STATE MACHINES APPLIED TO SUPERVISE THE LIVE LINE WORK IN ELECTRICAL ENERGY DISTRIBUTION SYSTEM

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Abstract – *We present a method based on Finite State Machine (FSM) to supervise actions performed by electricians when working on live line activities related with electrical energy distribution systems up to 34.5 kV. The Live Line Maintenance (LLM) is necessary for economic reasons. It is of major importance to electricians performing such activities that a series of steps and safety procedures are taken in order to guarantee that the undergoing work procedure will be carried out without causing injuries to the person executing the assigned task. The proposal is exemplified using a real scenario where images were taken from a fixed camera whose purpose is to verify that the prototype being developed is able to diagnose the activity being monitored. The work emphasizes a specific task chosen to exemplify and check the capabilities of the developed software to provide an automatic verification of the correctness of the task being monitored. The results show that the proposed method is feasible.*

Keywords – *finite state machine; artificial intelligence; live line maintenance; object recognition.*

1. INTRODUCTION

This study aims to develop a symbolic artificial intelligent system based on FSM to supervise actions performed by electricians when working on live line activities related to distribution systems up to 34.5 kV. The LLM is necessary for economic reasons, since disconnection of lines implies socioeconomic cost. Since these lines are energized the risk of accidents is high, which is minimized with specific training for this operation.

Before a technician gets involved in operational activities in LLM, it is required by law that a specific training in a controlled environment for this activity is made in order to allow the assessment by an instructor of the maneuvers performed by the technician. This is done to minimize risks related to the chance of an electrical discharge between the live parts and the technician. Risk assessment is basically the result of checking whether electrician deploys protection equipment such as insulating covers and blankets in the correct order [1, 2]. It is also assumed that electrician is correctly using his own protection equipment.

Of course, other risks such as fall, injury from tools and others, exist but these are considered outside of the scope of this work, as well as the rescue of the worker, in case of casualties, is also not considered, despite protection conditions may also apply to the rescuer. Deployment of safety covers follows standard procedures based on Brazilian occupational safety standard NR10 [3] and also the standard IEEE516 [1].

For the purpose of this work, one of these activities, namely Insulator Replacement on a cross-arm holding electric conductors, has been chosen to be monitored. It shows the results of the FSM modeling developed so far in what concerns image analysis and interpretation in accordance with the procedure described for insulator replacement.

The remainder of this article describes the state of art of activity monitoring particularly the use of machine vision and FSM for surveillance as shown in section 2. A brief description of the main parts of the software developed is shown in section 3. In section 4 some preliminary results with discussion are presented and the final conclusion is in the section 5.

2 MACHINE VISION AND FINITE STATE MACHINE

Different from the work in some hazardous environments where the person may be working in a restricted area and measuring sensors may be placed around him in order to establish a virtual safety working region [4], LLM activities restrict the type of equipments that can be placed in the area where work will be performed. As described earlier, electricians working in these activities are exposed to conditions which may have unpredicted and fatal effects if proper protection devices are not used. Since the live line work is performed without electronic measuring support, the only guarantee the person has that no accident will happen comes from the observance of task procedural steps that shall be followed in a specific order to avoid dangerous situations while executing the task. So far these procedural steps are elaborated by senior electricians that share their knowledge with less experienced workers. Once training is concluded, the senior electricians evaluate candidate's abilities to perform the taught procedure according to a set of predefined procedural steps. Nowadays, this evaluation process is performed visually by seniors using their own expertise to check whether candidate is performing correctly task and it is not in an unsafe situation.

Moreover, this evaluation is made at certain distance, since trainees practice and test their abilities in a training field, emulating real working conditions and the instructor cannot be placed next to trainees. This distant assessment of the examiner may be prone to errors that cannot be detected by the instructor. Finally, no exam documentation is produced of how the apprentice executed the activity being tested, apart from a general report. The lack of exam documentation makes it difficult to indicate to the apprentice what exactly he did wrong or not and, moreover, the risks involved. Due to this situation, a system is being developed whose preliminary requirement is to support the senior electricians on following the apprentices ability to correctly perform the assigned activity as well as to provide some advice on possible potential dangerous situations that may occur and pass unnoticed to the instructor.

