

# Design and Prototype of a Hot Wire Cutting Machine

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## Abstract

A hot wire cutting machine equipped with a supervisory control and data acquisition system (SCADA) was developed. For engineering change management the FBS linkage method was applied. In the concept phase a generic PDP product development process was used with support from elements of the MRM mechatronics reference model. For the construction of the prototype each component was designed establishing the best operating conditions according to the dimensions and thermophysical properties of the wire. The SCADA system consists of a PLC and a PC with a graphical interface where the input parameters are configured and the thermal and electrical history of the monitored wire is displayed. The monitoring system uses a PC with a 32-bit Windows 7 operating system and an OPC software package that was run on the academic LabVIEW platform. This paper describes the important components of the system, including its architecture, software development, and prototype operation.

**Keywords:** Engineering change management; hot wire cutting machine; FBS bonding; PDP; MRM; MRM

## I. INTRODUCTION

Modifications to technical system descriptions are called engineering changes (ICs) [1]. ICs can be triggered by customers, company management or internal departments, suppliers or partners, and market drivers such as technology and regulation. During the last two decades, academic interest in IC management led to the creation of the Function-Behavior-Structure linkage method called "*FBS Linkage*", which models the product in more detail and allows a more detailed analysis of IC within the product development cycle. Recently, Cambridge University improved this methodology through development and detailing approaches [2] and [3].

Among the wide variety of technologies in which FBS can potentially be applied is hot wire cutting. Thermal cutting of soft materials by hot wire requires measurement of the tool temperature and evaluation of the cutting behaviour of the material in order to record the thermal history and understand the physical phenomena inherent in the process. The hot wire cutting machine uses a chromium-nickel alloyed wire between 0.5 and 1 mm in diameter that is heated under the Joule effect [4] which is produced by an electrical energy source that circulates current through the wire. When setting the operating parameters of the machine it is always required to specify the temperature of the wire and the speed at which the cutting progresses [5]. In addition, the wire must be kept under tension to cut certain materials such as foams and icopor [6].

The supervision and control of the variables is done through a

*Supervisory Control and Data Acquisition (SCADA)* system. This interaction occurs through the use of a graphical interface platform such as Labview from National Instruments and the STEP 7 Micro WIN application for programming the *Programmable Logic Controller (PLC)* [7]. Other applications have been designed for laboratory data acquisition and variable control [8]. However, it has not been possible to develop a sophisticated temperature control system [9], [10], [11], although results have been achieved without interference in the signal.

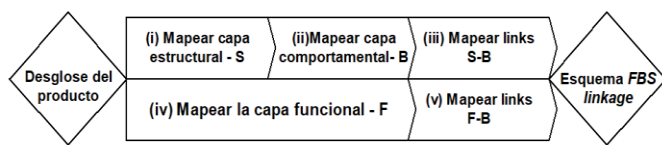
This paper provides an overview of the FBS linkage method and its application in the development of a hot wire cutting machine. The validity of the method within a generic product development process (PDP) adopted in a small technology-based company is evaluated. The hot wire cutting machine presented in this work was developed using a SCADA system and, consequently, sub-processes were carried out with PLC to use a single graphical interface from a personal computer. A *Human Machine Interface (HMI)* was designed with a control panel where the user can make settings and regulate operating parameters. Engineering details resulting from the validation and approval of the designs are shown at the end.

## 2. METHOD OF LINKING FUNCTION - BEHAVIOUR - STRUCTURE

The function-behavior-structure linkage method "*FBS Linkage*" models a product in greater detail and allows a more thorough analysis for engineering change management. This method supports the representation of conceptual product knowledge and has a fundamental common goal: to capture the tacit knowledge that remains as experience in the minds of designers and make it explicitly and formally available throughout the team [12].

