KINEMATIC CONCEPTION OF A HYDRAULIC ROBOT APPLIED TO POWER LINE INSULATORS MAINTENANCE

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Abstract. *The focus of this paper is to show the development, the kinematic conception and the system architecture of a new remote controlled hydraulic robot specially designed to perform the maintenance task of insulators cleaning in live-power lines. In this case, dust or salt deposition on power line insulators combined with high humidity can represent a major problem in local power electric distribution companies specially the ones located along coast lines. Current leakages start to occurs that might trigger interruption of the service leading to great financial loses. In this case, maintenance work should be done in order to prevent the appearance of such deposition which is usually made with the aid of water jets spread from noses specifically designed for this type of work. This robot is currently been developed by Federal University of Santa Catarina in collaboration with CEMAR, a local electrical distribution company located in the northeast region of Brazil.*

Keywords: *Kinematic conception; Hydraulic robot; Automated maintenance of insulators.*

1. INTRODUCTION

Robotics is presented in several areas of research and application. Most robots are developed for industrial automation and used in processes such as welding, assembling and transporting. Another class of robots are developed for special operations, such as recovery of the surface of turbine blades (Guenther *et al*, 2004); drilling of the fuselage of aircrafts (Jayaweera and Webb, 2007) among others.

This paper is focused on the kinematic conception and on the design aspects of a new robot designed to clean, by washing with a water jet, electrical insulators of 13.8kV installed in distribution network poles. In Brazil, many power transmission lines are located in coastal regions and therefore have a strong process of degradation due to the weather. The main problem is concentrated in the loss of dielectric strength of insulators due to the accumulation of salt. As a result, electrical current leakage between the lines and ground might occur, triggering failures in the lines of distribution. To minimize these consequences local electrical distribution companies perform maintenance services regularly, washing the insulators with tap water.

Usually, this service is performed by means of a hydraulic crane and an improvised mechanism for washing, with two operating modes: a) manual, where a crane aerial bucket is used to drive the operator close to the insulators and from there, an operator run the service through a water jet; and, b) remote, where the operator remotely controls the direction of the water jet, with the assistance of a two degrees of freedom device installed at the end of the crane.

However this maintenance service is inefficient because it presents difficulties in operation (control in the joint space), demands an excessive amount of water and therefore, results in a very time-consuming task. Moreover, due to the arrangement of wires on the poles, there is a special difficulty for the water jet to reach both sides of the insulators, mainly caused by the restricted crane's workspace. As a consequence, more frequently maintenance service tasks must be performed to keep the insulators cleaned, resulting in higher costs.

There are others robotic solutions developed to work on live-line maintenance tasks (Nio and Maruyama, 1993),(Aracil *et al*, 2002), but their approaches do not adapt to the desired requirements in this work due to the poles structures and some operational aspects.

A review on published articles showed that the automation of the maintenance of electrical systems is composed of a series of operations that go beyond washing (Yano *et al*,1995) (Aracil *et al*, 2002) (Cho *et al*, 2006) (Park *et al*, 2008) (Kim *et al*, 2007). These works treat the problem from a simple inspection, demonstrating the difficulties of design and security issues, to more advanced work, like in operations of fault detection in electrical networks.

This research is concerned to the automation of the task of washing insulators of distribution power line networks, through the design and construction of a service manipulator remotely operated that aims to: a) increase the efficiency of washing, b) facilitate the operation by performing the motion control in the Cartesian space and, c) allow the inspection and the control motion with the aid of two cameras.

The methodology of study and the kinematic conception are presented and discussed according to the arrangements of wires and poles within a specified workspace. Results of task washing simulations are presented in a virtual ambient and, at the end, the resulting service manipulator developed, already mounted on a truck, is shown. This project is a partnership between Federal University of Santa Catarina (UFSC), through the Departments of Automation and Systems Engineering (DAS) and the Department of Mechanical Engineering (EMC), and the Maranhão Energetic Company (CEMAR).

2. ROBOT REQUIREMENTS AND WORKSPACE

The kinematic conception starts with an analysis of operational requirements. According to technicians from CEMAR, the resulting robot must achieve the following system requirements and objectives:

- Improve the system security and isolation of the truck;
- Improve the quality of the washing of insulators;
- Reduce cleaning-time per post;
- Build a cleaning-head to direct the water jet composed with two servo-motors;
- Develop routines for automatic trajectories.

