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Design of a methodology for a SCADA expert system: massive transportation ropeway

Quintero M., O. Lucia* Villa, Luisa. F. *Castañeda, L. ** Trujillo, Alexander ***

** Department of Basic Sciences, Mathematical Modeling Research Group, Universidad EAFIT, Carrera 49 N° 7 Sur – 50, Medellin, Colombia, (e-mails: oquinte1@ eafit.edu.co, lvillamo@ eafit.edu.co).*
*** Department of Mechanical Engineering, GEMI Research Group, Universidad EAFIT , Carrera 49 N° 7 Sur – 50, Medellin, Colombia, (e-mail: lcasta@ eafit.edu.co)*
**** Metro de Medellín Ltda. Calle 44 N° 46-001, Bello, Antioquia, Colombia, (e-mail: ATrujillo@metrodemedellin.gov.co)*

Abstract: This paper presents a methodology for the design and implementation of a SCADA expert system for a ropeway of massive transportation in Metro de Medellín Colombia. The SCADA uses real time information from sensors located in the interface grip-cable (Patent, 2013) for the fulfillment of the requirements of operability, maintainability and safety of Metrocable. The methodology hybridizes the SCADA design, fuzzy logic expert systems and the concept of Condition Based Maintenance (CBM). This system satisfies the normative (ISO 13374-2:2007 (E), 2007) in which the requirements for processing architecture in CMD (Condition Monitoring Diagnosis) are specified for the case of OSA-CBM (Open System Architecture – Condition Based Maintenance). This work is part of the results of the project "Diagnostic system of the interface grip-cable of the Metrocable", project developed between the entities COLCIENCIAS (Administrative Department of Science, Technology and Innovation), Metro de Medellin and Universidad EAFIT.

Keywords: SCADA, Expert systems, Fuzzy SCADA, Ropeway, Massive Transportation systems.

1. INTRODUCTION

The Metrocable system located in Medellin-Colombia is the first massive transportation ropeway in the world. The system operates around 19 hours per day, consequently the maintenance requirements of the system are higher than others ropeways and it is extremely necessary verify the conditions of operability, maintainability and safety of the users and the system itself (Dávila, 2012), (Dale, 2013). Cable transportation systems are used conventionally for tourism and sporting tasks. These applications set the operational time to seasons or few months a year. Due to that exploitation conditions, the maintenance personnel have enough time to perform the maintenance tasks suggested by the manufacturer. The mentioned operative conditions do not require automated maintenance practices and neither a SCADA expert system for supervision, data acquisition and monitoring of the system conditions to carry out condition based maintenance (CBM). Until now, the studies in this kind of transportation systems have been developed in the field of dynamic analysis, vibration analysis, mathematical simulations, nonlinear analysis, among others, but all of them, basically focused on design topics more than maintenance topics. Current maintenance tasks in the Metrocable system are performed following the manufacturer instructions, but due to the nature of the operation of the system, engineers have developed other tasks associated with the new dynamics of the ropeway operation. New maintenance routines have been established and expert knowledge has been accumulated trough time. This expert knowledge relates the measured variables of the cabin and station with possible failure modes of parts and components. The SCADA expert system presented in this work will focus on the modeling of the human knowledge of engineers to estimate the behavior of the system in terms of Condition Based Maintenance (CBM). The development of the SCADA expert system contains a specific phase of instrumentation of the interface grip-cable that relays on the real time acquisition of some measurements related to the station and the cabin (not presented in this work), these measurements will be the inputs to the system. Real time measurement of these variables gives to the SCADA designers important information about the system state and provides the inputs to the expert system. The inference system of the expert system is based on the system failure modes. These failure modes are generated from the historical data coming from the maintenance work orders and the expert knowledge achieved by the maintenance personal through the years. The result expected from the SCADA expert system is to have knowledge of: a) the system state, b) the causes of failures, c) the effects generated by failures and d) the component where the failure arise, all this presented in a optimized maintenance work order. This paper is organized as follows: section 2 presents the Metrocable system description, in section 3 the SCADA Intelligent systems are introduced, section 4 presents the methodology for the design of the SCADA expert system for Metrocable, finally section 5 shows the conclusions.

