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RETROFITTING OF A TWO-DEGREES-OF-FREEDOM WELDING TORCH DISPLACEMENT SYSTEM

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Abstract. *Welding procedures are widely employed in engineering, in the most diverse application scenarios. The operation of the welding equipment is a key factor in welding, presenting two major concerns that, left unresolved, can lead to possible issues. The first is related to health hazards, given that, in some applications, the welding process can pose risks to equipment operators due to fumes, radiation and high temperatures. The second one concerns the weld quality, which can be heavily dependent on the operator's experience and skills. In extreme and repetitive application scenarios, both health and quality concerns become more urgent. In order to prevent or mitigate the aforementioned issues, the automation of welding procedures presents itself as a valuable alternative. Automated welding procedures may further aid researchers to develop detailed studies on process variables and their influence in weld characteristics, due to improvements in reproducibility and reliability of the processes as a whole. An important aspect of automated systems concerns their usability and user experience. Ideally, user interfaces should be simple to understand, allowing for rapid configuration, control, and monitoring of the equipment. Several welding equipments however, offer only dedicated user interfaces which usually have steep learning curves and are difficult to manipulate. Even though state of the art automation systems incorporate better user interfaces, cost constraints may prevent their widespread adoption. In this work we propose the retrofitting of a welding system with two orthogonal prismatic axes. With the development and deployment of an alternative control to the system we support not only the implementation of new user interfaces, but also the use of the original/legacy one. In order to evaluate the retrofitted system, we implemented a desktop application that provides an intuitive and simple user interface, which translates in an enhanced user experience. By coupling an Wifi adapter to the welding system we also allow for remote control, enabling the implementation of alternative user interfaces, for instance, in mobile devices. The resulting system allows for safer and easier operation of welding equipment.*

Keywords: *Process automation, Retrofitting, Cartesian Manipulator, Welding.*

1. INTRODUCTION

The automation of production processes is an ongoing and, most likely, irreversible phenomenon. In order to keep up with the global demand for high end, increasingly complex products, there is a call for the development of a multitude of techniques that enable industrial facilities to scale up production. Since the start of production processes mechanization, industries have achieved different degrees of automation, but the ultimate goal is human interaction independence. As the Fourth Industrial Revolution (Industry 4.0) advances, automation emerges in different scenarios (Jasperneite *et al.*, 2020; de Souza *et al.*, 2020), leading to deep discussions about expected outcomes to economy and society (Marengo, 2019).

The field of welding is no exception to the aforementioned trend. This arises due to several factors observed in manual welding procedures. Traditional, manual welding procedures are highly dependent on operator's experience and skills. In particular application scenarios, however, skilled and certified welding professionals may be difficult to locate (Robertson *et al.*, 2020). Even if qualified professionals are readily available, the welding procedure itself poses high risks to the operator's health due to the exposure to fumes (Rahul *et al.*, 2020), radiation (Rybczyński *et al.*, 2019), and high temperatures that may lead to burns (Cezar-Vaz *et al.*, 2015). Not surprisingly, due to occupational health hazards, welding professionals must undergo proper training and adhere to strict safety procedures. The adoption of such measures, combined with eventual reworking costs, build up to a labor expense that represents from 70% to 80% of the total cost of the process, as pointed by Norrish (2006).

Besides being considerably less expensive, manual welding is not suitable for all application scenarios. Pires *et al.* (2006) points out that for products requiring a large number of welding procedures (where precision is usually a key factor) automation is not optional but mandatory, at least in some level/degree. This arises due to higher reliability and repeatability observed in automated welding processes in comparison to human aided ones. Moreover, there is a direct link with the control of the parameters and variables during welding execution, especially those directly related to the welding energy. Specified by AWS (American Welding Society, 1990) as the energy produced by the heat source used in the welding process per unit length of the obtained weld bead, the welding energy, given by Equation (1) is an important parameter that is useful in the analysis of the welding metallurgical effects (Marques and Modenesi, 2014). In this equation H is the welding energy (in J/mm), V is the welding arc voltage (in Volts), I is the welding current (in Amperes) and v is the welding speed (in mm/s).

