



# ING. MECATRÓNICA

**Thesis submitted prior to obtaining the degree of  
Mechatronics Engineer.**

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Sistema de control automatizado para la regulación dinámica de una máquina de bruñido horizontal.

Automated Control System for the Dynamic Regulation of a Horizontal Honing Machine

Quito-2026

### Aprobación del Tutor del Trabajo de Integración Curricular

Yo Veronica Patricia Grefa Aguinda, en calidad de tutor del Trabajo de Integración Curricular denominado: *Sistema de control automatizado para la regulación dinámica de una máquina de bruñido horizontal.*, realizado por César Nicolás Mejía Flores, ha sido orientado y revisado en todas sus partes y considero que cumple los requisitos establecidos por la institución. En virtud de ello doy mi aprobación a fin de continuar con el proceso académico correspondiente.



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A handwritten signature in black ink, consisting of several overlapping loops and strokes, representing the author's name.

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### **Dedicatoria**

Quiero dedicar este proyecto de titulación a mi padre, César Mejía, por ser mi apoyo, mi amigo, y la persona que me apoya con las locuras que conlleva el estudiar una carrera tan innovadora, por incentivarme el amor a la mecánica e inculcarme la importancia del estudio y ser constante con lo que es importante en la vida. A mi madre, Jimena Flores, por ser un gran apoyo, por estar para mí en los momentos difíciles de la carrera, por ser la persona que siempre me ha impulsado y no ha dejado que me rinda o me desvíe del camino, por siempre buscar lo mejor para mí y apoyarme en lo que necesite. A mi pareja, Camila Bayas, por ser la persona que me ha motivado a querer más en la vida, por ser la razón de querer resaltar y no quedarme en la mediocridad, por apoyarme en más de un sentido durante la carrera y ser mi compañera a lo largo de este camino. Quiero dedicar este proyecto de titulación a mi familia, que ha estado presente y han sido de apoyo cuando los necesitaba.

### **Agradecimiento**

Quiero agradecer a mis padres por haberme dado el estudio y haber sido una motivación y un ejemplo a seguir, a mi pareja por ser mi apoyo. Al Ing. Patricio Quishpe por su ayuda y capacitación a lo largo de la carrera, por su asesoría y buena predisposición cuando necesitaba su ayuda en temas de la carrera. Al Ing. Renato Noriega por su asesoría y recepción durante mis practicas preprofesionales, por ser un gran referente y consultor durante el proceso y desarrollo de este proyecto de titulación. A mis compañeros de curso, con los que he compartido cuatro años y medio de mi vida y con los que he vivido cosas muy lindas e interesantes en este tiempo. A mis profesores que han puesto sus conocimientos y han sabido compartirlos para hacer de mi la persona capaz de realizar este proyecto de titulación, al Decano de la facultad Marcelo Moya y al Director de la carrera Guillermo Mosquera por ser una motivación y referentes, por compartir su experiencia y brindarnos experiencias reales y prepararnos para afrontar la vida laboral.

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## Resumen

Este trabajo presenta el desarrollo de un sistema de control automatizado para una bruñidora horizontal existente, orientado a mejorar la repetibilidad, continuidad y supervisión del proceso de bruñido de camisas y cilindros hidráulicos. La propuesta se concentró en la capa de automatización mediante PLC, HMI, servodrivs, sensores de posición, apertura neumática de la herramienta y monitoreo de torque del eje de rotación, considerando la estructura mecánica de la máquina como una condición de integración. La metodología se organizó con base en el modelo en V y se desarrolló mediante dos prototipos. El prototipo 1 permitió comprobar la comunicación, el control de movimiento y el conteo de ciclos, pero evidenció problemas de seteo, apertura y operación. A partir de estos resultados se implementó el prototipo 2, incorporando aprendizaje de torque, apertura por pulsos, revisión intermedia, continuación sin reinicio y control manual mediante joystick. La validación funcional en camisas de aproximadamente 100, 108 y 152 mm mostró mejoras en continuidad de trabajo, tiempo operativo y acabado visual.

*Keywords:* automatización industrial, bruñido horizontal, retrofit

## **Abstract**

This work presents the development of an automated control system for an existing horizontal honing machine, aimed at improving the repeatability, continuity, and supervision of the honing process for sleeves and hydraulic cylinders. The proposal focused on the automation layer through a PLC, HMI, servo drives, position sensors, pneumatic tool expansion, and torque monitoring of the rotation axis, while considering the mechanical structure of the machine as an integration condition. The methodology was organized according to the V-model and was developed through two prototypes. Prototype 1 verified communication, motion control, and cycle counting, but revealed limitations related to tool setting, expansion, and operation. Based on these findings, prototype 2 incorporated torque learning, pulse-based tool expansion, intermediate inspection, continuation without restarting, and manual control using a joystick. Functional validation on sleeves of approximately 100, 108, and 152 mm showed improvements in process continuity, operating time, and visual surface finish.

*Keywords:* industrial automation, horizontal honing, retrofit

**TABLE 1**  
Relationship between ABET criteria, Bloom's taxonomy, and project evidence.

| ABET Criterion                                                                                                                                 | Bloom's taxonomy level        | Evidence within the project (section)                                                                                                                                                                                                                                                                                                       |
|------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. Ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.     | Analyze, apply, and evaluate. | Demonstrated in the sections <i>Prototype 1: specific design of the control system, Electrical system, inputs, outputs, and communication</i> , and <i>Prototype 2: evaluation of implemented functions</i> , where speed calculations, servomotor control, PLC–HMI–servo driver communication, and torque-based supervision are developed. |
| 2. Ability to apply engineering design and produce solutions that meet specific needs while considering safety, welfare, and economic factors. | Create, apply, and evaluate.  | Demonstrated in the sections <i>Conceptual design and prototype definition, Analysis of alternatives, Prototype 1: physical integration</i> , and <i>Prototype 2: functional implementation</i> , where the <i>retrofit</i> solution, safety logic, assisted operation, and process protection are defined and implemented.                 |

Continues on the next page

| ABET Criterion                                                                                                                                       | Bloom's taxonomy level | Evidence within the project (section)                                                                                                                                                                                                                                                                                                                                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 3. Ability to communicate effectively with different audiences.                                                                                      | Apply and analyze.     | Demonstrated in the sections <i>Prototype 1: system architectures</i> , <i>Prototype 1: HMI interface design</i> , and <i>Comparison between prototype 1 and prototype 2</i> , where the document presents architectures, requirement tables, operating diagrams, HMI screens, programming structure, and validation results.                                          |
| 4. Ability to recognize ethical and professional responsibilities in engineering and make decisions considering the impact of engineering solutions. | Apply and evaluate.    | Demonstrated in the sections <i>Initial condition of the machine and requirements</i> , <i>Electrical system, inputs, outputs, and communication</i> , and <i>Prototype 2: evaluation of implemented functions</i> , where operator safety, preservation of the existing machine, reduction of repetitive manual intervention, and continuity of work are prioritized. |

Continues on the next page

| ABET Criterion                                                                                                                               | Bloom's taxonomy level        | Evidence within the project (section)                                                                                                                                                                                                                                                                                                                                                                                       |
|----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 5. Ability to function effectively on a team, establish goals, plan tasks, and meet objectives.                                              | Apply, analyze, and evaluate. | Demonstrated in the sections <i>Analysis of alternatives</i> , <i>Prototype 1: physical integration</i> , and <i>General evolution: prototype 0, prototype 1, and prototype 2</i> , where workshop requirements, component availability, integration constraints, and feedback from prototype testing are considered.                                                                                                       |
| 6. Ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions. | Apply, analyze, and evaluate. | Demonstrated in the sections <i>Preparation for property verification</i> , <i>Applied experimental criterion</i> , <i>Prototype 1: functional results and detected problems</i> , and <i>Prototype 2: validation with real liners</i> , where functional tests are planned, prototype 1 failures are analyzed, and prototype 2 is validated through real workpieces, operating times, cycle continuity, and visual finish. |

Continues on the next page

| ABET Criterion                                                                                  | Bloom's taxonomy level | Evidence within the project (section)                                                                                                                                                                                                                                                                                                                                                                                                       |
|-------------------------------------------------------------------------------------------------|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 7. Ability to acquire and apply new knowledge as needed, using appropriate learning strategies. | Apply and analyze.     | Demonstrated in the sections <i>Prototype 1: specific design of the control system</i> , <i>Prototype 1: modular PLC programming</i> , <i>Prototype 2: correction of the rotation speed</i> , and <i>Prototype 2: functional implementation</i> , where knowledge of honing, industrial automation, PLC programming, communication with servo drivers, HMI design, torque-based control, and adjustment of operating parameters is applied. |

## Chapter I

### Introduction

Honing is a high-precision finishing process applied mainly to internal cylindrical surfaces, where diameter geometry, roughness, and tribological condition directly influence the component's operation [2, 3]. In this context, the process is not limited to material removal, but rather seeks to correct bore irregularities and produce a functional surface for contact, lubrication, and wear conditions, especially in engine liners, hydraulic cylinders, and elements operating with internal relative motion [4, 5].

An important characteristic of honing is the formation of the crossed pattern or *cross-hatch*, which appears due to the combination of tool rotation and the alternating axial movement of the abrasive stone [6, 7]. This pattern has a practical function because it contributes to lubricant retention and contact stability between surfaces, so the selection of axial speed, rotational speed, and contact pressure cannot be treated as an independent decision within the process [8, 9].

The reviewed literature shows that a large part of honing studies focuses on engine liners, surface textures [3, 7, 10]. However, the same technical principle is applicable to the reconditioning of hydraulic cylinders, where internal scratches, localized wear, or a non-uniform surface can compromise the subsequent performance of the cylinder and require a controlled finishing process before returning the part to service [11].

In the industrial field, modern commercial horizontal honing machines incorporate control functions through PLCs, touch screens, load measurement, *dwell* functions, localized machining through *short-stroking*, and regulation of tool expansion [12]. These characteristics show that the trend of the process is not to depend solely on the operator's manual skill, but to integrate drives, monitoring, and control in order to improve work-cycle repeatability [13].

Even so, the purchase of a new machine is not always a viable solution for workshops or companies that already have a functional mechanical structure. In these cases, *retrofitting* makes it possible to preserve the machine base and incorporate sensors, actuators, controllers, and supervision layers to increase control capability without replacing the entire equipment [14]. This vision is also related to the digitalization of machine tools, where the objective is to take advantage of existing equipment through the integration of communication, data acquisition,

and industrial control [15].

The case of Carmet Ingeniería Aplicada falls within this need. The company works in hydraulic cylinder repair and surface finishing processes, and it has an existing horizontal honing machine whose mechanical structure can still be used; however, the regulation of tool expansion and part of the intervention in the cycle still depend on the operator's manual judgment. For this reason, the technical problem is not focused on designing a honing machine from scratch, but on implementing an automated control system on an existing machine, respecting the mechanical conditions provided by the company and concentrating the scope of the thesis on automation, control, the operating interface, and the functional validation of the process.