2. METROCABLE SYSTEM DESCRIPTION

Metrocable system operates under the modality of ropeway of continuous cycle, uncouple single cable. This means that uses a single cable that serves as carrier and tractor cable. As the cable is in continuous movement, the system disengages and engages the cabin to the entry and exit of each station respectively (A. Orro, 2003). The cabins have a unidirectional or circulating movement; the movement direction not changes, at least in normal conditions. The route of the cabin is performed at constant speed, once it enters to the station, the cabin uncoupling of the cable and coupling in the station slowing gradually to be boarded by the passengers, see Figure 1. The union of the cabin with the cable is temporary, meaning that the cabin joins to the cable once it leaves the station and that is uncoupling of the cable when it enters to the next station. The connection between the cabin and the cable is performed through a detachable grip (M. O. Löhr, 2002).

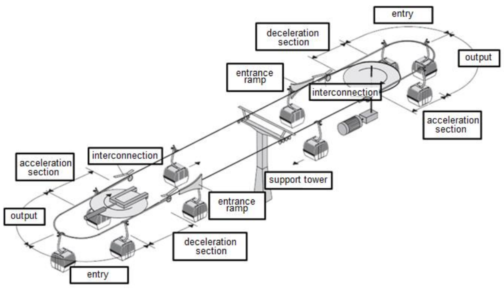

Fig 1. Graphic description of the Metrocable operation (M. O. Löhr, 2002).

The description of each of these two components is presented below:

2.1. The grip

The grip is an assembly composed of several elements that act together to allow the cabin coupling and uncoupling completely from the cable during his route for the station. The grip uncoupling when enters the station and this requires the interaction with the three tracks that make the station: the stabilization rail, the circulation rail and the coupling and uncoupling rail. The coupling function is performed when leave the station, and for this should also contact with the three rails mentioned above. Figure 2 shows the main components that constitute the grip (POMA, PIN 001).

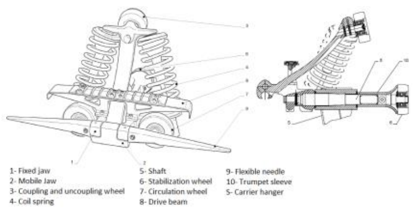

Fig 2. Main components of the grip (POMA, PIN 001).

2.2. The station

The station is composed by three rails: the stabilization rail, the circulation rail and the coupling and uncoupling rail. It also has a drive system consists of tires. This is supported by supporting beams and columns type swan neck. Figure 3 shows a transversal cut of a section of the station (POMA, VOI 001).

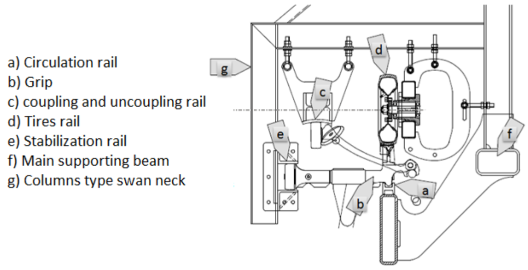

Fig 3. Main components of the station (POMA, VOI 001).

The study focuses not only on the proper use of the information extractable from the real time data, obtained to monitoring the variables located in the grip and the station. But also, on the fusion of the information with the knowledge of the system dynamics to design a SCADA expert system that satisfies requirements and standards.

