FUNCTIONAL PROTOTYPING OF AN AUTOMATED CRIMPING AND WIRE FEEDING MECHANISM

Adrian Bogdan Olariu, *Babeș-Bolyai University, Cluj-Napoca, ROMÂNIA*
Adrian Bosioc, *Babeș-Bolyai University, Cluj-Napoca, ROMÂNIA*
Costel-Relu Ciubotariu[*]**,** *Babeș-Bolyai University, Cluj-Napoca, ROMÂNIA*

ABSTRACT: The present document details the design, three-dimensional modeling, and functional prototyping of a mobile mechatronic arm developed to automate crimping and controlled aluminum wire feeding into the molten steel bath. The objective of this system is to enhance process reliability, precision, and operator safety. It integrates kinematic modeling in SolidWorks, SKF bearing assemblies, and component fabrication by fused deposition modeling (FDM) 3D printing using polylactic acid (PLA) with optimized parameters. The control system is implemented through an Arduino UNO platform that is equipped with a joystick and keypad interface, which operates SG90 and S3003 servomotors. The continuous wire feeding process is facilitated by a direct current (DC) motor that is connected to a gearbox and a gear-roller transmission. The motor is powered by a lithium cell. Preliminary experimental testing confirmed the operational feasibility of the system, while concomitantly highlighting the necessity for enhanced servo torque, refined thermal management mechanisms, and the incorporation of a Battery Management System (BMS) with closed-loop control for industrial implementation. The present study addresses the need for localized automation of metallurgical processes by developing a demonstrative prototype capable of controlled wire feeding and crimping operations. This prototype serves as a laboratory-scale proof of concept for future industrial implementation.

KEY WORDS: PLA Components; Crimping System; Control Architecture; Safety Improvement; Functional Prototype

1. INTRODUCTION

In the contemporary industrial context, the competitiveness and sustainability of manufacturing processes are contingent on the extent to which automation and the integration of mechatronic systems within production flows are employed [1,2,3]. In the steel industry, the processes of alloy addition and dosing represent critical stages, as they directly influence the chemical homogeneity, structure, and mechanical properties of the final steel. One of these essential operations is the controlled feeding of aluminium wire into the molten bath, a procedure that is widely used for deoxidation and refining [4,5,6,7,8,9].

Conventional feeding methodologies, predicated on manual manipulation or semi-automated apparatuses, continue to exhibit significant constraints with regard to dosing accuracy, reproducibility, and operator safety [10,11,12]. The presence of personnel in close proximity to elevated temperatures, the incorporation of alloy additions in variable quantities, and the absence of synchronization with subsequent refining stages have been identified as factors contributing to the

inefficiency and difficulty in standardizing these processes [13,14].
Consequently, contemporary industrial trends are directed towards local automation solutions that are characterized by flexibility, cost-effectiveness, and ease of adaptation to existing installations [15,16]. Within this context, mechatronics provides the ideal framework for designing autonomous and intelligent systems capable of performing high-precision operations under harsh industrial conditions [17,18]. A mechatronic arm, designed for crimping and aluminium wire feeding, can be utilized to replace manual interventions. This ensures programmable trajectories, controlled dosing, and reduced reaction times. The integration of electronic control, precise actuation, and optimized mechanical structures has been demonstrated to result in significant improvements in process efficiency, safety, and repeatability [19,20,21].
The present paper introduces the conception, three-dimensional design, and functional realization of a mobile mechatronic arm prototype developed for the automation of the crimping and aluminium wire feeding process into the molten steel bath. The proposed project capitalizes on the advantages of modern three-dimensional (3D) modelling and additive manufacturing technologies, specifically Fused Deposition Modeling (FDM) using Polylactic Acid (PLA) filament, combined with a control architecture based on the Arduino UNO microcontroller platform. The system utilizes servomotors of the SG90 and S3003 variety, in conjunction with a crimping mechanism that is driven by a direct current (DC) motor and a metal gearbox. An independent power supply, provided by a 18650 lithium-ion (Li-ion) battery, completes the system. The proposed solution employs modular design and accessible components, demonstrating the feasibility of achieving precise and safe automation of the crimping process. In addition, it provides an experimental foundation for future developments, including the integration of a Battery Management System (BMS), closed-loop control, and a Human–Machine Interface (HMI). This approach is consistent with the strategic direction of industrial process digitalization within the framework of the Industry 4.0 concept, offering a practical mechatronic automation application adapted to the specific requirements of the steelmaking environment. In light of these considerations, the subsequent section delineates the design methodology and component selection for the proposed prototype. In consideration of the aforementioned industrial requisites, the document under consideration herein presents the conceptualization, fabrication, and functional evaluation of a mobile mechatronic arm that has been developed for the purpose of automating the crimping and aluminum wire feeding process.