$$H = \frac{1}{vT}\int_0^T VI dt \approx \frac{VI}{v} \tag{1}$$

Furthermore, welding energy is widely used in the welding technology field as a parameter for specifying welding conditions. It is important to emphasize, however, that it is possible to obtain weld beads with different characteristics even when these are produced with similar welding energy values. These results can be obtained by changing the welding variables that directly influence the welding energy, namely: arc voltage, current and welding speed. These variables, individually, can affect the process operational characteristics and, consequently, the characteristics of the weld beads produced. In this context, it is essential to control these variables in order to ensure repeatability and thus the success of the welding operation. In order to ensure welding speed control, welding torch displacement devices are usually employed. These devices range from relatively simple ones, containing only one degree of freedom, to considerably complex ones, as is the case with anthropomorphic robots (Carvalho, 2009). Regardless of the complexity of these equipments, the purpose of their use is, among other things, to guarantee the adequate value of the welding speed. Therefore, it is useless to employ extremely accurate welding power sources if the value of the welding speed has considerable variations during the execution of the process.

Even though welding automation has became widespread in a number of industrial settings, its adoption is not straightforward in all scenarios. This is the case particularly in small industries and laboratories, where legacy (older) equipment is already in use and full replacement may not be a viable option, due to financial constraints. In such scenarios, a cheaper alternative is to add features or functionalities to an existing equipment, that is, to retrofit it. Retrofitting may also be an interesting option in the case of welding equipment that do offer some degree of automation, but trough Human-Machine Interfaces (HMIs) that have a steep learning curve and/or are difficult to operate (possibly, due to outdated interfaces).

In the present work we propose the retrofitting of an existing welding equipment, more specifically a SPS's Tartílope V2F (SPS, 2021), which is shown in Figure 1. The Tartílope V2F is composed of a manipulator with two orthogonal axis mounted on two rails and is controlled by a customized processing unit. In brief, it is a two-degrees-of-freedom welding torch displacement system, being the "x axis" for longitudinal movement (speed up to 160 cm/min), and the "y axis" for transverse movement (speed up to 300 cm/min). Although the specified equipment allows for some degree of automation, its original Human-Machine Interface (HMI) presents a steep learning curve for new users. Even experienced users, however, may find its HMI difficult, laborious, and time consuming to operate. Such difficulties arise mainly because of the original HMI design, which is based on a two line LCD screen (see Figure 1). To access and modify processes variables (which are often poorly described due to display size limitations) the operator has to go through a series of nested menus, requiring some effort and specialized training on the operator's side. Moreover, the equipment's HMI allows for control and programming only from short distances, given that it is wired.

Figure 1: The Tartílope V2 (left) and its original HMI shown in detail (right).

In order to deal with the aforementioned issues, we retrofitted the original equipment, working on both new hardware and software. Regarding hardware, we developed, manufactured and incorporated into the original device a PCB (Printed Circuit Board) and two off-the-shelf microncontrollers. These hardware additions allowed us to implement the following improvements to the Tartílope V2F: (i) an alternative controller, (ii) a new Human-Machine Interface (HMI), and (iii) a new connection interface between HMI and Machine/Controller. It is important to note that despite these hardware expansions, the legacy (original) controller and HMI remain fully operational, that is, the user can easily select which pair of controller and HMI he/she wants to handle. Regarding software, in addition to the new controller, we also implement and make available a new HMI, which can be programmed and operated from any personal computer. Besides its ease of use, the new HMI can connect to the welding equipment through WiFi, allowing for distant/remote operation and, therefore, increased user safety.

The remainder of the paper is organized as follows. In Section 2, Materials and Methods, we discuss the techniques applied to plan and develop the new command system. Results from the retrofitting of the manipulator are presented in Section 3. Finally, in Section 4 we draw the main conclusions of our work.