In general terms the most important elements of this system are: sensing elements which shall provide key situational measurements from collected data; information processing by a computer; and some decision making to be performed by the accompanying person. Its key parts are the sensing technology to be used and the processing performed on it. A brief overview of sensing technologies is given on Table 1 [5].

Table 1: Sensor Types and Usage

Class	Type	Application
Identification sensors	Cameras, RFID Laser detectors	Generally used to identify objects and their format
Distance sensors	Ultrasonic Laser scanners Cameras, Optical	Used to measure distance from a certain point
Detection sensors	Hall, Capacitive Optical, Infrared Electromagnetic Ultrasonic	Used to detect object presence
Measuring sensors	Hall, Capacitive Optical, Ultrasonic Electromagnetic and other transducers	Used to measure physical quantities
Safety sensors	Optical, Capacitive Laser scanners Inductive	Used to prevent that a certain area is trespassed
Protection sensors	Relays Contact switches	Used to stop a process
Positioning sensors	Encoders, Inertial sensors such as accelerometers	Used to detect relative object positioning

The type of environment to be monitored is basically constituted of the following objects: electrician working in bucket mounted in an insulated boom, overhead conductors, voltage insulators supporting conductors and pole with a cross-arm to support insulators and keep conductors at safety distance from ground and constructions. A simplified sketch of the elements to be monitored is shown in Figure 1.

As previously mentioned, the process under monitoring by the proposed system is the LLM, whose aspect of interest is basically the relative positioning of the electrician in relation to electrified parts, notably when the electrician is between energized parts at different levels of potential, there may be an electric discharge or short circuit through him. It is noteworthy that no problem shall happen to the electrician if he comes close to an energized cable wearing appropriate insulating cloth and protective insulating material, suitable to the voltage level of the distribution network under maintenance. It can be noticed that monitoring the electrician position in relation to the insulating protective equipment, provides the necessary information to evaluate whether he is under risk or not.

In order to perform this monitoring task, a set of sensing elements has to be deployed around the environment in order to gather situational data that enables to describe the activity being surveilled. Choosing the type of sensing equipment to be used becomes an important issue in this type of system, since it will establish the system overall capability. At first one may think on using traditional distance and detection sensors, such as the ones based on capacitive effect or ultrasonic technology for instance. In this situation a sensing area is built around the environment to be monitored, discrimination and positioning of objects would then be obtained [6, 7]. The drawback for using this type of technology would be the limited sensing range as well as the
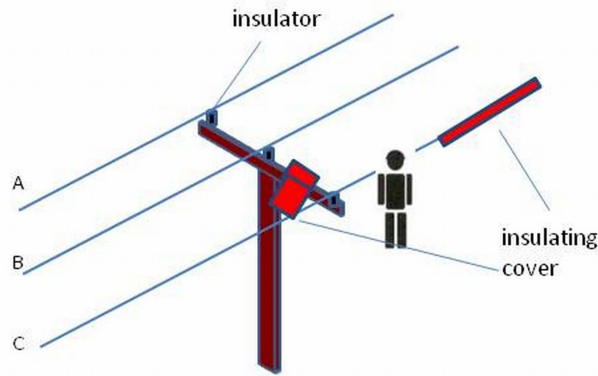
Figure 1: Simplified sketch.

necessity of an extensive deployment of sensors requiring a network of them. This situation, rather undesirable, would demand sensors displacement all over the environment or even build a specific arrangement where they could be used, thus modifying the situation where electricians normally work. An exception would be the use of RFID tags for object localization by means of radio signal triangulation [8] and identification [9], since the simplicity of their usage gives them a certain attractiveness.

