Prototype design education for the teaching of mechanism kinematics: Application to the Scotch yoke mechanism

Enseñanza del diseño de prototipos para la enseñanza de la cinemática de mecanismos: Aplicación al mecanismo de yugo ESCOCÉS

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Abstract

The present research focuses on the design, construction and manufacture of a didactic prototype based on the Scottish yoke mechanism. This device aims to provide an effective tool to visualize and understand the fundamental principles of its operation, as well as the associated kinematics. The integration of the traditional method of kinematics, the Velocity Polygon, with modern technologies such as computer-aided design (CAD), additive manufacturing, and automatic control is a key component of this project. The central objective of this controllable didactic prototype is to enable undergraduate students in mechatronics, mechanics, and industry to acquire technical skills and solve specific problems related to the mechanism of the Scottish yoke. To achieve this, an instrumentation system developed in LabVIEW is used to collect real-time information on the kinematics of the mechanism's joints (nodes). In addition, motion simulation is used through CAD design and the graphical method of the Velocity Polygon. A relevant discovery of this research is the confirmation that the device based on the Scotch yoke allows an effective representation of the kinematics, supported by the coincidence of the velocity of the sliding node in the three methods used (database generated by LabVIEW, CAD simulation and graphical method of the Velocity Polygon). This validates the efficacy of the prototype and highlights its usefulness as a practical educational tool for the development of technical skills and the resolution of problems specific to the mechanism of the Scottish yoke.

Kinematics, Mechanisms, Instrumentation

Resumen

La presente investigación se centra en el diseño, construcción y manufactura de un prototipo didáctico basado en el mecanismo de yugo escocés. Este dispositivo tiene como objetivo brindar una herramienta efectiva para visualizar y comprender los principios fundamentales de su funcionamiento, así como la cinemática asociada. La integración del método tradicional de cinemática, el Polígono de velocidades, con tecnologías modernas como el diseño asistido por computadora (CAD), la manufactura aditiva y el control automático constituye un componente clave de este proyecto. El objetivo central de este prototipo didáctico controlable es permitir a los estudiantes de licenciatura en mecatrónica, mecánica e industrial adquirir habilidades técnicas y resolver problemas específicos relacionados con el mecanismo del yugo escocés. Para lograr esto, se utiliza un sistema de instrumentación desarrollado en LabVIEW para recopilar información en tiempo real sobre la cinemática de las juntas (nodos) del mecanismo. Además, se emplea la simulación de movimiento a través del diseño CAD y el método gráfico del Polígono de velocidades. Un descubrimiento relevante de esta investigación es la confirmación de que el dispositivo basado en el yugo escocés permite una representación efectiva de la cinemática, respaldada por la coincidencia de la velocidad del nodo corredera en los tres métodos utilizados (base de datos generada por LabVIEW, simulación CAD y método gráfico del Polígono de velocidades). Esto valida la eficacia del prototipo y destaca su utilidad como herramienta educativa práctica para el desarrollo de habilidades técnicas y la resolución de problemas específicos del mecanismo del yugo escocés.

Cinemática, Mecanismos, Instrumentación

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Introduction

This scientific paper presents a comprehensive exposition of the design process of a specific mechanism, focusing on the Scottish yoke, along with a kinematic analysis approached both analytically and through simulations. The successful implementation of a prototype designed to validate the operation of the mechanism is highlighted. Throughout the brief, the computer-aided design procedure is painstakingly detailed, with a special emphasis on fabricating the links through 3D printing technology. Kinematic analysis is executed holistically, making use of advanced tools such as SOLIDWORKS MOTION. In addition, a graphical approach is applied to carry out kinematic analysis analytically, thus deepening the understanding of the specific kinematic behavior of the Scottish yoke, both in the virtual domain and in the physical prototype.

