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Proposal of a Flying-Cutting Plant for the Development of Control Systems in Academic Environments*

Diego Fernando Ramírez-Jiménez*

Abstract: This paper presents a proposal for a flying-cutting plant designed using the SketchUp tool for 3D modeling and constructed with electronic devices and other low-cost components. The proposed prototype aims to facilitate the implementation of control strategies in academic settings, such as laboratory practices. The primary contribution of this work is the development of a scaled, cost-effective industrial prototype that can be operated and controlled using various software and hardware tools. The plant features a conveyor belt and a mechanical arm for continuous cutting, enabling it to emulate the operation of large-scale industrial processes. To validate the design, the plant was simulated using a continuous and discrete transfer function as its mathematical representation, obtained through an identification process performed with MATLAB's PID Tuner. Performance tests were then conducted using tools such as Simulink and Code Composer Studio by Texas Instruments. After validation, operation and shear tests were carried out on the physical prototype, employing a classical control technique.

Keywords: 3D Modeling; Academic Environments; Digital Control; Flying Shear; Flying-Cutting Plant; Industrial Prototype; Real-Time Control

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a Electronic Engineer, Universidad del Quindío, Armenia Q., Colombia. M.Sc. Electronic Engineering, Universidad del Valle, Cali, Colombia. Full professor at the Electronic Engineering at the Universidad del Quindío, Armenia., Colombia.
Email: dframirez@uniquindio.edu.co; ORCID: https://orcid.org/0000-0001-9050-666X

Propuesta de Planta de Corte Volador para el Desarrollo de Sistemas de Control en Ambientes Académicos

Resumen: Una propuesta de planta de corte al vuelo es presentada en este artículo. La planta fue diseñada usando la herramienta SketchUp para modelado 3D y construida usando dispositivos electrónicos y otros elementos de bajo costo. El propósito del prototipo propuesto centra su aplicación en entornos académicos a través del desarrollo de estrategias de control en prácticas de laboratorio. Una contribución importante del trabajo realizado estuvo en el diseño de un prototipo industrial a escala y de bajo costo, que brinda la posibilidad de ser operado y controlado a través de diferentes sistemas embebidos que integran elementos tanto a nivel de software como de hardware. La planta cuenta con una banda transportadora y un brazo mecánico para corte continuo que permite emular el funcionamiento de procesos industriales de gran escala. Como resultados, se realizaron simulación de la planta mediante una función de transferencia continua y discreta como representación matemática, la cual fue obtenida a través de un proceso de identificación realizado en PIDTuner de MATLAB. Posteriormente, se realizaron pruebas de desempeño a través de herramientas como Simulink y Code Composer Studio de Texas Instruments y, una vez validado su funcionamiento, se implementaron pruebas de operación y de corte en el prototipo construido empleando una técnica de control clásica.

Palabras clave: Modelamiento 3D; Ambientes Académicos; Control Digital; Cizalla Volante; Planta de Corte al Vuelo; Prototipo Industrial; Control en Tiempo Real

Proposta de planta de corte volante para o desenvolvimento de sistemas de controle em ambientes acadêmicos

Resumo: Uma proposta de planta de corte em voo é apresentada neste artigo. A planta foi projetada utilizando a ferramenta SketchUp para modelagem 3D e construída com dispositivos eletrônicos e outros elementos de baixo custo. O propósito do protótipo proposto centra sua aplicação em ambientes acadêmicos por meio do desenvolvimento de estratégias de controle em práticas de laboratório. Uma contribuição importante do trabalho realizado foi o design de um protótipo industrial em escala e de baixo custo, que possibilita sua operação e controle através de diferentes sistemas embarcados que integram elementos tanto de software quanto de hardware. A planta conta com uma esteira transportadora e um braço mecânico para corte contínuo, permitindo emular o funcionamento de processos industriais de grande escala. Como resultados, foram realizadas simulações da planta por meio de uma função de transferência contínua e discreta como representação matemática, obtida através de um processo de identificação realizado no PIDTuner do MATLAB. Posteriormente, foram conduzidos testes de desempenho utilizando ferramentas como Simulink e Code Composer Studio da Texas Instruments e, após a validação de seu funcionamento, foram implementados testes de operação e corte no protótipo construído, empregando uma técnica de controle clássica.

Palavras-chave: modelagem 3D; ambientes acadêmicos; controle digital; cortador de parafusos volante; planta de corte em voo; protótipo industrial; controle em tempo real

Introduction

The training of new engineers in automation and control requires knowledge and close contact with processes developed in the industry. However, this proximity, particularly with large manufacturing companies, is sometimes limited or even nonexistent due to the lack of large companies or facilities with automated systems that train engineers to meet regional needs. An example of this is observed in the department of Quindío, Colombia, where manufacturing companies in 2021 contributed only about 6.5% of the Gross Value Added (GVA). This contrasts with departments like Valle del Cauca, where the manufacturing industry occupies large areas and, in the same year, contributed approximately 72.4% of the department's GVA [1], [2].

An alternative in educational practices to keep engineering students in contact with the daily challenges of the industry is to strengthen training in areas such as analog electronics, digital electronics, dynamic systems, automation, and process control. This ensures that students not only develop skills in process supervision and management but also gain the ability to design test plants that enhance their learning. In the laboratories of the Electronic Engineering program at Universidad del Quindío, there are few test plants capable of emulating large-scale industrial processes in diverse contexts and scenarios beyond the academic environment. In recent years, test plants have gained special relevance due to the importance of process automation and control in companies and the alignment of academia with these needs [3].

For this reason, this research presents a prototype of a flying-cutting plant and its application in educational settings for automation and control within the Electronic Engineering program at Universidad del Quindío.

Applied research activities aimed at developing laboratory equipment or prototypes that emulate industrial processes are increasingly common in public higher education institutions in Colombia. This trend responds partly to the free education policy implemented by the national government in public higher education institutions [4], which has reduced funds previously generated by tuition fees, potentially threatening the financial sustainability of higher education [5]. Additionally, the high cost of didactic equipment from major manufacturers such as Festo, where a station designed to emulate an industrial process can cost around $60,000 USD [6], presents another significant challenge. Laboratory-scale equipment is essential for process automation, automatic control in companies, and integrating academia with industry [7], facilitating effective learning strategies.

The value of academic work in automatic control and automation lies in fostering skills such as resource optimization, process knowledge, evaluation of alternatives, and time management in tasks requiring precision. Various studies highlight these themes. For example, [7] presents a methodology for process automation using Allen-Bradley PLC programming. In [8], the control of a flying shear with electronic cams is described using a DC universal servo controller. In [9], Solidworks/COSMOS Motion and MATLAB/SimMechanics were used to develop a three-dimensional model for a centrifugal flying shear. Similarly, [10] applied a direct torque controller (DTC) to improve torque control in a steel mill flying shear system. Other works, such as [11], modeled the behavior of a flying shear using SolidWorks, conducting kinematic analyses of the three-dimensional design with assembly and animation.

These studies demonstrate that applications in flying-cutting plants often focus on cutting speed control and dynamic modeling, generally at the simulation level, as in [12], which emphasized the design of mechanical parts for cutting precision while neglecting critical aspects of implementation and validation of control systems using electronic devices. Some studies have progressed to validation in physical systems, such as [13], where a real-time FPGA-based controller was developed for application in hot rolling mill flying shears, utilizing tools like VHDL and Xilinx ISE. In [14], hardness tests, energy dispersive spectroscopy (EDS), and scanning electron microscopy (SEM) were employed on flying cutter blades. Additionally, [15] presented a test plant for remote connection to an industrial and mobile robot using Java Servlets.

This study introduces a prototype of a flying-cutting plant for academic use in automation and control within the Electronic Engineering program at Universidad del Quindío. The plant is controlled by a C2000 microcontroller, using the Texas Instruments LAUNCHXL-F28379D development kit to validate its operation. The methodology adopted offers a significant contribution to control and automation engineering by providing a practical approach replicable in educational settings and applying advanced control strategies across various experimental models. Supported by the CDIO (Conceiving - Designing - Implementing - Operating) initiative for engineering education [16], this methodology allows students to interact with real physical systems, facilitating the understanding of theoretical concepts through hands-on experimentation. Moreover, the system can be adapted to different control schemes and techniques, transforming the prototype into a versatile platform that bridges the gap between theory and practice in engineering education.

At a theoretical level, this research contributes to the body of knowledge in control and automation by conducting detailed analyses and modeling the dynamic behaviors of real systems implementable in laboratories, covering classical aspects of system dynamics and PID controllers. Furthermore, it explores the interaction between system mechanics and controller responses, analyzing how variations in operating conditions affect system performance. Finally, the implementation and operation of the proposed prototype not only enhance the understanding of control systems in industrial applications but also lay the groundwork for future research aimed at improving the accuracy and efficiency of automated systems in complex industrial environments.