3. INTELLIGENT SCADA SYSTEMS

The SCADA expert system basically consists of a traditional SCADA system combined with an expert system based on fuzzy inference systems (G. Johannsen, 1991) (T. L. Optin, 2007). Fuzzy logic is a powerful problem-solving methodology with a great number of applications in control and information processing (R. Babuska, 1998). One definition of the expert system is that it has the ability to store the rules as "data" as opposed to it being part of the program. When the expert system infers or processes knowledge it uses knowledge to make conclusions or make decisions. In the inference process, the inference engine evaluates or fires a set of rules, and then moves up or down the rule tree to come to a conclusion. This is called forward or backward chaining and is not necessarily deterministic. In the context of an intelligent SCADA, such a system has embedded sets of rules that convert process data into trends or facts and then use them to fire rules to determine the state of the plant. This is then used to come to conclusions or make decisions to aid the operator (T. L. Optin, 2007) (J. Alfredson, 2011) (G. Yang, 2011) (J. S. Kong, 2003) (K. Ravaie, 2002). The fuzzy logic is a mathematical theory developed to relate sets and variables associated to real world phenomena (L. A. Zadeh, 1965). The way humans understand the conditions of a variable is not a crisp structure, due to fact that value of a variable can belong to a category or another depending on the human appreciation. It means that the fuzzy logic fixes the paradigm that a variable can be multi evaluated and belong to several sets with a degree of membership to each one between the interval [0, 1]. This tool allows the development of a Fuzzy Inference System (FIS), widely used many years for controllers design in industrial applications. In a fuzzy controller these adjustments are handled by a fuzzy rule based expert system, which is a logical model of the human behavior of the process operator (Z. Aydogmus, 2009).

4. SCADA EXPERT SYSTEM FOR METROCABLE

As mentioned, the purpose of the development of a SCADA expert system relies in the necessity to preserve the human knowledge acquired in several maintenance tasks. Basically, this knowledge serves as rout map for the improvement of the common tasks, minimize costs and maximize efficiency.

Also, the learning of the details of the system under operation, have been used to overcome the contingences and develop a so called "maintenance work order" for several time frequencies of maintenance tasks. This order is the core of the routines in Metrocable system and represents a focus for optimization processes. As maintenance processes, mechanical conditions should be monitored constantly, for diagnosis and prognosis purposes. It means the acquisition of information from variables located in the grip-cable and the grip-station interfaces. To develop a SCADA system that fulfill the requirement of being an expert and runs in real time according with the normative, involves several activities from instrumentation and automation of signals and architectural design in layers. The developed system was designed in accordance with the ISO 13374-1:2003 (E) (ISO 13374-1:2003 (E), 2003) and (ISO 13374-2:2007 (E), 2007) (see Figure 4). According to the normative, the layers should be involved in the monitoring and diagnosis of some mechanical condition, in this case, the variables associated with conditions of safety, maintainability and operability of the system. Following this ideas, the SCADA expert system has as inputs the values of the measured variables and the configuration criteria of the system from previous analysis of historical data.

- The 18 variables measured in the SPD-CABLE system are delivered to the SCADA expert system duly acquired and manipulated physically and electronically fulfill layers 1 and 2 of the standard (ISO 13374-2:2007 (E), 2007)). That is, the SCADA system inputs are digitalized signals in the LabVIEW platform that will be used for the other layers of the same standard and additional functions designed for the system.
- The criteria for setting alarms and trend analysis of the mechanical conditions associated with the SPD-CABLE variables come from a quantitative and qualitative analysis of the historical maintenance Metro Company duly processed and analyzed by an expert mechanical maintenance.

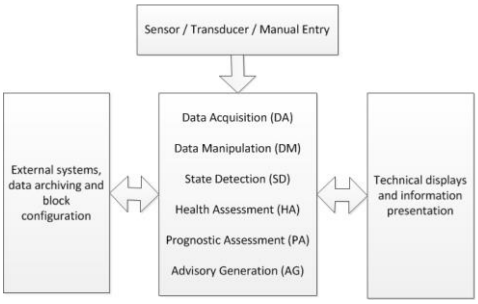

Fig 4. Block diagram of the data management (ISO 13374-2:2007 (E), 2007).

The requirements of the architecture for CMD (Condition Monitoring Diagnosis) are specified in the case of OSA-CBM (Open System Architecture – Condition Based Maintenance) (ISO 13374-2:2007 (E), 2007) (ISO 13374-1:2003 (E), 2003) (ISO 13379-1:2012 (E), 2012). The steps of defining the system architecture are:

1 Strategy of Operation: basically contains the sensing variables or real-time monitoring system, the comparison with limit values and / or alarms, making decisions based on rules, alarm generation software and finally an optimized maintenance order.