A distinctive aspect of this paper is the section devoted to the design of the prototype's instrumentation, which is designed to enable the study of the actual operation of the mechanism of the Scotch yoke. This section complements the information obtained through simulation and virtual analysis. The integration of these elements provides a complete perspective that amalgamates theory with practice, providing a comprehensive view of the specific mechanism addressed. In summary, this document not only delves into the design and analysis of the mechanism of the Scottish yoke in the virtual realm, but also supports these aspects through the manufacture and evaluation of a physical prototype. This comprehensive approach contributes to a deep and applied understanding of the mechanism of the Scottish yoke, highlighting its relevance in disciplines such as computer-aided design, kinematic simulation and prototyping.

Conceptual Framework

A. Didactic Devices

Teaching devices are educational tools specifically designed to facilitate the teaching and learning of theoretical concepts. These devices provide a hands-on, tangible experience that allows students to actively interact with content. According to Johnson (2010), teaching devices help improve understanding, retention, and knowledge transfer Theories of learning.

Diverse learning theories support the importance of hands-on experience and meaningful learning. The constructivist approach, proposed by Piaget (1977), holds that knowledge is actively constructed through interaction with the environment. In addition, Kolb's (1984) theory of experiential learning highlights the importance of direct experience in the learning process.

B. Pedagogy

Pedagogy refers to the study of the methods and approaches used for teaching. In this project, a student-centered pedagogical approach is adopted, where learning is facilitated through active participation and guided exploration. According to Vygotsky (1978), learning occurs in a social context and is strengthened through interaction with others and teacher mediation.

C. Mechanism

A system of mutually matched parts that work together but cannot constitute a complete machine. Designed to transmit and transform movements that can be defined as a powertrain.

D. Computer Aided Design

According to Klockner and Jowers (2015), CAD is defined as "a computational system that allows designers to create, modify and analyze digital representations of objects and systems, with the aim of facilitating decision-making in the design process".

E. Simulation.

According to Bechthold and Maier (2019), motion simulation in SolidWorks is "an analysis and evaluation process that uses digital assembly models to simulate motion and interactions between components in a virtual environment." Through motion simulation, designers can identify potential problems, optimize design, improve motion efficiency, and evaluate system performance prior to manufacturing.

F. Instrumentation.

According to Doebelin and Manik (2014), instrumentation is defined as "the art and science of measuring and controlling physical and chemical variables".

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It involves the selection and calibration of sensors, the design and assembly of electronic circuits, data acquisition, and signal processing, among other aspects. Instrumentation is applied in a wide range of industries and fields, such as medicine, engineering, scientific research, and industrial automation.

Methodology

In this project, a methodology was adopted that merged experimentation, pedagogical approaches and technical engineering principles, focusing exclusively on the Scottish yoke. This comprehensive approach allowed the project's objectives to be comprehensively addressed, promoting both hands-on learning and the development of technical skills specific to the Scottish yoke.

– Meaningful Experimentation:

Experimentation took on a pivotal role in facilitating empirical testing and analysis of the components and systems of the Scottish yoke. Through experimentation, real data was collected and the behavior of the elements in various conditions and situations specific to the Scottish yoke was evaluated.

– Adjusted Pedagogical Methods:

Pedagogical methods focused on the Scottish yoke were employed to facilitate the learning process. These methods included the use of teaching devices adapted to the Scottish yoke, specific practical demonstrations, contextualized theoretical explanations, and interactive learning activities geared towards the Scottish yoke. These pedagogical strategies not only supported comprehension, but also stimulated the retention of the technical concepts of the Scottish yoke, allowing participants to acquire knowledge effectively.

– Integration Centered on the Scotch Yoke:

The combination of experimentation with pedagogical methods and technical engineering principles, all focused on the Scottish yoke, resulted in a comprehensive and enriching approach to the development of the project.

This methodology not only facilitated the acquisition of specific theoretical knowledge of the Scottish yoke, but also promoted the practical application of the same, leading to significant learning and the successful achievement of the specific objectives of the Scottish yoke.

Position diagram design of the Scotch yoke mechanism

The scotch yoke mechanism is used in industry to perform operations where it is necessary to convert a rotary motion to a linear one, such as the application of automatically opening and closing valves or mechanical gates. In these applications it is often convenient to use constant-speed electric motors, however, servo motors can be used to improve the dynamic behavior of the mechanism.