*FBS Linkage* uses three layers of information: structure, behaviour and function. Structure refers to what the product consists of. Behavior refers to how its constituent parts act or react in their environment. Finally, function refers to the use of the behaviors [13]. To develop an FBS schema, the five steps described in Figure 1 are followed. First, (i) structural and (ii) behavioural attributes and their interlinked elements are defined within each layer. For the structural layer, a number of attributes are considered, ideally independent, such as material, geometry, surface, colour and controller. For the behavioral layer, preferably independent behaviors should be identified, such as mechanical (weight, moments of inertia, etc.), thermal (temperature and heat), and electrical (current, voltage, etc.). Then (iii) the structural elements determine the behaviour of the components which must be linked together. As the relationship between structure and behaviour is determined by

physical laws that apply to all components, the mapping between structural and behavioural attributes can be developed independently of the components. However, for some components, certain links may be irrelevant to IC propagation and can be omitted. For example, the influence of the structural attribute of color on thermal behavior is often negligible compared to the influence of the material on thermal behavior. In parallel, (iv) the functional layer can be mapped as a functional block diagram composed of functions interconnected by energy, material and signal flows based on the reconciled functional basis [14]. The functional layer considers the whole product and has a separate hierarchical structure, regardless of the level of decomposition of the product into systems, components or parts. Finally, (v) to obtain function-behavior links, functions can be assigned to the components that perform them and then specified for the behaviors of the responsible components.



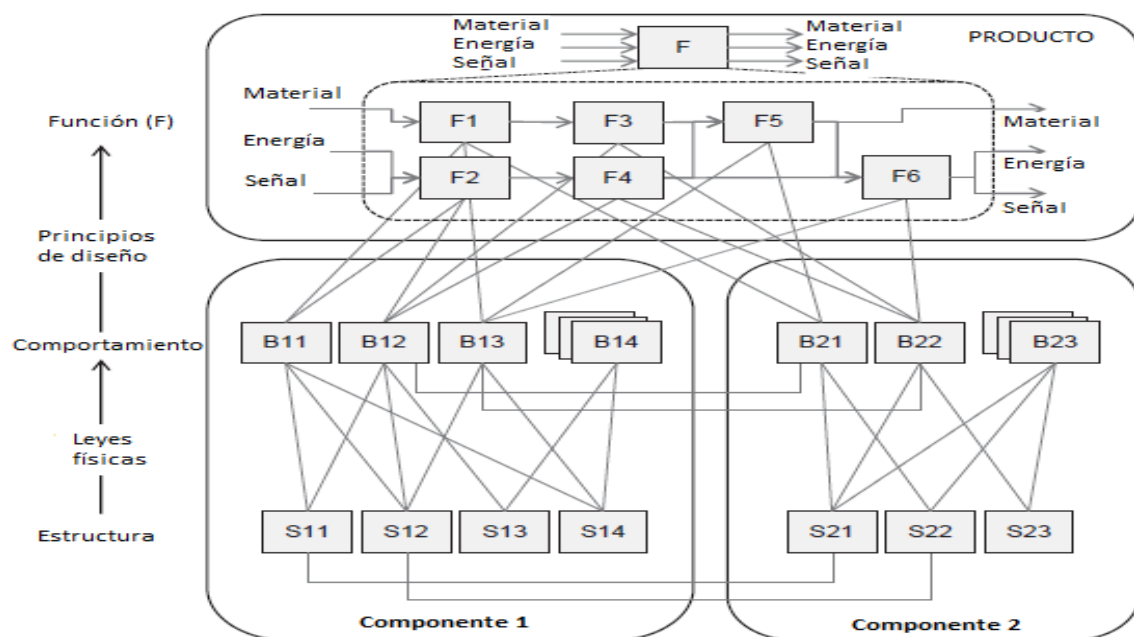
**Fig. 1:** Step-by-step for the development of the FBS scheme  
 Source: [3].