The conducted research provides several significant contributions, detailed as follows:

- **Application of Real-Time Microcontrollers:** Utilization of microcontrollers specifically designed for real-time control in various industrial sectors, including precision agriculture, automotive, medical, automation, motor control, power electronics, and others [17].
- **Digital Controller Design and Implementation:** Development of fully digital controllers where signal processing, process variable management, and controller structures are executed entirely within the microcontroller.
- **Development of a Versatile Test Plant:** Creation of a full-scale, modular, compact, robust, and cost-effective test plant. This platform enables students from the Automation and Control Department of the Electronic Engineering program at Universidad del Quindío to perform exercises and validate real industrial processes within an academic environment, mirroring rapid prototyping methodologies [18].
- **Research Initiatives with Industrial Relevance:** Promotion of research lines and projects that engage with the industrial sector, focusing on implementing efficient solutions for process improvement.
- **Emphasis on Technical Construction:** Development of prototypes that prioritize the technical aspects of their construction, including mechanical design, rather than focusing solely on control strategies or simulation-level modeling.

The content of this work is organized into the following sections:

Chapter II: Provides a concise review of the design and construction processes of the flying-cutting plant, the system dynamics modeling, and the controller used to validate its operation.

Chapter III: Details the results obtained from performance tests conducted on the flying-cutting system, both at the simulation and implementation levels.

Chapter IV: Concludes the research with the main findings and insights derived from the developed aspects of the study.

Materials and methods

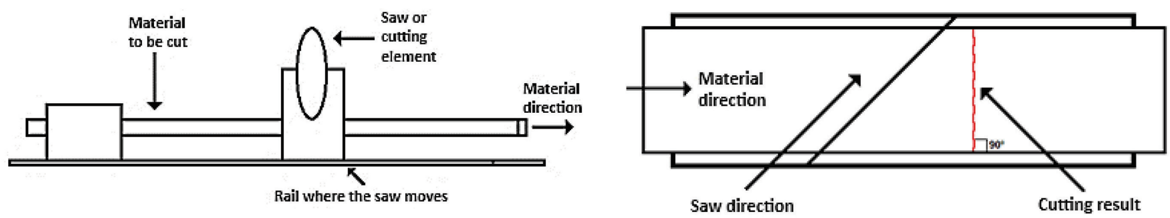
Materials

Flying-cutting plant

This paper presents the design and implementation of a flying shear system. Flying shearing machines, or flying shears, are continuous cutting mechanisms that operate either in synchrony between the blade and the material in motion or by adjusting speeds with the aid of additional electronic devices.

Various types of flying shears exist, often defined by their manufacturers. For instance, the Chinese company RISHBIN offers a range of flying shears for cutting metal plates and categorizes them based on the type of cut into rotary, crank-operated rotary lever, eccentric crank, and pendulum machines [19]. Figure 1 illustrates diagrams of some of the different types of industrial flying-cutting systems currently in use.

Figure 1. T1 type fly-cutting plant (left) and T2 type fly-cutting plant (right)



Source: The authors.

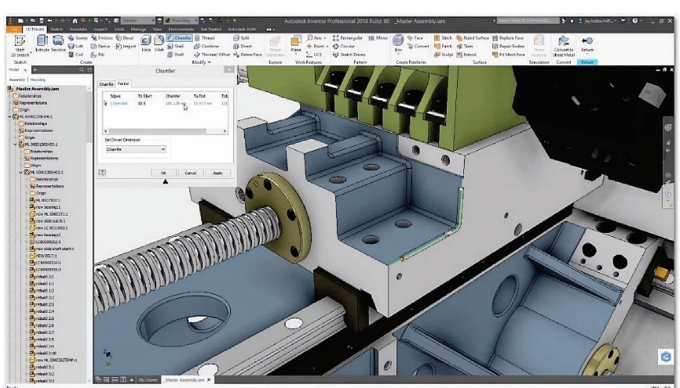
SketchUp 3D

SketchUp is a versatile 3D modeling tool widely used across various fields of engineering and design. Initially developed by Last Software and later acquired by Trimble Inc., SketchUp enables the creation of detailed 3D models using a surface-based approach and vector geometry.

One of SketchUp's key strengths lies in its intuitive user interface, which simplifies the manipulation of 3D models and drawing tools. Beyond designing mechanical components, the tool also supports their simulation and assembly, making it a valuable resource for comprehensive project development.

In terms of accessibility, SketchUp offers a free version (SketchUp Free), as well as educational versions with full functionality (SketchUp Pro), making it particularly suited for academic environments and fostering learning in various disciplines [20]. An example of the SketchUp desktop user interface is shown in Figure 2.

Figure 2. SketchUp user interface for desktop application



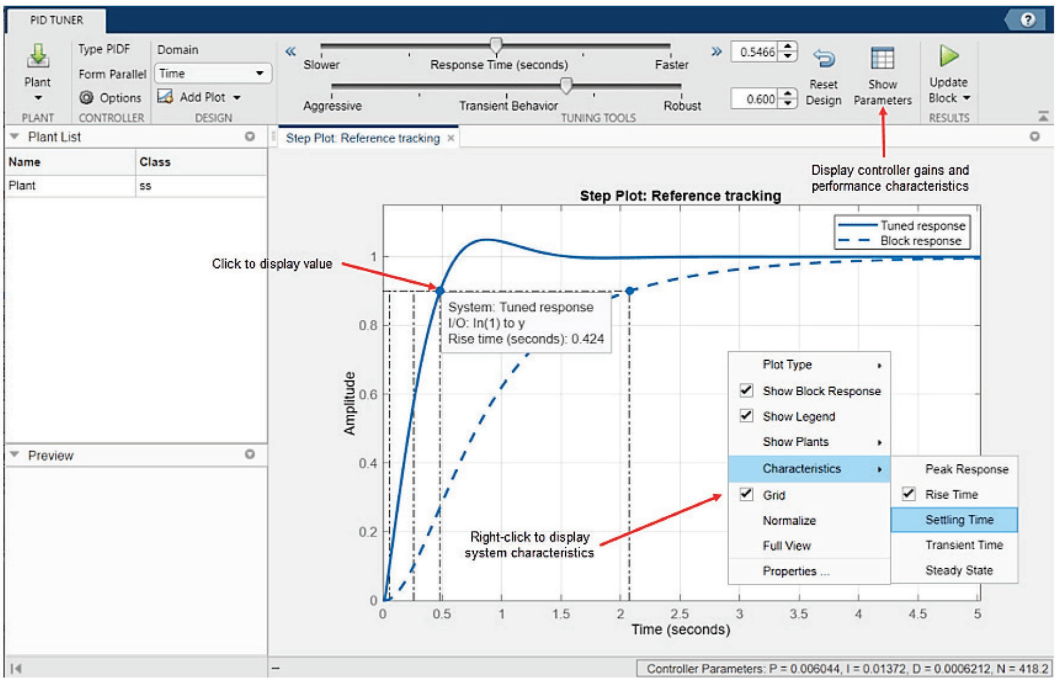
Source: [21].

PID Tuner

MATLAB offers a variety of tools and functions for designing and tuning PI-PID controllers and their various variants. Among these tools are the Sisotool, Control System Designer, and PIDTuner, among others. PIDTuner is particularly useful for interactively tuning and adjusting PID controllers through an intuitive graphical user interface. It features sliders that allow for the automatic adjustment of controller parameters to meet specified system performance requirements.

One of the key advantages of PIDTuner is, its ability to select different variations of controller configurations, such as standard or optimal, and to provide options for adjusting the controller structure as needed [22]. Figure 3, illustrates the MATLAB PIDTuner graphical user interface.