The workspace was defined considering the post structure used on power networks of Maranhão cities. The principal characteristics are the following:

- The robot will be used in 13.8kV distribution power lines.
- The most complex post structure that the robot will operate is called N1N1N3 CEMAR structure presented on Fig. 1.
- The truck will stop on the roads side-by-side with the post in a such way the washing head must be able to reach, with its water jet, both sides of any insulator fixed in the posts (in the manual operation this is not achieved).
- The robot must be user friendly to control.

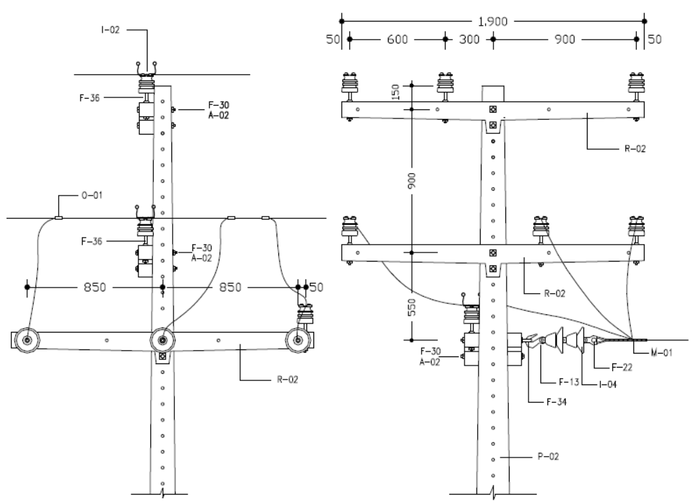


Figure 1. N1N1N3 CEMAR post structure

Although the post has a buried portion (approximately 10% of its height plus 60 cm), it was considered in the workspace study, that the post should be 12 meters high from the ground level. The reason for that is to cover situations where an adverse pole location precludes an optimal parking of the truck.

It can be seen in Fig. 1 that the insulator’s supports have a total length of 1900mm. In addition, the insulators are arranged in the following form: two on one side distant 600mm one from another and, one in the other side distant 900mm from the supporting post.

To start the cinematic design of the robot, the truck model was select according to the loads it will carry. The main loads taken into account in this selection were an 8000 liters water tank, its own weight and the weight of the crane. To that end, a Ford® truck model 1517-e was selected (Fig. 2).

Figure 2. Ford® truck model 1517-e

Using the Ford® 1517-e catalog specification (see "*manual do implementador*" at *www.caminhoesford.com.br* in chapters 3 and 14), it was possible to determine the parameters and dimensions of this truck that influence the design of manipulator kinematics. With this information, the workspace was determined and simulated, as it can be shown in Fig. 3.

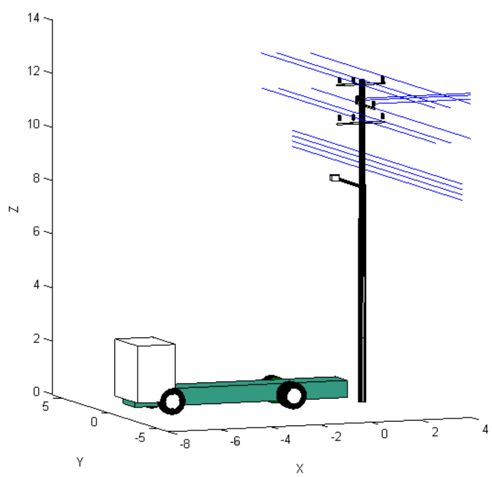


Figure 3. Simulated robot workspace.

