# The Development of a Robotic System for Maintenance and Inspection of Power Lines *

José Rocha(1)    João Sequeira(2)
jrocha@est.ips.pt    jseq@isr.ist.utl.pt
(1) Escola Superior de Tecnologia de Setúbal/Instituto Politécnico de Setúbal
Rua Vale de Chaves, Estefanilha, 2910-761 Setúbal, Portugal
(2) Instituto Superior Técnico/Institute for Systems and Robotics,
Torre Norte, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal

## Abstract

This paper describes preliminary studies on a prototype robot for the inspection/maintenance of electrical power lines. Faulty insulators or abnormal objects can be detected before causing a failure in the distribution of electrical energy.

The robot uses a statically stable variation of the brachistochrone motion to move along the power lines and overcome the standard obstacles present in the lines. The paper presents the kinematics and preliminary simulation results on the dynamics and control of the robot.

## 1 Introduction

This paper describes a robot for the inspection and maintenance of electrical power lines. The robot moves using the cabbage worm gait for free motion and a statically stable variation of the brachistochrone motion (see [5] for dynamically stable brachistochrone motion) for obstacle transposition.

Due to the exposure to different weather factors (e.g., sun, rain, wind and snow), materials loose electrical properties. Besides the natural aging factors, most components are not submitted to severe quality controls during manufacturing processes, thus being possible that some are faulty. Therefore, it is necessary from time to time, to carry out inspections, aiming at detecting any weakness in such electrical materials that may compromise the energy distribution.

Among the most common problems, requiring periodical inspections to the lines, there are, bad contacts near support points at electrical towers, often named hot spots, caused by an increase in electrical resistance after a thermic growth, abnormal objects near the electrical structure, e.g., tree branches or logs of wood, or directly over the lines, conductors aging, glass insulator chains aging or with broken elements, damages caused by storms, e.g., lightning strikes, excavation activities nearby the towers supporting the lines, and the aging of the metallic parts in the supporting towers leading to abnormal inclination and the consequent stress of the lines.

Together with the economical motivation, the reduction in the human risks associated with inspection and maintenance operations in power lines (such as the exposure to intense eletromagnetic fields) is also a main motivation vector to the development of the system proposed in this paper.

The paper is organized as follows. Section 2 provides a brief overview to some of the systems currently being used to inspect/maintain electric power lines. Section 3 details the main kinematics aspects of the proposed robot. The main aspects on the dynamics and control are focused in Section 4. Section 5 presents preliminary simulation results. The conclusions are presented in Section 6, along with the directions for future work.

## 2 State of the art

In this section three different approaches currently used for inspection/maintenance operations over electric power lines are described. The first one, installs fiber optic cables over power lines. The second uses a standard helicopter to move along the lines and detect malfunctions. The last approach uses a computer vision guided helicopter model for general purpose autonomous missions, including inspection to power lines.

### 2.1 The SkyWrap

This device was developed during the eighties by FOCAS, a British company operating in the telecommunications field, to navigate over power lines. The SkyWrap [3] was designed to helically wrap a fiber optic cable over the earth-wire or phase conductors up to 150KV of an overhead transmission line.

The device is remotely controlled by radio frequency. The operator is able to select among 11 mo-

*This work was partially supported by the FCT Programa Operacional Sociedade de Informação (POSI) in the frame of QCA III.

tion velocities, between 0 and, approximately, 0.33 m/s, The propulsion system weights 215 Kg and uses a standard internal combustion engine. Once hoisted up and installed, the Skywrap can move along a bay of 300 m in five minutes. With a crew of six to eight persons, FOCAS claims that it is possible to install 2.5 Km of cable per day.

### 2.2 The Corona Net-Spy

The Electrical Company of Minas Gerais (CEMIG) in Brazil, responsible for electrical energy distribution and transportation in the State of Minas Gerais, owns nowadays 21000 Km of power lines, from 34 to 500 KV. Inspection operations are carried out with an aerial monitorization system develop by the German company Grid Services, [2].

The system, known as Corona Net-Spy, is installed in a helicopter, and is capable of monitoring, in real time, the electrical field variations caused by high frequency disturbances. These disturbances, mainly due to natural electrical discharges, cause the enlargement of the electrical field nearby problematic points. Among several common faults are loose spacers, cables with broken wires, faulty insulators and other active parts of the line structure. The electrical field is received by an antena, digitalized and saved for processing. The resulting signal is showed in a monitor screen and analyzed by a skilled operator. By analyzing the frequency variations, the operator localizes the defect and takes a digital photo for further reference. In case it is impossible to determine the fault, the resulting signal is kept for further analysis, and the location of the faulty region registered via a GPS system. The Corona Net-Spy has a maximum speed of 50 Km/h, bounded by the acquisition and processing of the data.