In this context, machine vision was chosen to monitor the scene to be analyzed together with the elaboration of a software based on openCV [10] and used to segment and identify the elements of the scene. This technology enables a geometrical description of objects which in turn allows for the generation of discrete events that will feed a state machine.

A finite state machine or simply a state machine, is a mathematical abstraction sometimes used to design digital logic or computer programs. It is a behavioral model composed of a finite number of states, transitions between those states, and actions, similar to a flow graph which one can inspect by checking the logical sequence of events that describe the graph.

We feature the activities of the electrician as sequences of actions and these actions as short-term transitions taking place within some context. Then, at each time instant, the camera data generate an observation vector whose components contain information of the electrician movements and location context. It is performed an analysis of this observation vector that produces discrete events which are used as input for the state machine, modeling the electrician activities.

Besides machine vision and state machine simplicity of use on the proposed case, successful tests of its application in power line inspections either as a mean to track power poles [11] while performing their inspection or as a tool to extract power line information [12] suggest that this technology can be applied to monitoring electrician working on power cables. Moreover, it is possible by mean of this technology to link the objects detected by image processing with a description of the activities occurring on the scene under monitoring [13], thus providing the foundational basis for the system which is object of this work.

3   METHODOLOGY

The system used to perform activity monitoring is comprised of a camera, computer and web based HMI (Human Machine Interface) [14]. So far the system analyzes pictures taken in off-line mode, that is, the camera is not directly connected to the computer. A direct connection will be the next step on the prototype elaboration. An overview of developed image processing software is textually explained below, as well as showed in Figure 2.

After obtaining the image, an analysis is performed to eliminate certain patterns of colors and undesirable elements (step 1) by means of morphological and pyramid operations, also to perform edge extraction later used to detect lines. Color is mainly used for extracting insulating cover and blanket information from the image and this segmentation is obtained using a threshold on the maximum and minimum of histogram values taken from a sample of insulating material [15, 16]. Lines are obtained in two steps: applying a gradient filter to detect edges on the image and using the probabilistic Hough transform. For simplicity, the Haar transform [10] is used to detect the electrician, the cross-arm and the insulators (step 2). Once identified the objects of the image, the contours of the colored objects as well as the electrician, the cross-arm and the insulators are obtained together with the detected lines (step 3).

Having identified the volumes of each object in the image, a relationship between these volumes together with their identification and location in the image (step 4) is built. With this information, it is possible to identify which sequences of actions are present in the image (step 5), for instance, lines intersecting covering insulators.

