Robustness Increase of a Ceramics Finishing Prototype: Towards Meeting Industry Requisites

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Abstract. This paper presents the development of a polishing prototype with a rotating sponge to be applied in the automation of a finishing process for the ceramic industry, focusing on increasing mechanical robustness. The prototype includes an AC motor, encoder, microcontroller, motor drive, and a collaborative robot to assist in the tests. Validation experiments related to the speed and force control were performed followed by the trajectory control tests using pieces printed using 3D printing technology to simulate the ceramic pieces. The results were satisfactory and showed a good performance of the polishing prototype, being this a good teaching aid tool to assist in the teaching and practical classes of mechatronics.

Keywords: Ceramic industry · Automation · Prototype · Mechatronics education

1 Introduction

The automation applied in the ceramics industry, as well as in other industrial areas, has been an ally in reducing production time and costs, also allowing an increase in precision, quality, safety, and robustness in the production process of complex ceramic products [1–4]. In recent years, the advances adopted by industries towards digitization in the manufacturing process include the integration of technologies such as virtual and augmented reality [5], machine vision in combination with force control [6,7], robotic manipulators [8,9], and others.

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One of the final processes of the ceramic industry consists of deburring, in which the excess material kept in the edges of the ceramic piece after the casting process, is removed to clean the object, making the edge softer. However, if this process is performed by human operators, errors and imperfections can be introduced in the ceramic pieces, especially in irregular and complex forms [10]. For this reason, industries are replacing human labor with automatic robotic solutions to perform those kinds of processes [11,12].

An automatic polishing process is a complex task because it requires high performance with stabilization and force control, to measure the amount of pressure exerted on the product, avoiding the introduction of imperfections if some disturbance occurs. The process needs to be efficient for different shapes and irregularities that the ceramics pieces could have [13,14].

In an industrial environment, the conditions are harsher compared to a laboratory environment, where there may be higher levels of corrosive components, higher levels of vibration, and higher temperatures [15,16]. For this reason, the aim of the presented work is to increase both the physical and the behavioral robustness of the system, of prototype, presented in previous works [17].

AC motors are widely used in the industry for general-purpose applications where constant speed is sought [18], and to control the motor, frequency inverters are also used [19]. The implementation of programmable logic controllers (PLC) is essential for Industry 4.0, especially low-cost PLCs, based on Raspberry Pi and Arduino, which have proven to be very successful [20–22].

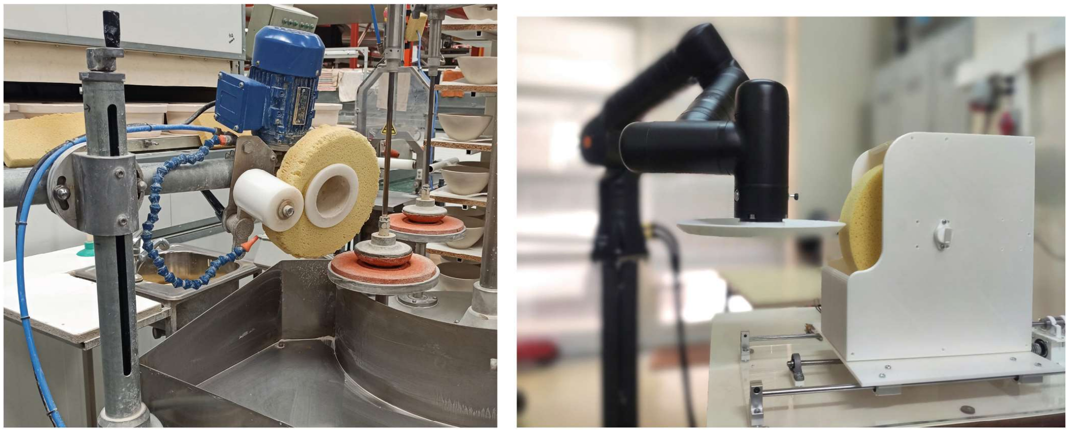
It has been verified in the literature that the creation of prototypes in laboratory environments and active learning has great advantages when it comes to student learning [23,24]. Implementing this prototype not only allows to apply the theoretical knowledge learned but also to experiment with different configurations.