### 2.3 The autonomous helicopter project

The autonomous helicopter project developed in Carnegie Mellon University is an example of a general purpose system that can be used to inspect high voltage electrical lines, [1]. This vision guided helicopter robot can autonomously accomplish multiple missions, e.g., search and rescue, surveillance, law enforcement and aerial mapping.

This project begun in 1991 with tests to initial attitude control system. The first prototype was finished during 1995 and evolved in the following years with a data fusion system used for state estimation, a laser mapping system, vision system capable of multiple object tracking, and a control system for autonomous takeoff, landing and smooth trajectory following. By July of 1998, the system was used in the exploration of the Haughton Crater in Devon Island, Canada.

## 3 Proposed robot

In what concerns the design of a robotic system for the inspection/maintenance, electric power lines constitute a relatively well structured environment. The shape of the lines, the types of connections between a line and the supporting towers, the type of insulators, the standard objects that may appear along the lines are well known. Abnormal objects caught by the lines must usually be handled on a per case basis, seldom being small enough for removal by a robotic system.

The proposed locomotion approach resembles the motion of a cabbage worm, which moves expanding and contracting his own body. This form of locomotion is well suited for the motion and obstacle avoidance along the power lines. Mainly due to the highly structured environment we believe that this locomotion form is appropriate.

Figure 3.1 shows a stick kinematics diagram for the basis element of the robot. The kinematics model for this basis structure is elementary. The robot has two claws, three revolution joints and two links. The claws, located at joints 1 and 3, are required for a statically stable brachiation motion gait. The locomotion gait has two different phases. Figure 3.1 shows the first phase in thick lines and the second phase in dashed lines. In this gait both claws are always in contact with the line.

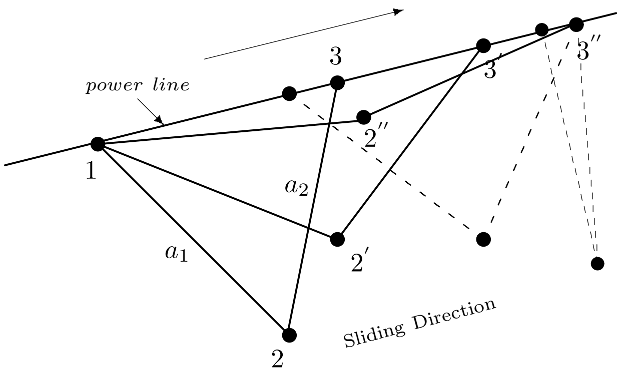
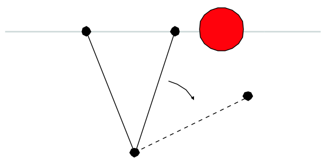



***Figure 3.1:*** *Basic structure, with two links of equal length, sliding along a power line.*

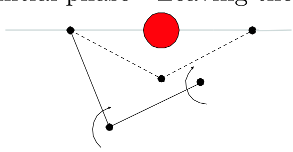
Assuming that the progression direction is from left to right, the claw 1 stays fixed whereas claw 3 moves along the line, in the direction of progression. Joint 1 and 2 moves the links $a_1$ and $a_2$ in the same progression direction. This motion stops when the arm is near the fully stretched configuration (a singularity in the kinematics). When the arm approaches the singularity, the roles of claw 1 and claw 3 are reversed. Claw 1 is now sliding along the line whereas claw 3 stays fixed. Initially we have an **expansion movement** symbolized in figure 3.1 by the solid line. When the robot approaches the stretched configuration the expansion movement is stopped and a new movement sequence begins. This new motion is characterized by a **contraction movement** (represented by the dashed line), with the claws approaching each other along the power line. The contraction movement finishes when the distance between de two claws tends to zero (another singularity). The composition of these two phases (expansion+contraction) determines a motion step approximatelly equal to the sum of the length of the links. The articulation of consecutive phases (gait) produces the progression of the robot along the line.