The motor electrical signal is a useful alternative for obtaining indirect information about the process, since in different machining operations the current or power of the drive has been used to infer load, tool wear, or changes in cutting conditions [16–18]. Although these works do not correspond directly to the honing of hydraulic cylinders, they do justify the use of drive signals as a low-invasive monitoring basis, especially when the objective is to modernize an existing machine without installing complex sensors inside the working area [19].

Based on the above, the present work proposes the development of an automated system for an existing horizontal honing machine, using a PLC, HMI, servo drives, position sensors, and assisted pneumatic expansion to regulate the operation of the tool during the process. The contribution of the thesis is centered on the control architecture, PLC modular programming, the HMI interface, speed calculation, torque monitoring, and the functional verification of the prototype; therefore, the mechanical adaptations related to support, transmission, assembly, and geometry are considered integration conditions provided or defined by the company, rather than the main design contribution of the work.

The general objective of this project is:

- To design and implement an automated control system for the dynamic regulation of an existing horizontal honing machine at Carmet Ingeniería Aplicada.

The specific objectives to achieve this goal are:

- To regulate the expansion of the tool based on motor signals.
- To execute honing cycles with greater repeatability.
- To evaluate the improvement achieved in operating time, process continuity, and visual finish of real liners.

## Chapter II

### Methodology and design

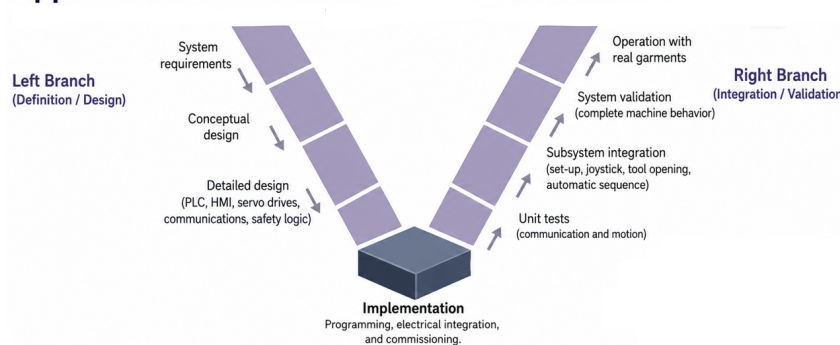
The project was developed as a *retrofit* automation, because the objective was not to build a new horizontal honing machine, but to incorporate a control, supervision, and communication layer onto an existing machine. This approach made it possible to reuse the available mechanical structure and to focus the contribution of the thesis on PLC programming, the HMI interface, communication with servo drivers, process variable acquisition, safety logic, and the functional integration of prototype 1, which is consistent with the modernization of legacy machines through new control and connectivity capabilities.

The methodology was organized based on the V-model proposed in VDI 2206 [1], in order to relate the initial requirements to the conceptual design, the analysis of alternatives, the specific design, the implementation of prototype 1, and the preparation of the functional verifications.

#### Application of the V-model

The V-model was used as a work guide to prevent the automation from being solved only through trial and error, since VDI 2206 presents it as a macro-cycle for the development of mechatronic systems. On the left side, the requirements, conceptual design, analysis of alternatives, and architectures were placed; at the vertex, the implementation of prototype 1 was located through PLC programming, HMI configuration, electrical integration, communication with servo drivers, and commissioning; and on the right side, the functional verifications were defined to evaluate communication, motion, safety, tool expansion, and the automatic cycle.

#### Application of the V-Model



**Fig. 1.** Application of the V-model to the development, implementation, and integration of the automation system, adapted from VDI 2206 [1].

The application of the model was adjusted to the actual scope of the thesis, because the mechanical support design and the physical adaptation of the machine were considered conditions already developed or provided by the company to enable control integration. Therefore, the mechanical parts appearing in this chapter are described only as interfaces necessary for automation; the contribution of the document is focused on the control layer, industrial communication, and the programmed operation of the honing machine.

Validation was proposed as a progressive verification of blocks rather than as a single final test. First, communication between the HMI, PLC, and servo drivers had to be verified; then the translation and rotation motions had to be tested; afterward, setup, the automatic cycle, cycle counting, pulse-based expansion, and stops were integrated; finally, the evaluation of machine behavior with real liners was prepared.

### **Initial condition of the machine and requirements**

The starting point was a locally manufactured horizontal honing machine used for the internal finishing of cylinders, liners, and hydraulic components. The machine had a functional mechanical structure, a translation system, a rotation system, and a commercial honing tool, but its operation depended largely on the operator: positioning, feed, return, visual inspection, stone expansion adjustment, and control of working time. In honing processes, the relationship between axial speed, rotational speed, contact pressure, abrasive, and the initial condition of the workpiece directly influences the obtained finish; therefore, the automation had to maintain controlled human intervention rather than fully replace the operator's judgment.

In its initial condition, the machine was able to perform real jobs, but it presented operational limitations: low repeatability, absence of automatic cycle counting, continuous dependence on the operator, lack of integration between feed, rotation, and tool expansion, and difficulty in maintaining constant conditions during long jobs. These conditions led to the definition of an assisted solution, capable of automating repetitive actions while maintaining the possibility of inspection and adjustment whenever the condition of the liner requires it.

The functional and non-functional requirements, together with the constraints considered to reach prototype 1, are presented in Tab. 2. This table defines the scope of the chapter, because the functions associated with later improvements of prototype 2 are analyzed afterward as results derived from the first implementation.

**TABLE 2**  
Requirements and design constraints of the automated system.

| ID    | Summary             | Description                                                                                                                                                    | Type       |
|-------|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| FR-01 | Translation control | The system had to control the axial displacement of the tool carriage between two working positions defined by start and end sensors.                          | Functional |
| FR-02 | Rotation control    | The system had to control the rotation speed of the honing tool according to the entered diameter and the limit allowed by the drive.                          | Functional |
| FR-03 | Automatic reversal  | The carriage had to reverse its direction of travel upon reaching the end sensor and the start sensor during automatic mode.                                   | Functional |
| FR-04 | Cycle counting      | The system had to count complete working cycles in order to stop the process when the quantity configured by the operator was reached.                         | Functional |
| FR-05 | Work continuation   | Once the cycles were completed, the operator had to be able to inspect the part, enter additional cycles, and continue the process without restarting the PLC. | Functional |
| FR-06 | Assisted expansion  | The machine had to allow automatic pulse-based expansion during the process through a pneumatic cylinder pressing the tool handwheel.                          | Functional |
| FR-07 | Torque learning     | The system had to learn the working torque during the first normal cycle, without taking as reference the peaks generated during pneumatic expansion.          | Functional |
| FR-08 | Setup mode          | The machine had to include a setup mode to position the carriage, adjust the tool, select setup speed, and prepare the start of the cycle.                     | Functional |
| FR-09 | Physical joystick   | The operator had to be able to move the carriage with a physical joystick, both in setup and during the inspection after cycle completion.                     | Functional |

Continues on the next page

| ID     | Summary                           | Description                                                                                                                                                                 | Type           |
|--------|-----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| FR-10  | Manual <i>short stroke</i>        | During automatic operation, the operator had to be able to manually reverse the direction of the carriage with the joystick without incorrectly discounting pending cycles. | Functional     |
| FR-11  | Extraction mode                   | At the end of the process, the system had to enable an extraction mode to remove the tool with controlled manual movement.                                                  | Functional     |
| FR-12  | HMI interface                     | The HMI had to allow the entry of diameter, cycles, speed selection, visualization of states, speeds, torque, and the enabling of window navigation.                        | Functional     |
| NFR-01 | Safety                            | The machine had to respond to the emergency stop, the physical pause button, calculation faults, and unsafe conditions by stopping speeds and blocking critical states.     | Non-functional |
| NFR-02 | Ergonomics                        | The controls had to be located so that the operator could observe the workpiece and access the buttons without unnecessary exposure to the working area.                    | Non-functional |
| NFR-03 | Maintainability                   | The PLC program had to remain modular to facilitate corrections without affecting all control blocks.                                                                       | Non-functional |
| NFR-04 | Operational <i>re-peatability</i> | The machine had to execute repeatable forward and return cycles, avoiding results that depend solely on the operator's manual skill.                                        | Non-functional |
| NFR-05 | Supervision                       | The operator had to be able to observe the process status and the main variables during operation.                                                                          | Non-functional |
| DC-01  | <i>Retrofit</i>                   | The mechanical structure of the existing honing machine had to be reused, avoiding a complete redesign of the machine.                                                      | Constraint     |
| DC-02  | Budget                            | The solution had to be implemented with available or acquirable components within the economic scope of the project.                                                        | Constraint     |

Continues on the next page

| ID    | Summary            | Description                                                                                                                                                                                                                                         | Type       |
|-------|--------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| DC-03 | Surface validation | Finish evaluation was carried out visually, due to the lack of an adequate roughness meter for measuring deep internal cylinder surfaces.                                                                                                           | Constraint |
| DC-04 | Mechanical scope   | The supports, couplings, transmission, and mechanical adaptations were considered integration conditions provided by the company; the thesis documents their interface with the control, but does not present them as the main design contribution. | Constraint |

### Conceptual design and prototype definition

The selected concept was an operator-assisted automation. The machine had to execute repetitive translation and rotation motions, count cycles, and actuate tool expansion, but without eliminating operator intervention during setup, inspection, and process correction. This criterion was maintained because repair honing depends on the initial condition of each liner and on the practical assessment performed during the process.

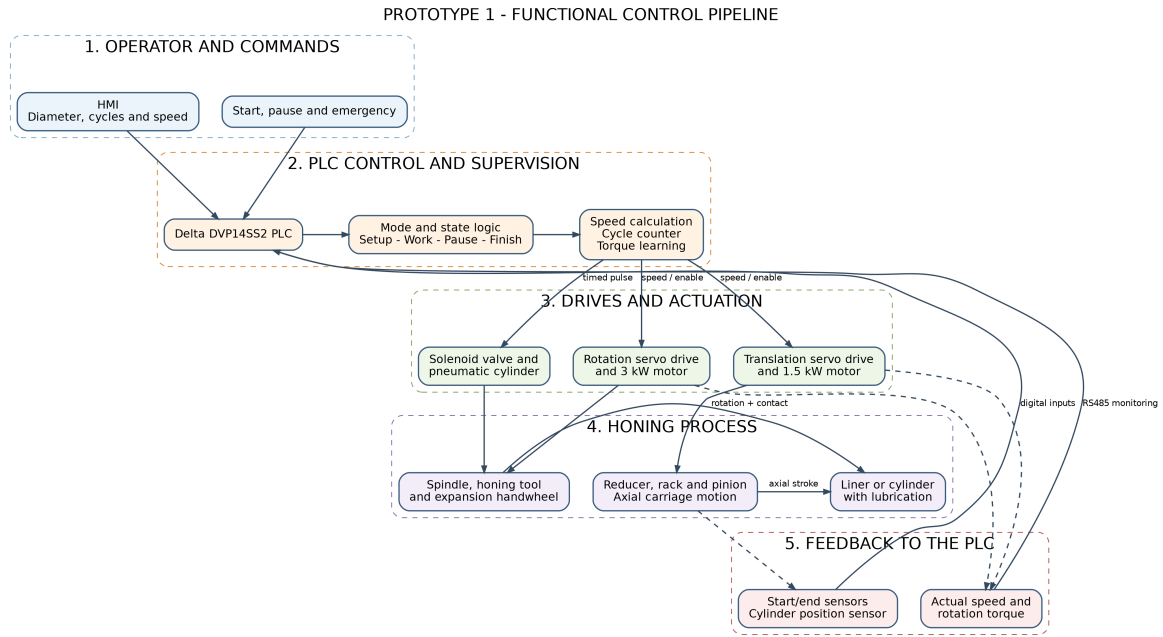
The conceptual strategy was divided into five functions: preparing the tool, executing the automatic cycle, supervising process variables, actuating pulse-based expansion, and allowing a controlled pause or completion. The three development stages used throughout the thesis are differentiated in Tab. 3, so every later reference to prototype 1 or prototype 2 corresponds to a specific hardware and software condition.