The result is a product linkage model: the FBS linkage schema. This schema can be represented as a network or a multidomain matrix (MDM). As illustrated in Figure 2, the FBS linkage network is composed of structural, behavioural and functional elements that are linked together within and between layers. By explicitly considering these attributes, the FBS linkage method transforms much of the tacit knowledge into available formal knowledge. Consequently, the method allows a more detailed analysis of changes affecting any attribute or linkage of the

product. Furthermore, it models the product in the context of its working functions and mechanisms and thus allows reasoning about the propagation of change and supports change containment and solution development. Then, direct FBS links can be quantified by the probability and impact of change propagation. This step can be performed simultaneously during the mapping of the different network layers during steps i-v or at the end, when the FBS linkage scheme is complete.

### 3. DESIGN OF THE HOT WIRE CUTTING MACHINE

The hot wire cutting machine was conceived as a mechatronic product that requires a methodology to model the product. The main functions provided by solutions combining mechanical, electronic and software technologies were considered. For this, methods and tools were applied based on a generic Product Development Process (PDP) [16], adopted by a technology-based company and enhanced with aspects of the Mechatronics Reference Model (MRM) proposed by Sanderson [17], in the product conception phase. This reference model comprised five phases: 1-Project planning; 2-Product design; 3-Product approval of the manufacturing process; 4-Product validation with the customer; and 5-Product monitoring. In the product conception, the technical characteristics of the product to be developed were specified and design alternatives were generated. The selection criteria were a combination of manufacturing capability and knowledge of parameters from experience. At this point, the modelling and systematization of the product design was carried out. This phase is critical and had to be well defined, for this reason the FBS linkage method was applied. Figure 3 shows the generic product development process and Figure 4 shows the MRM elements for product design.



**Fig. 2:** Components of the FBS linkage network and assumed ontologies. Source: [15].

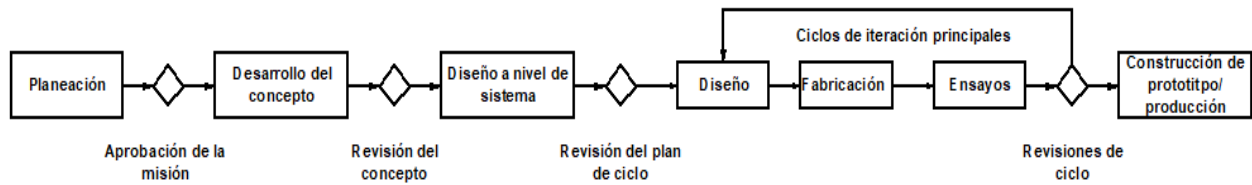


Fig. 3: Generic product development process. Source: [16].

