Advancing Entomological Research: Exploring Electronic Measurement Systems with a Case Study on Mapping Geometric Points of Beetle Elytra

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Abstract. This research project delves into the integration of sophisticated electronic measurement techniques to gain a meticulous understanding of insect morphology. An interdisciplinary team comprising six researchers merges diverse disciplines to explore the application of cutting-edge technologies in entomological studies. The primary focus lies on developing and deploying two measurement systems: an encoder sensor and a rotary encoder. Of note is the prototype designed, modeled, and 3D printed by the team. This prototype incorporates two 3D-printed buttons that enable manual control and data acquisition, thus serving as integral components for evaluating the measurement systems. The research methodology encompasses experimental testing, data analysis, and simulation studies. Simulations were conducted to evaluate the performance of the measurement systems across varied conditions. The results demonstrate that both measurement systems yield valuable insights into the anatomical structures of insects, with the rotary encoders and encoder sensors accurately capturing dimensional data. Additionally, the 3D-printed buttons offer customizable control options. The key findings underscore the enhancement of precision and reliability in insect morphology studies through the integration of advanced measurement techniques, particularly leveraging the capabilities of the team's prototype. This research significantly contributes to the advancement of entomological studies by introducing innovative electronic measurement technologies and methodologies. Future endeavors may focus on expanding the capabilities of the sensor system and exploring further applications in entomology and related domains.

Keywords: 3D printing. Rotary encoder. Encoder sensor. Arduino UNO. Distance.
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1 INTRODUCTION

The field of entomology is constantly evolving as researchers seek innovative methodologies to capture detailed information about the behaviors and characteristics of insects.

Electronic measurement systems in entomology utilize various methodologies to capture and analyze the behavior, movement, and morphology of insects. These methodologies include (1)

Radiofrequency identification (tracking the movements and behaviors of insects). (2) Acoustic monitoring (identifies communication patterns and activity levels of insects). (3) Inertial measurement units (measures the movements and orientations of insects in three-dimensional space). (4) Video tracking systems (quantifies parameters such as speed, trajectory, and interactions between insects). (5) Laser triangulation (creates a three-dimensional map of insect bodies for morphological studies). (6) Ultrasonic sensors (provide information on the distance and movement of insects). (7) Computer vision and image analysis (capture and analyze the movements of insects). (8) Wireless sensor networks (monitor environmental conditions and the presence of insects). (9) Telemetry systems (monitor the movements of insects over long distances). (10) Odometers and rotary encoders (measure the distance traveled by insects). (11) Environmental DNA (detects the presence of insects to assess biodiversity).

Several authors have written about these methodologies, including Blight et al. (2023) [1], who explored the potential of passive RFID tags to track the movements of three small species of ground beetles: a predator (Poecilus sericeus, Carabidae), a detritivore (Asida sericea, Tenebrionidae), and a granivore (Acinopus picipes, Carabidae), in a degraded Mediterranean dry grassland affected by years of cultivation. The data they obtained shed light on the biological rhythms and daily movement capabilities of the target species. In the results, the authors suggest that this knowledge could help predict the species' ability to recolonize degraded areas, allowing for the design of appropriate restoration actions based on landscape ecology principles.

Uthoff et al. (2022) [8] provide an overview of studies using acoustic and vibration recordings to determine the presence of queens and swarm indicators, presenting common methods and analyses while discussing challenges, limitations, and future areas of improvement to enhance their accurate use in apiculture. The researchers used microphones and accelerometers to record hives exhibiting these indicators, and the resulting data were analyzed and classified into different colony states.

Chirarattananon (2019) [2] proposes a strategy to estimate the altitude of a flying robot using a bottom camera by combining optical flow with measurements from an inertial measurement unit. Instead of relying on the predominant feature-based approach for optical flow computation, the researcher implemented a direct method that evaluates flow information through image gradients. Additionally, the author provides a more detailed analysis of the factors influencing flow quality and distance estimation in the paper.

In the study conducted by Li et al. (2016) [7], researchers mounted a small wireless system, or "backpack," on live beetles (Mecynorrhina torquata; length 62 ±8 mm; mass 7.4 ±1.3 g) flying freely in a large laboratory space. The backpack contains an inertial measurement unit (IMU) specially designed and manufactured for this purpose. Due to the small mass (~1.30 g) and dimensions (~2.3 cm2) of the backpack and the high precision of the IMU, researchers were able to remotely record the beetle in free flight.

Volponi et al. (2023) [9] developed the "buzzOmeter system" to record free-flying insects in their habitat, followed by file processing enabling precise measurements of acoustic parameters, including those dependent on the distance from the sound source to the microphone, i.e., signal magnitude measurements. They obtained recordings of nine insect species (bees, wasps, and lepidopterans) using their system in various habitats, demonstrating its viability for field studies.