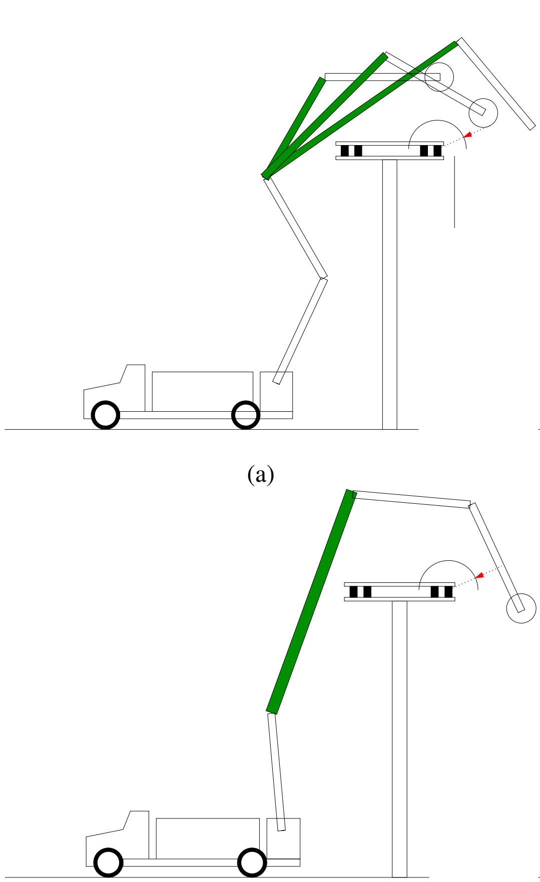
3. KINEMATICS CONCEPTION

The kinematic conception consists in the definition of the manipulator links and joints as well as the dimensions and limits of operation of these elements.

Considering the truck parked as described in Fig. 3, it was assessed the minimum and the maximum extension of the jet of washing in 2D space. The purpose of this simplification was to identify what types of joints were needed and what sizes of the subsequent links.

3.1. The study of the type of joint

Two types of joints were considered in the simplified two-dimensional model to facilitate the analysis: a) prismatic joints and, b) rotary joints. Figures 4(a), 4(b), 4(c) and 4(d) present the analyzed kinematics conceptions, where the hachured links correspond to prismatic joints.



(a) (b) (c) (d)

Figure 4. Kinematics conceptions studied

The use of prismatic joints allows an increase in the robot workspace together with other links of smaller sizes. It was a common sense among the design members, that the mechanical construction of this type of joint can be quite costly, both in terms of time and financial resources. Therefore, the adopted solution was to use only rotary joints. Figure 4(d) shows this initial conception.

It can be observed in Fig. 4(d), that the "elbow" strongly tends to collide with the post and its wires during the operation. Therefore, this conception was improved along with the idea presented in Fig. 4(c), converging to an appropriate conception. This conception is shown in Fig. 5.

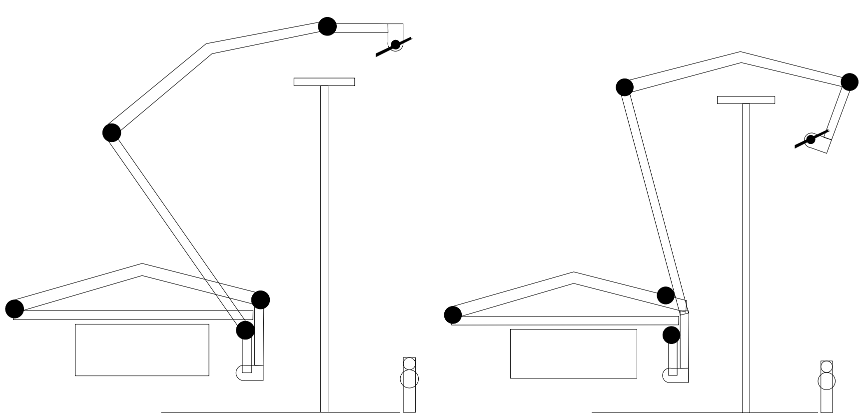


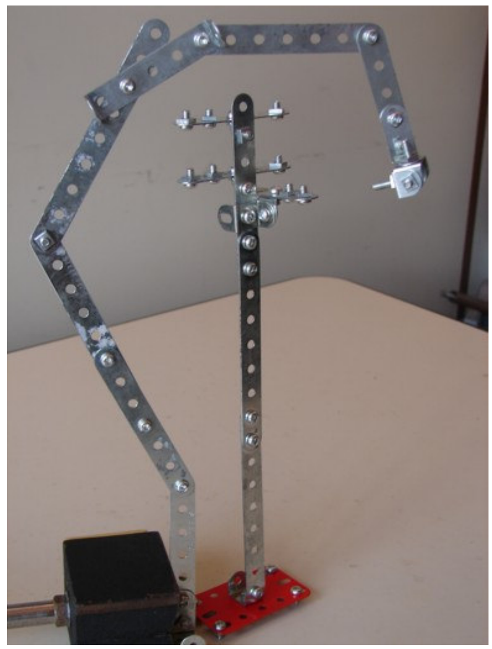
Figure 5. Proposed kinematic conception shown at two different positions

It can be observed in Fig. 5 that the second link needs to have a "V" shape to contour the post from above. This conception allows the use of a commercial crane in the base, only requiring a suitably redesign in the second link and the addition of a third end-effector link. The nozzle of the water jet is mounted on a spherical wrist structure type as a two-degrees-of-freedom device and is attached to the third link. This design allows to completely wash the insulators from both sides by approaching the nozzle at a suitably distance.