2 Requirements: real-time sensing, monitoring, visualization and report generation.

3 Structural program: basically is a system that meets the monitoring functions of variables that, in turn, enter to a base of inference rules (the engine of the expert system); these rules can generate software alarms to call the operator's attention. Simultaneously monitored variables are able to generate alarms origin in the SCADA system without having to go through the rules module (Figure 5).

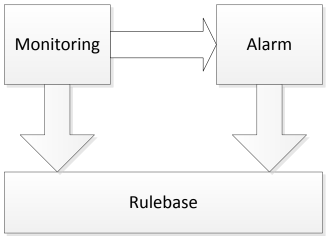

Fig 5. System architecture.

4 Module Design: the expert system must meet SCADA functions, for it include human machine interface modules and remote terminal units of data acquisition, both fed to the rule base mentioned in the numeral 3 generated as a result of inference is performed (Figure 6).

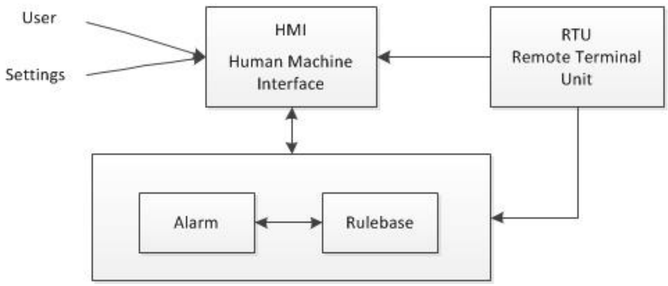

Fig 6. Module design.

5 Implementation of structural program: structurally the expert system consists of the same modules mentioned above but with the exception of the detail system configuration and its influence on decision making of the fuzzy inference system. This is a definitive parameter when making the transfer of knowledge from expert of maintenance about the system. It should be noted that this structural program gives great importance to the human machine interface, now as a receiver of the indications of the inference system of the SCADA (see Figure 7).

In addition, the SCADA expert system has to have all the standard layers of architecture established for information processing systems in ISO 13374-2:2007 (E) (ISO 13374-2:2007 (E), 2007) ,that said, the SCADA expert system shall comply with the other functions specified in the standard as are the layers 3-6 through architecture as presented below (see Figure 8).

To work with the system, users must have the possibility to control and evaluate the state of the system. What allows this to be done in an expert SCADA system is the human machine interface, through it, the user performs these operations (ISO 13374-2:2007 (E), 2007) (ISO 13374-1:2003 (E), 2003) (ISO 13379-1:2012 (E), 2012).

4.1. Human Machine Interface (HMI) design

The structural planning and implementation of HMIs are based upon physical process control strategy requirements. In general, improving production efficiency and yield is the main focus of plant managers, and the implementation of an HMI control strategy is instrumental in achieving this goal. It is not sufficient to merely implement the HMI system with standard modular software provided by the vendors. One must also consider carefully the requirements of all systems/users and the process control attributes, so as to customize the safest control mode (R. F. Chang, 2011).

The supervisory control system has its basic requirements, so the proposed HMI for the SCADA Expert system for Metrocable must include the following supervisory control functions:

- Control strategy and user requirements.
- Operating interface and HMI interaction mode.
- Simplified operation
- Dynamic graphics and information
- Prompt switching of GUI screen displays
- System testing and debugging
- Safety and reliability

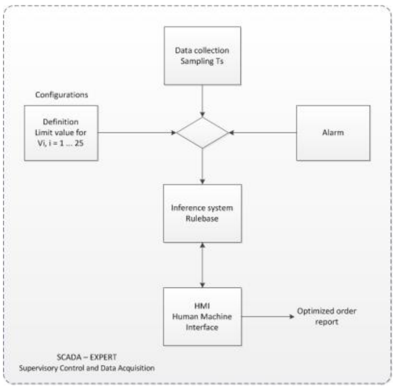

Fig 7. Implementation of structural program.