Figure 3. MATLAB PIDTuner graphical user interface



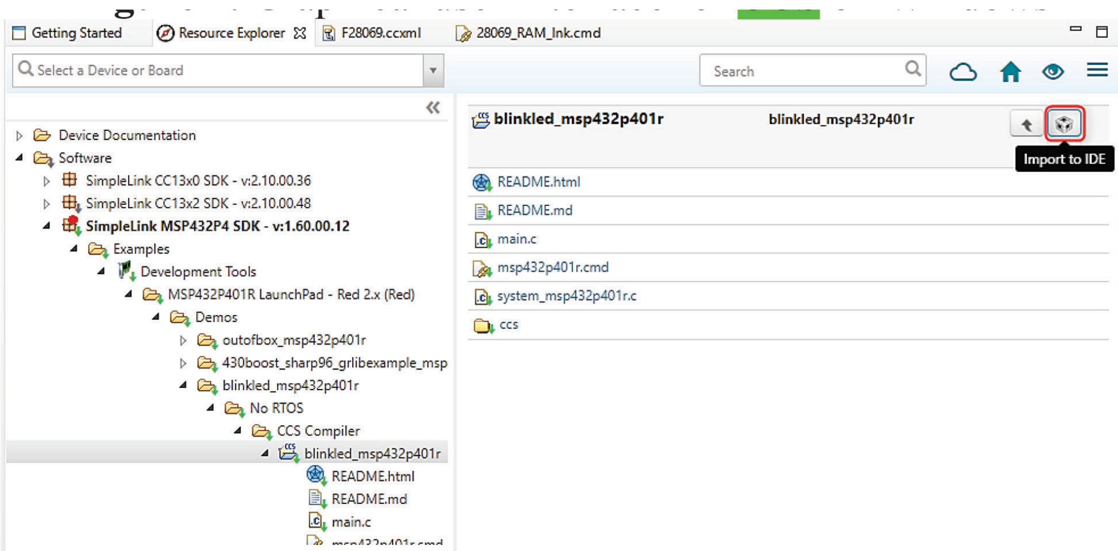
Source: [23].

Code Composer Studio – CCS

Code Composer Studio (CCS) is Texas Instruments' integrated development environment (IDE) designed for software development and programming of its microcontrollers and processors, including the MSP430, Tiva C, and C2000 series. Key features of CCS include an advanced code editor, real-time debugging tools, support for multiple TI devices, and simulation capabilities.

CCS also offers integration with other IT tools and version control systems, providing access to documentation and resources through the TI Resource Explorer. Its primary advantage over other platforms is its specific optimization for TI devices, comprehensive support, advanced debugging tools, and continuous updates for TI hardware. Figure 4, shows an example of the CCS graphical interface for Windows.

Figure 4. Graphical user interface for ccs on Windows



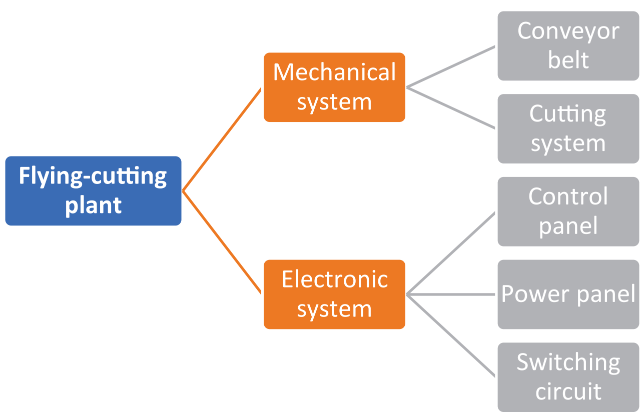
Source: The authors.

Methods

Proposed prototype structure

Figure 5, illustrates the proposed design of the structure on which the flying-cutting line is implemented. The mechanical system consists of a conveyor belt and a cutting mechanism, which operates in a three-dimensional plane through the X, Y, and Z axes. The electronic system includes the control board, which houses the peripheral devices, the power circuit that powers the main operating board, and the switching circuit. This switching circuit enables the plant to be controlled and operated either by the internal devices or by an external controller, such as a DSP, Raspberry Pi, or another embedded system. The control board facilitates access to information from the sensors and actuators.

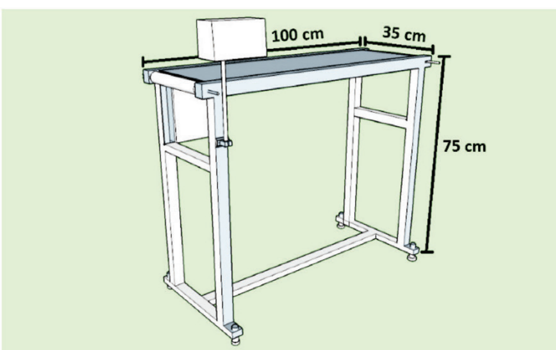
Figure 5. Block diagram showing the structure of the flying-cutting plant



Source: The authors.

The structure of the proposed plant was designed by considering the most important operational and design elements found in industrial plants and similar systems. This approach was chosen because the existing plants align with the types developed by industries such as RISHBIN [19] and Schneider Electric [24], which have been documented in the literature through previous works, such as the one conducted in [25]. Based on the results of the analysis described above, and with the goal of creating a plant that is easy to transport, modular (allowing the cutting system and conveyor belt to be used independently in other projects), low-cost, and easily repairable (with the ability to replace broken components quickly), we designed a 3D flying-cutting plant model in SketchUp. This design is open to be operated and controlled using various microcontroller and DSP technologies, including open-source solutions. Figure 6 presents the resulting model.

Figure 6. 3D model of the proposed flying-cutting plant prototype



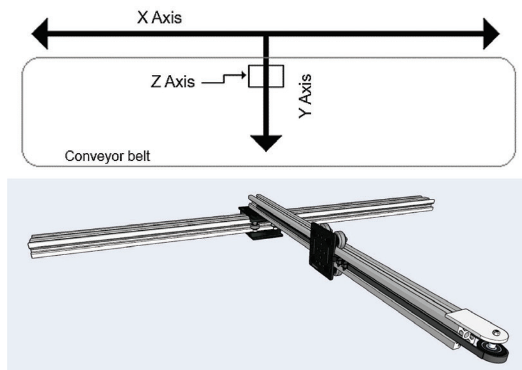
Source: The authors.

Cutting mechanism

One of the key factors that demonstrates the efficacy of the system is its ability to execute an accurate cutting trajectory, characterized by smoothness and the absence of erratic movements. Achieving these qualities requires precise alignment of the components that make up the cutting system, as well as high precision in the motors or actuators that dynamically integrate the cutting mechanism.

The system design is based on the X and Y coordinates, which are controlled by two motors, and a Z-axis coordinate, facilitated by a servo, for both the layout and subsequent cutting processes. After conceptualizing the cutting system, it was essential to consider various kinematic aspects for its design and implementation, along with the movement area of the conveyor and the spatial layout. Larger operational areas necessitate extended rails for the X and Y axes. Figure 7, illustrates the coordinate design for the cutting system and its 3D model, which was developed using SketchUp.

Figure 7. Coordinate design and SketchUp 3D model for cutting system



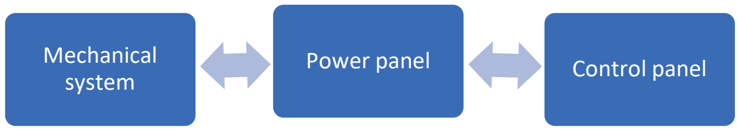
Source: The authors.

Electronic circuits

The circuits have been carefully engineered to ensure both the scalability of the system and the seamless interconnection of its various modules, as outlined in the block diagrams shown in Figures 8 and 9. These figures illustrate the interconnection of the overall system, categorizing it into three main components: the mechanical system, which includes the limit switches, encoders, motors, and servos; the power board, which houses the drivers and the necessary conditioning equipment to manage sensors, actuators, and the Texas Instruments LAUNCHXL-F28379D development kit; and the control board, which serves as the user interface for the fly-by-wire cutting system.

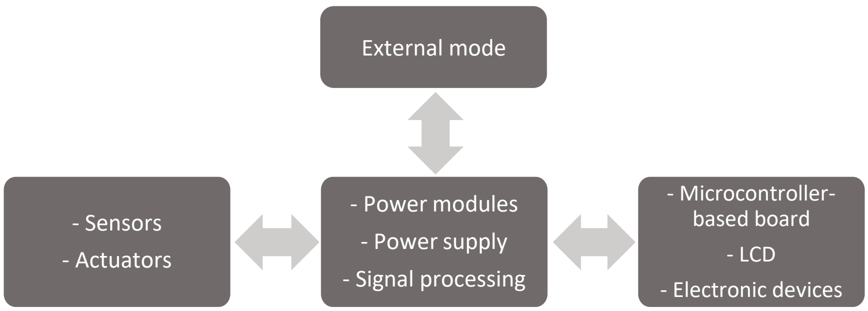
In addition to these three groups of electronic systems, Figure 9 further demonstrates that the flying-cutting system incorporates an external management or control module.

Figure 8. General wiring diagram for the flying-cutting plant



Source: The authors.