**TABLE 3**  
Definition of the development stages used in the thesis.

| Stage       | Implemented condition                                                                                                                                                                                         | Purpose within the project                                                                                |
|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Prototype 0 | Original machine with manual translation, manual expansion, visual inspection, and work-time control by the operator.                                                                                         | Establish the initial operational condition and identify the tasks that required automation.              |
| Prototype 1 | Initial integration of PLC, HMI, servo drives, position sensors, automatic cycles, torque reading, and pneumatic expansion.                                                                                   | Verify communication, motion control, cycle counting, and the feasibility of the automation architecture. |
| Prototype 2 | Corrected control with diameter-based rotation speed, manual initial setting, torque learning, physical joystick, intermediate inspection, continuation without PLC restart, and manual <i>short stroke</i> . | Resolve the limitations detected in prototype 1 and validate the machine under real workshop conditions.  |

### Prototype 1: system architectures

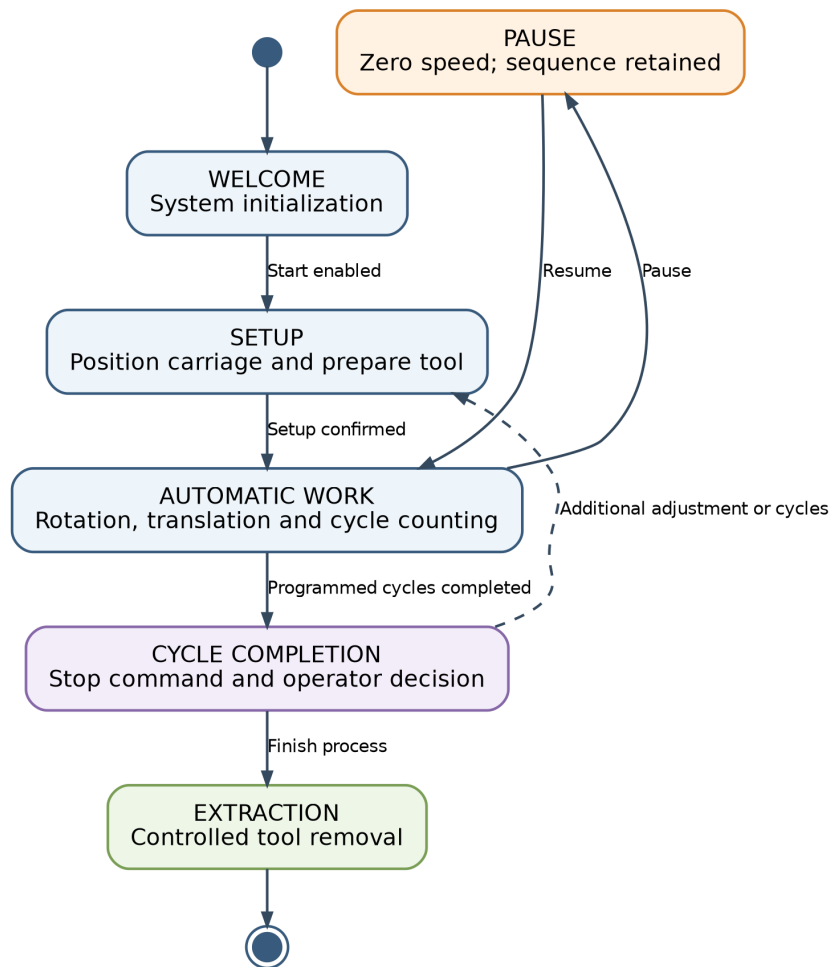
The functional architecture of prototype 1 is presented as a five-stage pipeline in Fig. 2. The first stage groups the commands entered from the HMI and the physical buttons; the second stage contains the PLC mode logic, speed calculations, cycle counting, and torque learning; the third stage contains the servo drives and the pneumatic valve; the fourth stage represents the mechanical action on the liner; and the fifth stage returns the position, speed, and torque signals to the PLC.



**Fig. 2.** Functional control pipeline implemented in prototype 1, from operator commands to process feedback.

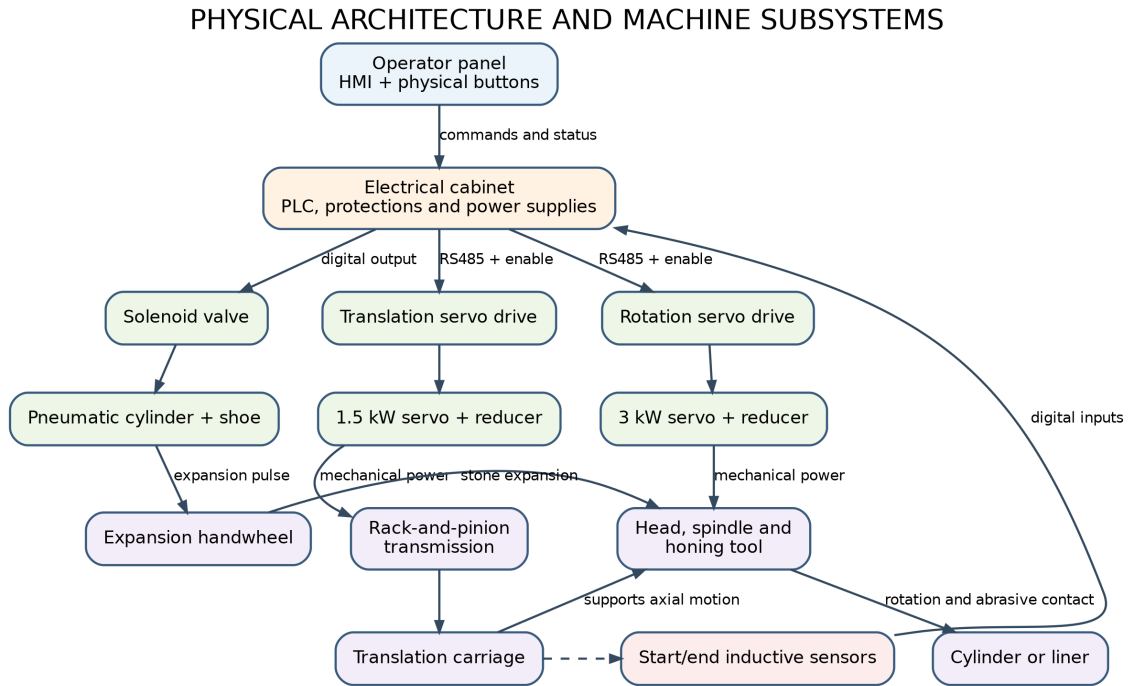
The operational logic of prototype 1 is separated into welcome, setup, automatic work, pause, cycle completion, and extraction states, as shown in Fig. 3. The arrows indicate the event that permits each transition, while the dashed return from completion to setup represents the additional adjustment that was still required when the operator decided to continue the process.

### PROTOTYPE 1 - OPERATIONAL STATE LOGIC



**Fig. 3.** Operational-state logic of prototype 1, including pause, completion, and extraction transitions.

The physical architecture in Fig. 4 identifies the machine subsystems and the type of connection between them. The translation branch includes the servo drive, the 1.5 kW motor, the reducer, the rack-and-pinion mechanism, and the carriage; the rotation branch includes the second servo drive, the 3 kW motor, the head, spindle, and honing tool; and the expansion branch includes the solenoid valve, pneumatic cylinder, actuation shoe, and expansion handwheel.



**Fig. 4.** Physical architecture of the machine, with the translation, rotation, sensing, and pneumatic expansion subsystems identified.

### Analysis of alternatives

The analysis of alternatives was carried out to select the control and interaction elements that would allow viable integration into the existing machine. The main criteria were availability, cost, ease of communication, operational safety, maintenance, and the possibility of continuing to use the structure of the honing machine, which preserves the focus on upgrading existing machinery. The comparison performed is presented in Tab. 4.

**TABLE 4**  
Analysis of alternatives for the main subsystems.

| Subsystem            | Alternatives considered                                                              | Decision criterion                                                            | Selection                                              |
|----------------------|--------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|--------------------------------------------------------|
| Main control         | Microcontroller, Siemens PLC, Delta PLC.                                             | Industrial robustness, availability, ease of connection with HMI and drivers. | Delta DVP14SS2 PLC.                                    |
| Axial movement       | AC motor with drive, servomotor, hydraulic system.                                   | Speed control, fast reversal, communication, and repeatability.               | 1.5 kW servomotor with reducer and rack-and-pinion.    |
| Rotation             | AC motor, drive, servomotor.                                                         | Speed variation, driver reading, and response to tool expansion.              | 3 kW servomotor with reducer.                          |
| Axial position       | External encoder, inductive sensors, mechanical limit switch.                        | Availability, cost, and ease of installation.                                 | Start and end inductive sensors.                       |
| Tool expansion       | Auxiliary motor, linear actuator, pneumatic cylinder on handwheel, manual expansion. | Simplicity, compatibility with the existing tool, and possibility of pulses.  | Pneumatic cylinder on the expansion handwheel.         |
| Operator interaction | HMI only, HMI with physical buttons, dedicated panel.                                | Cost, ease of implementation, and safety during setup.                        | HMI with physical start, pause, and emergency buttons. |

The selected alternative preserves the functional mechanical structure of the honing machine and incorporates new control, communication, and supervision layers. For this reason, the mechanical parts and assemblies appearing in the document are used to explain the physical interface of the automation, not to present a complete mechanical redesign as the main contribution of the thesis.

#### **Prototype 1: specific design of the control system**

The specific design of prototype 1 focused on the translation and rotation commands that the PLC had to send to the servo drivers. The calculation sequence was kept explicit

because each variable was later implemented as a PLC register or an intermediate value in the speed-calculation module.

