

Underactuated Robotic Finger: Dynamic Modeling and Experimental Validation of Passive Adaptive Grasping

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Abstract– This work presents the design and analysis of a tendon-driven underactuated robotic finger capable of adaptive grasping without individual joint control. The mechanism is actuated by a single input force while joint motion emerges from the interaction between stiffness distribution, inertia, and tendon transmission geometry. A dynamic model based on second-order rotational systems was developed to describe the behavior of each passive joint and predict the closing sequence. The finger was designed using CAD tools and fabricated through additive manufacturing using carbon fiber PLA and TPU materials. Experimental tests were performed to evaluate the closing behavior under constant actuation. Results show that the joints reach equilibrium at different settling times, producing a progressive grasping motion consistent with the dynamic model. The study demonstrates that adaptive grasping can be achieved through passive mechanical dynamics, reducing sensing and control requirements in robotic and prosthetic applications.

Keywords– Robotic prosthesis, micromotor, 3D printing, carbon fiber, TPU, PCB board.

I. INTRODUCTION

The development of robotics has experienced significant growth in recent years, expanding its applications in sectors such as industry, medicine, education, and human assistance [1]. In this context, the design of robotic prostheses and biomechatronic mechanisms has gained relevance due to their potential to improve quality of life and optimize processes that require high precision and repeatability. Humanoid robotics has promoted the creation of devices capable of more accurately mimicking the natural movements of the human body, particularly those of the hand, a complex and fundamental structure [2], [3].

The main considerations taken for the design were mobility, size, weight, and degrees of freedom. It is crucial that the final model can exert force without compromising the integrated structure within it [4], and the ability to exert force without compromising structural integrity. For this reason, the implementation of compact micromotors, lightweight materials, and 3D modeling is essential to achieve an efficient and functional mechanism [5], [6].

The objective of this project is the development of a robotic hand with four fingers, capable of manipulating basic objects, and that can be improved and adapted for an android in future research [7]. To this end, computer-aided design software such

as SolidWorks and SpaceClaim was used, along with 3D manufacturing techniques. Additionally, an electronic board was developed for powering and controlling the micromotors, enabling independent movement of each finger.

This work describes the mechanical design process, the selection and integration of electronic components, the implementation of the control system [8] [9] and the tests conducted to evaluate the functionality of the prototype. The obtained results demonstrate the feasibility of a compact, functional, and adaptable mechanism, laying the foundation for future developments in humanoid robotics and robotic prostheses [10] [11].

II. SYSTEM DESIGN

This research is focused on the development, implementation, and validation of a functional prototype in the field of robotics. The methodology used during the research involves evaluations of the prototype's physical system, definition of requirements, functionality specifications, design decisions, execution, and verification of the tests conducted.

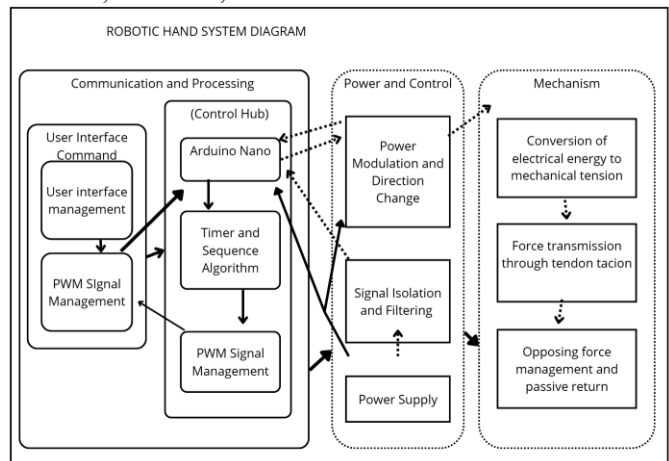


Fig. 1 Systems diagram in the final prototype

This study was conducted during the prototype development process, incorporating tests carried out in a controlled environment. In this way, the tests conducted allowed for obtaining measurable results of technical variables such as finger positioning, movement repeatability in each

joint, and the verification of transmission in the tendons that make up the hand.