2. MATERIALS AND METHODS

The experimental study was conducted through a series of design, modeling, fabrication, and control implementation stages. The system was conceptualized as a mobile mechatronic arm comprising multiple mechanical modules, including the base, translation support, lateral support, rotary support, guide and extension pipes, and the terminal gripper designed for crimping operations. The mechanical structure was designed in SolidWorks, where each component was modeled parametrically and assembled into a kinematic simulation of the full arm movement. The design was meticulously crafted to strike a balance between rigidity, weight reduction, and ease of assembly. The final virtual assembly of the complete arm is shown in Figure 1.

Figure 1. Complete mobile arm assembly

To enable low-cost prototyping, all components were fabricated using FDM additive manufacturing technology, with PLA filament serving as the primary material. The optimized printing parameters were as follows: The printer's operational parameters include a layer height of 0.2 millimeters, a print speed of 50 millimeters per second, and an infill density of 50%. These parameters were selected to achieve an optimal compromise between mechanical strength, dimensional accuracy, and fabrication time. While the selected material (PLA) is deemed suitable for laboratory-scale prototyping, it is not intended for direct industrial use, where the necessity of metallic or composite components would be essential. Subsequent to this, the printed parts were finished and assembled using mechanical fasteners and standardized SKF ball bearings (Figure 2). The purpose of this assembly was to reduce friction and ensure rotational precision.

Figure 2. Model SKF

The electronic control system was developed on an Arduino UNO microcontroller platform. The motion control apparatus utilized two types of servomotors: SG90 micro servos, which were employed for small angular motions, and S3003 standard servos, which were utilized for joints requiring higher torque (see Figure 3). The implementation of manual operation and calibration entailed the utilization of a 4x4 keypad and a joystick interface, which functioned as a conduit for transmitting movement commands to the Arduino board (Figure 4). To prevent voltage drops and ensure stable operation, each servo channel was powered through an independent supply circuit.

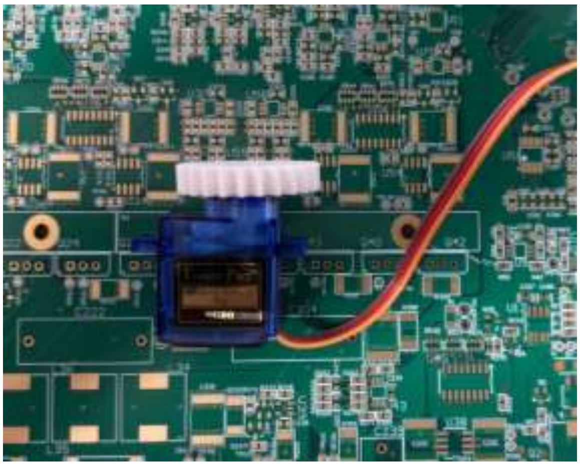

Figure 3. SG90 servomotor in working position

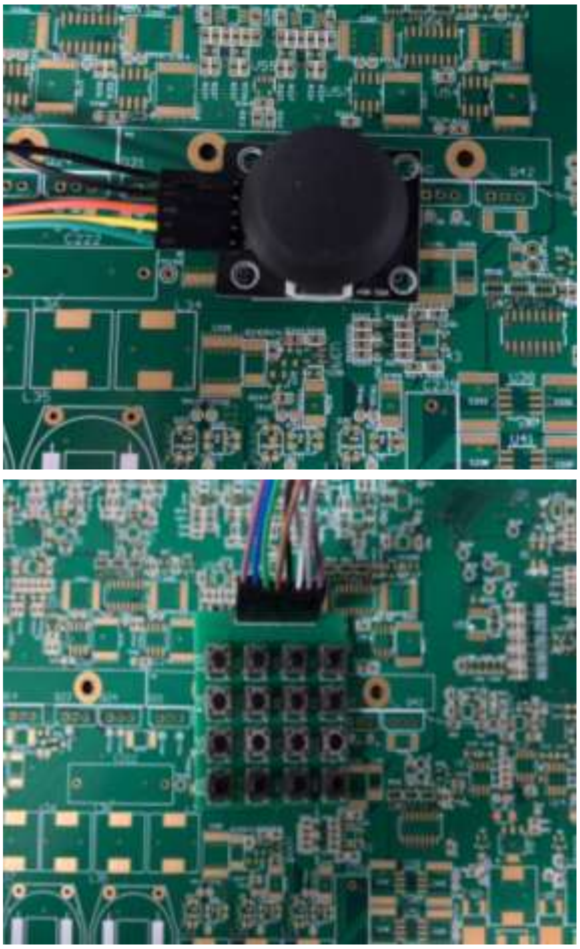

Figure 4. Joystick and keyboard connected to Arduino board

As illustrated in Figure 5, the wiring and logic diagram demonstrate the implementation of several key components, including the separation of power lines, the incorporation of protection diodes, and the integration of filtering capacitors to ensure voltage stabilization.