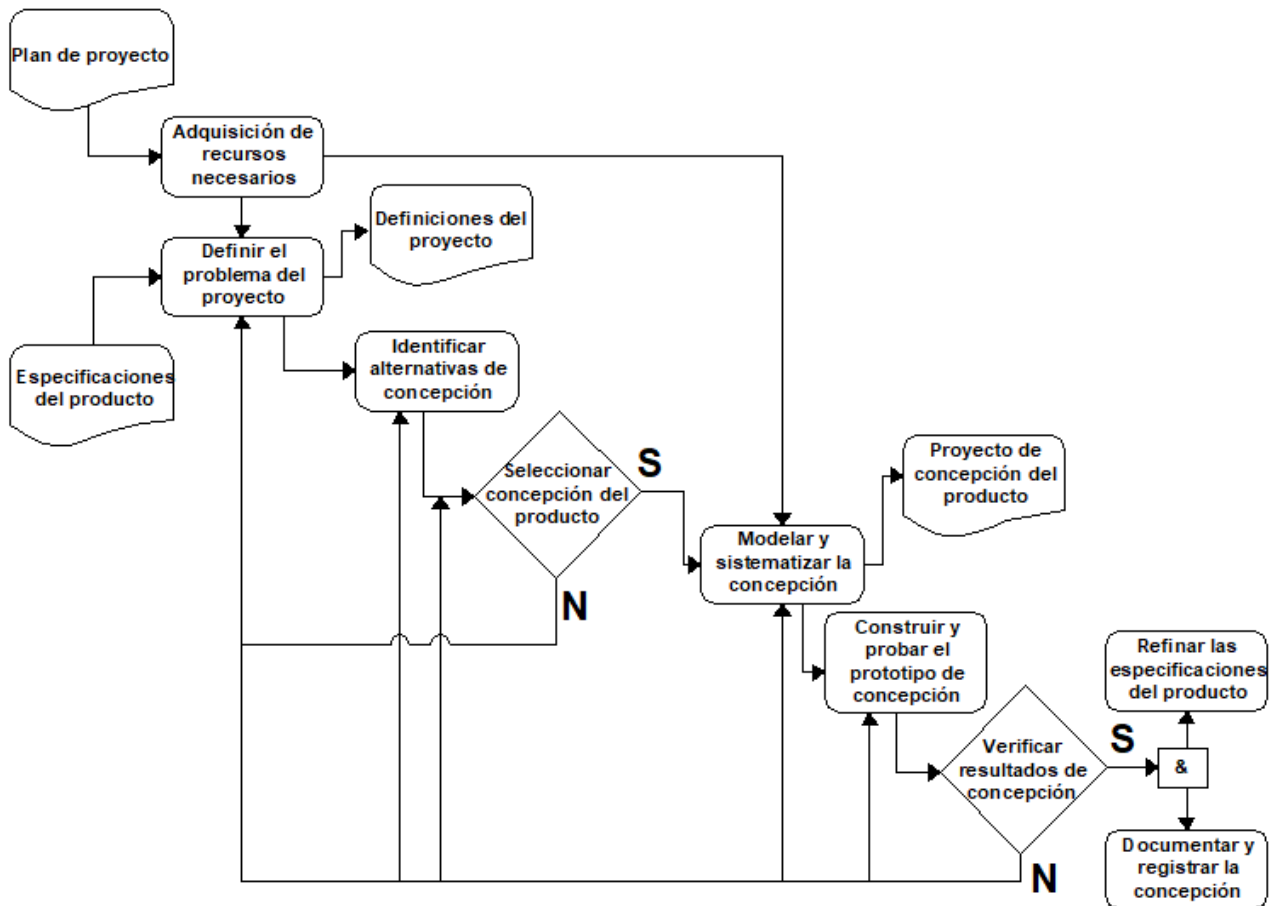


Fig. 4: Mechatronics reference model: Product conception phase. Source: [17].

To assist the MRM phase, which is more technical and engineering, the FBS linkage stages defined for the hot wire cutting machine are shown below.

### 3.1 Basic Engineering

The automated system of the hot wire cutting machine consists of an HMI interface. The interface is in charge of the supervision of the wire variables allowing the insertion of the initial operating parameters (cutting speed and wire tension). A PLC commands the feed movement of the piece by means of a motor and acts on a variable voltage transformer while receiving the signal from current and wire expansion sensors. The basic engineering of the cutting machine is concentrated on these components as shown in Figure 5.

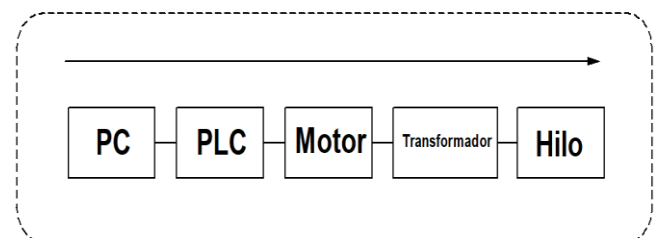


Fig. 5. Basic engineering of the hot wire cutting machine.

### 3.2 Structural Layer

Figure 6 shows a breakdown of each of the basic components with each of its constituent elements, product of the engineering applied to each part of the machine.