By composing multiple kinematic structures like the one in Figure 3.1, a robot with enhanced capabilites can be obtained. For example, the mission payload, e.g., infrared cameras and cleaning devices, can be distributed among the basic elements in the structure. Furthermore, if the chain length is increased, alternative locomotion gaits can be used, also improving obstacle transposition.

Figure 3.2 shows two different snapshots of an obstacle transposition. In the first phase one tip of the structure looses contact with the power line and acquires a configuration that will allow the transposition of the obstacle. In the final phase the loose tip grabs the line after having moved around the obstacle.



a) Initial phase - Leaving the line



b) Final phase - Grabbing again the line

***Figure 3.2:*** *Obstacle transposition*

## 4 Control approach

This section details some of the relevant aspects related with the dynamics of the basis structure in Figure 3.1. The standard Newton-Euler algorithm was used to obtain the dynamic model for the robot in Figure 3.1. When one of the end tips is free, the dynamics of this robot is similar to that of a two link serial manipulator. When both tips are in contact with the power line, the dynamics of the resulting closed kinematic chain can be easily obtained by extending the serial manipulator dynamics to account for the contact forces at the loose end (sliding claw).

A standard inverse dynamics control scheme is considered, (see for instance [6]). In the absence of parametric or structural disturbances, this scheme yields a double integrator control problem, for which PID control can be used. Due to the modelling uncertainties, the exact linearization performed with this scheme seldom yields a double integrator problem. The estimation of a realistic model for the structure of such a robot is highly dependent of technological factors, e.g., dimension/weight of the actuators, the specific materials used, and the particular mission assigned. However, given the simplicity of the kinematic structure, these factors induce, mostly, parametric errors. In such cases PID control may still be a reasonable option, specially as in this case, in a viability study for a project. If necessary, robustness terms can be added to the standard control law to account for any eventual structural uncertainties.

The PID gains are identical to all controllers and were obtained after a manual tuning process. The key concern was primarily to avoid high peaks in the torques to ensure that these can be generated by off-the-shelf motors. Table 4.1 shows the main data values used in the simulations.

| | | |
|---|---|---|
| $K_{P_i} = 25$ | $K_{I_i} = 0.0016$ | $K_{D_i} = 10$ |
| $a_i = 0.7$ m | $m_i = 5$ Kg | |

***Table 4.1:*** *Robot data*

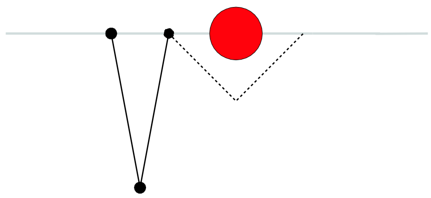
## 5 Experimental Results

The 0.7m length of each link was chosen from the tradeoff between the necessary length to overcome the standard obstacles in power lines (e.g., insulators and marking devices) and the length yielding reasonable torques (longer links yield high torques which may be unachievable from a practical perspective). Furthermore, longer links also lead easily to structural problems caused by the flexibility of material and hence to modelling errors in the dynamics of the system. The 5 Kg mass of each of the links also reflects an a priori tradeoff between the maximal allowed weight that can be hanged in typical power lines (around the tens of Kg) and the practical feasibility of the system.

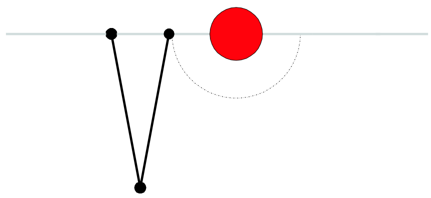
The simulations in this sections considered external disturbances caused by aerodynamic forces generated by winds blowing on the robot The exact modelling of these perturbations is usually not feasible and hence they are not accounted for in the model based decoupling/linearizing control law. Instead, additional robustness terms has to be included in the control laws (see for instance [6] for an example using a manipulator or the work by [4] using neural networks as robust controllers for biped robots).

The following experiments assess the performance of a robot composed of a single basis element (see

Figure 3.1) in the initial and final phases of the transposition of an obstacle. Its worth to mention that, obstacle transposition is the worst situation in what concerns the joint torques. Two cases were considered: using a piecewise linear trajectory and a circular trajectory (see Figure 5.1).



a) Using a piecewise linear path



b) Using a circular path

***Figure 5.1:*** *Alternative techniques for obstacle transposition*

Figures 5.2 to 5.4 show the simulation results for a transposition using a triangular path with and without disturbances. Disturbances were caused by aerodynamics forces generated from wind pulses with maximum speed 7 m/s blowing along a direction in the plane of the power line. The initial configuration is $(q_1, q_2) = (\frac{-\pi}{3}, \frac{15\pi}{18})$ rad.