Figure 1 Position Diagram
Source: Own Source

As can be seen in the image above, the design of the mechanism contains 4 links counting the base or also called origin.

List of Links with Measurement

– Link AB 55.00 mm (crank)
– CD Link 110.00 mm (Vertical Slider)
– EF Link 230.00 mm (Sliding)
– Link AG (base or support)

This position diagram allows you to perform kinematic analysis by graphical method using velocity polygons, as well as position analysis performed using *SolidWorks software*.

Analysis of the velocity polygon

Next, the analysis of the kinematic polygon method of velocities is presented, which consists of evaluating through a graphical method that relates the absolute and relative velocities of the nodes of the mechanism.

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It is worth mentioning that this method is also known as instantaneous velocity analysis as the conducted nodes experience multiple velocities along their different positions. The AB link is a mechanism known in the theory of classical mechanisms as a motor link which is responsible for receiving the input movement, this element has the main characteristic that its speed is constant throughout the operation of the mechanism so its acceleration is zero. As long as you do not change the input velocity of mechanisms.

The DC link represents the groove where node B will move, which is the link known as the transducer that transforms the circular movement into linear movement of the driven link, it should be noted that this is the main characteristic of the Scotch yoke mechanism
Finally, it is the EF link that is the final or led link, this link can also be considered as an extension of the previous link since it physically belongs to the same piece, but for the purposes of analysis it is considered as an independent element.

To obtain the angular velocity of the crank, the angular velocity in RPM and the length of this link are required. These data are the following 50 RPM and 55 cm of crank length, so we proceed to use the following formulas to find the value of the angular velocity and then obtain the value of the velocity of the EF link, which corresponds to the slide of the Scotch yoke.

$$\omega = RPM * 2\pi$$

A value of 314.15 rad/min is obtained, which represents the angular velocity of the drive link using the general velocity formula for the links.

$$Vb = \omega * AB$$

Where:

Vb = Velocity of node B (cm/min)
ω= Link angular velocity AB (rad/min)
AB= link length(cm)

Performing the proposed formula analysis we obtain that the velocity of node B is equal to 17278.7595 cm/min. Thus obtaining the following velocity polygon representing the velocity of all the nodes of the mechanism in question.

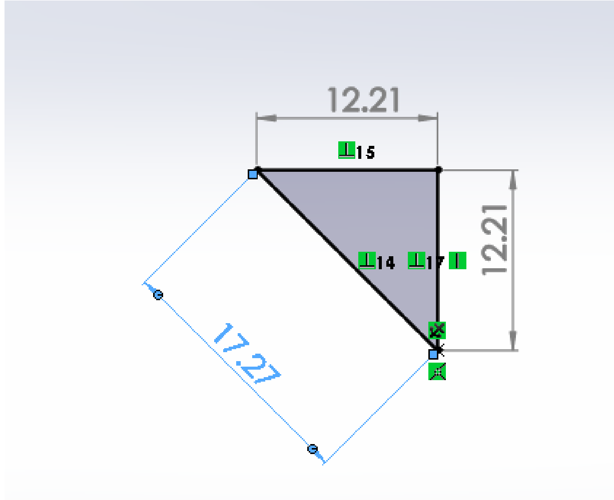

Figure 2 Polygon Velocities
Source: Own Source

Applying the graphical method of velocity polygon, we obtain the results shown in Fig. 2, where the velocity of node B is equal to the vector of 17.27 while the relative and absolute velocities of node F is equal to 12.21.

According to Shigley and Uicker (2007), the velocity polygon method is based on the idea that the velocity of a point in a mechanism is composed of two components: the absolute velocity and the relative velocity. Absolute velocity refers to the velocity of the point with respect to a fixed frame of reference in space, while relative velocity refers to the velocity of the point with respect to another point or body in the mechanism.