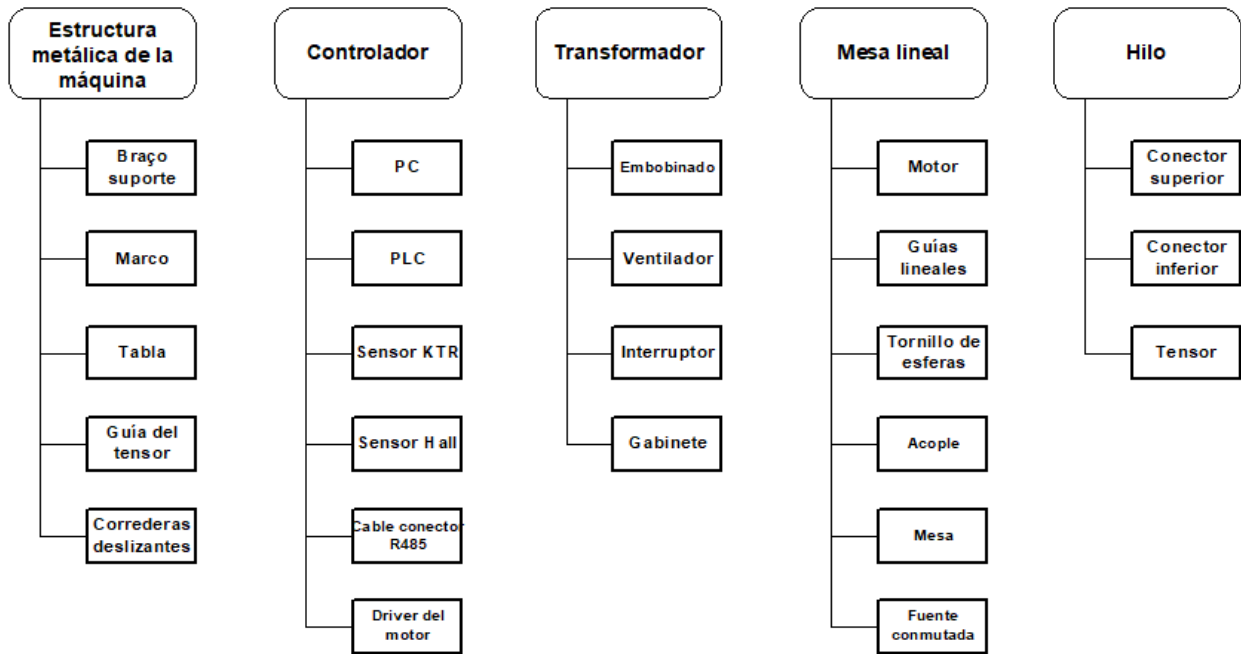


Fig. 6. Structure and components of hot wire cutting machine

### 3.3 Functional layer

Figure 7 shows the general scheme of operation of the hot wire cutting machine separating physical actions, signals and energy.

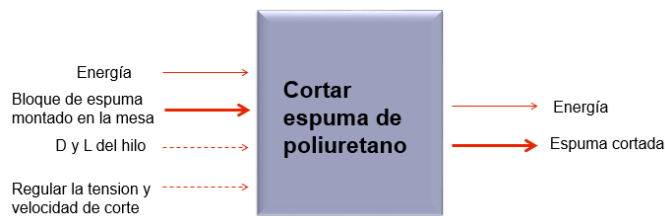


Fig. 7. Functional analysis of the hot wire cutting machine

The actions necessary to perform the cut are detailed in Figure 8.

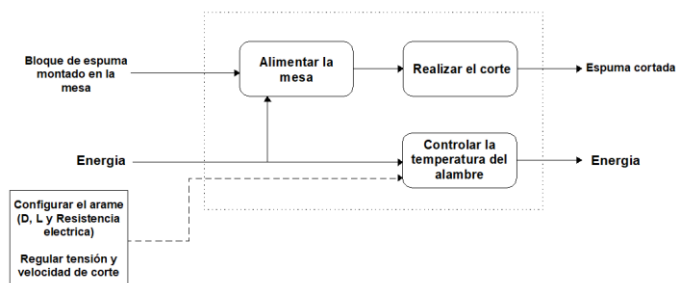


Fig. 8. Functional structure of the hot wire cutting machine.