This paper is structured as follows. Section 2 describes the STC 4.0 HP project in which this prototype was developed. Section 3 presents all the materials and methods included in the prototype and Sect. 4 is intended to present the validation experiments focused on speed, force, and trajectory control. Lastly, the conclusion and future work are presented.

2 STC 4.0 HP Project

The STC 4.0 HP project (New Generation of Stoneware Tableware in Ceramic 4.0 by High-Pressure Casting Robot work cell) emerged in partnership with the GRESTEL industry located in Portugal. This project aims to develop an automatic deburring process to support GRESTEL in the manufacturing of innovative products.

The finishing process of the ceramic piece in GRESTEL is performed by a wet rotating sponge, in which the ceramic products are pressed to remove the excess material on the edge, as presented in Fig. 1a. This process was only suitable for regular circular ceramics pieces, therefore this project has the purpose to develop a solution for any kind of shape.



(a) (b)

Fig. 1. a) The polishing system implemented in the GRESTEL industry. b) Automatization for a polishing process developed by STC 4.0 HP project

This project includes a partnership between the industrial company GRESTEL and several universities, being them the Polytechnic Institute of Bragança (IPB), the Polytechnic Institute of Leiria, and the Research Group from Limerick School of Art & Design of the Limerick Institute of Technology (Ireland).

In [25] and [26], the machine that includes the sponge rotation and force control was developed and described in detail. Then, a collaborative robot was integrated into the project system, as shown in Fig. 1b. A laser system is also applied to generate all the points of the ceramic edge trajectory to send this data to the robot, this work is better explained in [27]. After that, some improvements related to the robustness for the industrial environment were performed and presented in the next sections of this paper.

3 Industrial Adaptation

In previous work, a laboratory prototype was designed using a DC motor as an actuator to rotate a sponge, together with a current sensor which was applied to measure the current consumed by the motor and thus obtain an estimate of the force applied to the ceramic piece [25].

In an industrial environment it is necessary to have higher robustness both in the actuators and drivers, as well as in the mechanical structure, which was why it is sought to replace the DC motor with an AC motor, for its control it is necessary to use a variable-frequency drive (VFD). With this controller, it is possible to control the speed of rotation, and it is also possible to obtain the value of the torque carried out by the motor.

3.1 AC Motor

The motor chosen to upgrade the project was a SIEMENS three-phase electric motor with a power of 0.35 kW and a nominal speed of 1445 rpm. This motor is ideal for standard applications such as pumps, fans, or conveyor belts.

For this application, the motor is the actuator applied to rotate a sponge, which will be in charge of removing excess material from ceramic pieces. The sponge rotates at a speed of 15 rad/s, this speed is kept constant using a closed loop controlled by a Proportional-Integral (PI) controller. To obtain a reading of the speed of rotation of the sponge, an OMRON E6A2-CW5C incremental rotational encoder was applied [28].

3.2 Encoder

The applied encoder has a resolution of 100 P/R, that is, 0.062 rad per transition of the encoder, and two channels in quadrature, which allow not only to know the angle of rotation but also the direction. To read the pulses coming from the encoder, a state machine with 4 states was implemented, which detects each time the encoder signals change its state. In this way, the angular displacement is obtained, and through a first-order integration, the angular speed of rotation can be calculated.

3.3 Microcontroller

The data acquisition is carried out by an Arduino-based programmable logic controller (PLC) with an industrial shield model M-duino from the company Industrial Shields [29]. This controller allows the signals acquisition coming from actuators and industrial drivers without the need to adapt the voltage levels, where a program that captures the signals received from the encoder channels is implemented, and the frequency of reading is 10 kHz. These signals are processed to obtain the current rotation speed of the sponge, which is compared with the reference value set by the operator, and utilizing a PI controller, a control signal is obtained that is sent through one of the controller's analog outputs. These signals are processed and sent with a frequency of 30 Hz. The outputs have an integrated low-pass filter that eliminates the switching frequency of the pulse width modulation (PWM), granting a constant voltage that goes from 0 to 10V. This signal is connected to the analog input 1 of ABB's ACS355 model frequency converter.