CAD design of the prototype

The design of the links that will make up the prototype was carried out by means of the *CAD* software *SolidWorks* in which the measurements proposed in the position diagram were taken into account in order to carry out the movement simulations necessary for this project. Below are the diagrams of the links and base designed for the Scotch yoke mechanism.

1. Base Design

In this piece, the distances of the crank, the height of the encoding motor, the distances of the slides and the thickness of the latter were taken into account. Due to the structure, it was necessary to design the base as a three-piece assembly. It is worth mentioning that internal tunnels were added to hide the cables of the electrical system in question. The design can be seen in this figure.

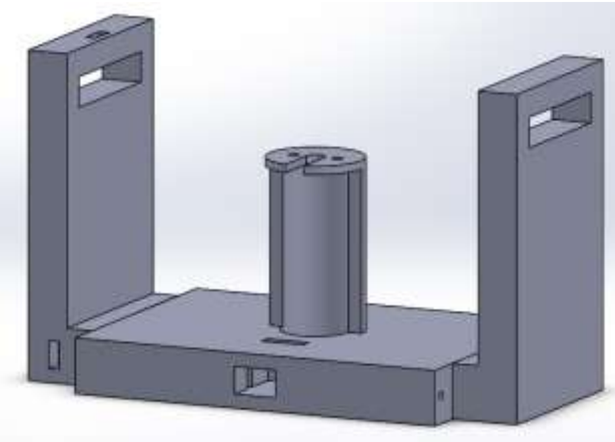

Figure 3 Assembled base design in SolidWorks
Source: Own Source

2. Link Design

The design of the links also respected the measurements propose in the position diagram using the base design. Separations and spaces were considered for the optimized operation of the mechanism taking as an axis the constructive lines of the diagram in *SolidWorks*.

Crank

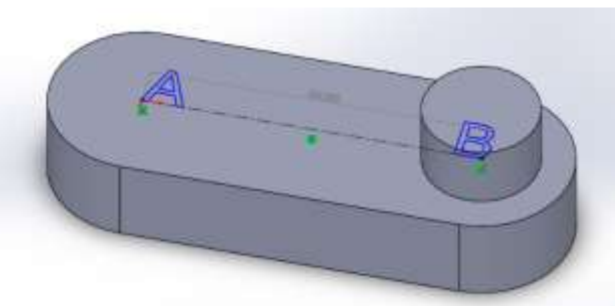

Figure 4 Crank link design
Source: Own Source

The crank is a mechanical component that is used to transform the circular motion into a reciprocating motion or vice versa. It consists of an arm or lever that is connected to a rotating shaft and is used to transmit movement to another component of the mechanism, such as a connecting rod or connecting rod.

In this particular case, the crank is connected to a crank motor, which in turn provides the driving force to rotate the crank. On one end is a hole in which it connects to the motor shaft, while on the opposite end is a pivot that will connect to the vertical slider slot that is part of the slide assembly.

There are two ways to design a crank for this type of mechanism. The first option is to use the design of a disc with the axis and pivot to perform the transmission of movement, but the drawback is the extra use of material when 3D printing it. So you opt for the second option which consists of the arm with the axis and pivot, as it fulfills its purpose, is lighter and does it doesn't take up too much material when 3D printing it.

Vertical slider with slide

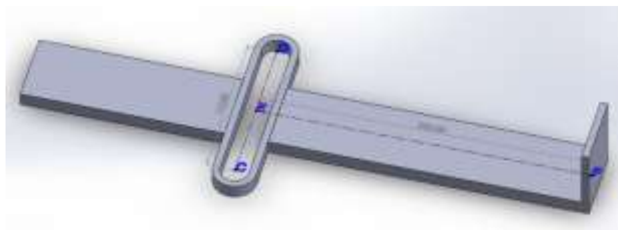

Figure 5 Slide with vertical slider made in SolidWorks
Source: Own Source

The design of this assembly encompasses three fundamental pieces. The first piece corresponds to the vertical slide that is located in the central part of the assembly. This piece is responsible for transmitting the rotary movement produced by the crank and then transforming it into an alternative harmonic linear movement.