From the basic engineering components a diagram relating the functions of each of the elements was established as shown in Figure 9. It is possible to see the main interrelationships and understand the operation of the machine.

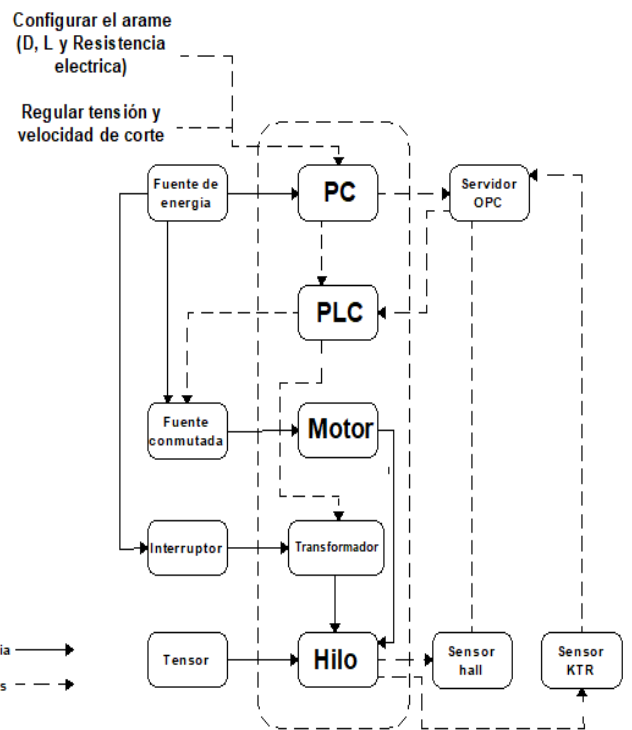


Fig. 9. Functional diagram of the hot wire cutting machine.

### 3.4 Behavioural layer

To represent each one of the operating states of the machine, a behavioral diagram was elaborated (Figure 10), which is closely associated with the programming of the software that controls the PLC, the HMI software and the communication protocols.

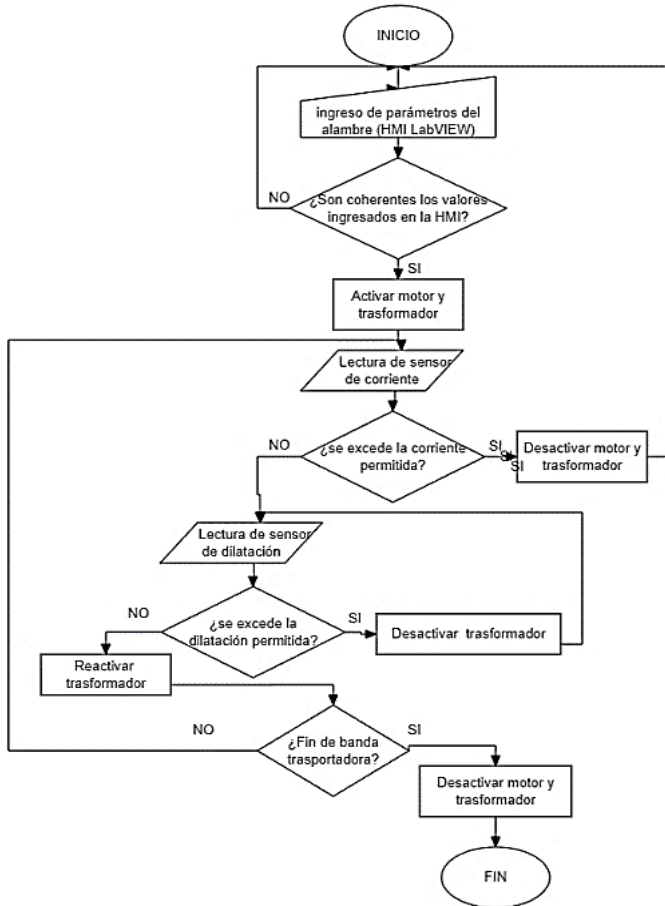


Fig. 9. Behavioural map of the hot wire cutting machine.