3.4 Motor Driver

The VFD allows the management of the AC motor both by V/f control and vector control. For this application, the standard ABB application macro was applied, where Analog Input one (AI1) is used as a reference value to establish the rotation speed of the motor, and Digital Inputs one and two (DI1, DI2) to determine the start/stop and direction of rotation, respectively. At the same time, some necessary parameters were defined for the correct operation of the frequency inverter. These principal parameters defined were the motor parameters, the chosen macro, and the analog output configuration. This output was configured to show the value of the torque performed by the motor, and the parameters of the output were configured so that the output range was adjusted to the necessary ones. The analog output is a current signal, that goes from 4 to 20 mA, so a 510 Ω resistor was added to have a suitable voltage so that the microcontroller can obtain the torque value information.

3.5 PC Program

After obtaining the measurements of the torque and the speed of rotation, the microcontroller sends these signals by serial communication, with a frequency of 30 Hz, these signals are read by the PC in which a program was implemented through the Lazarus software, an open-source development tool, which uses a Free Pascal compiler and Pascal programming language. The PC is in charge of receiving the data from the microcontroller and also of controlling the collaborative robot. This program also receives the files that the data acquisition system sent for each ceramic piece, here came the value of the center point, and all the perimeter points [27].

3.6 Collaborative Robot

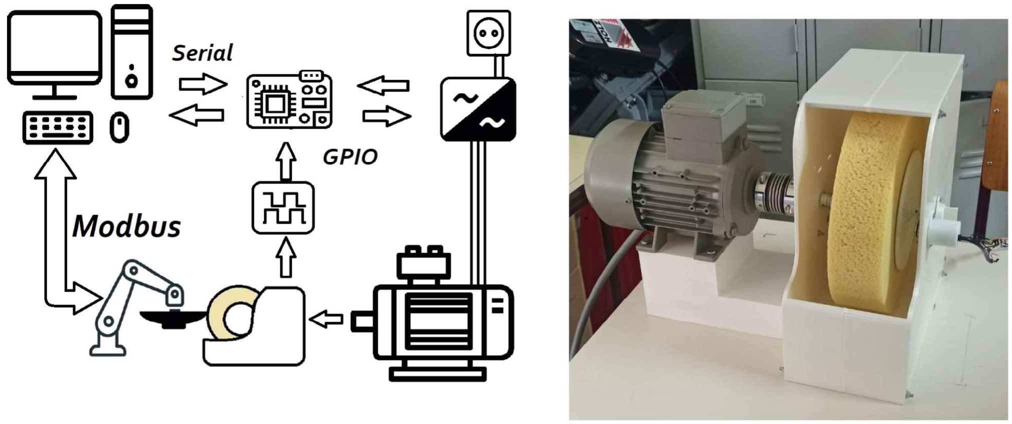
The collaborative robot used is a KR810 model from the Kassow Robots' brand [30]. It is a robot with 7 degrees of freedom, with a payload of 10 kg. The communication between the robot and the PC was carried out by means of Modbus TCP through an Ethernet connection. In the end effector, the different pieces were attached to perform some tests. To test the prototype, a plate was 3D printed with PLA material, with a circular shape and a radius of 125 mm.

Figure 2a shows a diagram with the interconnections between the different devices and their communications. The AC motor is controlled by the inverter which is connected to a single-phase outlet. The microcontroller sends the control signal to the inverter and receives from it the torque signal that the motor performs. At the same time, it reads the signals from the encoder to calculate the speed. At a frequency of 30 Hz, these data are processed and sent to the PC through the serial port. The PC contains the main program that is in charge of processing all the signals and calculating the trajectory that the robot must follow with the ceramic piece. The PC communicates with the robot through a Modbus protocol.

In Fig. 2b the implementation of the new devices is shown.

4 Validation Experiments

This section describes the validation experiments made and the obtained results after improving the mechanical robustness and its performance. The tests consisted of verifying the correct reading of the speed of rotation of the sponge, verifying that the power of the motor is sufficient to carry out the finishing, and analyzing if the levels of the output signal of the inverter are adequate for a correct reading of the torque. After these analyses, the trajectory generation tests began, testing with different geometries, as well as a comparison between the finishing with and without force control.