3.2. Dimensioning of links and joints

Using a scaled 2.54:100 prototype and the simulation model, the dimensions of links and joints were defined. These scale prototypes are presented on Fig. 6.

(a)



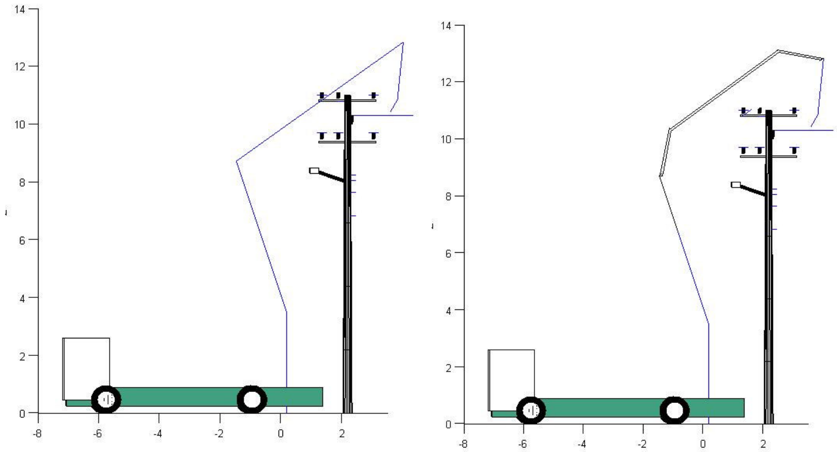
(b)

Figure 6. (a) Scaled model of the post N1N1N3 (b) Scaled model of the hydraulic robot and post

For this analysis a set of additional specification must be satisfied. These specifications are presented as follows:

- The dimensions of the commercial crane model specified to be acquired (3.5m high, 5.5m in the first link and 6.35 for the second link);
- The inclusion of a third link with a length of 2m (to conduct the nozzle, depicted in Fig. 5);
- In agreement with resolution number 12/CONTRAN (Brazilian Counsel of Transit) of 06/02/1998, published in 07/02/1998, the maximum dimensions for this special motor vehicle should be: maximum width: 2.60m and maximum height: 4.40m;
- Inclusion of a “V” format in the second link.

Considering the commercial model specified and the fact that the size of the first link (5.5m) can not be changed, the size of the second link must be reshaped. Therefore, the size of the second link should be at least 6 meters so that the cleaning of the insulators can be made from both sides. From simulation software, as shown in Fig. 7(a), it can be seen that the second link collides with the wires of the post structure, justifying the inclusion of form in "V" for this link. Considering the maximum height permitted for the robot when it is in retracted position on the truck (4.40 m), the shape of "V" for the second link can not exceed 1 meter. Remodeling the second link leads to the shape as depicted in Fig 7(b).



(a) (b)

Figure 7. (a) Preliminary kinematic conception (b) Final kinematic conception with an altered “V” form in the second link

3.3. Final kinematic details

A CAD model was also implemented allowing to determinate the final dimensions and to simulate an operation. Figure 8 shows in a simple draw the overall hydraulic robot dimensions.

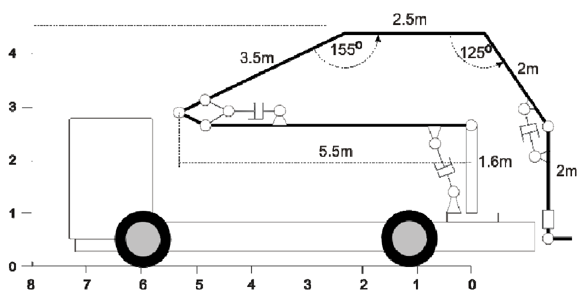
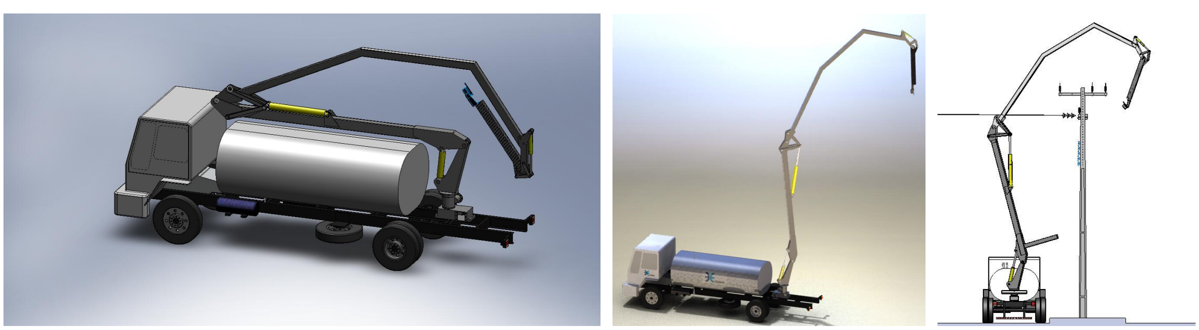