The interdisciplinary group led by Ph.D. Dina Rochman from the Metropolitan Autonomous University Cuajimalpa campus comprises experts in robotics, computer science, mechatronics, mechanics, 3D printing, and descriptive geometry. Together, they propose the development of two innovative measurement systems designed to map the geometric points of insects in two dimensions. The first system utilizes an encoder sensor, while the second system employs a rotary encoder.

Professor Miriam Hernández, a robotics specialist from the National Autonomous University of Mexico, Faculty of Higher Studies Acatlán, contributes to the project by focusing on the integration of robotic components for controlled movement and positioning during insect morphology measurements.

Master Miguel Ángel Méndez, a specialist in computer science from the Anahuac University Mexico North, contributes to the project by focusing on the development of algorithms for data analysis and interpretation. This ensures that the electronic measurement systems generate accurate and meaningful data.

Academic technician Cruz Zaval, a mechatronics specialist from Anahuac University Mexico North, plays a crucial role in integrating mechanical and electronic components, optimizing the functionality and reliability of the measurement systems.

Master Jesús Hernández, a specialist in mechanisms from the Metropolitan Autonomous University Cuajimalpa campus, provides valuable knowledge and experience in the design, analysis, and optimization of mechanical systems, ensuring that the project's components are well-designed and function effectively.

Professor Enrique García's expertise in 3D printing at Metropolitan Autonomous University Cuajimalpa campus contributes to the project by facilitating the effective use of additive manufacturing techniques, from material selection to the production of high-quality printed components.

Ph.D. Dina Rochman brings expertise in descriptive geometry and 3D printing. Her role is crucial to ensuring precision in geometric analysis and leveraging advanced 3D printing techniques for the visualization of models and prototypes.

The main objective of this research is to integrate new and advanced electronic measurement techniques to provide a meticulous and precise understanding of insect morphology. Currently, we are validating the use of encoder systems to accurately determine the numerical values of the x and y coordinates of the tracked points on insects. This process allows us to obtain reliable numerical data that precisely represents the location and position of each point on the beetle's elytra.

Once these measurement systems are validated, our next step in the lab will be to extend this process to find all the points on the beetle's elytra. Using the numerical values obtained through the encoders, we will be able to map out all points of the elytra comprehensively and in detail in a digital environment.

Subsequently, these numerical values will be transferred to a specialized vector program, where they will be used to recreate the structure of the beetle’s elytra faithfully and accurately in a three-dimensional environment. This process of transfer and 3D representation will enable us to visualize and analyze the morphology and characteristics of the beetle's elytra accurately, providing a faithful and detailed representation of this particular organ.

It is important to note that this integrated approach of validating encoder systems and subsequent representation in a vector program ensures the precision and fidelity of our digital representation of the beetle's elytra. This will allow us to advance in the understanding and analysis of the structure and function of this specific organ, providing a valuable tool for research in the field of comparative biology and biomedical engineering.

The morphological analysis of beetle elytra serves as a focal point in our entomological study, delving into the intricate details of these forewings and utilizing electronic measurement systems for comprehensive exploration. Elytra, often rigid and protective, play a crucial role in safeguarding the delicate hindwings and body of beetles. Our methodology involves the careful preparation and dissection of beetle specimens, ensuring the preservation of insect integrity.

The morphological analysis of beetle elytra holds significance not only within the realm of entomology but also in broader ecological and evolutionary studies. Understanding the intricate features of these forewings contributes to our knowledge of adaptation, biodiversity, and evolutionary processes shaping beetle morphology.

This article comprises the following sections: Section 2 describes the measurement systems. Section 3 outlines the systematic procedure undertaken to achieve the results. Section 4 details the structure's design. In Section 5, the operation and results of the measurement systems are discussed, and finally, Section 6 presents the conclusions. All figures and the 3D printing presented in this document are original and were created at the Metropolitan Autonomous University Cuajimalpa campus.

2 MEASUREMENT SYSTEMS

The evolution from odometers to the contemporary use of rotary encoder systems and encoded sensors underscores the pivotal role of technology in the advancement of distance measurement throughout history.

In antiquity, the odometer was employed as a measurement system to calculate distances traveled. Throughout history, the odometer has undergone significant evolution from its humble beginnings, transforming through various mechanical and electronic iterations. Today, it has become an essential component in modern vehicles, playing a crucial role in accurately measuring distances traveled.

Several ancient cultures contributed to the development of odometers to facilitate their daily activities. One of the most well-known odometers was designed by Leonardo da Vinci in the late 15th century. Also known as "Da Vinci's wheel" (Figure 1) this ingenious gear mechanism was conceived to measure the distances traveled by wheeled vehicles. As the vehicle advances, the rotation of the wheels activates the gears, causing a weight to fall. This descending weight, in turn, rotates a series of gears that move numerical dials, indicating the distance traveled.