The prototype's firmware was developed using the Arduino IDE, incorporating libraries for servo actuation and analog input reading from the joystick. To complement the arm, a dedicated crimping and wire-feeding device was designed and fabricated. This module integrates a direct current (DC) motor with a metal gearbox, a gear-roller transmission mechanism, and a double pole double throw (DPDT) switch to reverse the feeding direction.

The operating principle is illustrated in Figure 6. The device's power is derived from an 18650 lithium-ion (Li-ion) rechargeable cell, a component that facilitates both mobility and autonomy. The mechanical subassembly is mounted on the same platform as the arm to ensure synchronized movement and continuous wire feeding. The assembly of all subsystems into a functional prototype was conducted, followed by the implementation of operational calibration procedures.

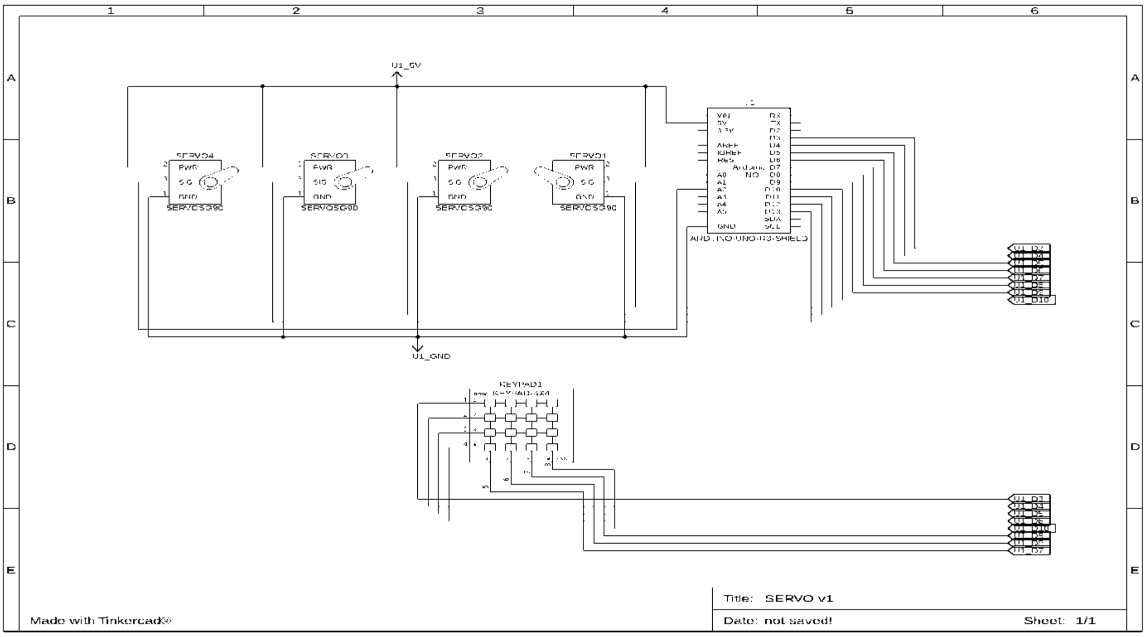

Figure 5. Electrical diagram for power supply and connection of modules

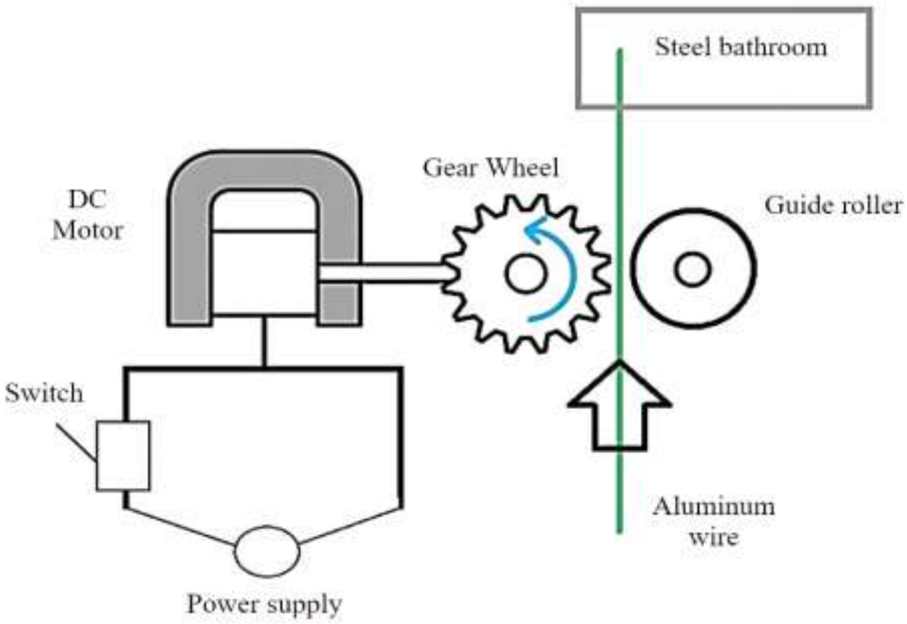

Figure 6. Schematic representation of the crimping mechanism

3. PROTOTYPE TESTING AND PERFORMANCE EVALUATION

Following the comprehensive assembly of the mobile mechatronic arm and the crimping–feeding module, experimental tests were conducted to evaluate the functional behavior, motion precision, and system stability. The objective of this stage was twofold: first, to validate the feasibility of the proposed automation solution, and second, to identify potential improvements for industrial implementation.

The kinematic verification was executed through direct manual operation using the integrated joystick and numeric keypad of the control interface. The resulting movements accurately followed the programmed trajectories, and the SG90 and S3003 servomotors provided precise actuation of the articulated joints. During continuous operation, a slight increase in servo temperature was observed, a phenomenon associated with constant torque loads. This indicates the need for improved thermal management or the use of higher-torque actuators.

The crimping and wire-feeding mechanism operated reliably, ensuring uniform advancement of the aluminum wire and consistent crimping performance. The geared DC motor exhibited stable rotational speed (see Figure 7), while the DPDT switch facilitated rapid reversal of rotation direction, thereby enabling wire repositioning between working cycles. The system operated without mechanical blockage, and the supporting structure remained stable throughout the testing process. The independent power supply, based on a 18650 lithium-ion cell, provided stable and continuous energy delivery during the functional tests, with only minor voltage drops observed during simultaneous servo activation. These fluctuations underscore the necessity of integrating a Battery Management System to oversee and safeguard the supply circuit and to enhance current distribution.

From a mechanical standpoint, the components manufactured through FDM using PLA maintained their structural integrity throughout testing, with no visible deformation or joint displacement. This finding validates the efficacy of PLA for lightweight mechatronic applications where moderate dynamic load resistance is adequate.