Figure 8. Overall dimensions of the hydraulic robot mounted on the truck.

The CAD model is presented in Figs. 9(a), 9(b) and 9(c) which was quite useful to simulate the operation and discuss the operational modes.



(a) (b) (c)

Figure 9. Hydraulic robot CAD model: a) Retracted position; b) Extended position; c) Position to wash the other side of the insulators.

The simulation of the operation was carried out and the model was validated. The sequence in Fig. 10 shows a set of movements commonly used to washing the insulators.

Figure 10. Sequence of the washing insulator operation.

3.4. Operational modes

With the objective of both ensure security in the washing and facilitate the operation of the robot there were determined three modes of operation:

- *Joint-to-joint movements* - where the operator controls one joint each time;
- *Pre-washing* - where the operator acts leading the end-effector in the Cartesian space. This operational mode keeps the last three joints operating on joint-to-joint control strategy. The end-effector orientations are kept fixed in relation to the base.
- *Washing* - in this operational mode the latter two joints are responsible for guiding the water nozzle. The joints act together to increase the area of operation of the washing.

4. SOFTWARE AND KINEMATIC CONTROL SYSTEM

The control system design was implemented starting from a Channel/Instanced Petri net (C/I net) (Belan, 2007). This diagram (Fig. 11) shows all the interaction between internal and external resources.

The analysis of this diagram allows defining the requirements of WHMI (Wireless Human-Machine Interface), the robot and the control system.

The system architecture was modeled through API's (Application Programming Interface) that incorporate the structural and procedural aspects. The computational model is based on an Open System for Robot (Ford, 1994). This computational model allows the development and implementation of the computer program to control the system, and also to develop alternative control strategies.

4.1. WHMI – Wireless Human-Machine Interface

Figure 11 presents the use-case diagram of the WHMI using UML (*Unified Modeling Language*). This model expresses the behavior of how the operator will interact with the system through User Interface (UI) with support of hardware TPC 2012 and IEEE 802.11 protocol for wireless operation.

The operator visualizes in the UI the following use cases.

- *View* - Shows the visualization of the tools from the camera mounted on the end-effector;
- *Jet* - Turns on or off the water jet tool;
- *Increment* - Increments the robot Cartesian position;
- *Decrement* - Decrements the robot Cartesian position;
- *Stop* - to immediately stop the robot.