On the right side of the image you can see a rectangular piece that is known as a slide, which is responsible for sliding over the support to generate the alternative harmonic linear movement. On the far right of this last piece is a wall that protrudes, whose main purpose is to serve as a barrier for measuring distance using an ultrasonic sensor, which in turn will serve to calculate the speed and acceleration of the sensor when moving.

Finally, an auxiliary bracket is located on the left side of the vertical slider. The function of this auxiliary part is to maintain the stability of the entire assembly at the time of generating the reciprocating linear motion.

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Motion simulation in SolidWorks Motion

SolidWorks offers a motion simulation engine called SolidWorks Motion in which, in order to perform the kinematic analysis, the corresponding assembly of the links is previously made, which allows limiting the degrees of movements of the model made in order to determine the boundaries that will result in the simulation corresponding to the Motion Studio.

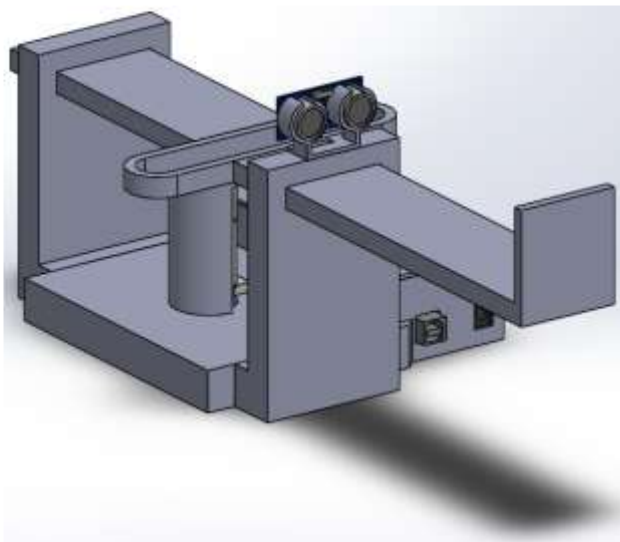

Figure 6 Assembling the links in SolidWorks Motion
Source: Own Source

In the parameters of the kinematic analysis, the study was carried out for the displacement, speed and acceleration of the slide with a constant angular velocity in the crank (link AB) of 50 RPM - SMR. These values were used to produce the following graphs:

In the image below, you can see that the linear displacement of the slide generates a sinusoidal graph over time. This is a characteristic of the Scotch yoke mechanism.

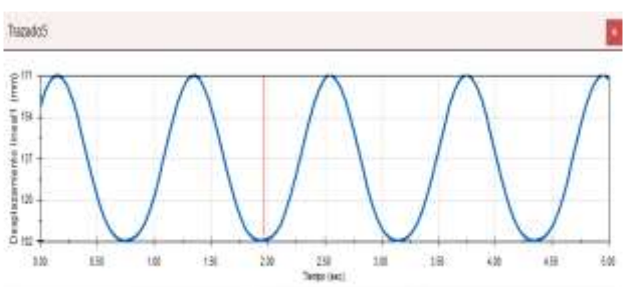

Figure 7 Linear sliding displacement in SolidWorks Motion
Source: Own Source

In the linear velocity graph it can be seen that there are points where the velocity reaches zero and then increases again, giving the illusion of "jumps" or a "rectified sinusoidal signal". This is because the mechanism of the Scotch yoke has a lower velocity at the P.M.S. (Upper Dead Center) and P.M.I. (Lower Dead Center) ends, which are part of the slide end.