(a) (b)

Fig. 2. a) Prototype devices interconnected and their communications. b) Implementation of the new devices

4.1 Speed Control

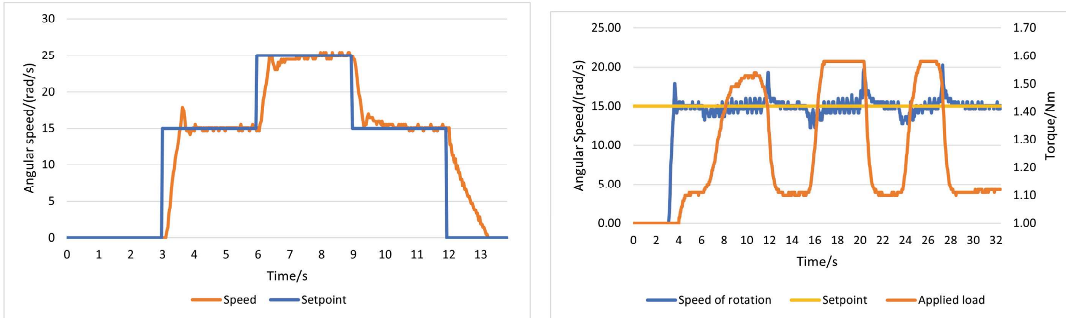
Once the encoder was installed in the prototype, an interface was created to test different speeds, Fig. 3a can be seen as a graph with the system response to speed changes. First, a signal was sent for the speed to be 15 rad/s, after a few seconds it went to 25 rad/s, then returned to 15 rad/s, and finally stopped. It can be seen that the speed reaches the reference value, and it remains constant.

Then another test was carried out to calibrate the closed-loop control of the speed. The motor was set to a constant speed of 15 rad/s, and then a load was applied to it by pressing the test plate against the sponge several times. This was done to check the stability of the speed in the face of load disturbances.

The graph of Fig. 3b shows the results of the experiment. It can be observed that for a large load variation, the speed returns to the reference quickly.

With these tests, it was also possible to verify that the power of the motor is sufficient to maintain the necessary speed while facing load variations produced by the finishing process.

The torque measurements are obtained from the VFD, which gives a current signal through the Analog Output 1 (AO1), ranging from 4 to 20 mA. This signal is proportional to the force that the motor is exerting at that instant, with 100% being the nominal torque of the motor. To have a higher resolution in the torque reading, the output range was limited between 50% and 65%, in this way the measurements in the working range of the system were obtained. Since the motor has a nominal torque of 2 Nm, the range is between 1 and 1.6 Nm.



(a) (b)

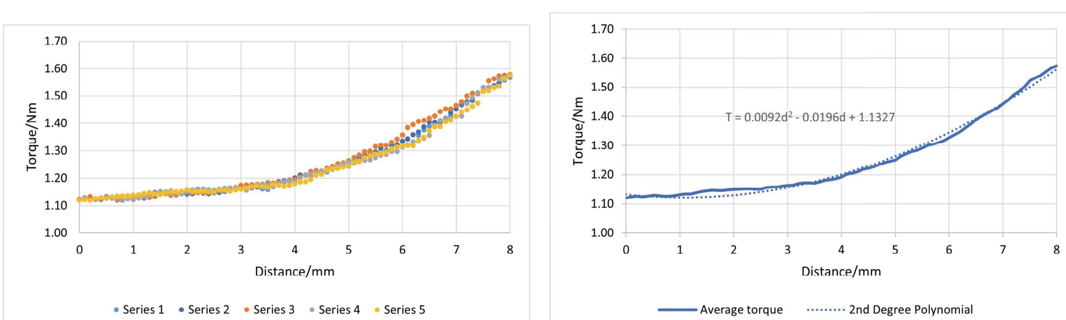
Fig. 3. a) Test of different speeds as a function of time. b) Stability of the speed while facing load disturbances.

4.2 Force Control

To have a high degree of repeatability, it is necessary to have control of the force applied to the ceramic piece, in order to cope with the changes produced by differences in production or differences in the positioning of the piece. That is why, the torque measurement, is used to correlate with the force applied to the ceramic piece, but to perform a correct control it is necessary to do a calibration. For this, a series of measurements was carried out where the torque made by the motor was measured as the circular plate was pressed mm by mm. With these measurements, a function of torque vs. distance was obtained.

Figure 4a shows data capture from a series of 5 iterations where the test plate was pushed against the sponge, starting from 0 mm until reached 8 mm, and then returned to the start point.

Then an average of the 5 samples was made (Fig. 4b), and an equation was obtained through a second-degree polynomial approximation.