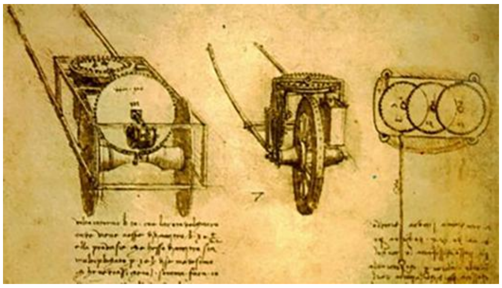


Figure 1: Da Vinci’s wheel [3].

Da Vinci's wheel represents a significant innovation in the history of the odometer, capturing the essence of creativity and engineering from the Renaissance era. Today, odometers provide a cost-effective, flexible, and accessible solution for distance measurement applications, catering to a wide range of users, from enthusiasts to professionals.

Unlike odometers, which are measurement instruments designed to calculate the total or partial linear distance traveled by an object or vehicle, expressed in configured length units (such as meters or miles), and whose application is versatile, commonly used to evaluate fuel performance, estimate speed through brake marks, make perimeter measurements, guide the laying of cables or pipelines, and contribute to workspace design, encoders are electromechanical or electronic devices designed to measure the rotation of a shaft and convert it into electrical signals representing angular position.

These devices are commonly used in industrial, electronic, and automation applications to detect and control the position of rotating elements, such as motor shafts, wheels, and other mechanical components.

In the context of our project, the rotary encoder serves as a key electronic component that detects and measures the rotation of the wheel. The overall setup, including the encoder, is part of a measurement system designed to determine the distance traveled by the wheel, as the signals from the rotary encoder are electronically processed to calculate the distance based on rotation information, using Arduino UNO.

With Arduino UNO, being an open-source platform that uses a simplified programming language, it will facilitate the rapid development and prototyping of the rotary encoder and measurement system as we can easily adapt it to the structure designed specifically for this project. With Arduino UNO, we will process data in real-time, allowing us to perform instant calculations and display distance measurements, either on a computer or an LCD screen.

Another measurement system we are proposing to map the geometric points of the beetle's elytra is an encoder sensor. An encoder sensor is a device designed to measure the position, rotation, or displacement of an object and convert this mechanical information into electrical signals. In our project, we have designed a button for the encoder sensor that incorporates a tip. When pressing this button, the tip contacts with the tracks printed on a board, displaying the X coordinate of each geometric point of the beetle's elytra contour on the LCD screen and in the serial monitor simultaneously. After thoroughly reviewing the academic literature on our research topic, we found no previous studies that specifically addressed the method or approach we are developing.

The selection of the encoder sensor and rotary encoder technologies for our target application was based on several key factors. Firstly, our interdisciplinary team comprises experts in robotics, computer science, mechatronics, mechanics, 3D printing, and descriptive geometry. This diverse expertise allowed us to evaluate various measurement technologies and determine the most suitable options for mapping the geometric points of insects in two dimensions.

The encoder sensor was chosen for its precise measurement capabilities, particularly in capturing fine details of insect morphology. Its sensitivity and accuracy make it ideal for our application, where high-resolution data is crucial for analyzing and understanding the intricate structures of insects.

On the other hand, the rotary encoder offers advantages in capturing rotational movements and providing angular measurements. This technology is essential for mapping the curvatures and rotations of insect body parts, complementing the capabilities of the encoder sensor.

Overall, the selection of these specific technologies was driven by their capabilities to meet the precision, resolution, and functionality requirements of our target application, as determined by our multidisciplinary team's expertise and evaluation process.

After thoroughly reviewing the academic literature on our research topic, we found no previous studies that specifically addressed the method or approach we are developing. This absence of similar works underscores the originality and relevance of our research in the field. Notably, we identified only three investigations, further emphasizing the innovation of our approach and the potential impact of our findings on the scientific community.

Dalboni et al. (2023) [4] analyzed two types of absolute rotary encoders based on the Vernier method for controlling synchronous machines. These solutions provide precise measurements of absolute angular position and velocity and were compared with other technologies, showcasing their effectiveness and ease of implementation, particularly on low-cost microcontrollers. However, they noted that the half-Vernier encoder might experience slight performance degradation at low speeds and high accelerations. However, it remains more compact and cost-effective compared to alternatives such as the gray encoder.

Guraukis et al. (2022) [5] discussed the widespread use of optical linear encoders in manufacturing due to their accuracy, relatively high resolution, and good repeatability. However, they highlighted potential side effects that could impact encoder performance, noting that appropriate design considerations for the reading head can minimize these effects. Their paper delves into the working principles and common errors in optical linear encoders, presenting three different mechanical designs implemented in an experimental reading head to evaluate their influence on displacement measurement accuracy and overall encoder performance.

Hojjat et al. (2011) [6] introduced a straightforward method for direct two-dimensional measurements using an inductive approach. This method involves the movement of a flat coil over another, generating induced voltages that provide displacements in the x and y directions. Their experimental setup, comprising five flat coils with specific patterns, demonstrated a resolution of 10 μm and no interference between axes, with the potential for higher resolution with more precise experimental devices.