### **Translation-axis sizing**

The translation axis uses a 1.5 kW servomotor coupled to a reducer. In Equation 2.1,  $i_{tra}$  is the dimensionless transmission ratio between the servomotor and the reducer output; the value 29 : 1 means that the motor performs 29 revolutions for one output revolution.

$$i_{tra} = 29 : 1 \quad (2.1)$$

The calibrated linear advance is defined in Equation 2.2. The variable  $L_{rev}$  is the axial displacement of the carriage for one reducer-output revolution and is expressed in millimeters per revolution.

$$L_{rev} = 213.5 \text{ mm/rev} \quad (2.2)$$

The operator enters the desired axial speed as  $v_s$  in meters per minute. Equation 2.3 converts this value into  $v_{ax}$ , the axial speed in millimeters per minute, so that it can be combined with  $L_{rev}$  using consistent units.

$$v_{ax} = 1000 v_s \quad (2.3)$$

In Equation 2.4,  $n_{out,tra}$  is the required reducer-output speed in revolutions per minute. Equation 2.5 then obtains  $n_{m,tra}$ , the translation-servomotor speed in revolutions per minute, by multiplying the output speed by the transmission ratio  $i_{tra}$ .

$$n_{out,tra} = \frac{v_{ax}}{L_{rev}} \quad (2.4)$$

$$n_{m,tra} = i_{tra} n_{out,tra} \quad (2.5)$$

The DA200A driver receives an integer register value. Therefore, Equation 2.6 defines  $WRSpeed_{Tra}$  as the PLC translation-speed command, scaled by a factor of ten with respect to  $n_{m,tra}$ .

$$WRSpeed_{Tra} = 10 n_{m,tra} \quad (2.6)$$

For the verification case  $v_s = 15$  m/min, Equation 2.7 produces  $n_{m,tra} = 2037.4$  rpm and the corresponding integer command  $WRSpeed_{Tra} \approx 20374$ .

$$n_{m,tra} = 29 \left( \frac{15000}{213.5} \right) = 2037.4 \text{ rpm}, \quad WRSpeed_{Tra} \approx 20374 \quad (2.7)$$

### **Prototype 1: initial rotation-axis sizing**

Prototype 1 used an initial geometric criterion that linked axial motion, tangential motion, and the desired trajectory angle. This criterion belongs only to prototype 1; the diameter-based correction incorporated in prototype 2 is presented later in Section 3.5.

In Equation 2.8,  $i_{rot}$  is the dimensionless transmission ratio between the rotation servomotor and the honing-tool shaft. A ratio of 3.75 : 1 means that the motor performs 3.75 revolutions for one tool revolution.

$$i_{rot} = 3.75 : 1 \quad (2.8)$$

Equation 2.9 defines  $v_t$ , the tangential speed of the abrasive contact in meters per minute, from the axial speed  $v_{ax}$  and the desired trajectory angle  $\alpha$ , expressed in degrees.

$$v_t = v_{ax} \tan(\alpha) \quad (2.9)$$

In Equation 2.10,  $n_{tool}$  is the honing-tool speed in revolutions per minute and  $D$  is the inner diameter of the liner in millimeters. Equation 2.11 converts the tool speed into the required rotation-motor speed  $n_{m,rot}$ . Equation 2.12 defines the integer PLC command  $WRSpeed_{Rot}$ .

$$n_{tool} = \frac{1000 v_t}{\pi D} \quad (2.10)$$

$$n_{m,rot} = i_{rot} n_{tool} \quad (2.11)$$

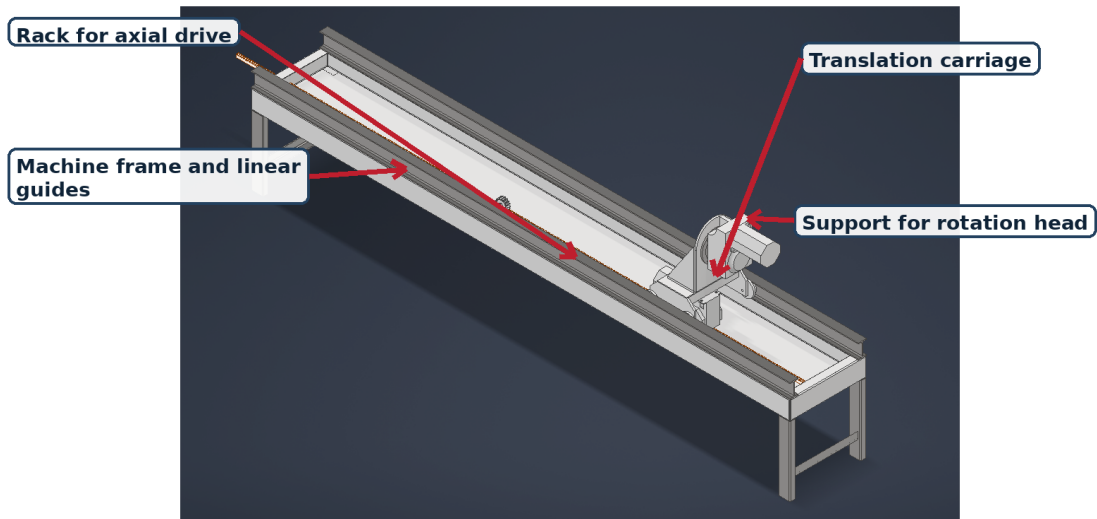
$$WRSpeed_{Rot} = 10 n_{m,rot} \quad (2.12)$$

Equation 2.13 expresses the inverse relationship, where  $\alpha$  is calculated from the ratio between  $v_t$  and  $v_{ax}$ . This equation remained a design reference because prototype 1 did not include an external encoder for closed-loop measurement of the actual trajectory angle.

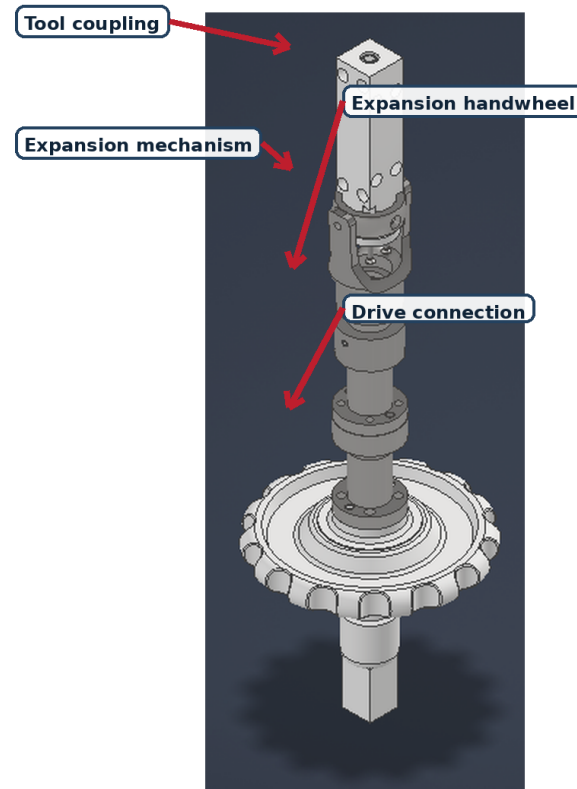
$$\alpha = \tan^{-1} \left( \frac{v_t}{v_{ax}} \right) \quad (2.13)$$

### ***Mechanical conditions received for integration***

The CAD models in Figs. 5 and 6 identify the mechanical interfaces used by the control system. Figure 5 labels the machine frame, linear guides, axial rack, translation carriage, and support for the rotation head; Fig. 6 labels the tool coupling, expansion mechanism, expansion handwheel, and drive connection.

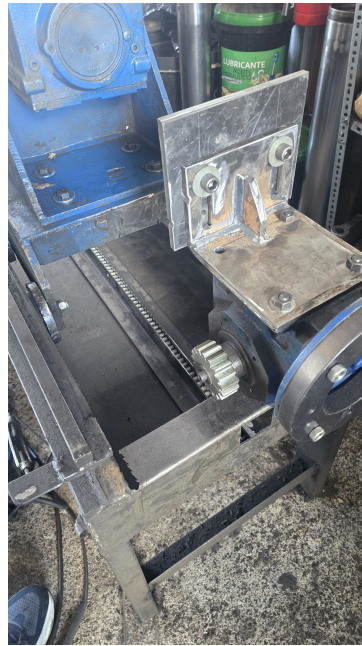


**Fig. 5.** Annotated CAD model of the carriage assembly and the mechanical interfaces used by the translation control.



**Fig. 6.** Annotated CAD model of the head, expansion handwheel, coupling, and drive connection.

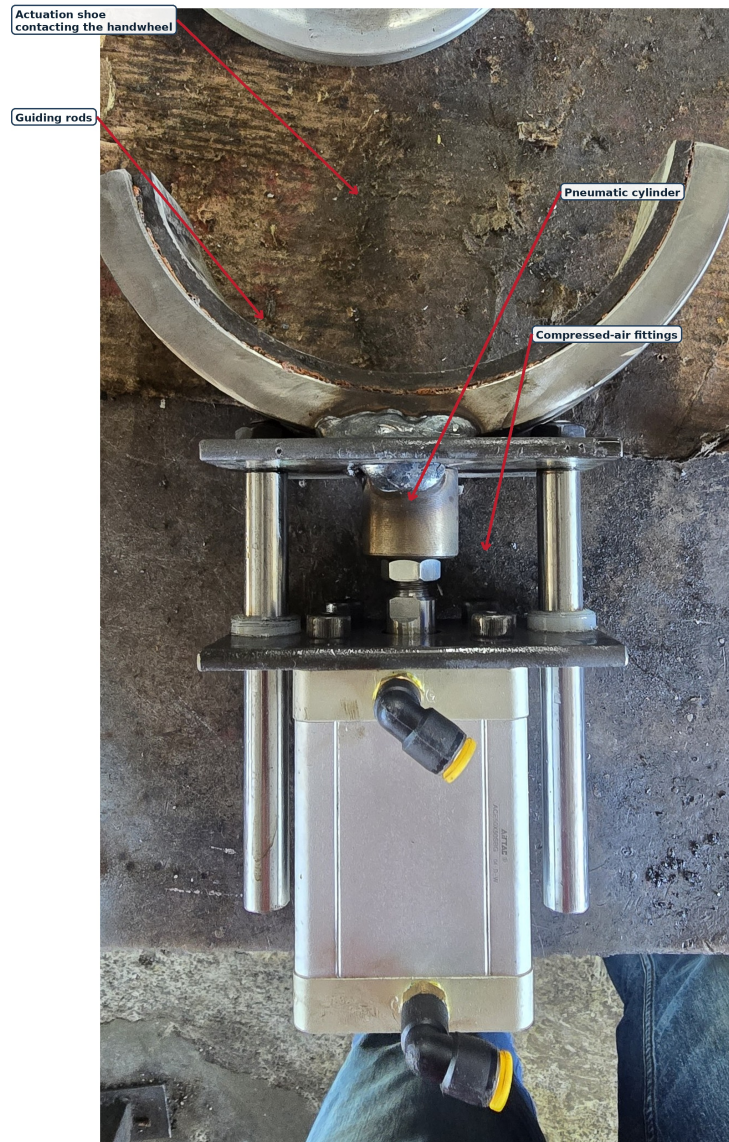
The rack-and-pinion system presented in Fig. 7 made it possible to transform the reducer output rotation into linear motion of the carriage. For this reason, it was maintained as part of the base machine and integrated into the new speed control of the translation servomotor.