Figures 5.2 shows the trajectory performed by the loose end of the robot. Despite the presence of wind disturbances the robot shows an acceptable performance. The maximum absolute error between the reference path and the output path in the presence of disturbances is 4.79 cm (see Figure 5.3). The overshoot at 10 s in Figure 5.3 is due to the change in the vertical direction of the reference trajectory.

Figure 5.4 shows the torques required from the actuators. As expected, the torque required by joint 1 (the one with a fixed position in the line) grows along the entire movement. The values achieved indicate the difficulty of jumping aroung the obstacles with this very simple kinematics.
The magnitude of these torques can be slightly reduced at the cost of reducing also the clearance between the robot and the obstacle.

Figures 5.5 to 5.7 refer to the circular path for the transposition of obstacles. As in the case of the triangular path, the robot exhibits a fairly acceptable

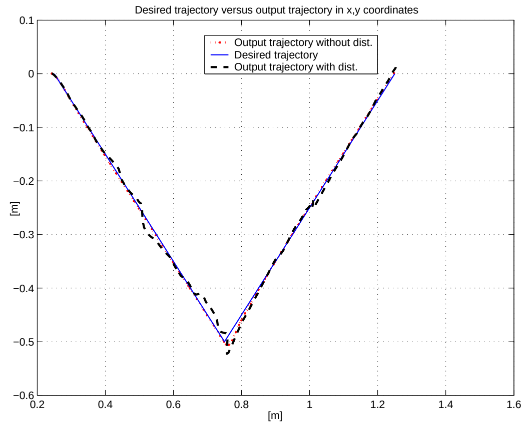



***Figure 5.2:*** *Trajectory for the loose tip of the robot under the triangular reference path*

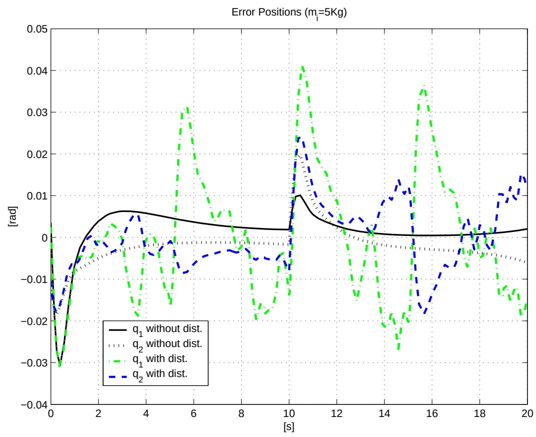



***Figure 5.3:*** *Position error for the loose tip of the robot under the triangular reference path*

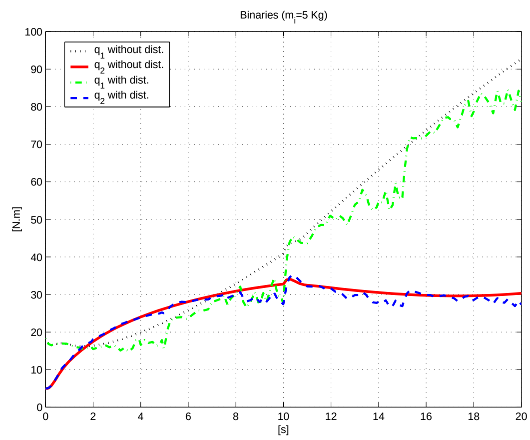



***Figure 5.4:*** *Joint torques for the triangular movement*

performance under the wind disturbances. The maximum position error is around 5.27 cm during the initial stage of the motion mainly caused by the inertia propeties of the robot and the need to reverse joint rotations.