3 SYSTEMATIC PROCEDURE

The systematic procedure followed to achieve the intended results is detailed below: (1) 3D modeling and printing of components: The creation and design of the base, posts, rails, buttons, table, and wheel were carried out using 3D modeling techniques. Special attention was paid to tolerances during assembly, especially in the toothed rail and wheel, to ensure that the structure was sturdy and functional. (2) Button calibration: A detailed comparison of the position and distance in placing the buttons on each of the rails, both toothed and non-toothed, was performed to ensure the accuracy of distance measurements. (3) Interval selection: The measurement intervals to be programmed into Arduino for each of the measurement systems were determined. This selection was based on specific considerations of each component and the purpose of the measurements. (4) Data collection: Experimental tests of the two electronic measurement systems were initiated to record distance readings from both buttons at each stopping point. (5) Code validation: The code used in Arduino UNO was verified and validated through various tests to ensure its correct operation.

This systematic approach allows for an organized and effective development of the project, ensuring the accuracy and reliability of the measurements to be taken.

4 STRUCTURAL DESIGN

The points, along with other geometric elements like lines and planes, constitute the fundamental units of geometry. Points are often identified and located using coordinates. In a two-dimensional coordinate system, a point is represented by an ordered pair (x, y), where 'x' is the horizontal coordinate and 'y' is the vertical coordinate.

In the context of the research we are conducting, where we propose electronic measurement systems to map the geometric points of the beetle's elytra, the coordinates of these points would be determined by two systems: a sensor encoder and a rotary encoder.

For both measurement systems, a structure consisting of a base, two prisms, a worktable, a toothed rail, a non-toothed rail, a wheel, and four buttons was designed, 3D printed, and assembled (Figure 2).

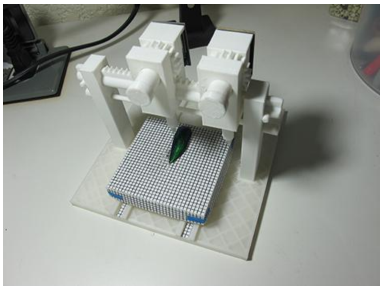


Figure 2: 3D prototype.

The base measures 120 x 116 x 5 mm and features a rail that allows the worktable to slide every 2 mm, according to markings on a cardboard sheet. The worktable measures 60 x 60 x 10 mm, on which a cardboard sheet with a grid printed at 2mm intervals in both directions will be placed. Each intersection of the grid serves as a reference point. The beetle's elytron will be affixed to the center of the cardboard sheet to establish a reference point (30, 4).

The toothed rail features a geometric shape resulting from the intersection of a cylinder and a rectangular prism, with a row of teeth designed to allow the wheel to slide smoothly. Alongside Professor Rochman and Professor García, we conducted a series of tests on this rail to ensure that the wheel, placed in the rotary encoder, rotated correctly without getting stuck. During this process, it was necessary to adjust the tolerance for 3D printing on the teeth of the rail several times due to error detection. Finally, a tolerance of 0.3 mm per side was established.

The non-toothed rail exhibits the same geometric shape as the previous rail. The wheel measures 11 mm in radius, has 20 teeth, and its module is 1.

Two key considerations were considered in the design of button 2 (Figure 11, page 14). Firstly, the placement of a needle used for insulin injection at the end of the button was anticipated. Secondly, a spring-loaded movement system was incorporated, characterized by an internal cone that, when pressed, contacts the plate of the encoder sensor system.

Similarly to button 2, in button 1 (Figure 3(a) and 3(b)), an insulin injection needle is incorporated into its base. Button 1 consists of an intermediate hole to place the wheel inside the cylinder of the rotary encoder and a cylinder that enters the final part of the rotary encoder, serving as a button to return the encoder measurement to zero.

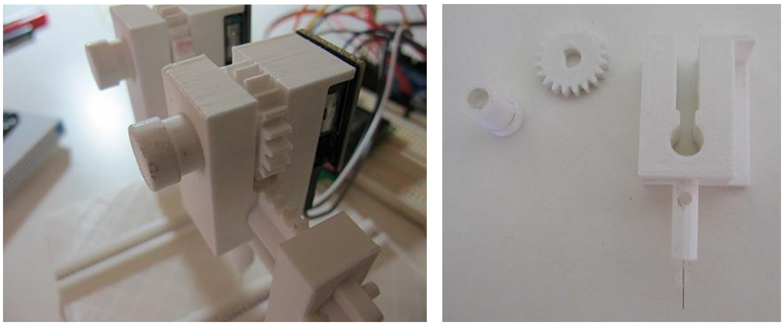


Figure 3: 3D printed (a) Button 1 and (b) Detail.