III. TECHNIQUES AND INSTRUMENTS USED

A. CAD Design

Due to the difficulties encountered in the tendon transmission system, it was necessary to redesign the base where the actuators are mounted. The original orientation, which was vertical, was changed to a horizontal orientation. This change took up more space compared to the original design, and as a result, the motor cover, the full hand cover, and the thumb cover were adjusted to fit the new design.

For the transmission system, the wiring of each of the actuators and the satin cord that transmitted movement to the tendons were considered. Each of the fingers is composed of three parts: distal, middle, and proximal phalanges, which are made up of two types of filaments. The rigid structure is made of carbon fiber filament, joined together with pins made of the same material. On the outside of the fingers are TPU covers, allowing for a flexible and softer texture compared to carbon fiber. One of the improvements made is related to the pins. Initially, once they were placed, they could no longer be removed, but in the new design, they were made removable, allowing assembly and disassembly, thus facilitating the maintenance of the whole hand. This small improvement allowed greater efficiency in each of the iterations carried out as a test.

B. 3D Printing

A large percentage of the prototype's structure is made of 3D printing; various factors were taken into account for this. The equipment used was a Bambu Lab A1 Mini 3D printer. The print bed of this printer measures 256 x 256 mm, which is small, but is faster compared to other printers. The software from this brand is Bambu Studio, which allowed the printing properties to be configured, resulting in a sturdy print and improving processing times.

As mentioned earlier, the prototype is made up of two different filaments, each with different properties, making their applications and use different. For the Overture carbon fiber PLA filament, a print height of 0.16mm was used. The printing of components was done in groups of parts, due to the available space, and because printing too many pieces together resulted in failures, requiring the process to be started again, causing loss of material and time. On several occasions, the pieces detached from the bed, and the printer ended up printing in midair.

To avoid this type of failure, each part was secured with the correct orientation, avoiding the use of support and preventing misuse of material and time. For the TPU 95HF components, more printing time was required compared to carbon fiber PLA, due to the material properties and the complexity of the component shapes. The internal geometry of the TPU covers caused an excess of support, making support removal difficult and, in turn, creating challenges during assembly.

C. PCB Design

The space available at the base of the motors was essential, as this defines the limits of the PCB. Due to this restriction, the final PCB was two layers, making maximum use of the available space. Due to its size, an Arduino Nano was chosen as the system controller. Likewise, DRV8833 can control two motors per module, optimizing the use of materials and space. For voltage protection, two Schottky diodes (SSR32) were implemented at the beginning of the PCB's power supply.

The PCB was manufactured using a homemade method, using materials like muriatic acid and hydrogen peroxide. A small hole was made in both layers, ensuring the correct alignment of the tracks. The diameters of each of the component holes were quite small, requiring high precision to avoid damaging the copper traces. The same precision was required when mounting the components with solder.

IV. RESULTS

A. Transmission and Return Mechanism

The method for transmitting movement in each finger was with a satin cord, which runs through the entire structure of the finger. The finger is composed of three phalanges: proximal, middle, and distal. This cord has a knot tied at the distal phalanx, preventing the cord from getting trapped inside the structure. The other end of the cord is tied to the pulley that is connected to the micro motor. In this way, when the motor begins to rotate, the cord starts to wind around the pulley, causing the finger to begin closing. The more rotations the motor makes, the more the finger closes, but this has a limit.

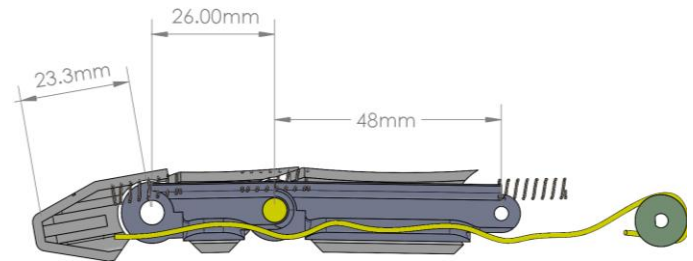


Fig. 2 Side cut of finger mechanism for closing and opening.