2. DEVELOPMENT

In this section we detail the retrofitting process applied to the Tartilope V2, alongside the hardware and techniques involved in the development of both the micro-controlled system and it's corresponding software.

2.1 Retrofitting

In order to effectively develop a new command/control system that also allows for the maintenance of the machine's original capabilities, it is of great importance to have a broad knowledge of the device's internal system as a whole. Particularly, it is important to fully comprehend the subsystem responsible for the execution of tasks by the manipulator. To achieve such understanding, a detailed schematic of the internal components of the machine was developed/derived. The main components of the machine's architecture is shown in Figure 2, alongside with the proposed modifications. In this figure, orange and white boxes account for the original system, whereas the boxes in blue represent components of the new system, which are introduced by this paper.

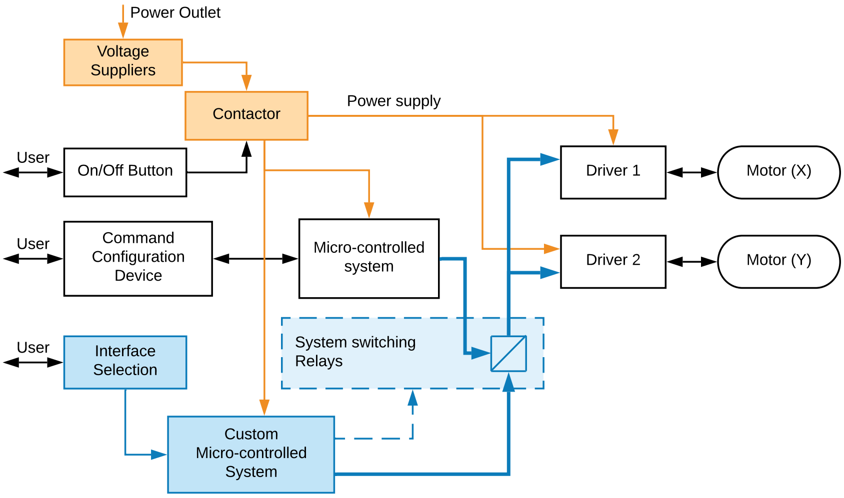

Figure 2: Diagram of the machine's main components and the retrofitting strategy.

The retrofitting strategy presented in Figure 2 is justified by two main project requirements, namely: (i) the new Control System and Human-Machine Interface (HMI) should be capable to operate independently (as a standalone system); and (ii) the original Control and HMI should be kept operational. With such a strategy in mind, we decided that the new system would be attached in parallel to the existing one. This allows the machine operator to decide which task programming system he/she wants to use. To accomplish that, a relay based switch was added between the controller and the motor drivers (see Figure 2). This strategy adds the possibility to switch between systems both by hardware and software, with the later design implemented in our application.

2.2 Micro-controlled command system

Given that the original command system is closed, that is, we cannot reverse engineer or effectively modify it (at least not straightforwardly), it was necessary to develop a new controller. The controller should be capable of interpreting commands from the HMI and translating them into movements of the motors. For that, a micro-controlled system was developed, following the application requirements commonly found in the equipment's operating site, the Welding Technology Laboratory (Laboratório de Tecnologia da Soldagem - LTS)[1]. The new controller is capable of receiving and sending messages via WiFi connection using a message system that is described later on this paper. The Espressif's ESP32 Devkit[2] (hereafter referred to as ESP32) was used to implement this functionality. This micro-controlled launchpad enables quick prototyping alongside integrated WiFi and Bluetooth communication. To ensure a robust execution of tasks, a second micro-controlled launchpad was added, namely the Texas Instruments EK-TM4C123GXL (Texas Instruments, 2014), henceforth simply referred to as Tiva. Given that the Tiva operates at a $3.3V$ logic input signal, a signal switching circuit was required, as the machine's drivers operate on $5V$ logic input signal.