The insulating covers are identified by their segmented color whose pixels are grouped in contours that permit to perform a geometric characterization of their positioning on the image. Once a sequence of actions is detected, events are generated and passed to a finite state machine [17] that will decide whether current action is acceptable according with a state description of the procedure the electrician is performing. A state machine has been chosen due to its suitability for behavioral modeling, while other inference techniques being also possible [13]. Events transition sequence for this state machine is depicted on Table 2.
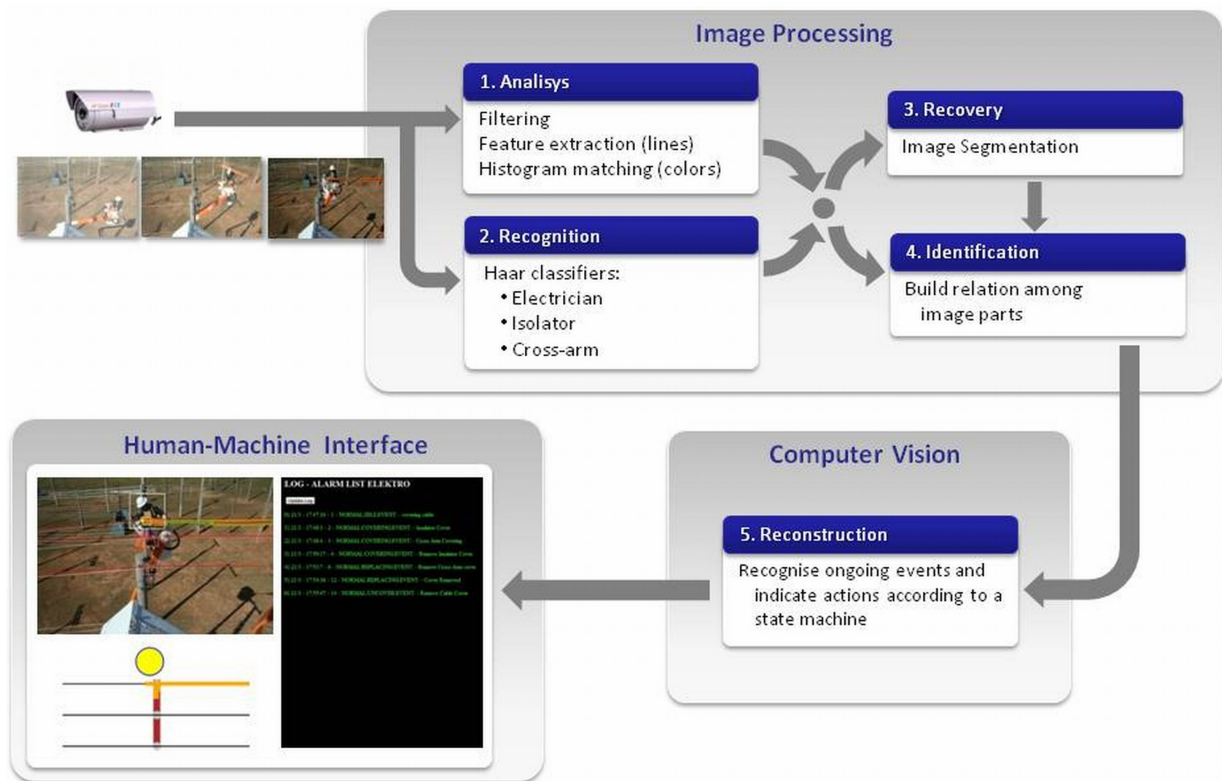
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Figure 2: Processing overview.

Table 2: Events transition

Event	State	Description
Cablecovering	covering	Process is initiated by covering cables.
Crossarmcovering	replacing	After cables being protected together with area surrounding insulator, then it is replaced.
Insulatoruncover	uncovering	After replacement takes place cover begins by removing insulating cover from cross-arm.
Uncover	idle	After cross arm is uncover together with insulator the process returns to idle state.

The state checking together with geometric description of elements allow to get a graphic and a textual report to be generated and display by the HMI. A typical state machine for the problem is shown in Figure 3. It is a simplified version to exemplify the main aspects of the activity being monitored. Faulty events and drawback procedures are not shown.
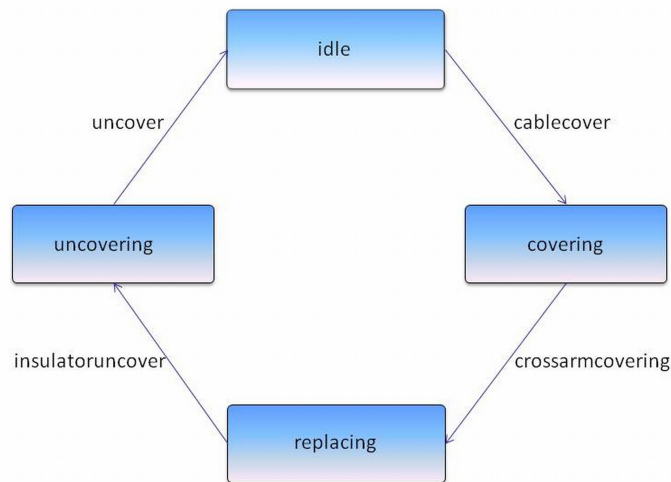

Figure 3: Insulator replacement state machine.