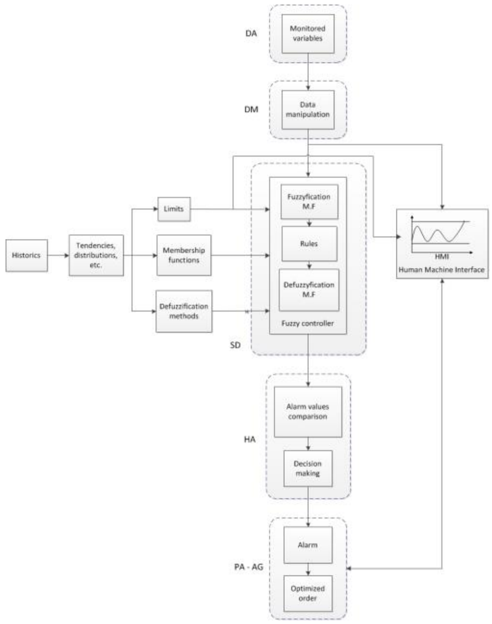

Fig 8. SCADA expert architecture for the SPD – CABLE.

After selecting the specific HMI hardware and standard software functions, the next steps are to plan and design the user-defined dynamic supervisory control application software and then to test and verify the integration of individual subsystem supervisory control hardware and application software functions. The structural design and implementation procedure of physical process HMI constructability is depicted in Chang (R. F. Chang, 2011).

4.2. System inputs

4.2.1. Variables:

From the knowledge of the maintenance routines that define the components and variables that require greater monitoring in the interface grip-cabin and grip-station are determined the variables to be monitored. Some of the characteristics that are verified in the maintenance routines that guarantee the security and integrity of the transportation system are the verifying of the geometric dimensions that monitor the correct location of the cable, the contact of the grip with the different ways of the station and the possible fluctuations in the cabin at entrance or exit of the station and the impacts these may produce in the fixed parts of the station. In total are 18 variables that define the operation, availability and maintainability of the system, these variables belong to systems located in the clamp and systems located at the station.

4.2.2. Definition of limit values and alarms

To determine the limit values and alarms of the SCADA expert system, information is needed the physical meaning of the variables that are being monitored. For limit values, should be available those provided by the manufacturer in the maintenance manual, these values are taken from tests that were performed to the system or the components that conform it, is also very important to have the knowledge acquired by maintenance engineers during system operation, especially in this case because, as mentioned earlier the Metrocable system is the first ropeway used for mass passenger transport resulting in greater amounts of hours of operation that reduce the lifespan of the components in a more accelerated form and therefore not all the limits set by the manufacturer apply to this case. Alarm levels are consistent with trends from historical data extracted from maintenance orders and the knowledge acquired by maintenance engineers.

4.3. Inference engine of the expert system

For data processing will be used a fuzzy system, the aim of a fuzzy system is to create a system based on behavior and human thought from a fuzzy logic based on experience.

A fuzzy inference system has three parts (L. A. Zadeh, 1965) (P. Ponce, 2010):

1. Fuzzification:

Fuzzification is the process in which a variable is categorized, and the value of variable is assigned to a sets. These sets are called membership functions and are descripted for the value of membership of variable to a set, this is a fuzzy number. Membership functions (MF) can be described as follows:

Triangular membership function:

$$\mu_A(x) = \begin{cases} x, & a < x \le b \\ -x, & b < x < c \end{cases} \qquad (1)$$

Where a, b, c determine the three corners of the underlying triangular MF.

Trapezoidal membership function:

$$\mu_A(x) = \begin{cases} x, & a < x \le b \\ 1, & b < x < c \\ -x, & c \le x < d \end{cases} \qquad (2)$$

Where a, b, c, d determine the four corners of the underlying trapezoidal MF.

Gaussian membership function:

$$\mu_A(x) = e^{-\frac{1}{2}\left(\frac{x-c}{\sigma}\right)^2} \qquad (3)$$

Where c represents the MF center and σ determines the MF width.

Bell membership function:

$$\mu_A(x) = \frac{1}{1 + \left|\frac{x-c}{a}\right|^{2b}} \qquad (4)$$

Where the parameter b is usually positive, (if b is negative, the shape of this MF becomes an upside-down bell.)