2.3 Communication

As a result of the decision to insulate the communication and the actuation systems into two different micro-controllers, following a modular design approach, it was necessary to implement a communication protocol that could build a bridge between these independent devices. In Figure 3 we provide an example of the communication scheme adopted in order to implement message exchanges between the desktop application (HMI) and both micro-controllers. Two major categories of messages were implemented: (i) one-way messages, that communicate movement commands or a change in movement settings to the control system; and (ii) request-response messages, in that requests are made by the application (HMI) and answered by Tiva with positioning and status information. Note that in both cases communication between HMI (desktop application) and Tiva (control system) goes through the ESP32.

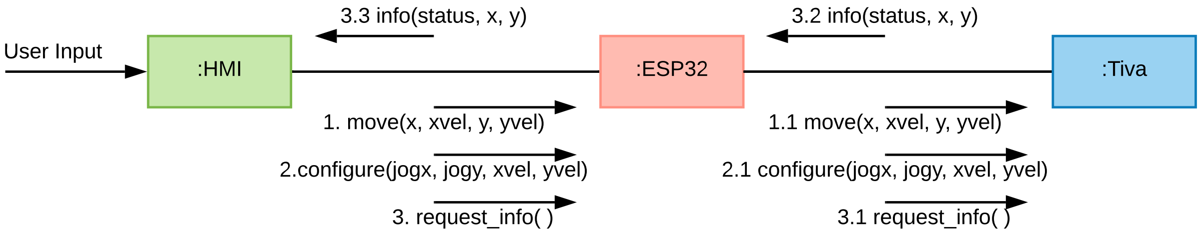

Figure 3: Simplified communication diagram.

Two communication links were established, one between the desktop application (HMI) and the ESP32 and another between the ESP32 and the Tiva. The first communication channel makes use of HTTP requests with URL encoded messages for each one of the available commands, while the second one uses UART serial communication based on a custom message system implemented for the application. Each message consists of two bytes that identify the command followed by the necessary payload, which may carry useful data as number of steps to be performed or the moving speed. The low payload associated with each message combined with the high baud rate and error detection provided by Tiva's UART peripheral results in a reliable communication between the two micro-controllers.

The adoption of Tiva's UART communication peripheral allows for the incorporation of an important feature to the task execution system: parallelism between the execution of tasks and the reception of new commands. The motor stepping and the determination of its appropriated speed are achieved by timer interruptions that vary accordingly to the speed specified by each given command received from the HMI. This happens in parallel to the reading of new messages from UART peripheral. With the high priority assigned to the timers and new messages being stored in the UART buffer, stepping occurs as close as possible to the expected rate without any loss of information. The precise position of the manipulator can be easily maintained by simply counting the number of interruptions raised during movement, given that for each step, stepper motors turn a fixed and predetermined number of degrees.

2.4 Desktop Application

In addition to the development of the new control system, a new and convenient Human-Machine Interface (HMI) was developed. This was accomplished with the design and implementation of a GUI (Graphical User Interface), alongside a

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[1] `https://lts.ufsc.br/`

[2] `https://www.espressif.com/en/products/devkits/esp32-devkitc/overview`

core application to support its functionalities. Development was carried out with the QT Framework (The QT Company, 2014) and the C++ programming language (ISO, 2014). The core application makes use of the communication protocol (briefly described in the previous section) to communicate between the HMI and the ESP32. Based on the user's requirements, several functionalities were implemented, resulting in the HMI shown in Figure 4 (in Portuguese). The HMI shows the current status of the machine, alongside the manipulator's current position. In brief, users can: connect/disconnect the HMI (switching between command interfaces); halt the machine (emergency stop); specify movements of the manipulator per each axis; jog the manipulator (step movements), and specify movement velocity.

Status: Ocioso
X: 85
Y: 70
Eixo X: 0mm
Eixo Y: 0mm
Mover para: 0 0
Velocidade: 100cm/min

Passos/mm eixo X: 48
Passos/mm eixo Y: 83
Vel. padrão eixo X: 100cm/min
Vel. padrão eixo Y: 100cm/min
mm / Jogging: 10
Periodo INFO: 5,0s
☑ Atualizar Status
X: 85
Y: 70

(a) (b)

Figure 4: Desktop application Graphical User Interface (GUI).