If the motor continues to rotate beyond the operational limit of the cord, the cord begins to entangle, forming a knot within the internal structure. This condition subsequently hinders the unwinding process when the motor reverses its direction of rotation. Therefore, the proper opening of the hand mechanism is adversely affected.

For the hand-opening mechanism, the following process is employed: once the finger has fully closed, the motor reverses its rotation, causing the cord to unwind. The yellow line in Fig. 1 represents the cord passing through the internal structure of the finger. In this manner, the tensile force that was previously contracting the finger is released. When the finger is no longer

subjected to a closing force and becomes intentioned, an auxiliary element is required to return the finger to its initial “open-hand” position. This necessitates the use of a material capable of pulling the finger back to its starting configuration.

TABLE 1
MATERIALS FOR OPENING

Type of Material	Elastic Bands	Springs
Cycles	7 cycles before loss of elasticity.	More than 50 cycles without difficulties.
Observations	Humidity, heat exposure, and natural material degradation.	Proper positioning to prevent excessive stretching, necessary restoring force to return to its open position.

Several tests were conducted with different materials. In an earlier prototype, elastic bands were attached from the distal phalanx to the hand structure, providing the restoring tension needed to return the finger to its initial position. However, this material proved inefficient, as after approximately seven iterations, the bands either ruptured or lost elasticity. Consequently, they were replaced with pen springs. These springs were affixed to the carbon filament that forms each phalanx. Three springs were employed, each positioned between phalanges to establish the connection at every joint comprising the fingers.

Thanks to the properties of springs governed by Hooke’s Law, they are capable of applying tension to each attachment point. This is achieved because each finger, except for the thumb, incorporates three independent springs. In other words, each finger joint closes sequentially—from the proximal phalanx to the middle phalanx, and finally to the distal phalanx—depending on the degree of cord winding on the pulley.

$$F = kx \quad (1)$$

The force is proportional to the displacement, which facilitates both control and the design of the return mechanism. In contrast, a rubber-based elastic material is not considered linear; its effective stiffness increases with extension. Consequently, the return motion is not proportional, complicating the control of the hand mechanism.

B. Dynamic Modeling

The dynamic behavior of the finger was analyzed using a lumped mechanical model based on concentrated elements. The mechanism consists of two passive joints actuated by a single tendon; therefore, joint motion is not individually imposed but emerges from the internal distribution of forces transmitted by the common tendon.

The equivalent mechanical plant is represented as a rotational mass–spring–damper system excited by a single tendon tension $T(t)$. Each joint is modeled as a second-order system, where the equivalent inertia J_i represents the distributed mass of the phalanx with respect to the rotation axis,

and the torsional stiffness k_i represents the restoring elastic element at each joint. Accordingly, two independent elastic elements are considered, one per passive joint.

Energy dissipation — mainly caused by the tendon friction, joint contact losses, and viscoelastic material behavior — is grouped into a single equivalent viscous damping coefficient b , shared by both joints. This approximation captures the global dissipative behavior of the mechanism while avoiding over-parameterization.

Applying Newton’s second law for rotational motion, the dynamics of each joint are described by:

$$\begin{aligned} J_1 \ddot{\theta}_1 + b \dot{\theta}_1 + k_1 \theta_1 &= r_1 T \\ J_2 \ddot{\theta}_2 + b \dot{\theta}_2 + k_2 \theta_2 &= r_2 T \\ J_3 \ddot{\theta}_3 + b \dot{\theta}_3 + k_3 \theta_3 &= r_3 T \end{aligned}$$

where r_i denotes the effective tendon moment arm at each joint. Due to the underactuated nature of the mechanism, both joints receive the same input but respond differently according to their mechanical parameters.