(a) (b)

Fig. 4. a) Calibration test. b) Average torque in function of the distance.

The formula of torque as a function of distance for the circular plate is defined by (1),

$$T = 0.0092d^2 - 0.0196d + 1.1327 \quad (1)$$

where the variable T is the torque made by the sponge and the independent variable d is the distance traveled by the ceramic piece.

However, in order to control the applied force, it is necessary to clear the distance variable and use the torque as the new independent variable, which is shown in the Eq. (2).

$$d = 10.43(\sqrt{T - 1.122}) + 1.065 \quad (2)$$

Once this equation is obtained, it is applied in the main program to make a correction of the piece's position to maintain the pressure in the determined range.

4.3 Trajectory Control

After performing the necessary calibrations, a series of tests were carried out using the printed test piece.

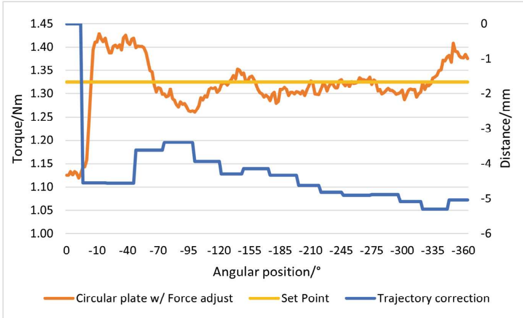
The first test was used as a pattern, where the circular plate was placed in the end effector, and the program was run without the adjustment of the position made by the force control.

Once the control tests were carried out, the force control was activated in the program, whereas the finishing process is carried out, the controller sends the torque data generated by the motor, to be processed and adjusts the position if necessary. For these tests, the desired torque value was changed to a value of 1.32 Nm. In Fig. 5a it can be seen the reading of torque when applying the force control to the process. In this case, the control of the trajectory continues to be correct and the pressure exerted is close to the pre-established one.

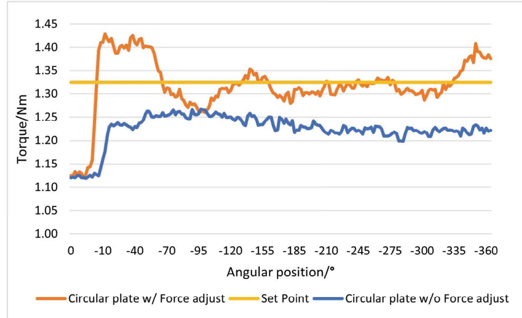
The value of the correction made to the trajectory is also shown in blue. Initially, a first adjustment is made and then it is adjusted to maintain the pressure close to the preset value.

In Fig. 5b a comparison is shown between the finishing process having the force control vs the process without the control. The improvement can be seen when the control is activated, exerting pressure similar to the desired one.

These were the analyses carried out for the proposed tests, with them it was possible to obtain the necessary data to be able to have a discussion and draw conclusions.



(a)



(b)

Fig. 5. a) Test with the circular plate and with force control. b) Comparison between the circular plate with force control and without.

5 Conclusion

To have good results in an industrial environment, it is necessary to be able to withstand harsh environmental conditions, such as high vibrations, high temperatures, and a large number of particles in the air, which is why an adaptation of the devices used in stages was carried out. In order to make them suitable for the industry, among these devices, the motor that rotated the sponge was replaced along with its controller, as well as the previously used microcontroller.

The control of the force in the finishing processes is a very important factor, especially when working with fragile materials such as stoneware. Another important factor when it comes to having great variability in production is the ability to obtain the exerted force applied to the ceramic piece. The devices applied in this work met the requirements for the finishing process. Achieving greater turning power along with a more accurate and stable reading of the exerted pressure by the sponge. The compatibility of these devices for an industrial environment like the one found in GRESTEL was possible. In addition to meeting the requirements proposed for this work, the laboratory prototype serves as a tool to help with the learning of theoretical-practical concepts in subjects such as control, electrical machines, and mechatronics.

To continue with the adaptation of the prototype towards the industry requisites, it is also proposed to change the material of the structure that supports the sponge to a more resistant material such as aluminum or metal sheet, it is also necessary to make this change since to carry out the finishing it is necessary to moisten the sponge, so the material must be waterproof.

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