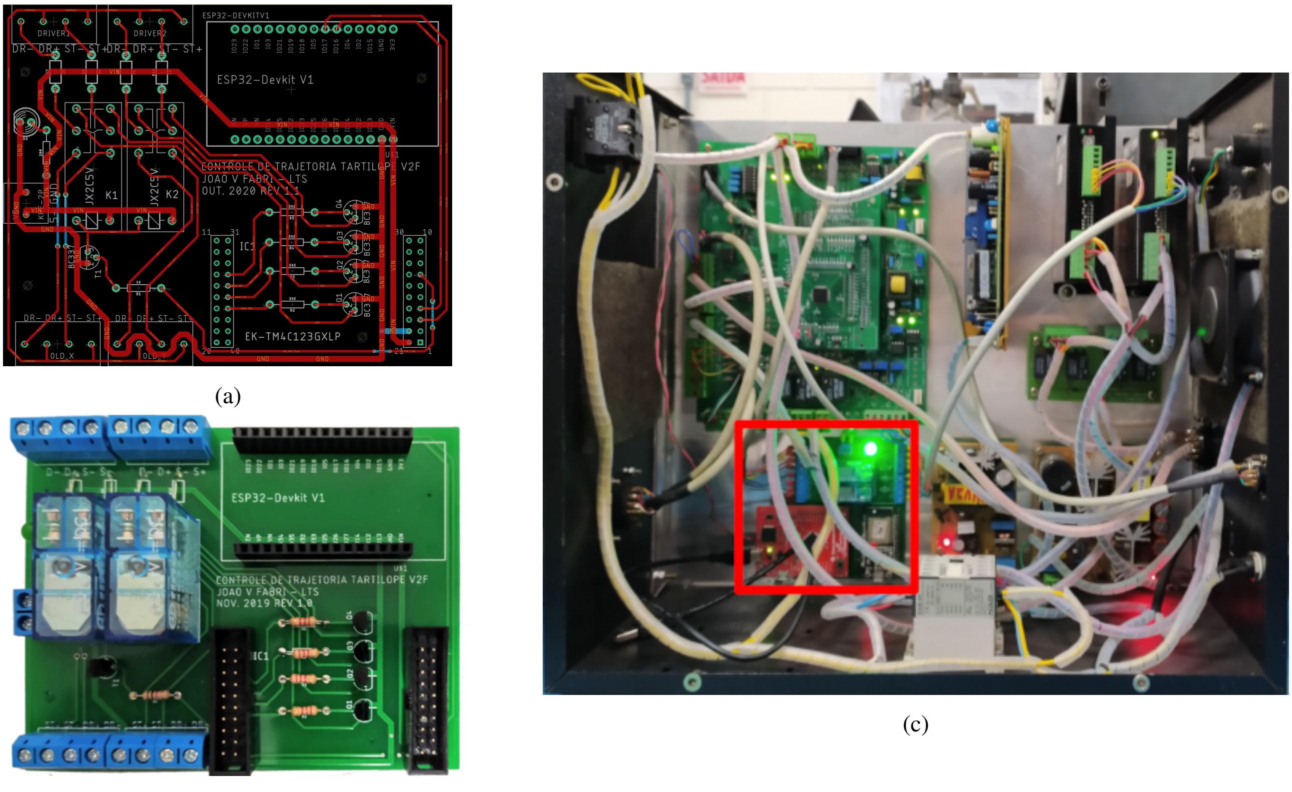
Figure 4(a) presents the first page of the application, which encompasses all major functionalities related to movement. The user is capable of sending relative move commands for each axis, sending small steps (named as jogging) or a linear movement to a given position. While the machine is working, the position and status of the machine is updated on constant intervals. A emergency stop can be made using a button. Figure 4(b) shows the settings page of the application, consisting of a set of variables that determine unit conversions between the values typed on the application and the actual commands given to the machine. Saving the setup variables sends a configuration command to the machine and prompts the user to save all settings to local storage, alongside current position. Updating the origin to the current position of the manipulator is also available through this menu, alongside a visual feedback of the current position.