Figure 9. Internal diagram of the devices, connections, and external mode of the modules shown in Figure 8

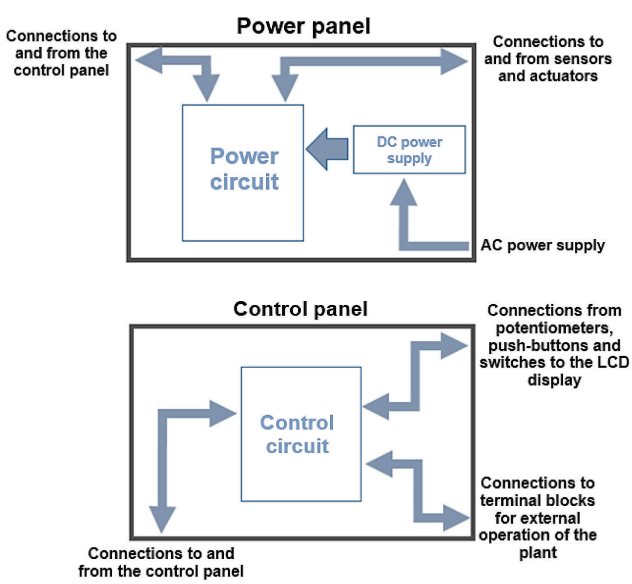


Source: The authors.

Power and control panels

The protection of the electronic circuits, wiring connections, and power supply was accomplished through two panels that organize and manage the various sensors and actuators of the plant. Figure 10, shows the block diagrams of the power and control panels. In the first panel, the connections from the actuators and sensors of the mechanical system are consolidated. The entire system is powered by a switched-mode power supply with 5V and 12V outputs, which are fed directly to the power circuit and then distributed to the other devices. The second panel consolidates the connections from the power supply board and the interface devices that are part of the graphical user interface.

Figure 10. Block diagram for the power panel

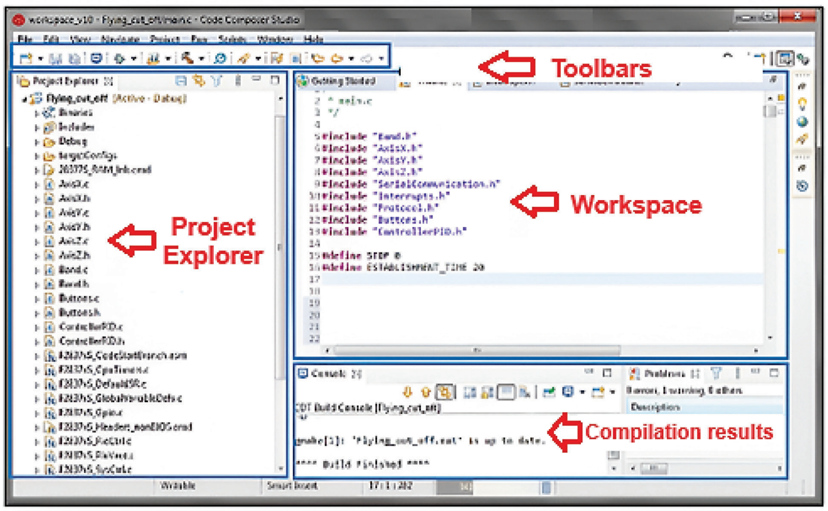


Source: The authors.

Environment and programming structure

The integration of all functionalities of the flying-cutting plant was achieved through programming the LAUNCHXL-F28379D development kit, which is responsible for processing the various signals coming from the sensors and control panel. There are several alternatives for programming these embedded systems. One option is Energia, an open-source IDE based on the Arduino framework, which, as demonstrated in [17], facilitates programming for some of Texas Instruments' boards and embedded kits. Another option is to use CCS, which supports all development kits and microcontrollers manufactured by Texas Instruments. For this research, CCS was chosen because it provides comprehensive support for all C2000 microcontrollers and allows access to all their functionalities. Figure 11, shows the CCS IDE for developing projects and applications for TI C2000 microcontrollers.

Figure 11. CCS graphical user interface



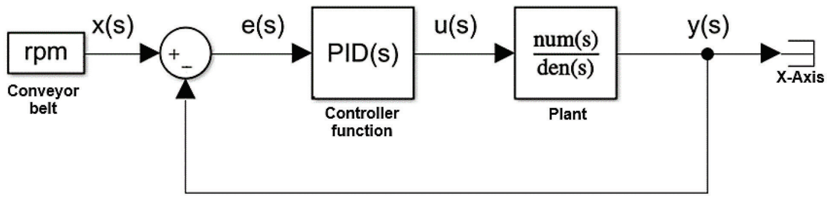
Source: The authors.

Control strategy

The control system for the plant must ensure that the cutting system creates a perpendicular trace on the conveyor belt while it is in motion. If the belt speed varies, the cutting system must adjust to match the speed of the belt; otherwise, the trace will be irregular. A fundamental aspect of the control strategy is to ensure that both speeds (X-axis and conveyor belt) are synchronized, and that the trace forms a 90° angle with the horizontal (X-axis). We selected a classical control technique, specifically the Proportional-Integral (PI) controller. This approach allows us to validate whether the plant meets the characteristics of systems found in industrial settings.

The PI controller can be implemented in various configurations, such as parallel, series, or standard, similar to those used for the design and implementation of PID controllers. Some basic configurations of these classical controllers are discussed in [26], [27], [28], [29], where different PI or PID controller configurations are applied to control various dynamic systems. The control loop proposed for the flying-cutting plant is shown in Figure 12.

Figure 12. Proposed control loop for the flying-cutting plant



Source: The authors.

Results

Building a conveyor belt structure

With the structure of the flying-cutting plant and its 3D model in place, construction began. The process started with the development of rollers to rotate the conveyor belt, designed for easy alignment and calibration. At one end of the belt, an 8 mm shaft bearing system was used to ensure proper alignment of the roller, which senses the traction from the motor via pulleys. This roller is a fixed drum that moves with the smooth shaft, enabling movement through the bearings. At the other end of the belt, there is a free drum roller that rotates on its own axis via bearings. This shaft is also 8 mm threaded, allowing it to be clamped at both ends after calibrating and aligning the conveyor belt. Belt alignment is achieved through grooves in the profiles where the rollers are located, using clamping nuts and tensioners to pull the shaft outward.

The belt structure was constructed using rectangular iron tubes with dimensions of 4x2 cm and a gauge of 0.8 mm. The various cuts forming the structure were joined using electrode welding, ensuring greater stability and sturdiness. One of the horizontal profiles supporting the rollers uses screws for quick and easy replacement of the conveyor belt. The construction and placement of the rollers with the pulleys, along with the conveyor belt structure, are shown in Figures 13 and 14, respectively.

Figure 13. Rollers and pulleys used in the building of the conveyor belt structure

Source: The authors.

Figure 14. Structure built for conveyor belt

Source: The authors.

Conveyor belt material

The conveyor belt is a crucial component in the development of any transport mechanism. There are various types available, and selecting the best material for its construction depends on the intended application. In this research, several conveyor belts were tested using materials such as parasol tarpaulins, polyester tarpaulins, and even foam. After multiple tests, the material selected was a 2 mm thick lamella, or microporous sheeting, coated on one side with white adhesive vinyl. The lamella adhered securely to the rollers without slipping, while the vinyl on the upper surface allowed for marking during the cutting tests. The conveyor belt installed in the constructed structure is shown in Figure 15.

Figure 15. Conveyor belt placed on the rollers of the conveyor belt structure

Source: The authors.

Cutting mechanism

The linear motion of the cutting system is achieved using V-SLOT extruded aluminum profiles and high-precision bearings, mechanisms that are commonly implemented in the manufacture of 3D printers, CNC machines, cartesian robots, and similar systems. For our plant, a working area limit of 80% of the conveyor belt surface was defined. This decision was made with the understanding that the cutting system would be scalable and could be adapted for other applications requiring cartesian movement, such as CNC machines or a modular laser cutting system. Lastly, the movement of the Z-axis is driven by a servo motor through a mechanism similar to those used in drawing machines [30], [31]. The 3D model developed in SketchUp, along with its real-world implementation, is shown in Figure 16.