The results obtained demonstrate that the prototype fulfills its primary design requirements, including precise and repeatable motion, stable wire feeding, safe operation, and adequate energy autonomy. The identified limitations — servomotor heating, minor voltage variations, and the absence of position feedback — can be addressed by integrating a closed-loop control system, optimizing the actuation components, and implementing a dedicated Printed Circuit Board (PCB) with a Human–Machine Interface (HMI) for improved command and monitoring capabilities.

Figure 7. The DC geared motor

4. CONCLUSIONS AND FUTURE DIRECTIONS

The experimental development and testing of the mobile mechatronic arm have demonstrated the technical feasibility of automating the crimping and aluminum wire feeding process through an integrated mechanical–electronic approach. The proposed system successfully integrates low-cost additive manufacturing with accessible control technologies, thereby providing a functional prototype capable of performing precise and repeatable operations under realistic conditions.

From an analytical perspective, the experimental results confirm that the chosen kinematic configuration and actuation strategy are suitable for semi-industrial automation tasks. The SolidWorks-based design ensured structural stability, while the FDM-printed components achieved sufficient rigidity for repeated operation cycles. The utilization of open-source control hardware (Arduino UNO platform) and standard SG90/S3003 servomotors substantiated the viability of accessible mechatronic components for functional prototyping and educational research. The primary limitations identified — localized servo heating, moderate torque capacity, and voltage drops during peak demand — do not compromise the fundamental operation but indicate the need for optimization in future iterations. The integration of a Battery Management System (BMS), closed-loop feedback control, and a dedicated Printed Circuit Board (PCB) with Human–Machine Interface (HMI) is expected to enhance system reliability, responsiveness, and user interaction.

From a broader perspective, the present work demonstrates how rapid prototyping and digital control integration can accelerate the transition toward locally automated systems that are aligned with Industry 4.0 principles. The project makes significant contributions to the field, both in terms of theoretical concepts and practical applications. It demonstrates an adaptable, modular, and cost-efficient approach to process automation in metallurgical environments.

In summary, the developed prototype validates the functional concept of a compact mechatronic system designed for automated crimping and controlled wire feeding. Despite its implementation at a laboratory scale, the prototype demonstrates the technical feasibility of the approach and can serve as a foundation for scaling toward industrial applications.

The obtained results confirm the potential of such systems to enhance operational safety, dosing precision, and process repeatability when adapted to larger-scale configurations. Subsequent advancements will prioritize mechanical reinforcement, actuator optimization, and the incorporation of advanced control modules, thereby facilitating comprehensive industrial implementation.

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