**Fig. 7.** Rack-and-pinion system used for the axial displacement of the carriage.

### ***Tool expansion system***

The honing tool used has an adjustment handwheel, so directly automating its rotation with an auxiliary motor was complex because the handwheel rotates together with the tool. The available physical solution was a pneumatic cylinder that presses the handwheel by means of a shoe during short intervals, as shown in Fig. 8; the control contribution consisted of actuating the solenoid valve, timing the pulse, reading the cylinder condition, and relating expansion to the driver torque reading.



**Fig. 8.** Annotated pneumatic expansion assembly: cylinder, guiding rods, actuation shoe, air fittings, and handwheel contact zone.

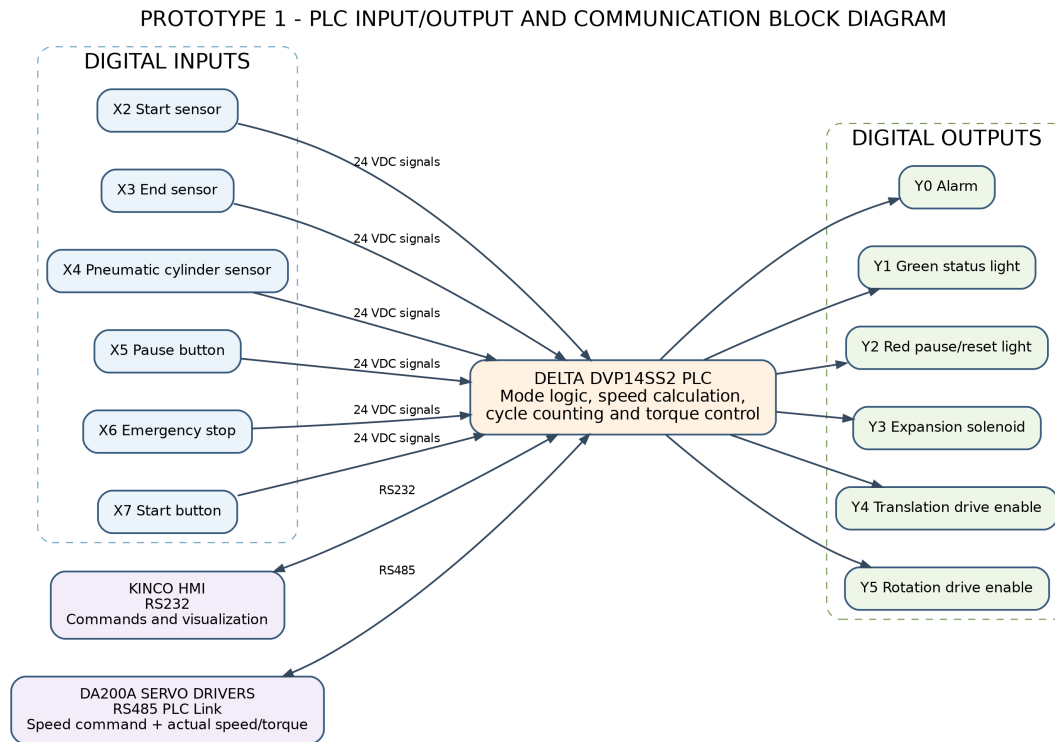
In prototype 1, assisted expansion was made available from the control, but the initial setup of the tool still depended on the operator's adjustment and the condition of the liner. After setup, the PLC was responsible for learning a torque reference during the first normal cycle and for requesting expansion pulses during automatic operation.

### **Electrical system, inputs, outputs, and communication**

The electrical system was organized around a Delta DVP14SS2 PLC, a Kinco GL070E HMI, and two Delta DA200A servo drivers. The HMI communicated with the PLC through RS232, while the PLC communicated with the servo drivers through RS485 using PLC Link, with one assigned station for translation and another for rotation. This architecture made it

possible to write speed commands and read real variables from the drivers, which is consistent with digitalization and monitoring strategies for existing machine tools.

The PLC input/output and communication structure of prototype 1 is summarized in Fig. 9. The diagram separates the digital inputs, the digital outputs, the RS232 link with the HMI, and the RS485 PLC Link connection with the two servo drivers, making the signal direction and the function of each block explicit.



**Fig. 9.** PLC input/output and communication block diagram for prototype 1.

The PLC Link configuration used to connect the PLC with the servo drivers allowed the PLC to write the translation and rotation speed registers and to read monitoring variables such as actual speed and torque without adding invasive sensors inside the working area.

The distribution of the main inputs and outputs of prototype 1 is presented in Tab. 5. This assignment made it possible to separate command signals, position sensors, pneumatic signal, lights, servo enabling, and emergency functions within the PLC program.

### Prototype 1: modular PLC programming

The programming was divided into modules to prevent motion control, HMI, communication, setup, work, torque, and completion from being mixed into a single routine. Tab. 6 summarizes the programming blocks used to structure prototype 1.

**TABLE 5**  
Main inputs and outputs used in prototype 1.

| Input | Function                                       | Output | Function                              |
|-------|------------------------------------------------|--------|---------------------------------------|
| X2    | Start-of-stroke inductive sensor.              | Y0     | Alarm or warning signal.              |
| X3    | End-of-stroke inductive sensor.                | Y1     | Green light indicating start enabled. |
| X4    | Sensor associated with the pneumatic cylinder. | Y2     | Red light for pause or reset enabled. |
| X5    | Red pause button.                              | Y3     | Pneumatic expansion solenoid valve.   |
| X6    | Emergency stop.                                | Y4     | Translation driver enable.            |
| X7    | Green start button.                            | Y5     | Rotation driver enable.               |

**TABLE 6**  
Modular programming structure implemented in the PLC.

| Module                                   | Function within the control                                                                                             |
|------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| Initialization<br>(Inicializacion)       | Clears markers, loads base values, enables initial conditions, and prepares communication.                              |
| Communication<br>(Comunicacion)          | Commands register reading and writing between PLC, HMI, and servo drivers.                                              |
| Setup mode<br>(Modo_Seteo)               | Allows preparation of the tool, carriage movement, selection of setup speed, and confirmation of the initial condition. |
| Speed calculation<br>(Calculo_Velocidad) | Calculates translation speed and initial rotation speed, applies command scales, and validates limits.                  |
| Work mode<br>(Modo_Trabajo)              | Executes the automatic cycle, reverses by sensors, discounts cycles, and manages pauses.                                |
| Torque control<br>(Control_Torque)       | Reads the rotation-axis torque, learns the initial reference, and manages expansion pulses.                             |
| Completion<br>(Finalizacion)             | Stops speeds, enables extraction, and clears markers when the process is completed.                                     |

### **Setup mode**

The setup mode was designed to prepare the tool before starting operation, allowing carriage movement, setup speed selection, and confirmation of the initial position. For prototype 1, three low, medium, and high speed levels were defined, equivalent to 25%, 50%, and 100% of a maximum setup speed, with the objective of preventing the operator from entering

numerical values during this stage.

### ***Automatic work mode***

The work mode starts when setup has been confirmed and the operator presses the green button. In this mode, the PLC writes the rotation speed to register WRSpeed\_Rot, writes the translation speed to register WRSpeed\_Tra, reverses the carriage between the start and end sensors, and discounts cycles only when a valid forward-and-return sequence is completed.

### ***Torque learning and pulse-based expansion***

Torque is read from the rotation driver and used as an indirect indicator of tool load, following the criterion of taking advantage of drive signals to monitor process conditions without adding invasive instrumentation in the working area. In prototype 1, the working torque was learned during the first normal cycle before considering expansion pulses, because the pneumatic cylinder could generate peaks associated with contact with the handwheel and not necessarily with the actual cutting effort.

In Equation 2.14,  $T_{rot}(k)$  is the rotation-driver torque sample at sampling instant  $k$ , and  $T_{work}$  is the maximum torque observed during the first normal cycle, excluding pneumatic-expansion pulses. The percentages  $p_{low}$  and  $p_{high}$  define the permitted decrease and increase relative to  $T_{work}$ ; therefore,  $T_{min}$  and  $T_{max}$  in Equations 2.15 and 2.16 are the lower and upper monitoring thresholds.

$$T_{work} = \max(T_{rot}(k)), \quad k \in \text{first normal cycle} \quad (2.14)$$

$$T_{min} = T_{work} \left( \frac{100 - p_{low}}{100} \right) \quad (2.15)$$

$$T_{max} = T_{work} \left( \frac{100 + p_{high}}{100} \right) \quad (2.16)$$

Automatic expansion was controlled through solenoid-valve pulses parameterized from the PLC. The objective of this logic was for the tool to be able to progressively increase its contact with the liner without depending on continuous manual action, maintaining torque reading as an indirect reference of process load.

### Prototype 1: HMI interface design

The HMI was organized into welcome, setup, process, completion, and extraction windows so that the operator would not have to search for critical functions on a single screen. The welcome screen concentrates the general start-up, the setup screen prepares the tool, the process screen displays speeds, torque, and cycles, the completion screen allows the operator to decide the process exit, and the extraction screen allows the tool to be removed with manual control.

The process screen implemented in prototype 1 is shown in Fig. 10. This window allowed the operator to review speeds, torque, process status, and cycles during machine operation.

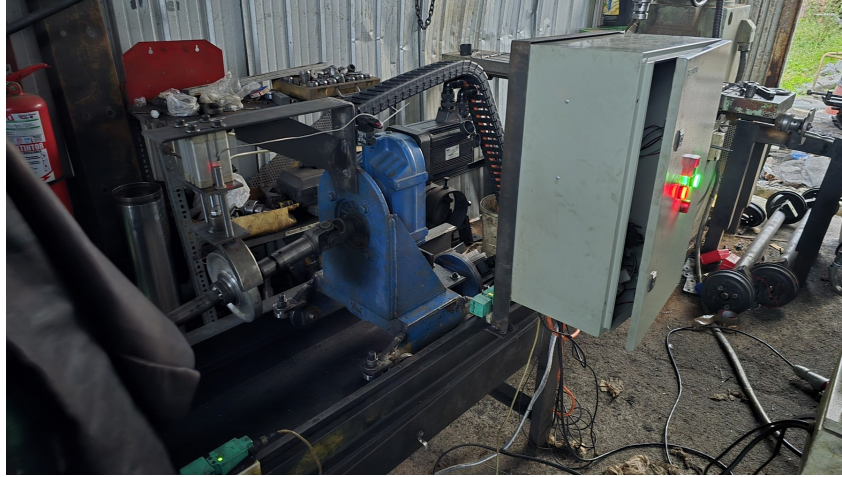


Fig. 10. Process screen implemented in the HMI of prototype 1.

### Prototype 1: physical integration

The integration of prototype 1 consisted of connecting the control system to the existing machine, including servomotors, drivers, sensors, solenoid valve, HMI, physical buttons, and control cabinets. This integration is documented because it makes it possible to understand the operation of the automated system, but the main contribution of the thesis remains the commissioning of the control and not the structural design of the honing machine.

The physical arrangement of prototype 1 is presented in Fig. 11. At this stage, the elements necessary to execute axial motion, rotation, sensor reading, pneumatic expansion, and operation from the HMI were integrated.



**Fig. 11.** Physical integration of prototype 1 onto the horizontal honing machine.

Integration was carried out progressively: first, basic signals were connected and tested; then communication was verified; afterward, individual movements were tested; and finally setup, automatic operation, pulse-based expansion, pause, completion, and extraction were integrated. This sequence made it possible to reach a functional prototype before beginning the detailed analysis of results.