Figure 16. SketchUp 3D model and real implementation for cutting system

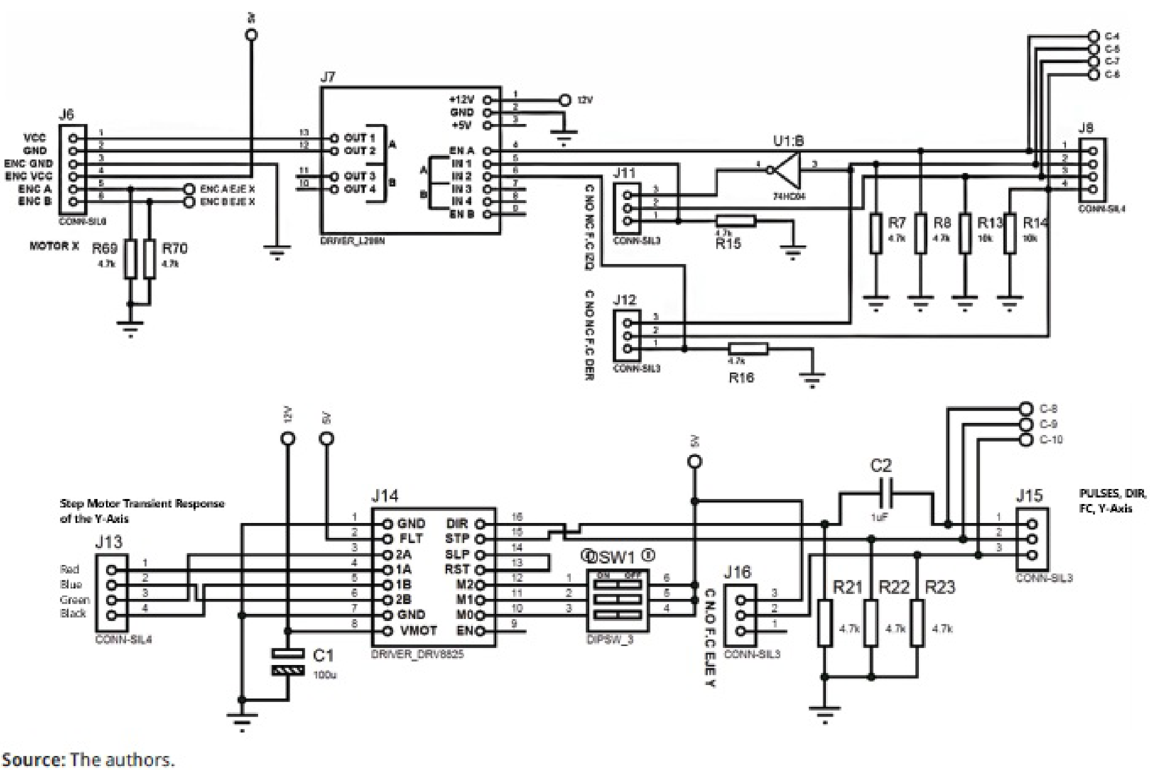
Source: The authors.

As shown in Figure 16, the real implementation of the cutting mechanism for the flying-cutting plant closely resembles its 3D model, highlighting the importance of design processes in engineering and the use of tools like SketchUp.

Power circuit

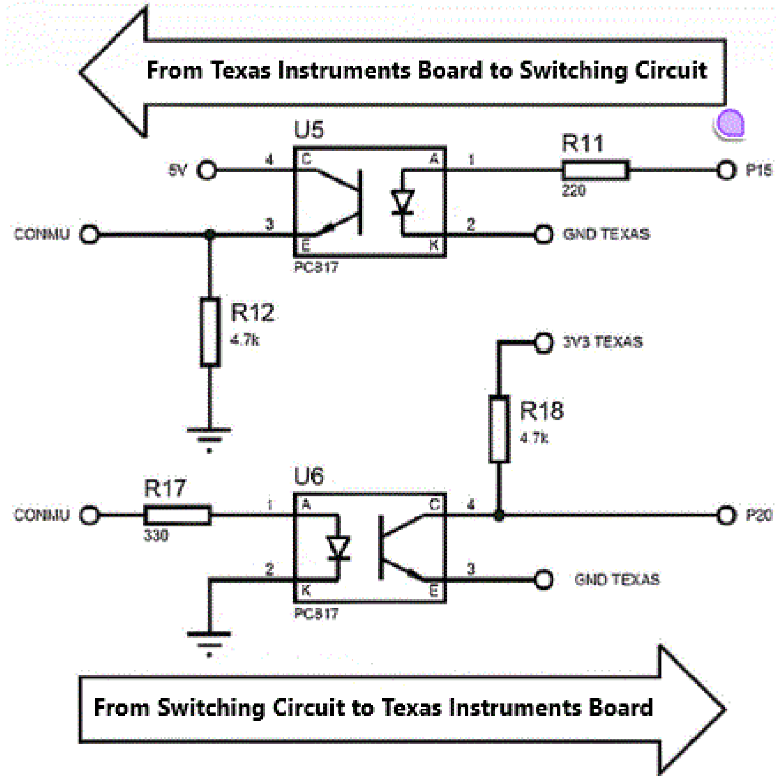
The power circuitry shown in Figure 17 utilizes an L298N driver for the gearmotors that control the conveyor belt and the X-axis of the cutting system, along with a DRV8825 driver to manage the Y-axis stepper motor in the cutting system. It also includes pins to connect the LAUNCHXL-F28379D development kit [18] and connections to the switching circuit. This circuit features terminal blocks, Molex, USB, and RJ-45 connectors for interconnecting various components of the flying-cutting plant, such as the power supply, sensors, actuators, control circuit, and programming interface, among others. An additional complement of the power circuit is presented in Figure 18, where an optocoupler isolation circuit is shown between the digital input/output pins of the Texas Instruments development kit and other electronic components of the plant. This circuit also functions as a voltage regulator, converting between 3.3V and 5V.

Figure 17. Power circuit for L298N driver - top. Power circuit for DRV8825 driver - bottom



Source: The authors.

Figure 18. Optocoupler isolating circuit

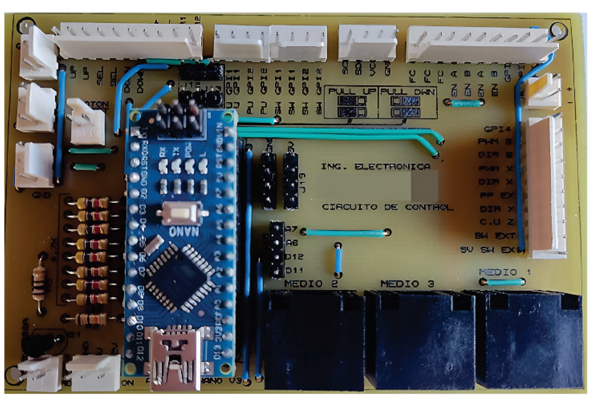


Source: The authors.

Control circuit

The control circuit functions as a bridge between the user interface and the power board. To facilitate this, the circuit is equipped with three RJ-45 ports, which enable the exchange of signals for managing sensors, actuators, serial communication, general-purpose elements, and the mode switch. The mode switch is used to define the system's operating mode (internal or external). An Arduino Nano manages the display of menu information on an LCD, processes user interaction signals, and sends the corresponding values via the serial port to the main power board. Figure 19 shows the developed control circuit

Figure 19. Control circuit for user interface and power panel

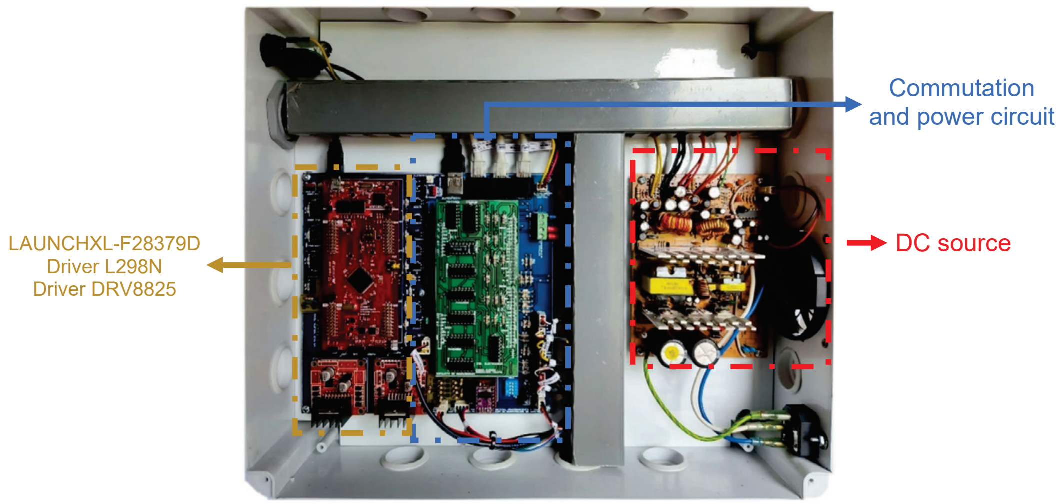


Source: The authors.

Power and control panels

After designing and fabricating the PCBs for the power, control, and commutation circuits shown in Figures 17, 18, and 19, the implementation of the power and control panels, which manage the flying-cutting plant, was completed. The finished power and control panels with their respective boards are shown in Figures 20 and 21.

Figure 20. Power panel for the flying-cutting plant



Source: The authors.