## 4. SYSTEM LEVEL DESIGN

### 4.1 Hardware

The system architecture is composed of an HMI interface, as mentioned above. The interface monitors the thermal variables of the materials being worked with and inserts the initial parameters for execution. The PLC, connected to each machine, is an Amsamotion S7-200 with 14 digital inputs and 10 digital outputs.

In the cutting machine, the PLC controls the movement of the motor and regulates the wire voltage by taking current and wire expansion readings (Figure 11). This information is sent to the HMI interface so that the operator can see the thermal behavior of the machine.

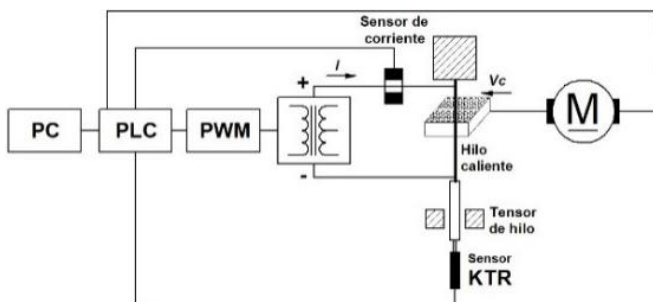


Fig. 11. Hardware installed on the hot wire cutting machine.

For the operation of the Brushless motor, a controller was added, which allowed orienting the direction of the motor rotation and varying the speed. Also, Hall effect sensors were connected to the PLC input pins to determine the exact position of the motor rotor.

For the hot wire cutting machine, a linear expansion sensor and a current sensor were connected to the PLC and manipulated by means of *Pulse Width Modulation* (PWM) pulses. Also, the output Q0.2 was connected to an electrical circuit to allow the average voltage across the wire to be varied.

### 4.2 Software

At the interface of the hot wire cutting machine (Figure 12), the wire configuration is specified according to its type, dimensions, maximum current, temperature, expansion, length and electrical resistance. Next, the operating parameters, namely source voltage and cutting speed, are adjusted. A graph is displayed for the current flowing through the wire and another for the temperature measured by the thermal expansion of the wire.

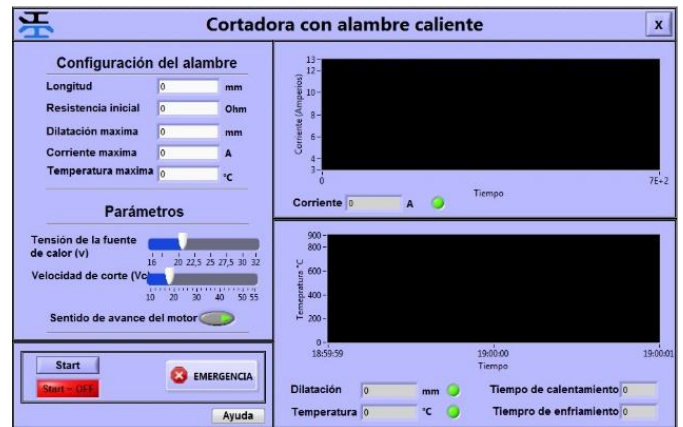


Fig. 12. Main screen of the HMI of the hot wire cutting machine.

At the software level, in addition to the VIs for the interfaces, the automation was designed in a control algorithm for the PLC with the functionalities of the three machines. The PLC programming language used was Ladder, together with the "*Object Linking and Embedding for Process Control*" (OPC) module of LabVIEW for communication between the PC, the PLC and the sensors.

The logic of the hot wire cutting machine (Figure 9) checks the consistency of the values entered, verifies the allowable current and expansion and finally disables the motor and transformer.