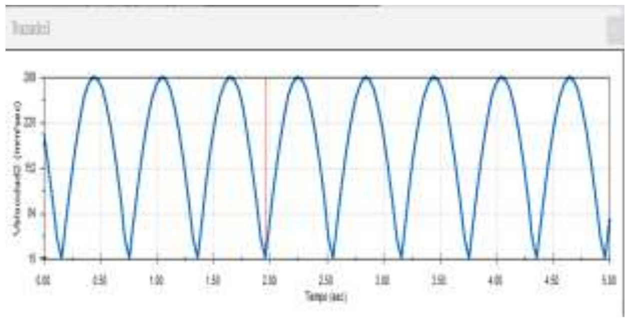

Figure 8 Linear Slider Velocity in SolidWorks Motion
Source: Own Source

In the case of linear acceleration, the peculiarity of the graph is notorious, since it has a lot to do with what was mentioned above for displacement and linear velocity. Because of this, it is possible to see a graph with these representative peculiarities.

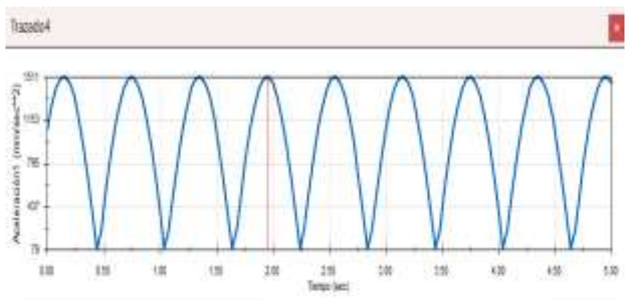

Figure 9 Linear acceleration of the slide in SolidWorks Motion
Source: Own Source

Additive manufacturing (3D printing)

A model of the mechanism designed in SolidWorks was made using additive FMD technology. The mechanism was printed in PLA material in order to carry out the physical instrumentation of the prototype to corroborate the data generated in the simulation and the analysis of the graphic method.

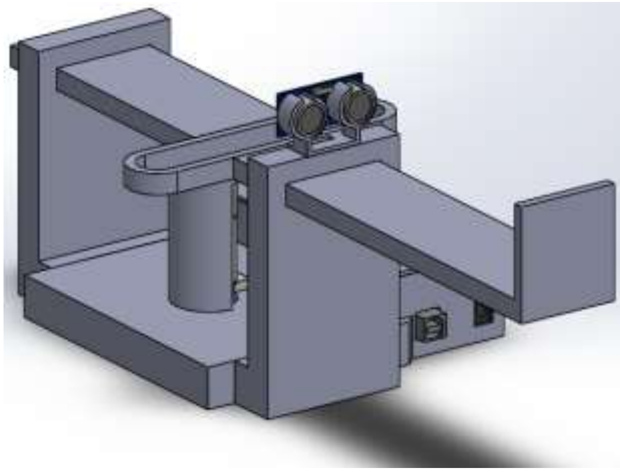

Figure 10 Prototype of the Scottish yoke 3D printed
Source: Own Source

Instrumentation

For this prototype, the following variables were monitored in the 3D-printed Scottish yoke prototype.

Revolutions per minute (RPM).
Displacement (cm).
Linear velocity (m/s).
Linear acceleration (m/s^2).

To measure the RPM of the crank, the Hall effect sensor installed in the encore motor was used, in this way it is possible to calculate its rotational speed. To control the speed of the motor, a PID controller was implemented using an Arduino board.

An HC-SR04 ultrasonic sensor was used to measure the distance between the sensor and the barrier at the end of the slide. The code to calculate the distance in cm was made in the Arduino IDE and then loaded to an Arduino Uno board that is responsible for performing the entire control process and necessary calculations of the variables.

To measure linear velocity, the displacement variable is used together with the time variable. The displacement is sampled from time to time to perform the corresponding operation to obtain the linear velocity of the end of the slide. The formula used is as follows:

Linear velocity = (Distance f – Distance i) / Time

To measure linear acceleration, the velocity variable calculated in the previous point is used, together with the time variable.