Sigmoid membership function:

$$\mu_A(x) = \frac{1}{1 + e^{-a(x-c)}} \qquad (5)$$

Where a controls the slope at the crossover point x = c.

Membership functions were created for each of the monitored variables; these functions were set up from the limit values, alarm levels, trends and expert knowledge of maintenance engineers.

2. Rule base:

To build a fuzzy inference system, there is necessary to generate a rule base from the knowledge about the phenomenon. The rule base has two parts: the antecedent and the consequent. The former is composed by the logical (AND/OR) combination of the input variables and the latter is the consequence of that interaction. That is: **IF** (variable 1) is (Set A) AND (variable 2) is (Set B) AND (variable 3) is (Set C) … **THEN** (output 1) is (Set D) AND/OR (output 2) is (set E). The logical combination of the inputs and its membership value (through operators max, min, product, probor or custom) provides the so called fulfillment degree; which represents the degree of membership of the outputs to the sets established in the rule. For the generation of the rule base was taken into account the degree of importance of each of the variables that affect the failure mode and the cause-effect relationships between them.

3. Defuzzification:

As seen before, the rule base delivers the output variables in sets associated to a category. The category or membership function doesn't have real meaning for humans and it is necessary to convert it to a physical value. Defuzzification process allows the user to define a value for each output variable. The fulfillment degree must be converted into a numerical value in the range of the variable. Deffuzzification process can be performed to several methods like Center of Gravity, Smallest of Maximum, Mean of Maximum, Largest of Maximum and Bisector. The output of each fuzzy inference system is the probability of occurrence of the failure mode analyzed (L. A. Zadeh, 1965). In the case of the SCADA expert system development for the Metrocable system, a fuzzy inference system was generated for each failure mode of the system. These failure modes come from the relationship of the variables monitored with the elements of the system and the different faults that can occur in each element (see Figure 9).

Fig 9. Structure of a failure mode.

4.4. Decision making and diagnosis model

To define the structure of decision making in the SCADA Expert system, was used the general approach to the choice of a diagnostic model that present the norm ISO 13379-1:2012 (E) (ISO 13379-1:2012 (E), 2012), this general approach is presented in Figure 10. Evidently the problem to solve in this case does not involve only one of the methodologies cited for this purpose, because data and knowledge are available. Several previous analyses of the phenomena were performed to extract causal relationships, first principles equations; rule based reasoning and real data. Interviews with expert maintenance personnel were developed and experimentally tested the failure modes to be monitored and the knowledge based new rules.

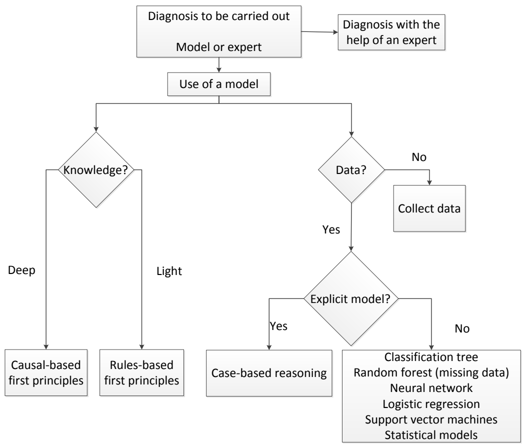

Fig 10. General approach to the election of a diagnosis model (ISO 13379-1:2012 (E), 2012).

5. CONCLUSIONS

This paper presented the methodology for the development of a SCADA Expert system for the Metrocable, running in real time with purposes of guarantee the operability, maintainability and safety. The goal of this work is the use of real time measurements, historical data and expert knowledge for the development of a SCADA expert system that fulfills the normative. The features of a SCADA intelligent system were presented and the relationship of the developed SCADA expert system with the normative ISO 13374-2:2007 (E) in which the requirements for processing architecture in CMD (Condition Monitoring Diagnosis) are specified for the case of OSA-CBM (Open System Architecture – Condition Based Maintenance.

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