5 OPERATION AND RESULTS OF MEASUREMENT SYSTEMS

5.1 Rotary Encoder

The basic operation of a rotary encoder involves converting rotary motion into electrical signals.

The rotary encoder is mounted on a shaft that can rotate and detect the rotational movements of the shaft. As the shaft rotates, the encoder produces electrical signals that vary according to the direction and speed of the rotation. These electrical signals are sent and encode information about the position and angular displacement of the shaft. This process allows electronic systems to interpret and use the information from the rotary motion for various applications, such as motor control, navigation, robotics, and position feedback in industrial machinery and equipment.

In our project, we utilize the rotary encoder to accurately measure distances and map the geometric points of the beetle's elytron. This encoder is integrated into a button that we manually move along a toothed rail, from right to left, where the tip of the button, which is an insulin needle, contacts the end of the worktable (Figure 4).

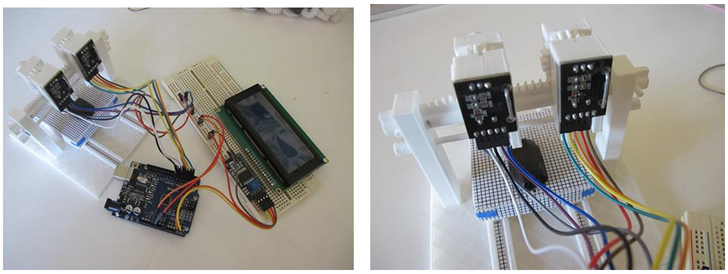


Figure 5: Arduino UNO connection diagram.

When rotating the wheel using the rotary encoder along the toothed rail, the distance traveled by the wheel is displayed on the LCD screen and the serial monitor. The same process is repeated with a second button, whose travel is from right to left, until the tip of the button, which is an insulin needle, contacts the beetle's elytron.

By subtracting the two distances obtained from the total measurement of the table, 60mm we obtain the measurement of the width of the beetle's elytron starting with 4 mm on the "y" axis. This procedure is repeated as necessary until the total length of the beetle's elytron.

The rotary encoder we use, the KY-040 (Figure 6), has a resolution of 15 cycles per revolution. This means that the encoder produces 30 pulses for each complete revolution of the shaft.

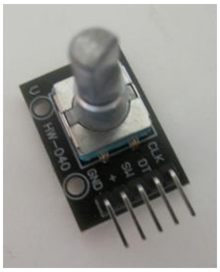


Figure 6: Rotary encoder KY-040.

Using the formula (5.1.1), where D is the distance traveled by the rotary encoder, Pi is approximately 3.14159, R is the radius of the wheel (in our case, the wheel measures 11 mm), and N is the number of cycles per revolution (in our case, it's 15), we calculate that the distance per step is approximately 3.45577 mm.

$$D = \frac{2\pi R}{N} \qquad (5.1.1)$$

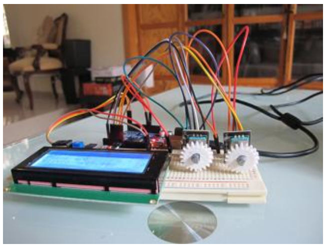
The distance traveled by the encoder in each step is directly proportional to the radius of the wheel. If the wheel's radius is larger, the circumference the wheel travels in each revolution is greater, meaning the distance traveled in each step will also be greater. Conversely, if the wheel's radius is smaller, the distance traveled in each step will be smaller. In our case, it would be advantageous to use a wheel with a smaller radius to achieve a closer approximation to the real distance. However, the challenge we face is that we might encounter difficulties in 3D printing a wheel with a diameter smaller than 11mm while maintaining the necessary tolerance for the rotating component in the rotary encoder.

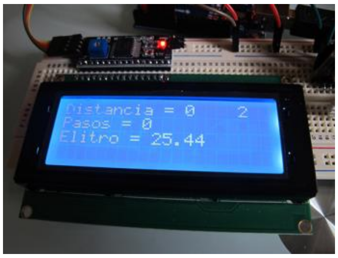
The results presented in Table 1 represent the distance the rotary encoder wheel would travel in each step, considering the radius of 11, 8, 7, and 5 mm. Each step increases the distance traveled, up to 20 steps.

steps	radius 11	radius 8	radius 7	radius 5
1	3.455749	2.513272	2.199113	1.570795
2	6.911498	5.026544	4.398226	3.14159
3	10.367247	7.539816	6.597339	4.712385
4	13.822996	10.053088	8.796452	6.28318
5	17.278745	12.56636	10.995565	7.853975
6	20.734494	15.079632	13.194678	9.42477
7	24.190243	17.592904	15.393791	10.995565
8	27.645992	20.106176	17.592904	12.56636
9	31.101741	22.619448	19.792017	14.137155
10	34.55749	25.13272	21.99113	15.70795
11	38.013239	27.645992	24.190243	17.278745
12	41.468988	30.159264	26.389356	18.84954
13	44.924737	32.672536	28.588469	20.420335
14	48.380486	35.185808	30.787582	21.99113
15	51.836235	37.69908	32.986695	23.561925
16	55.291984	40.212352	35.185808	25.13272
17	58.747733	42.725624	37.384921	26.703515
18	62.203482	45.238896	39.584034	28.27431
19	65.659231	47.752168	41.783147	29.845105
20	69.11498	50.26544	43.98226	31.4159

Table 1: Distances traveled by the wheel in 20 steps, values are given in mm.