Cable covering event is generated once an insulating cover is detected in the conductors, which in terms of image processing refers to the intersection of insulating cover contour with the line describing the cable. A similar reasoning applies to crossarm-covering event which is generated by the intersection of the insulating cover contour with cross-arm contour. Uncovering events are issued when no insulating cover contour is detected provide they have already appeared in previous images.

4. RESULTS

The initial prototype for the system has been conceived in order to be able to analyze the simple task of replacing one the three insulators supporting the three phase conductors. The main steps of this procedure are given in Figure 4 which are represented by previously shown state machine (Figure 3).
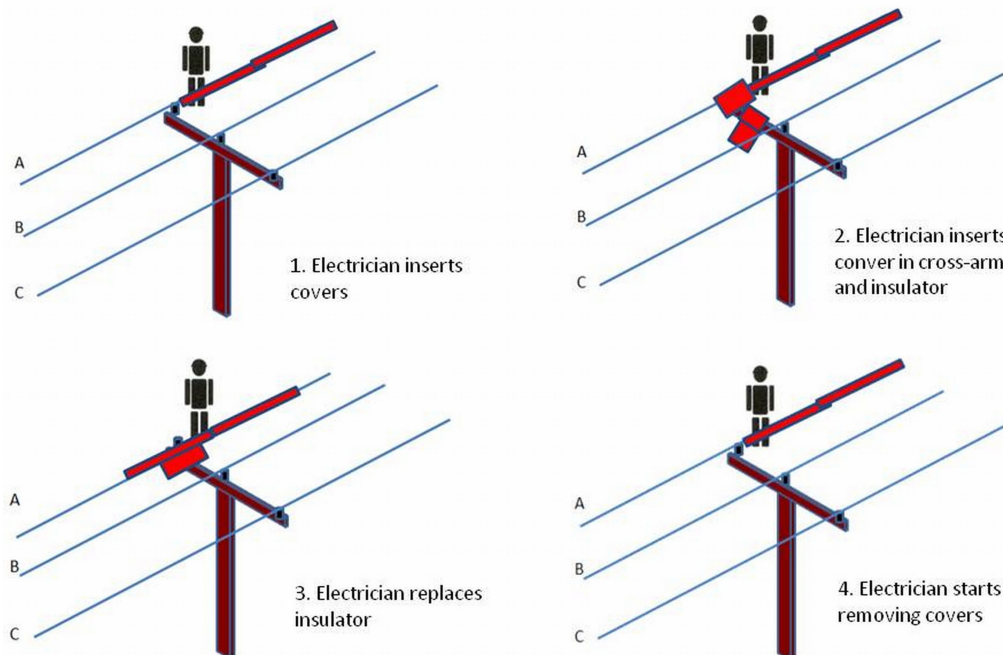

Figure 4: Main steps.

The results depict a real photo sequence where electrician performs these steps. It can be seen from the pictures, the developed software is able to recognize elements in pictures and translate them to virtual representation as well as to a sequence of actions

translated to text for logging purposes.