## 5. DESIGN, MANUFACTURE AND TESTING

Based on the applied engineering, a transformer with variable voltage between 18 V to 30 V of alternating current (AC) was initially designed and installed. The control was done from the PLC by means of an Optotriac used as an interface between the controller and the power Triac of the transformer, in order to vary the voltages. The maximum amperage reached was 9 A. Figure 13 shows the back center of the transformer cabinet,

which was equipped with a fan for cooling the transformer. Above this is the PLC and the power supplies for the other components of the machine. The structure, frame, table and sliding guides were specially designed according to customer requirements and material selection criteria for mechanical design. The linear sliding table of the cutting part was designed and manufactured using a recirculating ball screw coupled to the motor, together with two linear slide guides on both sides of the screw. This device was bolted to the machine table and was fitted with a clamping mechanism to fix the parts to be cut onto the moving flat base.



**Fig. 13.** Functional prototype of the hot wire cutting machine.

A gravity tension system was implemented for the wire. Thus, a counterweight was used hanging to the wire, in such a way that when this weight was heated it did not exceed the yield point, in order to keep the hot wire in continuous operation without breaking it. Once the elastic behavior of the wire was assured, a KTR type displacement sensor coupled by contact to the lower part of the counterweight was placed. This sensor measures the linear expansion by heating of the wire. The measuring range of this sensor is from 0 to 2.5 cm with a maximum error of 0.02 mm. The thermal expansion is then converted into an indirect temperature measurement using the following equation:

$$T_f = T_0 + (L_f - L_0) / \alpha L_0 \quad (1)$$

Where,  $L_f$  and  $L_0$  is the final and initial length of the wire, respectively.  $T_f$  and  $T_0$  is the final and initial temperature of the

wire, respectively. And  $\alpha$  is the coefficient of thermal expansion obtained from the wire manufacturer.

Tests were conducted using a variable voltage transformer and a 20 V fixed voltage transformer (designed for the construction of a production prototype). The tests validated the reliability of the SCADA system function and verified the consistency of the measurements. This established the feasibility of using PWM to manipulate the output to obtain different voltages to heat the wire (Table 1). A wire diameter of 0.7 mm was used and three wire lengths (800 mm, 900 mm and 1000 mm) were worked with. To obtain an acceptable margin of error, three iterations were performed for each length value, with a total of 9 samples for each source.

Tests with variable voltage transformer and fixed voltage transformer.

Length (mm)	$T_{\max}$ (°C)	I (A)	$T_{\max}$ (°C)	I (A)
800	788	8,7	779	8,60
800	791	8,7	780	8,60
800	790	8,7	784	8,60
900	651	8,2	642	8,15
900	654	8,2	640	8,15
900	649	8,2	640	8,15
1000	583	8,0	576	8,00
1000	585	8,0	578	8,00
1000	580	8,0	576	8,00
		Variable voltage	Fixed voltage	

When comparing the temperatures measured with each source, a maximum error of 5 °C can be seen. Having this error clear, the use of the sensor can be considered as a good alternative to measure the temperature indirectly in the wire. It was also validated that the results obtained with variable voltage are consistent with those obtained with fixed voltage.

## 6. CONCLUSIONS

The product was designed, manufactured and tested following a generic product development process based on the function-behavior-structure linkage scheme. This model contributed to a better understanding of the product by the organization and contributed to the efficient management of the engineering changes that occurred in the different phases of the PDP. Additionally, it helped the organization to save direct costs and provided a basis for improved integration with other disciplines for mechatronic product development.

The strategy of integrating elements of the mechatronics reference model in the conception phase together with the FBS linkage, facilitated the understanding of the technological details of the product and allowed a more detailed case study. It contributed to the correct modelling and systematisation of

the product design which is a critical phase, which needs to be well defined.

The fact that it was conducted only on a case study, turns out to be the main limitation of this research. The result obtained cannot be generalized, but the exploratory nature of the research topic calls for this type of case study under an action research protocol. Further research in new contexts and with different models will help to develop useful engineering science for machine builders in different sectors and facing different market conditions.

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