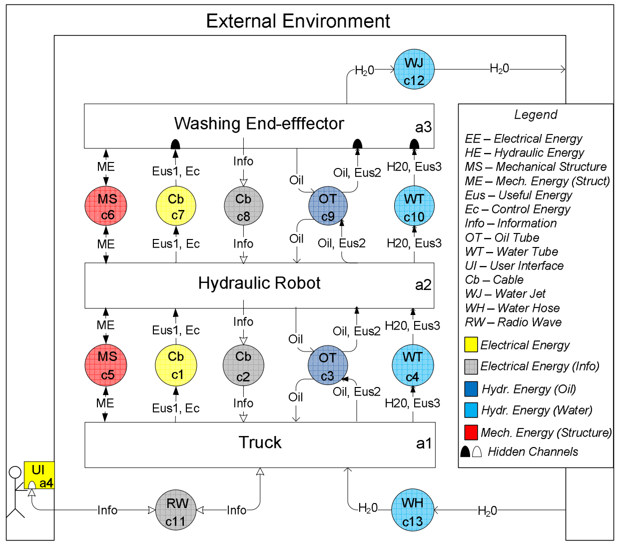


Figure 11. Channel/Instance net: Structural model of the system

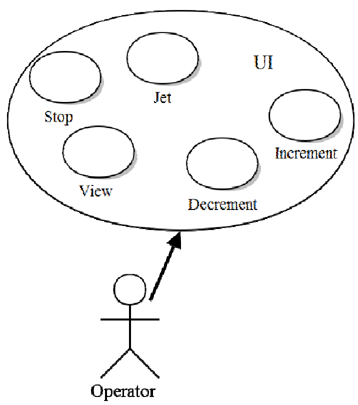


Figure 12. Use-case diagram of the WHMI

The user graphic interface was designed in the use-case diagram of the WHMI using the C++ Builder and their components. The proposed layout will be displayed as illustrated in Fig. 13.

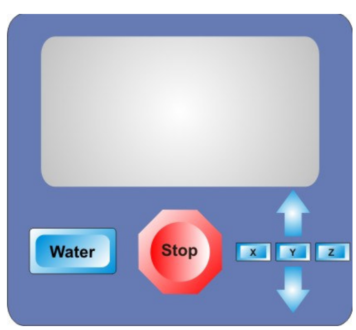


Figure 13. WHMI layout.

The panel interface allows the operator to visually inspect the electric insulator and check whether the maintenance has been efficient. The operator could turn *On* or *Off* the water jet according to the operation condition. The operator can also move the robot in Cartesian space in the X, Y and Z directions. The UI center panel has an emergency key to stop robot at once, if necessary.

4.2. Controller

The controller manages the tasks of the robot using the computer system and the servo-amplifier. The controller was modeled logically accordingly with the following software components:

- *GUI* (*Graphical User Interface*): It models the graphical user interface that will be available in the HMI.
- *Tool*: It models the tools and jet inspector that will be used by the robot.
- *Robot*: It models the robot manipulator.
- *TG* (*Trajectory Generator*): It models the trajectory generator to be used by the robot.

The controller will operate in an Industrial PC (model 1036 from National Instruments®) with bus PXI (*PCI eXtensions for Instrumentation*) card with central processor 8106 and control movements card 7344, all from National Instruments. Figure 14 shows all the specified hardware.

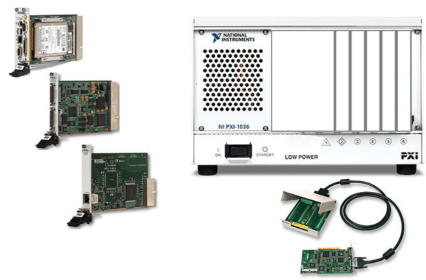


Figure 14. Controller hardware

4.3. Direct and inverse kinematics algorithm

The functionality of the *TG* system depends on the functions of direct and inverse kinematics of the robot. Except the last two joints (joints responsible for the direction of the water jet), the others rotating joints are driven by hydraulic cylinders. Therefore, procedures have been developed for calculating the angular positions and velocities of the joints as a function of the positions and velocities in linear hydraulic cylinder according to each mechanical assembly. Similarly, the reverse procedure was also developed, that is, the conversion of positions and linear velocities of the cylinders into the angular positions and velocities of the joints. Additional procedures implement the geometric Jacobian and the analytical inverse kinematics.

All these procedures work together with the *TG* system which in turn is integrated into the control system of the robot.

5. CURRENT STAGE OF CONSTRUCTION OF THE ROBOT

In the current stage of the project the robot is already mounted on the truck with all the specifications defined in the project. Figures 15(a) and 15(b) show the truck with the robot mounted on it but still without the end-effector.

(a) (b)

Figure 15. Robot mounted on the truck: (a) without water tank; (b) with the water tank.

The next steps of the project include the integration of all systems, implementation of automatic routines, validation procedures and the training of operators.

6. CONCLUSIONS

This work presented a systematic approach and the kinematic design of an electro-hydraulic robot designed to clean, by washing with a water jet, insulators of 13.8kV distribution network poles. The relevant aspects about the definition of the robot dimensions were discussed in details resulting in a very suitable methodology to design such manipulator.

The kinematic conception was developed with the aid of scaled models that were computationally validated through several simulation softwares. We presented the main aspects of control system, such as diagrams C/I net and layout of Human-Machine interface. The main specification treated in this project was the security of operator, robot and power line distribution networks.

The next steps of the project are the construction of end-effector and the project of direct and inverse kinematics algorithms to position and velocities. Finally, get all the systems both hardware and software working together.

7. ACKNOWLEDGEMENTS

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