### **Preparation for property verification**

Verification of the prototype was planned before presenting results, defining the technical question, experimental unit, controlled factors, fixed factors, noise factors, and response variables. In this project, the experimental unit was considered as one complete honing run on a real liner, from setup to visual finish inspection, because this unit represents the actual way in which the workshop evaluates the usefulness of the machine.

The elements considered for the experimental verification of the prototype are presented in Tab. 7, it organizes the conditions that had to be observed during the later testing phase.

With this methodology, the development of prototype 1 was concluded: the requirements gave rise to the architecture, the architecture made it possible to implement the control, and the control was left ready to be evaluated through functional tests and real honing tests. The results of these verifications, together with the corrections incorporated into prototype 2, are presented in the following chapter.

**TABLE 7**  
Elements considered for the experimental verification of the prototype.

| <b>Experimental element</b> | <b>Application in the project</b>                                                                                                                                                                                |
|-----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Technical question          | Verify whether the automation reduces manual intervention, keeps the process active, and makes it possible to obtain an acceptable visual condition in real liners.                                              |
| Experimental unit           | One complete work run on a liner installed in the honing machine, from setup to visual inspection.                                                                                                               |
| Controlled factors          | Entered diameter, number of cycles, translation speed, initial rotation speed, expansion-pulse time, and operating mode.                                                                                         |
| Fixed factors               | PLC, servo drivers, HMI, honing tool, stones, stone holders, lubrication system, start/end sensors, and pneumatic cylinder.                                                                                      |
| Noise factors               | Previous condition of the liner, scratch depth, stone wear, alignment, lubrication, pneumatic pressure, and the operator's visual judgment.                                                                      |
| Response variables          | Process time, cycle completion, number of inspections, visual finish, scratch removal, and observations of the technical supervisor.                                                                             |
| Measurement limitation      | A complete metrological characterization of internal roughness was not proposed due to the lack of an adequate instrument for deep interiors; initial verification was left as visual and functional inspection. |

## Chapter III

### Results

This chapter presents the results obtained after implementing prototype 1 and during the evolution toward prototype 2. The analysis was organized by stages to avoid mixing methodology with findings: first, the results of prototype 1 are presented; then, the design transition that emerged from its problems is explained; afterward, the functions incorporated into prototype 2 are documented; and finally, the functional validation with real liners is presented.

Validation was not proposed as a complete statistical characterization of surface quality, because there was no roughness tester suitable for deep internal surfaces, nor was there a sufficient replication campaign to apply a formal statistical analysis. For this reason, the results are interpreted as functional and operational validation: the machine had to execute repeatable cycles, keep the process active, allow safe operator intervention, reduce continuous manual operation, and obtain an acceptable visual improvement on real workshop parts.

#### **Applied experimental criterion**

Before comparing the prototypes, verification was organized using an experimental logic applied to mechatronic systems: a technical question, an experimental unit, controlled factors, fixed factors, noise factors, and response variables were defined. This organization was important because it made it possible to separate prototype 1 as a diagnostic stage and prototype 2 as a functional verification stage under real working conditions.

The technical question used to interpret the results was the following: *does the automation of the horizontal honing machine make it possible to execute repeatable honing cycles, reduce continuous manual intervention by the operator, and obtain an acceptable visual improvement in real hydraulic cylinder liners?* The planning used to answer this question is summarized in Tab. 8.

**TABLE 8**  
Experimental planning applied to the verification of the prototypes.

| Element                | Application in the automated honing machine                                                                                                                                                                     |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Experimental question  | Verify whether the automated system executes repeatable cycles, keeps the honing process active, and makes it possible to obtain a visually acceptable surface with less manual intervention.                   |
| Experimental unit      | One complete work run on a liner installed in the machine.                                                                                                                                                      |
| Controlled factors     | Entered diameter, translation speed, calculated rotation speed, number of cycles, expansion pulse time, and operator intervention mode.                                                                         |
| Fixed factors          | Delta DVP14SS2 PLC, Kinco GL070E HMI, DA200A servo drivers, servomotors, honing tool, stones, stone holders, inductive sensors, and pneumatic cylinder.                                                         |
| Noise factors          | Initial condition of the liner, scratch depth, stone wear, alignment, lubrication, pneumatic pressure, mounting variation, and the operator's visual criterion.                                                 |
| Response variables     | Total process time, scratch removal, internal visual finish, work continuity, executed cycles, need for additional cycles, and observations from the technical supervisor.                                      |
| Measurement limitation | Internal roughness was not measured due to the lack of a roughness tester suitable for deep internal surfaces; therefore, the finish was evaluated visually and according to the workshop acceptance criterion. |

### General evolution of the prototypes

The development is understood in three stages: initial condition or prototype 0, prototype 1, and prototype 2. The initial condition made it possible to identify the limitations of manual operation; prototype 1 verified that automation was feasible through PLC, HMI, servo drivers, sensors, and pneumatic expansion; and prototype 2 incorporated the necessary corrections to convert the initial integration into a functional workshop operation. This evolution is summarized in Tab. 9.

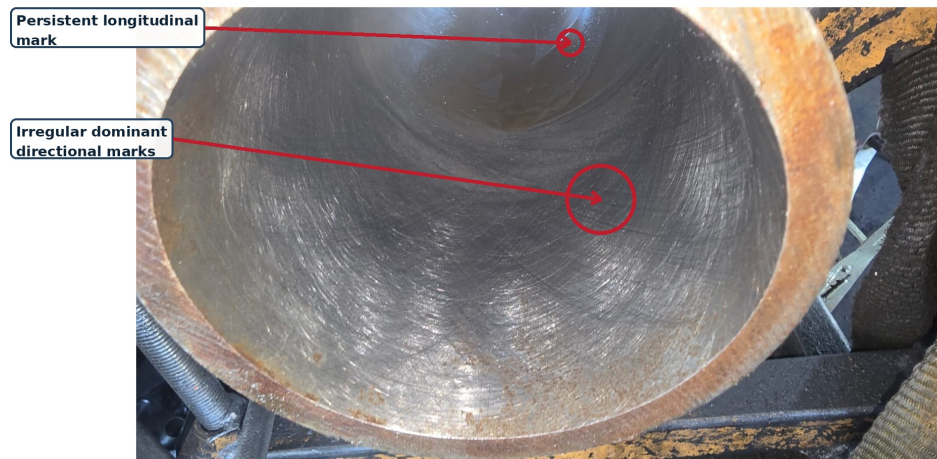
**TABLE 9**  
Evolution of the implemented solution by prototypes.

| Stage       | Achieved result                                                                                                                                                                    | Main lesson learned                                                                                                      |
|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Prototype 0 | Operational base machine, but dependent on manual intervention for translation, inspection, expansion, and time control.                                                           | It was necessary to automate repetitive tasks without eliminating the operator's judgment.                               |
| Prototype 1 | Integration of PLC, HMI, servo drivers, sensors, automatic cycles, torque reading, and pulse-based pneumatic expansion.                                                            | Automation was feasible, but problems were detected in setup, expansion, speed scaling, finish, and manual intervention. |
| Prototype 2 | Programming corrections, initial manual setup, physical joystick, intermediate inspection, cycle continuation, <i>short stroke</i> , automatic expansion, and improved ergonomics. | The machine achieved a more productive and useful operation for real workshop conditions.                                |

### Results of prototype 1

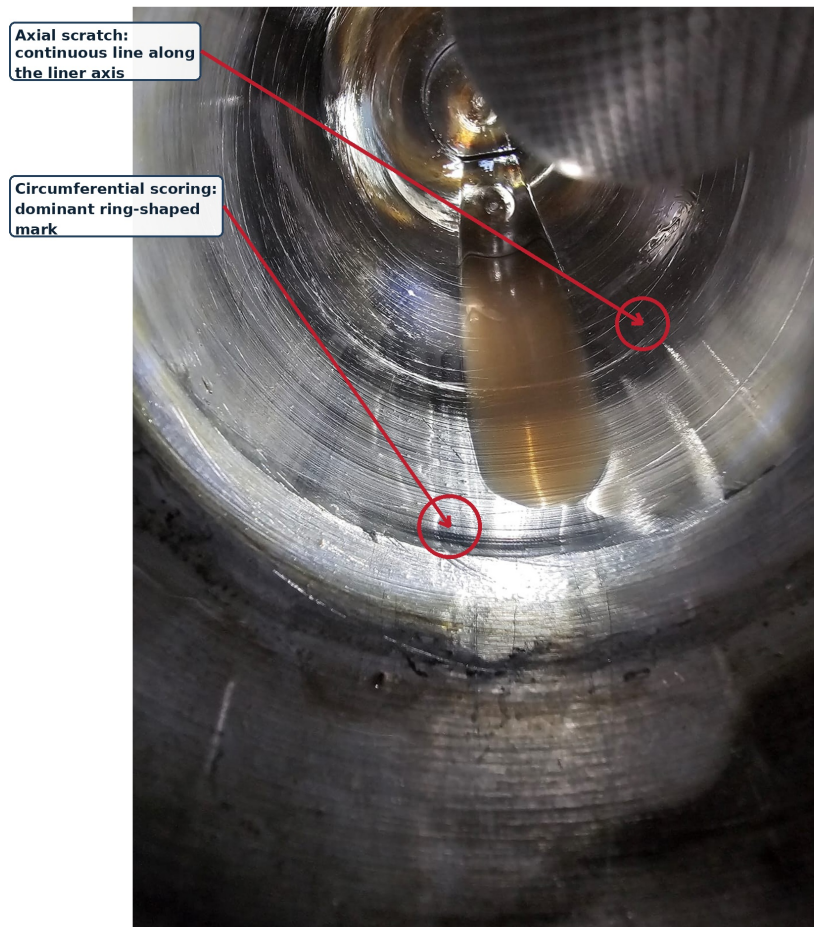
Prototype 1 fulfilled a diagnostic role because it demonstrated that the general architecture was feasible, but it also showed that the initial logic was not sufficient to obtain an acceptable honing condition. It was verified that the PLC could write speeds to the servo drivers, read actual variables, move the carriage between sensors, actuate the pneumatic solenoid valve, and display data on the HMI; however, the actual behavior of expansion, torque, and finish required later corrections.

The first relevant test was carried out on a liner of approximately 108 mm. Figure 12 identifies the two visual defects used in the diagnosis: a persistent longitudinal mark and an area with dominant directional marks instead of a uniform crossed texture. These callouts do not represent a depth measurement; they identify the regions that remained visible under oblique illumination and motivated the speed and expansion corrections.



**Fig. 12.** Annotated visual condition of the 108 mm liner during prototype 1.

In the 100 mm test, the defects were classified by their direction. The axial scratch in Fig. 13 is a continuous line approximately parallel to the liner axis, whereas the circumferential scoring is a dominant ring-shaped mark around the bore. Both remain visually distinguishable from the finer honing texture and were therefore used as the reference defects for the later before-and-after comparison.