In the IDLE state (Figure 5(a)) all fixed elements of the scene are detected whose positions are assumed not to change during the whole process. Cable and cross-arm detection are performed only during this phase.
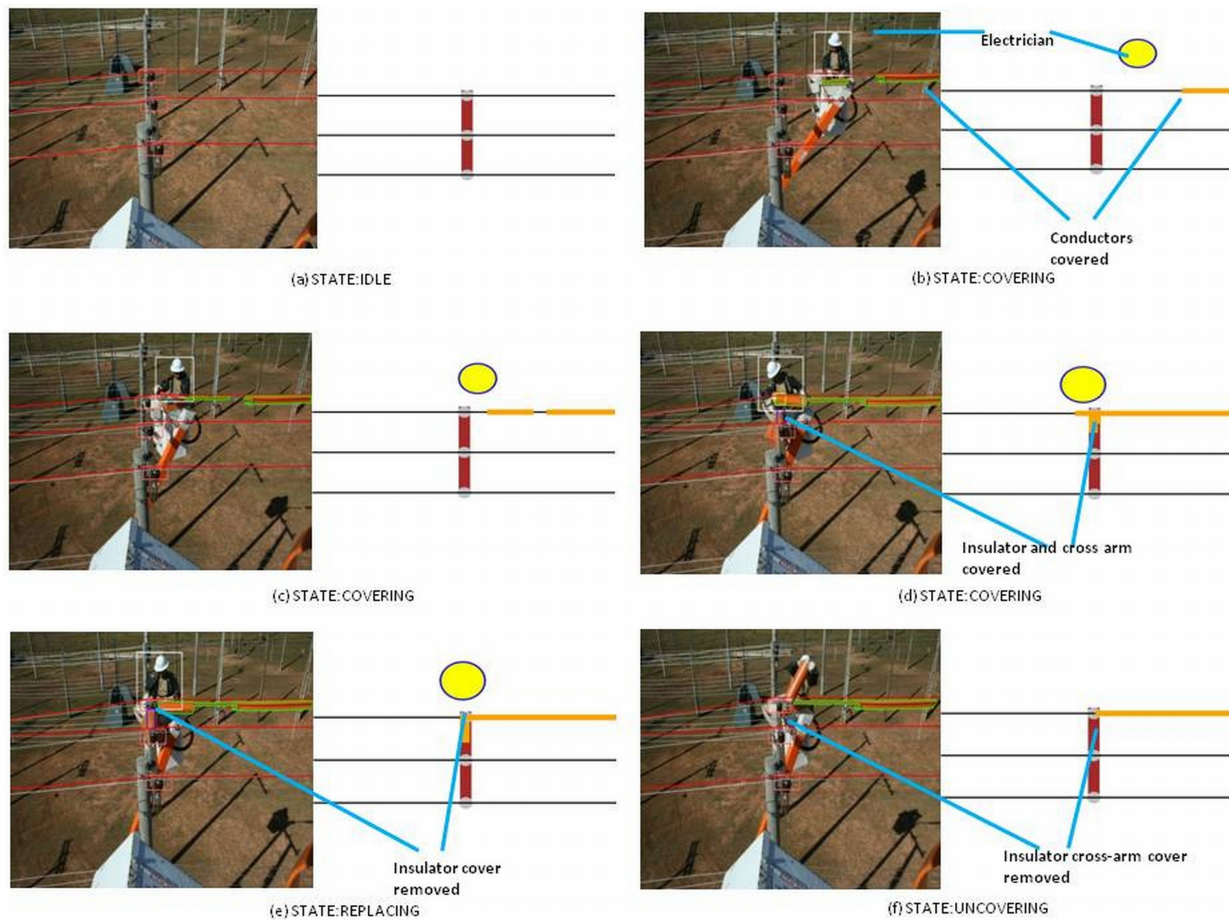

Figure 5: Recognizing elements in pictures.

In the COVERING state (Figures 5(b), 5(c) and 5(d)) and remaining states (Figures 5(e) and 5(f)), the dynamic elements of the scene, that is, the electrician and the insulating covers are detected. Their positions in relation to the fixed elements are evaluated, allowing a description of the process evolution by means of detected events.

Once a change in the dynamic elements deployment characteristics is detected at the scene, new events are generated reflecting this later fact.

At the end the whole replacing process can be described together with a reporting log as shown in Figure 6.

5. CONCLUSION

While the final system to be deployed for activity monitoring shall use an industrial camera connected to a computer by means of a GiGE interface online feeding the developed image processing software, the sequences shown on results section were taken manually using a single lens reflex camera. Despite the above fact it is our belief that the initial proposal of describing the actions of an electrician when performing his duties on Live Line Maintenance using machine vision is not only feasible but also provides good results as have been shown allowing further investigation of its use and deployment. Future works shall consider use of other methods of element detection besides Haar algorithm and improvement of line detection, as well as make use of hardware acceleration. Deployment of RFID as technology for monitoring of this type of activity shall also be tested and its use as alternative for monitoring shall be the subject of a future article.

Figure 6: Reporting log.

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