To validate the results presented in Table 1, we conducted a series of tests using Arduino UNO and two rotary encoders to simulate the results. Through the code implemented in Arduino, we verified that the distance marked at each step is accurate and consistent. By obtaining the distance readings from both rotary encoders, we subtracted these distances from the total length of the table to determine the exact measurement of the beetle's elytron (Figure 7).





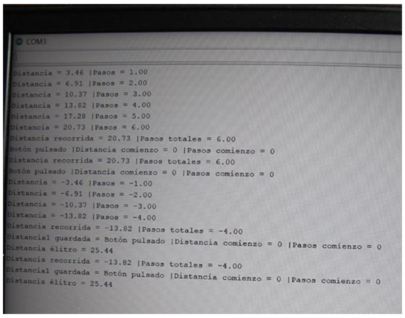


Figure 7. The first test of the rotary encoders with code programming on the Arduino UNO platform.

The results that we present in Table 2 represent the distance that the rotary encoder wheel would travel in each step, considering the radius of 11, 8, 7, and 5 mm. Each step increases the distance traveled, up to 15 steps.

steps	radius 11	radius 8	radius 7	radius 5
1	4.608	3.351	2.932	2.094
2	9.215	6.702	5.864	4.189
3	13.823	10.053	8.796	6.283
4	18.431	13.404	11.729	8.378
5	23.038	16.755	14.661	10.472
6	27.646	20.106	17.593	12.566
7	32.254	23.457	20.525	14.661
8	36.861	26.808	23.457	16.755
9	41.469	30.159	26.389	18.850
10	46.077	33.510	29.322	20.944
11	50.684	36.861	32.254	23.038
12	55.292	40.212	35.186	25.133
13	59.900	43.563	38.118	27.227
14	64.507	46.914	41.050	29.322
15	69.115	50.265	43.982	31.416

Table 2: Distances traveled by the wheel in 15 steps, values are given in mm.

Then, we conducted tests on the model using the corresponding buttons, and the results were satisfactory (Figures 8, 9, and 10). The rail, along with the wheel, operates in such a way that each step of the rotary encoder marks 4.608 mm in the LCD screen and serial monitor. The sum of each step provides us with the total distance that each of the buttons travels in the positive and negative directions. We subtracted these distances from the measurement of the table (60mm) to obtain the length of the beetle's elytron in the corresponding "y" coordinate.

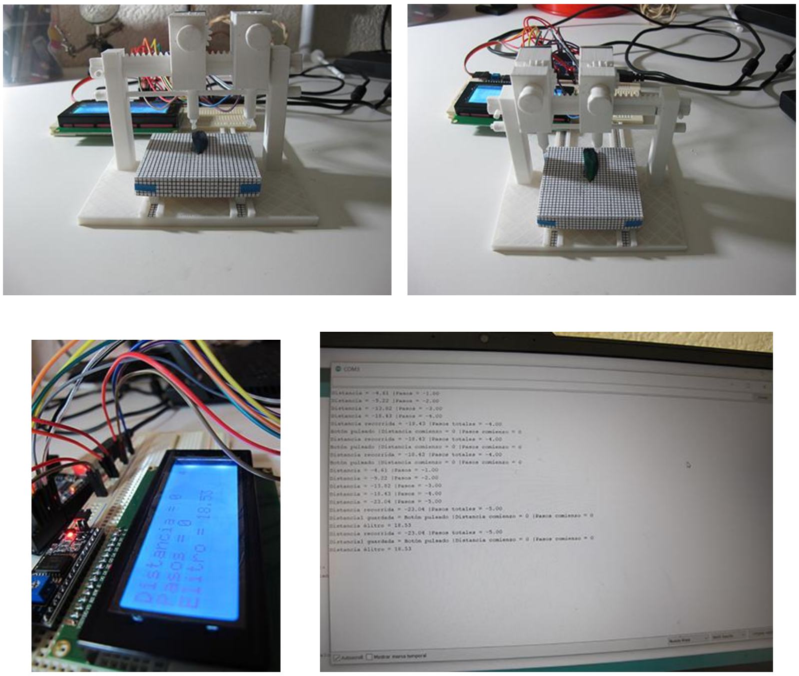


Figure 8: First test.