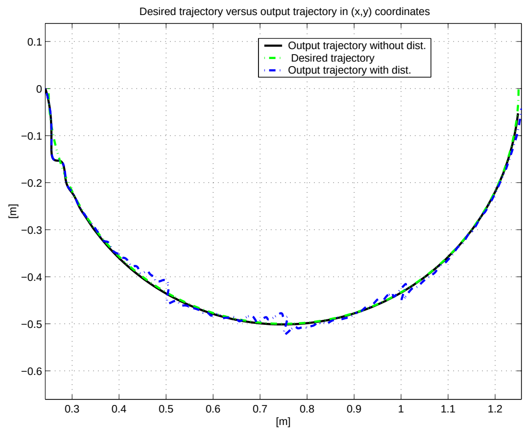



***Figure 5.5:*** *Trajectory for the loose tip of the robot under the circular reference path*

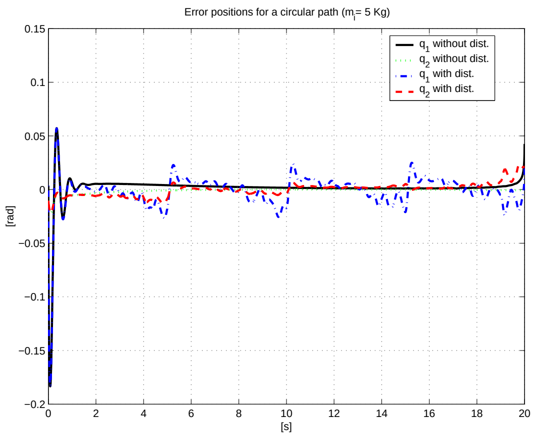



***Figure 5.6:*** *Position error for the loose tip of the robot under the circular reference path*

The overshoots in Figure 5.7 near the 20 s time are caused by the almost vertical motion the robot loose tip must perform to reach the final configuration. In the absence of disturbances both torques exhibit a regular behavior.

When the robot moves along the line, without any obstacle to overcome, both tips of the structure are in contact with the line and hence the robot dynamics is different from the previous situation (the moving tip has now to account for the reaction force, generated by the contact with the line, and the sliding force). Figures 5.8 and 5.9 show the trajectory of joint 2 with and without disturbances (wind speed at 10 m/s). It

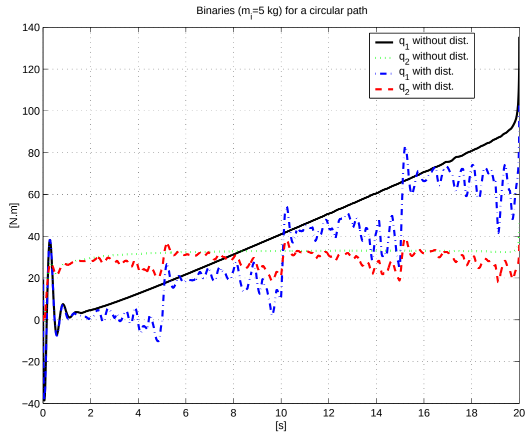



***Figure 5.7:*** *Joint torques for the circular movement*

is clearly shown that the control system handles adequately this type of disturbances for most of the time.