**Fig. 13.** Annotated axial scratch and circumferential scoring observed on the 100 mm liner during prototype 1.

During the same stage, damage to a honing stone also occurred, as shown in Fig. 14. This failure was interpreted as an unfavorable working condition, because the tool was advancing and expanding, but the relationship between rotation and feed was not correctly distributing abrasive contact over the internal surface.



**Fig. 14.** Fractured honing stone during prototype 1 tests.

The main problems of prototype 1 were four: HMI-based setup could leave the tool too tight, the torque logic could interpret a normal increase during expansion as a fault, some speed scales had to be corrected, and the operator did not have a practical way to intervene locally during the cycle. These findings justified the transition toward prototype 2, in which the automation was corrected without attempting to eliminate the operator's judgment.

#### **Prototype 2: corrections derived from prototype 1**

After the tests of prototype 1, the operating strategy changed: the system should not attempt to fully replace the operator, but rather automate repetitive tasks and allow controlled manual intervention when necessary. This change was consistent with the real behavior of repair honing, where each liner may require inspection and adjustments depending on its initial condition.

The first decision was to remove automatic expansion as the main initial setup action. Instead of expanding from the HMI until contact is achieved, the operator manually adjusts the tool from the handwheel to start from a safe condition; afterward, the system starts automatic operation and learns the reference torque during the first normal cycle. This avoided learning false values generated by expansion pulses or by an excessively tightened tool.

The second decision was to eliminate over-torque stop as a normal working condition. During the tests, it was observed that torque can increase during expansion because the tool acts as a brake while expanding, and this increase does not necessarily represent a fault. Therefore, torque began to be used as a process reference to decide contact or expansion,

while safety remained associated with emergency stop, pause, sensors, servo permissions, and recovery logic.

The third decision was to keep the motors enabled when the cycles ended, sending zero speeds and entering an inspection state. This allowed the operator to manually close the stones, partially withdraw the tool, inspect the liner, add cycles if necessary, and continue without restarting the PLC. This logic was key to transforming the automatic cycle into a useful workshop operation.

### **Prototype 2: correction of the rotation speed**

Prototype 1 showed that the initial rotation calculation did not provide the best finish, so in prototype 2 a speed criterion dependent on the working diameter was adopted. The technical reference used to define tool speed is shown in [20], and it was integrated into the PLC calculation so that the operator enters the diameter and the system calculates the corresponding rotation speed.

The corrected tool speed was calculated using Equation 3.1. In this relationship,  $D$  corresponds to the inner diameter of the liner in millimeters and  $n_{tool}$  corresponds to the tool speed in revolutions per minute [20].

$$n_{tool} = \frac{30000}{D} \quad (3.1)$$

Equation 3.2 calculates the rotation-motor speed  $n_{m,rot}$  in revolutions per minute from  $i_{rot} = 3.75$  and  $n_{tool}$ . Equation 3.3 defines  $WRSpeed_{Rot}$ , the integer command written by the PLC to the rotation driver.

$$n_{m,rot} = i_{rot} n_{tool} \quad (3.2)$$

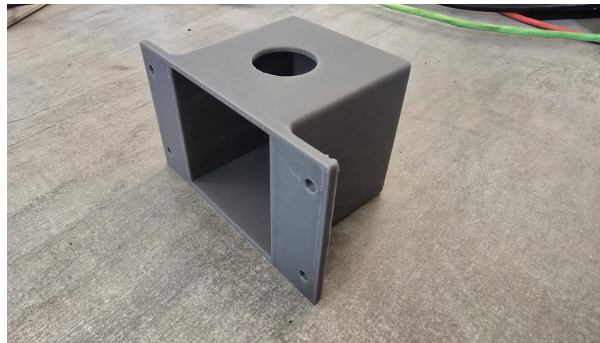
$$WRSpeed_{Rot} = 10 n_{m,rot} \quad (3.3)$$

This correction was relevant because it separated the initial geometric criterion used in the methodology from the technical decision obtained after testing prototype 1. For this reason, Equation 3.1 is not presented in the methodology chapter as an initial design, but in the results as an applied adjustment to solve the problem observed during the first tests.

## Prototype 2: functional implementation

Prototype 2 integrated the improvements needed for the machine to work productively under real conditions. The modifications were concentrated on five aspects: safer initial setup, torque learning during the first normal cycle, pulse-based expansion without unnecessary stopping, inspection at the end of cycles, and manual operation through a physical joystick.

The first visible improvement was the incorporation of a physical joystick and the relocation of the operating panel. The printed design of the joystick box is shown in Fig. 15.



**Fig. 15.** ABS-printed box used to install the physical operating joystick.

The location of the operating panel with HMI, buttons, and joystick is presented in Fig. 16. This modification allowed the operator to move the carriage more comfortably during setup, inspection, extraction, and manual *short stroke*.



**Fig. 16.** Relocated operating panel with HMI, physical buttons, and joystick.

The setup of prototype 2 changed with respect to prototype 1: the initial expansion of the tool is no longer carried out from the HMI as the main action, but manually from the handwheel. This decision reduced the risk of excessively tightening the stones before starting, and allowed the system to learn a more representative working torque during the first normal cycle.

Automatic expansion was maintained, but it was no longer used to stop the system due to over-torque. The PLC learns the reference torque from the first normal cycle and then uses that value to decide pulse-based expansions during work, avoiding the transient peaks generated by the pneumatic cylinder from being interpreted as a process fault.

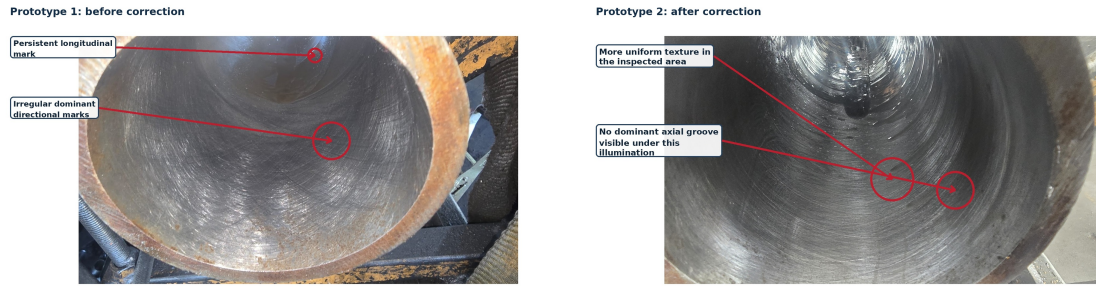
Cycle counting was simplified to avoid conflicts between actual cycles and partial movements. The cycle is considered complete when the carriage reaches the final end and then returns to the start sensor; if the operator reverses motion before completing the stroke by means of *short stroke*, the PLC does not count a false cycle. This difference allowed the operator to concentrate work on damaged areas without altering the official count.

At the end of the programmed cycles, prototype 2 enters an inspection state and does not disable the motors. In this state, the speeds are set to zero, but the operator can manually close the tool, move the carriage with the joystick, partially withdraw the tool, inspect the liner, enter additional cycles, and continue with the HMI button and the green physical button. This logic avoided unnecessary restarts and allowed inspection to become a normal part of the process.

### **Prototype 2: validation with real liners**

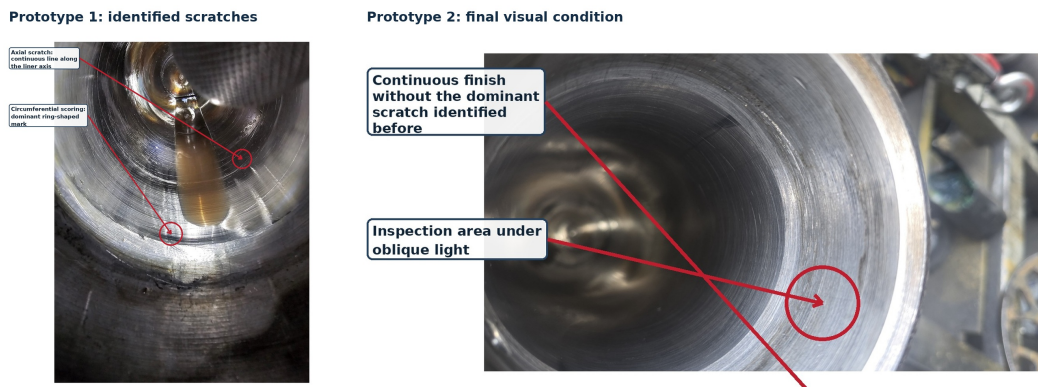
Validation of prototype 2 was carried out with real workshop liners, prioritizing cycle continuity, reduction of continuous manual intervention, and visual correction of the dominant defects identified in prototype 1. Visual inspection was performed with oblique illumination and considered three criteria: persistence of axial or circumferential scratches, uniformity of the visible honing texture, and the presence of isolated shiny bands. Because no internal roughness meter was available, this inspection does not quantify scratch depth or surface roughness.

The 108 mm liner was processed for approximately 70 cycles in 30 min. Figure 17 compares the prototype 1 condition with the prototype 2 result and indicates the same type of visual regions in both images. In the inspected area after prototype 2, the previously dominant longitudinal groove was no longer visually evident and the texture appeared more uniform under the available illumination.



**Fig. 17.** Before-and-after visual comparison of the 108 mm liner, with the inspected defects and corrected regions indicated.

The 100 mm case used the axial scratch and circumferential scoring identified in Fig. 13 as the visual reference. The before-and-after comparison in Fig. 18 shows the prototype 1 defects on the left and the final condition after prototype 2 on the right. The part reached the workshop delivery condition in approximately 45 min, although the result remains a visual acceptance rather than a metrological roughness measurement.



**Fig. 18.** Before-and-after visual comparison of the 100 mm liner, with the dominant scratch and the final inspection region indicated.

A 152 mm liner with severe scratching was also processed. Recovery required approximately 2 h and several intermediate inspections; during these intervals, the operator added cycles and continued the process without restarting the PLC. The measured automated times are summarized in Tab. 10.

**TABLE 10**  
Measured operating times during the functional validation of prototype 2.

| <b>Liner</b> | <b>Measured time</b> | <b>Working condition</b>                                                           | <b>Observed result</b>                                      |
|--------------|----------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------|
| 108 mm       | 30 min               | Approximately 70 cycles to correct the marks left by prototype 1.                  | Dominant groove not visually evident in the inspected area. |
| 100 mm       | 45 min               | Recovery of the axial and circumferential test marks with intermediate inspection. | Part accepted for workshop delivery.                        |
| 152 mm       | 120 min              | Severe scratching; cycle-based work and several inspections.                       | Visually acceptable condition for workshop operation.       |

Table 11 contrasts the historical manual records with the automated validation. The comparison shows that elapsed time depends strongly on the initial condition of the part; for the nominal 152 mm cases, the automated time of 120 min is within the manual range of 110 to 120 min. Therefore, the measurable benefit supported by these data is not a universal reduction in elapsed time, but the execution of automatic cycles, the removal of continuous manual stroking, and the possibility of inspection and continuation without restarting the controller.