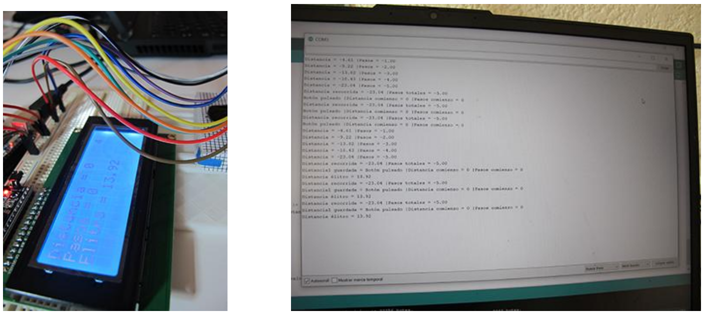


Figure 9: Second test.

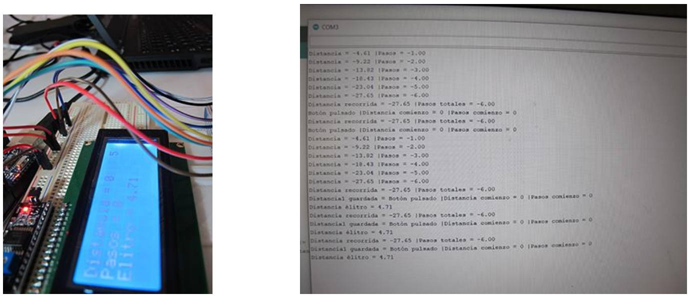


Figure 10: Third test.

5.2 Encoder Sensor

The operation of an encoder sensor involves detecting a physical phenomenon, which in this case would be distance, and converting this information into an electrical signal, either analog or digital. This signal is sent to an electronic circuit or a microcontroller for processing and subsequent display on an LCD screen and serial monitor, facilitating its analysis.

After having the geometric design and 3D printing of the structure and buttons for the encoder sensor done by Professor Rochman, Professor Hernández's suggestion is to place a plate on the toothless rail, on which tracks are printed at intervals of 2 mm or a smaller distance and connect them to a microcontroller and Arduino UNO. This will allow, upon pressing the two buttons, both from the right and left, to display numerical distance values on the LCD screen. This will facilitate subtracting the total measurement of the table to obtain the measurement of the beetle's elytron.

In the context of our project, a "track" refers to a series of markers printed or engraved on a plate at regular intervals. These marks represent reference points or specific positions along the surface.

The minimum distance at which tracks can be printed on a plate depends on various factors such as the manufacturing process of the plate, the precision of the printer used, and the printing resolution. In general, in most PCB (Printed Circuit Board) printing processes, track-to-track distances of around 0.1 mm (100 micrometers) or even less can be achieved.

However, in our project, the choice of the distance between each step depends on the button we designed. The 3D printing of the button was done using PLA (polylactic acid) material and it is divided into two parts, the trunk, and the pusher. The trunk is formed by a geometric shape of a square-based prism, 33 mm high, by 21 mm per side of the base. It has an orifice in the shape of the rail plus the tolerance so that we can manually slide it through the rail. At the bottom, it has a cylinder 20.5 mm high by 3.25 mm in radius, with a hole at the end of 3 mm in height to place the needle with which insulin is injected, which we will use to mark the location of the geometric points of the outline of the beetle's elytron. At the top, it has 4 holes where the springs from the pusher are inserted. The pusher, in addition to having the 4 cylinders to place the springs, in the center has a cylinder and a truncated cone with dimensions of 16.55 mm long, 3 mm in radius, and ends in a circle of 3 mm in diameter where we will place a reinforced stainless-steel needle 1.5 mm in diameter. When the button is pressed, the springs compress, and the needle goes down until it hits one of the steps of the plate (Figure 11).

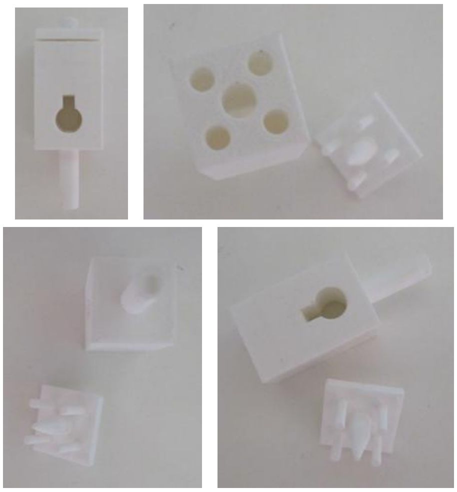


Figure 11: 3D printed button.

In both the upper part of the button trunk and the lower part of the pusher base, we propose to attach a high-quality copper sheet, with a copper purity greater than 99.9%, measuring 21 x 21 x 1 mm, to which we will solder the positive and negative cables that will go to the Arduino UNO at 5V voltage and ground respectively.

Finally, Professor Méndez conducted two simulations to test the operation of the sensor system. The results are available in a video with the MKV extension, which is an open-source and free software container format. Below are screenshots of the two simulations: one with 64 tracks and the other with 300 tracks.