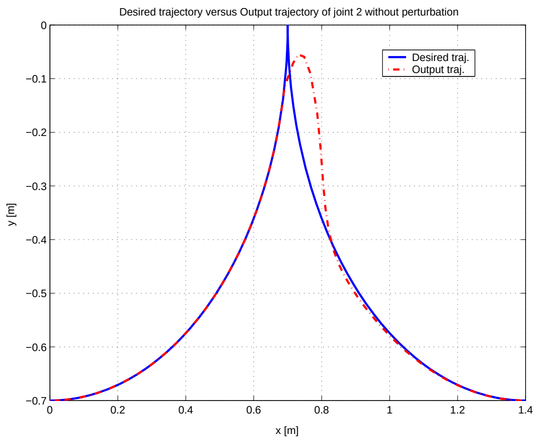



***Figure 5.8:*** *Joint 2 trajectory without disturbances*

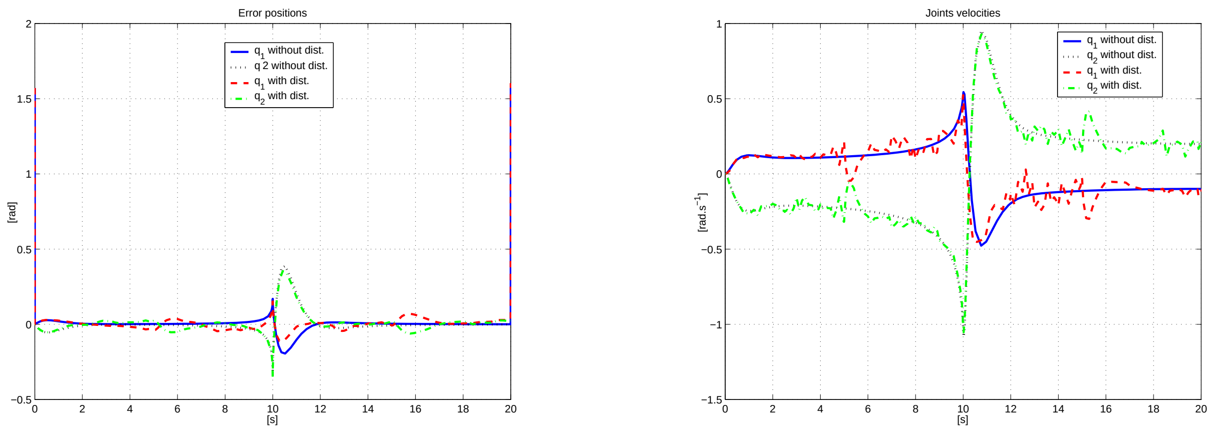
The corresponding torques, shown in Figure 5.10, are also demanding near the fully stretched singularity, specially when disturbances are present.

Figures 5.11a and 5.11b show, respectively, the joint position errors and the velocity profile of the joints for the free motion along the line.

## 6 Conclusions and Future Work

This paper describes the first steps in a feasibility study aiming at developing a robot for the inspection/maintenance of electrical power lines.

Even though the simplifying assumptions in the modelling of the robot dynamics, the linearization procedure considered (seldom verified in a realistic situation), and the standard PID control scheme considered, the simulations show promising results.




a) Joint position errors     b) Joint velocities

***Figure 5.11:*** *Free line motion*

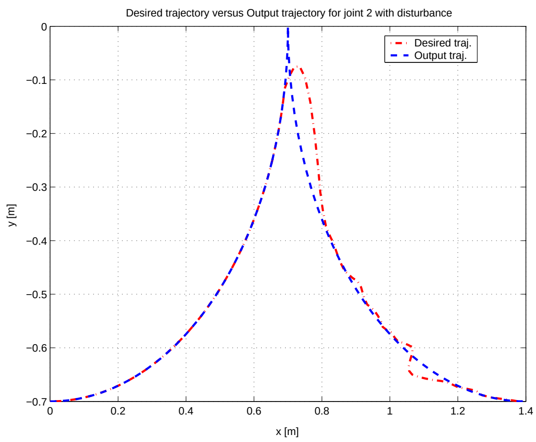



***Figure 5.9:*** *Joint 2 trajectory with disturbances*

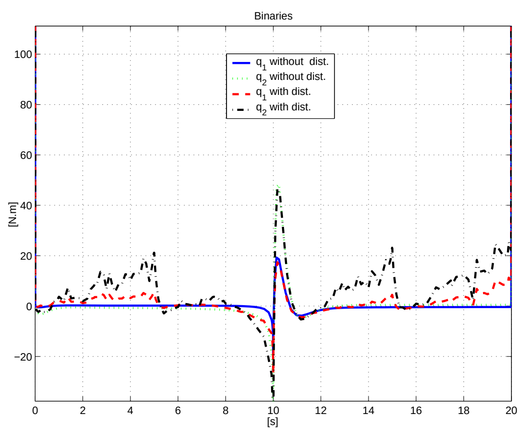



***Figure 5.10:*** *Joint torques for the free line motion*

Ongoing work includes considering sensor and actuator dynamics in the model, the design of alternative control schemes including robustness terms to compensate for modelling structural uncertainties, detailed modelling of aerodynamic perturbations, and definition of the global control architecture and of the associated hardware and software requirements.

## References


[1] Autonomous Helicopter Project, 1991-1998. Carnegie Mellon Robotics Institute, http://www-2.cs.cmu.edu.

[2] Grid services, http://www.gridservices.com.br, 2003.

[3] The skywrap, focas, http://www.alcoa.com/afl-tele, 2003.

[4] D. Katić and M Vukobratović. Survey of intelligent control techniques for humanoid robots. *Journal of Intelligent and Robotic Systems*, 37(2):117–141, 2003.

[5] J. Nakanishi, T. Fukuda, and D. Koditschek. A Brachiating Robot Controller. *IEEE Transactions on Robotics and Automation*, 16(2):109–123, April 2000.

[6] B. Sciavicco, L.and Siciliano. *Modelling and Control of Robot Manipulators*. Springer-Verlag, 1999.