Figure 21. Control panel for the flying-cutting plant. Electrical circuits - left, graphical user interface - right

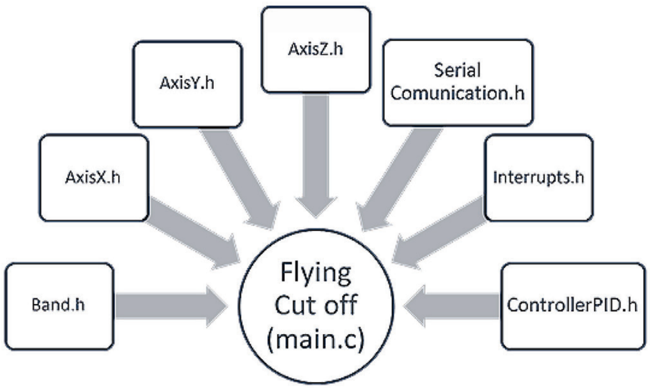
Source: The authors.

Flying-cutting plant programming

Since the software development is for an embedded system, a general file was created to compile the various files containing the necessary functions to manage the sensors and actuators in the flying-cutting plant. Figure 22, shows the libraries developed in CCS, which are loaded and executed from the Texas Instruments LAUNCHXL-F28379D development kit to manage each electronic device of the plant. For ease of understanding and use, libraries were developed for each component in the plant, with the required configuration for managing each respective actuator or sensor.

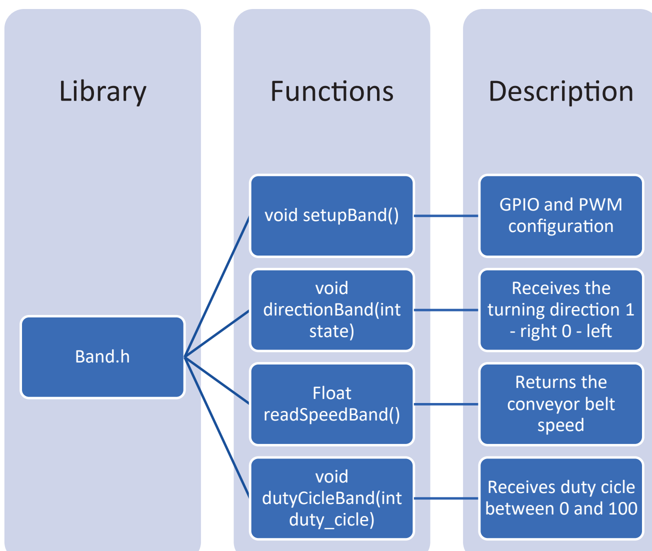
An example of using the libraries described in Figure 22 is shown in Figure 23. The conveyor belt library (Band.h) contains functions for pin configuration and PWM, as well as functions for defining the direction, duty cycle, and speed estimation of the motor encoder.

Figure 22. Libraries developed in CCS for programming the C2000 microcontroller in the LAUNCHXL-F28379D development kit



Source: The authors.

Figure 23. General content of the library developed for conveyor belt control



Source: The authors.

Design and implementation of control strategy

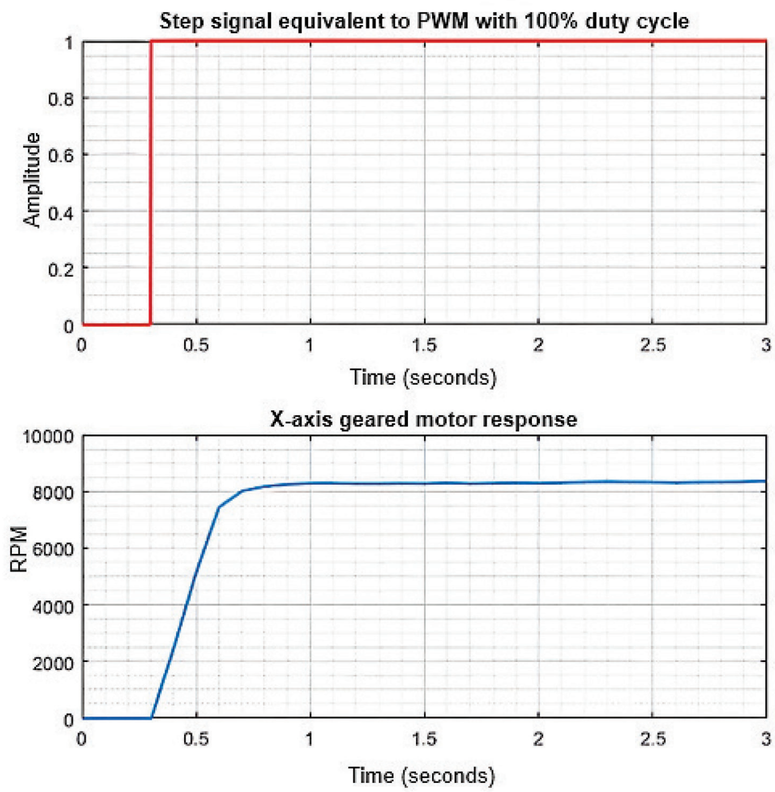
The development and deployment of the control architecture for the flying-cutting plant began with an extensive process of modeling and simulation within the MATLAB environment, aimed at thoroughly understanding its dynamic behavior. As mentioned earlier, during plant operation, the cutting mechanism must perform a perpendicular stroke to the conveyor belt movement. This means that if the conveyor belt speed varies, the cutting system must adjust its speed to match that of the belt, otherwise the cuts would be irregular.

Therefore, the control strategy in this research was designed to ensure that the speeds of both the conveyor belt and the X-axis in the cutting mechanism are synchronized, maintaining a 90° cutting angle relative to the horizontal axis of the belt. The control system will regulate the angular speed (in revolutions per minute, RPM) of the X-axis gearmotor of the cutting mechanism, while the angular speed of the gearmotor driving the conveyor belt will serve as a reference or set point.

The programming carried out in CCS to obtain the reaction curve of the actuator on the X-axis of the cutting system involved configuring and applying a PWM signal with a duty cycle ranging from 0% to 100% and reading data from its encoder. Subsequently, the PWM signal and encoder data were sent to MATLAB via the serial port to estimate a model for the system. The generated PWM signal and encoder data are shown in Figure 24.

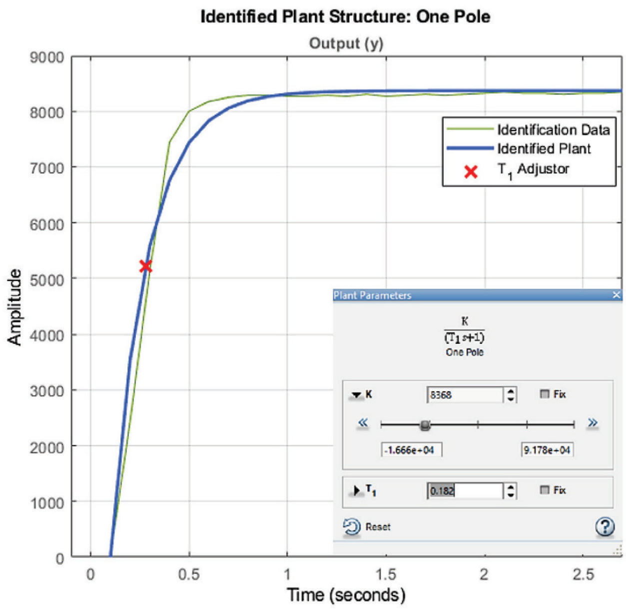
After determining the response of the X-axis gearmotor that forms the shear mechanism, MATLAB's PIDTuner was used to identify and estimate a model that represents its dynamics. Since the response exhibited first-order behavior [32], only one pole was included in the identification process. The result of the estimation in MATLAB is presented in Figure 25.

Figure 24. Transient Response of the X-Axis Gear Motor



Source: The authors.

Figure 25. Model identified with MATLAB PIDTuner



Source: The authors.

From Figure 25, the estimated transfer function is:

$$G(s) = \frac{8368.1}{0.182s + 1} \tag{1}$$

Subsequently, the tuning of the PI controller was performed using MATLAB's PIDTuner for the system described in equation (1). Recalling that the PI controller was designed using the structure of a parallel PID controller [33], [34], [35]. The parameters obtained for the PI controller are shown in Figure 26.