Each of the 64 tracks (Figure 12) represents a conducting line that is touched or selected at a specific moment. Given the large number of connections involved, the 'Detector' block generates a unique binary code of only 6 bits, which represents the track that has been activated or selected. These 6 bits allow for $2^6 = 64$ distinct combinations and physically consist of only 6 connections going from the Arduino UNO to the 'Detector,' plus a single connection going from the 'Detector' to the Arduino UNO. This connection indicates to the Arduino when to stop the internal counter, which will generate the combination corresponding to the track number.

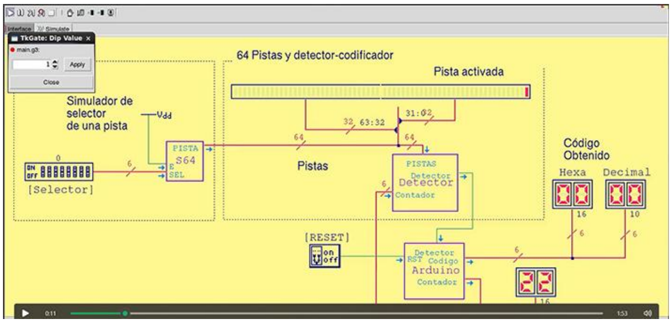


Figure 12: Circuit of 64 tracks.

The circuit of 300 tracks (Figure 13) is an extension of the 64-track circuit, with the main difference being that there are now 9 connections going from the Arduino UNO to the 'Track Detector.' Similarly, there is a connection from the 'Detector' to the Arduino UNO indicating when to stop the internal counter of the Arduino UNO to generate the code corresponding to the activated track. The 9 connections have the potential to generate up to $2^9 = 512$ track codes. However, due to space limitations, the simulation was limited to 300 tracks, which is the initially anticipated quantity for the measurement system.

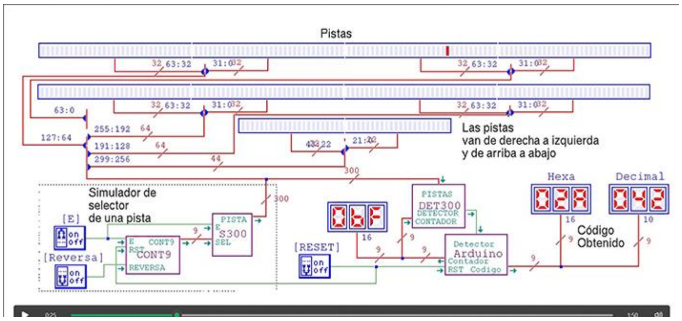


Figure 13: Circuit of 300 tracks.

6 CONCLUSIONS

During the development of this project, we encountered numerous challenges and conducted a series of tests and adjustments to ensure the effectiveness and precision of our encoders. The results obtained so far are promising and support the feasibility and utility of our research in the fields of comparative biology and biomedical engineering.

Below, we present some of the most relevant conclusions drawn from this interdisciplinary work and the implications they have for future research and practical applications.

The 3D printing of the buttons has been an integral part of our project, offering customized and functional solutions that have contributed to the success and effectiveness of the system as a whole. Its ability to adapt to our specific needs and its compatibility with other components have made 3D printing a valuable tool in our design and manufacturing approach.

It can be concluded that the encoder sensor designed and tested is effective for measuring distances and performing precise calculations based on the collected information. The encoder sensor has been shown to detect physical phenomena, such as distance, and convert this information into electrical signals for processing and visualization.

After a series of tests and adjustments, we have confirmed that the rotary encoder is an accurate and reliable tool for measuring distances in our project. Its ability to accurately record rotary movements has allowed us to obtain consistent and reproducible measurements.

The rotary encoder has been effectively integrated into our system, along with other electronic components and software. Its compatibility with Arduino UNO and other microprocessors has facilitated its implementation and use in our project.

We have observed that the rotary encoder adapts to the environment and application we have designed. Its ability to detect rotary movements in both directions has been crucial for our project, where we needed to measure distances in both directions along a rail.

In conclusion, both the hardware (sensors, Arduino UNO, boards, etc.) and the software (programming code) work efficiently to capture, process, and display data accurately and reliably.

However, we have identified some limitations in the two proposed electronic measurement systems, such as sensitivity to electromagnetic interference and the need for an appropriate holding mechanism to prevent displacement or step loss. These considerations should be addressed to ensure the reliability and precision of the systems under various operating conditions.

In summary, the interdisciplinary project has successfully integrated new electronic measurement techniques to study insect morphology. Both the encoder sensor and rotary encoder proved effective in measuring distances and physical phenomena. 3D printing has been crucial for adapting components to project needs. While efficient, limitations were identified regarding sensitivity to electromagnetic interference and securing mechanisms. These considerations must be addressed to ensure the reliability and accuracy of the systems.

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