3. RESULTS

To actually implement the hardware modifications and allow for the evaluation of the project's results, a Printed Circuit Board (PCB) was produced. Figure 5 illustrates both the footprint design and the resulting device (without both launchpads, i.e., microcontrollers, attached) in (a) and (b). The two microcontrollers (ESP32 and Tiva) were later attached to the PCB. These were allocated inside the Tartílope's manipulator and connected properly to its original hardware (c). The motor driver's signals were detached and reallocated to the board's designated headers, enabling the device to be tested.

The first tests to be held were the continuity test of the PCB and all it's components, which indicated that: (i) no production failures have occurred, and (ii) there were no failures on the board or on the soldering of the components. The second test was regarding the switching between the output signals and the effective actuation of the motor drivers after a signal was sent from the new system GUI. The test was executed first by reading the output signal using laboratory tools, like an oscilloscope. After observing the desired ranges of voltage were met (between $4,7V$ and $5V$) the system was attached to the machine and tested. No problems were observed, indicating that the board design was correct. Moreover this indicated that the hardware was fully functional and ready for use with the corresponding software.

The remaining tests were held in order to calibrate the new system's operation constants. Using the newly developed desktop application to send each command, we applied the same configurations observed in the original system to configure the number of steps required in each motor to achieve a predetermined displacement, that is, 48 and 83 steps/mm for



(a)

(b)

(c)

Figure 5: Proposed hardware employed in the retrofitting. The PCB footprint is shown in (a), with the actual PCB shown in (b). After coupling the ESP32 and Tiva, the PCB was installed and connected to the Tartílope's hardware (c).

the X and Y axis, respectively. After that, we performed twelve movements of 10, 20, 50 and 100mm for each axis, with a fixed speed of 60cm/min. Each movement was recorded by attaching a pen to the manipulator and using it to draw a line in a paper sheet. After each movement, the resulting line was measured using a pachymeter. The results from such an evaluation are presented on Table 1. As can be seen, the positioning error for both axes is between 0.1 and 0.4mm. Such results are considered consistent since a positioning accuracy of less than 1.0mm has been defined as a requirement.

Table 1: Profiling of Tartílope's new control system (in mm).

Expected Values	Measured Values			
	X Axis		Y Axis	
	Mean	Std. Deviation	Mean	Std. Deviation
10mm	9.467	0.330	9.995	0.174
20mm	18.078	0.167	19.973	0.147
50mm	47.109	0.339	50.859	0.460
100mm	96.450	0.226	102.700	0.293

4. CONCLUSIONS

In this work we retrofitted a commercially available welding torch displacement system using a micro-controlled approach, with the intention of improving it's user experience while also creating a platform for future improvements. In order to achieve our goals, an alternative command system was designed and developed, making use of two easy-to-use micro-controller launchpads, ESP32 Devkit and EK-TM4C123GXL (Tiva), maintaining a modular architecture during all project development. The first launchpad is responsible for maintaining communications, whereas the second launchpad is responsible for system movement control. As designed and implemented, each one of the modules can be updated or replaced independently, without the need of major system modifications and/or redesigns.

The communication module (ESP32) uses WiFi communication for receiving command requests and responding with process information. This particular module can also be adapted to handle Bluetooth connections, if needed. Given that we also provided a new Graphical User Interface (GUI) to the user, that is, a desktop application, the machine can now be controlled remotely, through a simple and intuitive graphical interface.

In future works we plan to add new features to the user interface, allowing for the creation and specification of weaving patterns. Moreover, we consider to incorporate Internet of Things (IoT) capabilities to the manipulator, possibly with a dedicated mobile application, allowing for easier supervision and control of the machine.

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