Figure 26. PI controller parameters obtained in MATLAB PIDTuner

Controller Parameters

	Tuned
Kp	8.6524e-05
Ki	0.00053054
Kd	n/a
Tf	n/a

Performance and Robustness

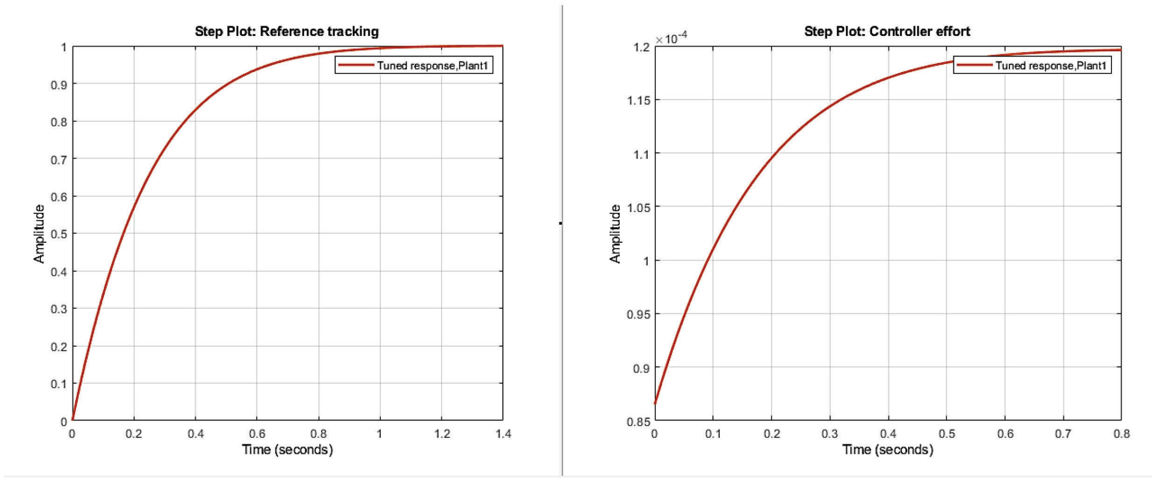
	Tuned
Rise time	0.482 seconds
Settling time	0.807 seconds
Overshoot	0.0073 %
Peak	1
Gain margin	Inf dB @ NaN rad/s
Phase margin	87 deg @ 4.27 rad/s
Closed-loop stability	Stable

Source: The authors.

The normalized step responses of the PI controller designed using the parameters from Figure 26, and the closed-loop system control effort are presented in Figure 27.

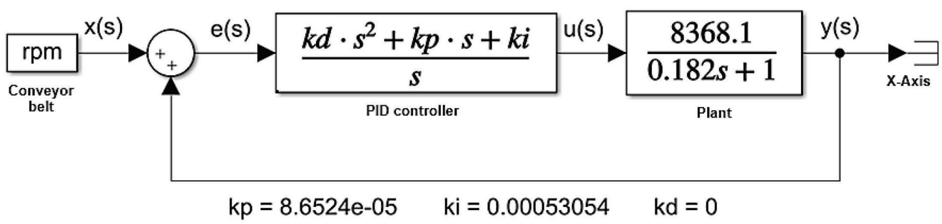
Then, the closed-loop controller for the continuous-time validation tests is presented in Figure 28.

Figure 27. PI controller parameters obtained in MATLAB PIDTuner



Source: The authors.

Figure 28. Closed-loop PI controller structure



Source: The authors.

Since the PI controller will be running on a microcontroller, a discretization process is required for the continuous model of the controller. This requires a sampling time that is a function of the processing capacity of the digital device and the mathematical analysis of the open-loop and closed-loop poles. Below is a brief description of how to calculate these poles to determine the plant sampling time.

The open-loop poles for the plant are described by:

$$s(0.182s + 1) = 0, \qquad s_1 = 0, \quad s_2 = -5.4945 \tag{2}$$

The closed-loop poles for the plant (feedback system) are described by:

$$(8.6524x10^{-5}s + 5.3054x10^{-4})8368.1 + 0.182s^2 + s = 0 \tag{3}$$

$$(8.6524x10^{-5}s + 5.3054x10^{-4})8368.1 + 0.182s^2 + s = 0$$

$$s^2 + 9.4728s + 24.3935 = 0, \quad s_{3,4} = -4.7364 \pm 1.4006i \tag{4}$$

Where the largest magnitude of the pole describes the maximum frequency of the plant ω_{max}, for this case it is 5.4945. With the above, the maximum sampling time is calculated:

$$f_m \geq \frac{10\omega_{max}}{2\pi}, \qquad Tm \leq \frac{2\pi}{10\omega_{max}} \tag{5}$$

$$Tm \leq 0.114s \tag{6}$$

Therefore, in the LAUNCHXL-F28379D Development Kit, a sampling time of $Tm = 0.1$ s is selected to read the encoders and execute the control strategy. We then used the sampling time (Tm) to calculate the PI controller constants in discrete time. There are several controller tuning techniques to perform this process, such as the Ziegler and Nichols methods [35], [36], [37]. For our research, we chose the Ziegler-Nichols rules shown in Table 1 because the controller constants implicitly have the value of Tm.

Table 1. Equivalence between the S-domain and Z-domain of the PID controller.

Gain	$Gc(s)$	$Gc(z)$	$Gc(z)$ including Tm and delay
Proportional	k_p	K_p	K_p
Integral	$\frac{k_i}{s}$	$\frac{k_i z}{z-1}$	$\frac{k_i Tm}{1-z^{-1}}$
Derivative	$k_d s$	$\frac{k_d(z-1)}{z}$	$\frac{k_d(1-z^{-1})}{Tm}$

Source: The authors. Adapted from [35], [37].

Using the continuous-time PID controller transfer function shown in Fig. 28 and applying the discrete-time transformation from Table 1 to obtain a representation of the differential equation, we implement the PI controller in the LAUNCHXL-F28379D development kit as follows:

$$Gc(s) = \frac{u(s)}{e(s)} = k_p + \frac{k_i}{s} + k_d s \tag{7}$$

$$Gc(z) = k_p + \frac{k_i Tm}{1-z^{-1}} + \frac{k_d(1-z^{-1})}{Tm}, \quad con\ Tm = 0.1\ s \tag{8}$$

$$Gc(z) = P(z) + I(z) + D(z) \tag{9}$$

Where:

$$p(z) = P(z)e(z) = k_p e(z) \tag{10}$$

$$i(z) = I(z)e(z) = \frac{k_i Tm}{1-z^{-1}} e(z) \tag{11}$$

$$d(z) = D(z)e(z) = \frac{k_d(1-z^{-1})}{Tm} e(z) \tag{12}$$

Then, the difference equation representation of the controller is:

$$p[k] = k_p e[k] \tag{13}$$

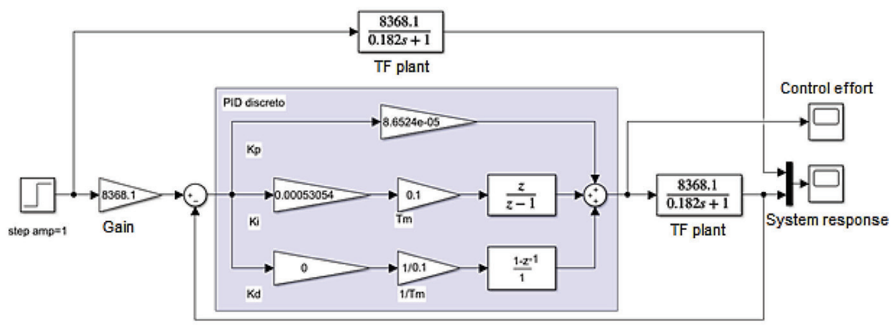
$$i[k] = e[k]k_i Tm + i[k-1] \tag{14}$$

$$d[k] = \frac{kd}{Tm}(e[k] - e[k-1]) \tag{15}$$

The closed-loop discrete-time PI controller block diagram shown in Figure 29 is obtained by implementing the control loop from Figure 28 with equations (10), (11), and (12).

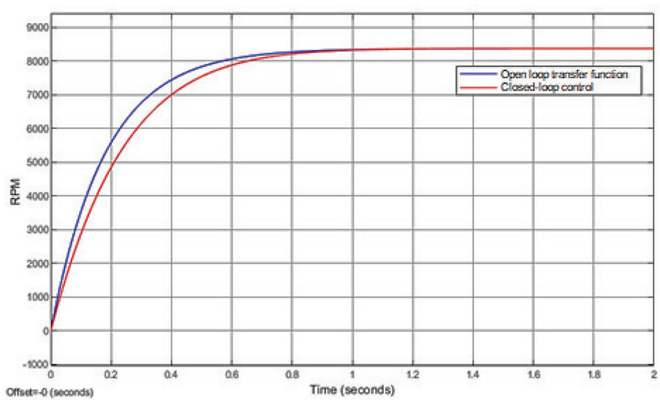
The transient response of the open-loop plant and the closed-loop controller is shown in Figure 30. To enable the plant to follow the established setpoint, the control effort is depicted in Figure 31.