The velocity is sampled from time to time to perform the corresponding operation to obtain the linear acceleration of the end of the slide. The formula used is as follows:

Linear acceleration = (Velocity f – Velocity i)/Time

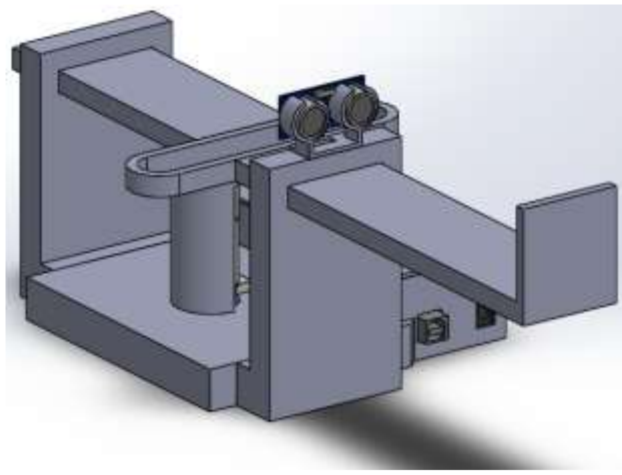

Figure 11 Ultrasonic sensor, enconder motor and Arduino board in the prototype
Source: Own Source

Therefore, *LabVIEW* software *was used for the monitoring panel*. By means of virtual instruments and programming, the interface was created to control and visualize by parameters of the mechanism. The Arduino board transmits the information to the computer using serial communication. On the panel you can control the speed of the enconder motor (RPM) as well as control the direction of rotation of the motor. On the right side of the panel are graphs showing the displacement, speed and acceleration of the slide. The collected data will then be exported to a spreadsheet for comparison of results.

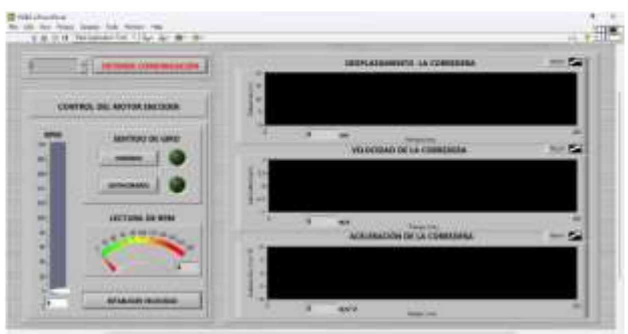

Figure 12 Control and monitoring panel in LabVIEW
Source: Own Source

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Results

The following are the results obtained in the kinematics simulation of the software as explained above: the velocity and acceleration analysis was performed with respect to node C. with a position of 45° already described above and with a velocity of 50 RPM.

		CORREDERA_LATERAL_SENSOR-1
		Velocidad2 (mm/sec)
Fotograma	Tiempo	Sistema de coordenadas de ref.:
1	0.000	1.5742E+02

Table 1

Acknowledgements

I am very grateful to my collaborators who, with their knowledge and advice, always supported me in the realization of this project, to my students who were also a fundamental part in the development and implementation of the work. Their contributions were key parts in the culmination of this work, and I hope it will be of great use to future generations.

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Conclusions

In summary, the congruence between the instrumental design and the empirical results showed a proximity that ranged between 5% and 10%. This close alignment is significant in providing users with the ability to discern the concepts inherent in operation and kinematics in diverse contexts.

The design of the instrument, developed through SolidWorks CAD software, was based on specific measurements, and considered the dimensions of the links established in the position diagram. The motion simulation in SolidWorks Motion enabled a detailed analysis of the velocity and acceleration of the mechanism's nodes, thus providing a detailed visual representation of the system's behavior.

The comparison of the results obtained in the simulation, in terms of speed and acceleration, with the theoretical data calculated using graphical methods, showed a close agreement, with a margin of error of 5% to 10%.

This indicates that the device, Designed and simulated, it was able to represent the operating concepts and kinematics of the connecting rod-crank mechanism accurately and reliably with slide.

The close correlation between instrumental design and experimental results is of great technical importance, allowing users to internalize and distinguish theoretical concepts in a practical and tangible environment. Observation of the actual functioning of the mechanism, contrasted with theoretical results, offers students the opportunity to consolidate and strengthen their understanding of the principles of operation and kinematics in various scenarios.

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