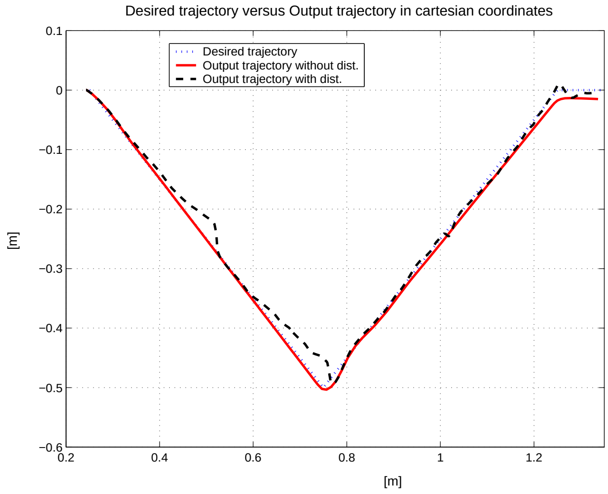


Figure 9. Trajectory of the loose tip of the robot under the piecewise linear reference path (with robust control)

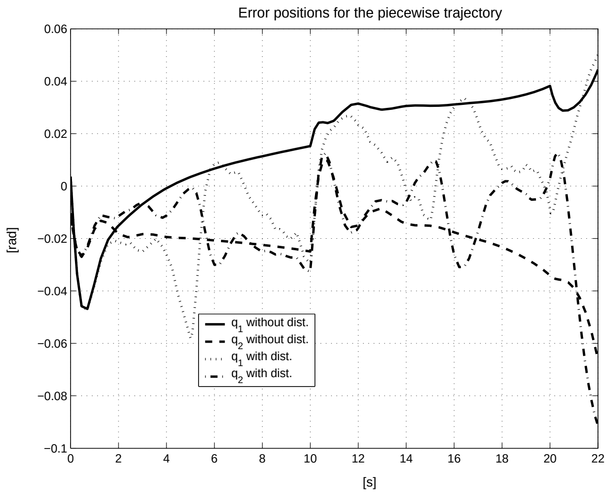


Figure 10. Position errors for the loose tip of the robot under the piecewise linear path (with robust control)

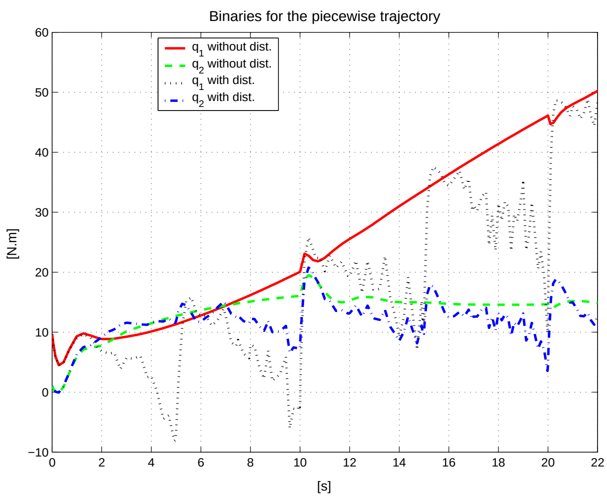


Figure 11. Joint torques during the piecewise linear reference path following (using robust control)

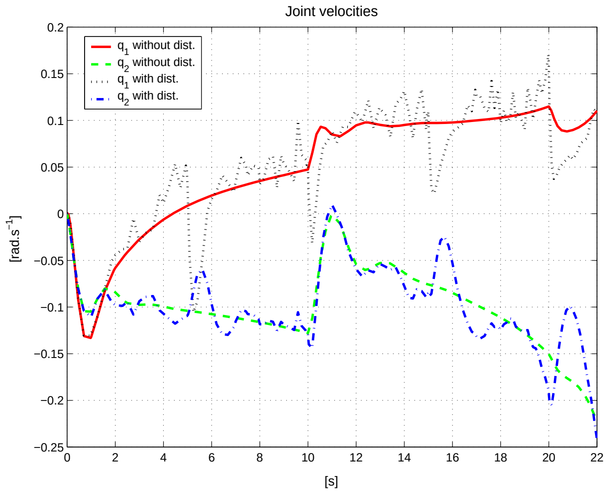


Figure 12. Joint velocities for the piecewise linear reference path (using robust control)

5. CONCLUSIONS AND FUTURE WORK

This paper describes a preliminary feasibility study aiming at developing a robot for monitoring/surveillance tasks moving over shield wires or electric power lines.

The simulations presented consider inverse dynamics robust control with additional PID controllers. The experiments presented compare standard and robust control schemes under aerodynamic disturbances caused by wind gusts. The results obtained are very encoraging and provide valuable clues both to alternative kinematic design and control schemes.

Ongoing work includes considering sensor dynamics, extension of the modelling of aerodynamics disturbances to the three dimensional space, selection of the optimal paths to overcome obstacles and definition of the hardware and software requirements.

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