Figure 29. Discrete-time PI controller for the flying-cutting plant



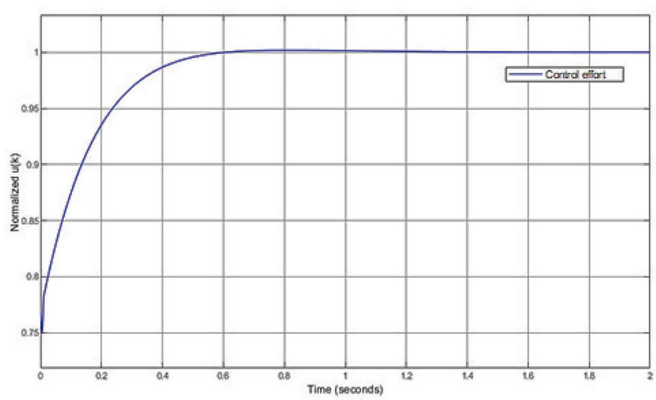
Source: The authors.

Figure 30. Open-loop and closed-loop plant response with controller



Source: The authors.

Figure 31. Control effort for PI controller

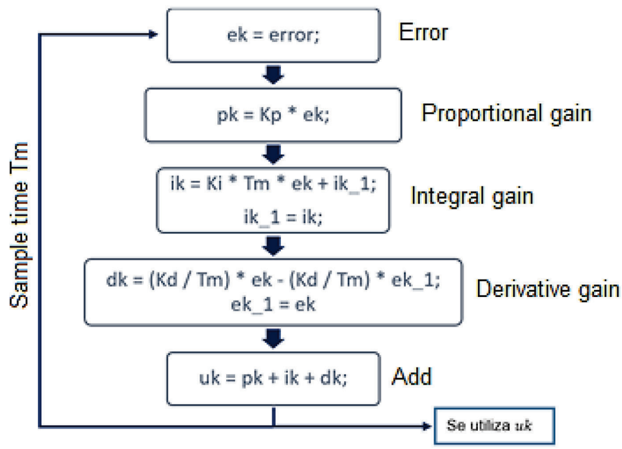


Source: The authors.

Using (13),(14) and (15), the PI controller was implemented in the LAUNCHXL-F28379D Development kit through CCS following the flow chart presented in Figure 32.

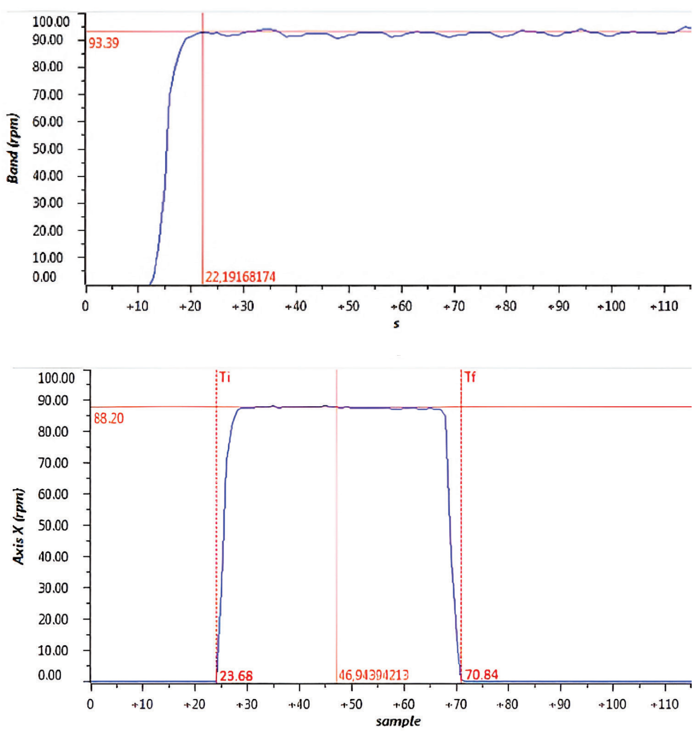
After implementing the PI controller in the Texas Instruments LAUNCHXL-F28377S development kit, PWM signals with a 100% duty cycle were applied to the conveyor belt and the X-axis motors in the cutting mechanism to validate their response and the maximum speed achieved. Figure 33, shows the responses for each of the motors using a 100:1 ratio gearbox.

Figure 32. Flowchart for the implementation of the PI controller in CCS



Source: The authors.

Figure 33. Maximum speed reached by the motors. Upper part of the conveyor belt motor and lower part of the X-axis of the cutting mechanism

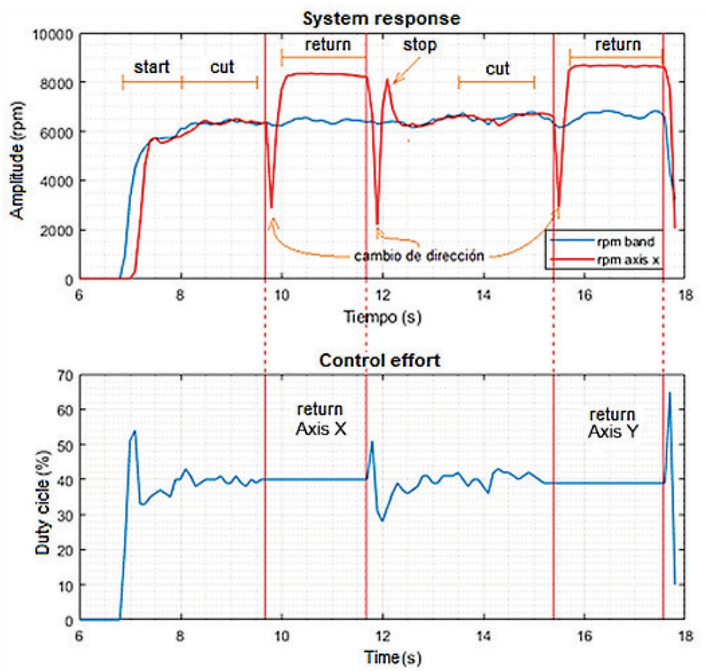


Source: The authors.

Once the motor speed was adjusted, the cutting plant was tested for validation and operation in a real-time cutting process. Figure 34, shows the system response. After 6 seconds, the cutting system reaches the starting position. At 6.8 seconds, a 50% duty cycle is set for the conveyor belt, and it takes 1.8 seconds for the belt speed to stabilize at approximately 6330 rpm.

Finally, the implemented flying-cutting plant is shown in Figure 35.

Figure 34. Response of the plant during a cutting process. Blue top conveyor belt, red top X-axis mechanism, and bottom control effort



Source: The authors.

Figure 35. Flying-cutting plant implemented

Source: The authors.

Conclusions

The results obtained from the design and implementation of a flying cutting plant for evaluating control strategies in an academic environment demonstrate that it is possible to develop robust, low-cost prototypes within educational institutions that serve two distinct yet complementary purposes. First, they provide invaluable support in training processes, allowing students to experiment with and validate theoretical concepts through practical applications. Second, they offer an alternative method of learning the complexities of real-world industrial processes.

The results validated the performance of the plant in the automation and control area of the Electronic Engineering Program at the Universidad del Quindío through controlled environment practices, characterized by low noise and minimal vibrations. A key highlight is the proposed system's ability to accurately replicate the operation of industrial-scale plants, and the enthusiasm of students in applying advanced control strategies to manage the plant in real time.

This research lays a significant foundation for future investigations addressing real-world needs and strengthening the collaborative relationship between academia and industry, particularly in developing new prototypes across diverse industrial sectors. The implementation of a proportional-integral (PI) controller facilitated the synchronization of speeds between the conveyor belt and the cutting device, achieving 95% cutting accuracy. This resulted in a considerable reduction of raw material wastage caused by cutting inaccuracies.

In the current plant setup, the working surface was constrained to 80% of the total area, limiting the dimensions of the parts that could be cut. A potential solution to this limitation would involve redesigning the cutting mechanism to a modular system, capable of adjusting its operating area from 0 to 100% by implementing optimal or adaptive control strategies. This approach would enhance the plant's flexibility and adaptability, allowing it to respond more effectively to varying production requirements.

The real-time control system was successfully implemented using the Texas Instruments LAUNCHXL-F28379D development kit. Tools like Code Composer Studio (CCS) have maximized the hardware capabilities of the C2000 microcontrollers, proving their effectiveness in academic settings for developing and testing both classical and advanced control strategies. This underscores the importance of sophisticated technological resources for advancing education and research in automation and control.

The experimental development focused on simulating the regularity of cutting parts in a continuous manufacturing process. Consequently, certain parameters, such as inertia, friction, and other dynamic forces that could impact the mechanical system's performance, were not considered in the design. It is recommended that the objective of such prototypes be clearly defined, as certain dynamic characteristics might be excluded to simplify the analysis of low-cost systems for academic purposes.

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