**TABLE 11**

Operational time reference: historical manual records versus prototype 2 validation.

| Mode                     | Diameter | Recorded time   | Interpretation                                                                                             |
|--------------------------|----------|-----------------|------------------------------------------------------------------------------------------------------------|
| Manual historical record | 80 mm    | 365 min         | Different part and condition; continuous operator participation was required.                              |
| Manual historical record | 116 mm   | 350 min         | Different part and condition; used only as an operational reference.                                       |
| Manual historical record | 152 mm   | 110 and 120 min | Two six-inch jobs; mean recorded time 115 min.                                                             |
| Prototype 2              | 100 mm   | 45 min          | Automated cycles with inspection and continuation.                                                         |
| Prototype 2              | 108 mm   | 30 min          | Approximately 70 automated cycles.                                                                         |
| Prototype 2              | 152 mm   | 120 min         | Comparable nominal diameter to the six-inch manual records, but with a different initial damage condition. |

**Prototype 2: evaluation of implemented functions**

Automatic expansion was one of the most important functions of prototype 2, because it made it possible to progressively increase tool contact without stopping the process for frequent manual adjustments. The key improvement was to separate working torque from torque during the pneumatic pulse, since the pulse can generate a temporary increase due to braking effect and not necessarily due to a cutting fault.

Manual *short stroke* by means of the joystick allowed the operator to reverse the direction of the carriage during work, reproducing a common practice of the expert operator: concentrating the honing effort on a specific area when the liner presents localized damage. This function does not replace automatic position measurement or a damaged-area detection system, but it combined automation with controlled human intervention.

Inspection at the end of cycles improved operational continuity because the system no longer forces the operator to completely finish the process when the number of cycles is reached. Instead of turning off the servos or restarting the PLC, the machine remains in a stable state with zero speeds, from which the operator can inspect, add cycles, or move to general extraction.

Safety was evaluated by differentiating pause, emergency, and end-of-cycles conditions. Pause allows temporary stopping and continuation, emergency stops the system and blocks critical states, and end of cycles keeps the machine ready for inspection. This separation prevents all stops from behaving the same way and makes it possible to adapt the control response to the real operating situation.

### Comparison between prototype 1 and prototype 2

The functional comparison between prototype 1 and prototype 2 is presented in Tab. 12. The table shows that prototype 1 was useful to verify the feasibility of automation, while prototype 2 solved the main problems of operation, ergonomics, expansion, and process continuity.

**TABLE 12**  
Functional comparison between prototype 1 and prototype 2.

| Aspect evaluated | Prototype 1                                                                                     | Prototype 2                                                                                              |
|------------------|-------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Rotation speed   | Based on the initial calculation of the relationship between feed, tangential speed, and angle. | Calculated as a function of diameter using the $30000/D$ criterion and converted into the motor command. |
| Initial setup    | Expansion from the HMI could leave the tool too tight.                                          | Initial manual adjustment from the handwheel and torque learning during the first normal cycle.          |
| Tool expansion   | Functional pneumatic expansion, but with risk of interpreting torque peaks as a fault.          | Pulse-based expansion during work, without over-torque stop as a normal condition.                       |
| Manual operation | Manual movement limited to interface functions and less comfort during work.                    | Physical joystick for setup, inspection, extraction, and manual <i>short stroke</i> .                    |
| Cycle counting   | Required corrections to separate complete cycles from partial movements.                        | Official count associated with complete cycles; manual reversals do not count false cycles.              |
| End of cycles    | Completion could interrupt process continuity.                                                  | Inspection state with zero speeds, motors enabled, additional cycles, and continuation.                  |

Continues on the next page

| Aspect evaluated | Prototype 1                                               | Prototype 2                                                                         |
|------------------|-----------------------------------------------------------|-------------------------------------------------------------------------------------|
| Visual finish    | Dominant scratches and stone damage during initial tests. | Improved visual finish on 100, 108, and 152 mm liners.                              |
| Ergonomics       | Less ease of access to operation during the process.      | Relocated panel, physical joystick, and more comfortable operation for supervision. |

### Functional compliance

The functional compliance of prototype 2 is summarized in Tab. 13. This table separates the fulfilled functions from the limitations that must remain clear within the scope of the thesis, especially the lack of quantitative internal roughness measurement and the need for future improvements in position measurement.

**TABLE 13**  
Compliance with functional requirements in prototype 2.

| ID    | Evaluated function             | Result                                                                           |
|-------|--------------------------------|----------------------------------------------------------------------------------|
| FR-01 | Axial translation control.     | Fulfilled. The carriage moves between sensors and allows manual reversal.        |
| FR-02 | Tool rotation control.         | Fulfilled. Rotation is calculated from the diameter and commanded to the driver. |
| FR-03 | Automatic reversal by sensors. | Fulfilled. The machine reverses between start and end during operation.          |
| FR-04 | Cycle counting.                | Fulfilled. Counting is associated with complete cycles and allows completion.    |
| FR-05 | Work continuation.             | Fulfilled. The operator adds cycles and continues without restarting the PLC.    |
| FR-06 | Assisted expansion.            | Fulfilled. The pneumatic cylinder executes expansion pulses during work.         |
| FR-07 | Torque learning.               | Fulfilled. Torque is learned during the first normal cycle.                      |
| FR-08 | Setup mode.                    | Fulfilled. It allows tool preparation with initial manual adjustment.            |

Continues on the next page

| ID     | Evaluated function           | Result                                                                                                                                          |
|--------|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|
| FR-09  | Physical joystick.           | Fulfilled. A physical command for manual motion was implemented.                                                                                |
| FR-10  | Manual <i>short stroke</i> . | Fulfilled. The operator can reverse direction during work without counting false cycles.                                                        |
| FR-11  | Extraction mode.             | Fulfilled. Extraction is enabled at the end and during general restart.                                                                         |
| NFR-01 | Safety.                      | Functionally fulfilled. The system responds to stop, pause, and emergency; additional physical interlocks are recommended in future versions.   |
| NFR-02 | Ergonomics.                  | Fulfilled. The panel was relocated and a physical joystick was added.                                                                           |
| NFR-03 | Maintainability.             | Fulfilled. The program remained divided into functional modules.                                                                                |
| DC-01  | Surface validation.          | Fulfilled with limitation. Validation was visual due to the lack of an internal roughness tester.                                               |
| DC-02  | Mechanical scope.            | Fulfilled as a delimitation. Mechanical adaptations are documented as an integration interface, not as the main mechanical design contribution. |

## Discussion of results

The functional results demonstrate a change in the operator's role rather than complete elimination of human intervention. Prototype 2 automatically executed the programmed forward-and-return cycles, counted only complete cycles, applied expansion pulses, and retained the process state for inspection and continuation. The operator remained responsible for initial tool adjustment, visual inspection, and the decision to add cycles or use manual *short stroke*.

The measured prototype 2 times were 30 min for the 108 mm liner, 45 min for the 100 mm liner, and 120 min for the 152 mm liner, as reported in Tab. 10. Historical manual records ranged from 110 to 365 min, but the parts and initial conditions were not equivalent. Consequently, the data do not support a universal percentage reduction in total process time; they support improved cycle continuity and reduced need for continuous manual stroking.

The visual correction is associated with the combined changes between prototypes:

diameter-based rotation speed, programmed axial feed, torque-referenced expansion, and controlled manual reversal. The annotated comparisons in Figs. 17 and 18 make the visual criterion explicit by identifying the dominant scratches before correction and the inspected regions after prototype 2.

The use of rotation-driver torque was useful as an indirect process signal, but the tests also showed that the signal must be interpreted according to the operating state. During a pneumatic expansion pulse, torque can rise because the tool is being mechanically loaded; therefore, the pulse interval was excluded from the normal-cycle reference and torque was not retained as a simple overload stop.

The principal limitation remains metrological validation. Visual inspection and workshop acceptance demonstrate functional usefulness, but they do not quantify roughness, crosshatch angle, cylindricity, or scratch depth. The results should therefore be interpreted as operational validation of the automated control system and not as a complete statistical characterization of surface quality.

### **Estimated implementation cost**

To complement the functional validation, an approximate cost summary of the implemented system is presented in Tab. 14. This estimate includes only the direct electrical, electronic, control, and labor costs associated with this thesis. Mechanical adaptations, workshop infrastructure, and general-purpose tools were excluded.

**TABLE 14**  
Estimated direct cost of the implemented thesis prototype.

| <b>Concept</b>                                                                                                                | <b>Estimated cost [USD]</b> |
|-------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| Servo actuation package: two servomotors, two servo drivers, CN1 terminal blocks, and associated power and encoder cabling.   | 1800.00                     |
| Delta PLC and programming cable: main PLC used in the control architecture of the prototype, including the programming cable. | 156.31                      |

Continues on the next page

| Concept                                                                                                                                                                                                       | Estimated cost [USD] |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Electrical and electronic materials: HMI, power supply, protections, panel auxiliaries, signaling elements, terminal blocks, and electrical installation accessories proportionally assigned to this project. | 405.04               |
| Engineering labor: approximate equivalent cost of the development work, estimated from 508 h of work and a reference rate of 4.62 USD/h based on a salary of 800 USD/month for a junior engineer.             | 2344.62              |
| <b>Total estimated cost</b>                                                                                                                                                                                   | <b>4705.97</b>       |

The economic estimate shows that the main cost of the work was associated not only with the automation hardware, but also with the engineering time required for integration, programming, testing, correction of prototype 1, and functional validation of prototype 2. Therefore, the implemented system represents both a technical and an economic effort focused on the modernization of an existing horizontal honing machine.

## Chapter IV

### Conclusions and recommendations

#### Conclusions

- A functional *retrofit* control system was implemented on the existing horizontal honing machine by integrating a Delta PLC, Kinco HMI, two servo drives, start/end sensors, physical controls, and a pneumatic expansion actuator. The implemented system executed translation, rotation, automatic reversal, cycle counting, pause, inspection, continuation, and controlled extraction on the real machine.
- Tool expansion was assisted with the rotation-driver torque signal. The reference  $T_{work}$  was learned as the maximum torque of the first normal cycle, while the pneumatic-pulse interval was excluded from that reference. This separation prevented the temporary torque increase produced by the expansion mechanism from being interpreted as a normal cutting overload.
- Prototype 2 completed the validated jobs in 30 min for the 108 mm liner, 45 min for the 100 mm liner, and 120 min for the 152 mm liner. Historical manual records ranged from 110 to 365 min; because the workpieces and initial damage were different, these values do not justify a universal percentage time reduction, but they confirm that the automated system can maintain the repetitive stroking cycle without continuous manual execution.
- The before-and-after visual comparisons showed that the dominant axial and circumferential marks identified during prototype 1 were no longer visually evident in the inspected regions after prototype 2, and the 100 mm part was accepted for workshop delivery. This conclusion is limited to visual and functional acceptance because roughness, cylindricity, crosshatch angle, and scratch depth were not measured with metrological instruments.

## Recommendations

- Incorporate an internal roughness measurement system in order to complement visual validation with quantitative data on surface finish.
- Integrate precise carriage position measurement by means of an encoder or linear scale in order to automate the *short-stroke* and improve control over specific liner zones.
- Implement a process data logging system to store variables such as diameter, number of cycles, working time, and torque, in order to facilitate historical analysis and parameter adjustment.

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