Taking the Laplace transform of each equation and assuming zero initial conditions:

$$\begin{aligned} J_i s^2 \Theta_i(s) + b s \Theta_i(s) + k_i \Theta_i(s) &= r_i T(s), i = 1, 2, 3 \\ (J_i s^2 + b s + k_i) \Theta_i(s) &= r_i T(s), i = 1, 2, 3 \end{aligned}$$

Dividing both sides by $T(s)$ and the polynomial term yields

$$\frac{\Theta_i(s)}{T(s)} = \frac{r_i}{J_i s^2 + b s + k_i}, i = 1, 2, 3$$

Since a single tendon tension excites all three joints simultaneously, the finger is represented as a single-input/multi-output (SIMO) system. Defining the output vector

$$\Theta(s) = \begin{bmatrix} \Theta_1(s) \\ \Theta_2(s) \\ \Theta_3(s) \end{bmatrix}$$

the transfer representation becomes

$$\Theta(s) = G(s) T(s)$$

with

$$G(s) = \begin{bmatrix} \frac{r_1}{J_1 s^2 + b s + k_1} \\ \frac{r_2}{J_2 s^2 + b s + k_2} \\ \frac{r_3}{J_3 s^2 + b s + k_3} \end{bmatrix}$$

This form captures three independent restoring springs through k_1, k_2, k_3 , a single equivalent damper through b , and the underactuated nature of the mechanism through the shared input $T(s)$.

The dynamic response was evaluated by applying a constant tension step input in MATLAB, allowing observation

of stability, overshoot, and settling time. This analysis characterizes the progressive finger closing produced solely by the interaction between stiffness, inertia, and geometric transmission, without requiring individual active control at each joint.

The step responses exhibit stable behavior with no sustained oscillations, indicating an adequately damped mechanical system. The joints reach steady state in a short time and with different settling times, producing a progressive closing sequence. This confirms that the adaptive grasping behavior emerges from the mechanical properties of the finger rather than active joint control.

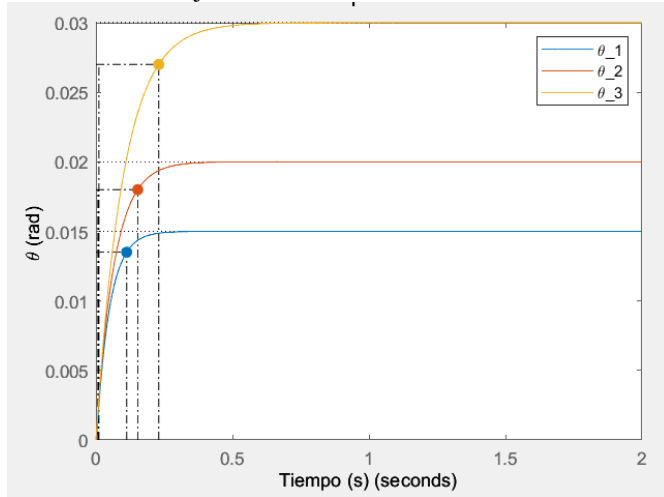


Fig. 4 Step response of the passive joints under constant tendon tension. The settling times differ according to the stiffness and inertia of each phalanx.

Regarding service life, the spring—being metallic—offers greater durability and can withstand a higher number of operational cycles before requiring replacement. Rubber, under constant load, tends to elongate over time and exhibits permanent deformation. When this occurs, the material undergoes relaxation, resulting in the loss of retraction capability [12]. Clearly, the advantages lie in the use of springs as the preferred material for the return system.

The mechanism implemented for the thumb differs, consisting of a pinion and gear system. This configuration was selected because the thumb’s motion is mechanically simpler compared to the other fingers of the hand.

C. Programming and Code

Before integrating the PCB into the system, tests were carried out using an Arduino Atmega, a breadboard, and two push buttons. The buttons allowed for changing the direction of rotation, either for closing or opening the finger, allowing trial-and-error work with each of the fingers and their joints. This process enabled design improvements until reaching the final prototype.

Due to the limited capacity of the Arduino Nano controller, there was poor data transmission caused by information overload. As a result, there were communication errors between the Arduino and the encoders.

Due to the limited capacity of the controller, information overload occurred, preventing proper communication between the Arduino and the encoder. To address this issue, a new programming approach was developed that controlled motor movement based on timed intervals. In this method, the motor position was determined through trial and error. Although less precise, replacing the controller would have compromised the compactness of the prototype.

The time-based programming method is influenced by several factors, including the supply voltage of the motors (ranging from 3V to 12V) and the distance between the pulley and the tendon, both of which affect the activation and deactivation timing of the motors.

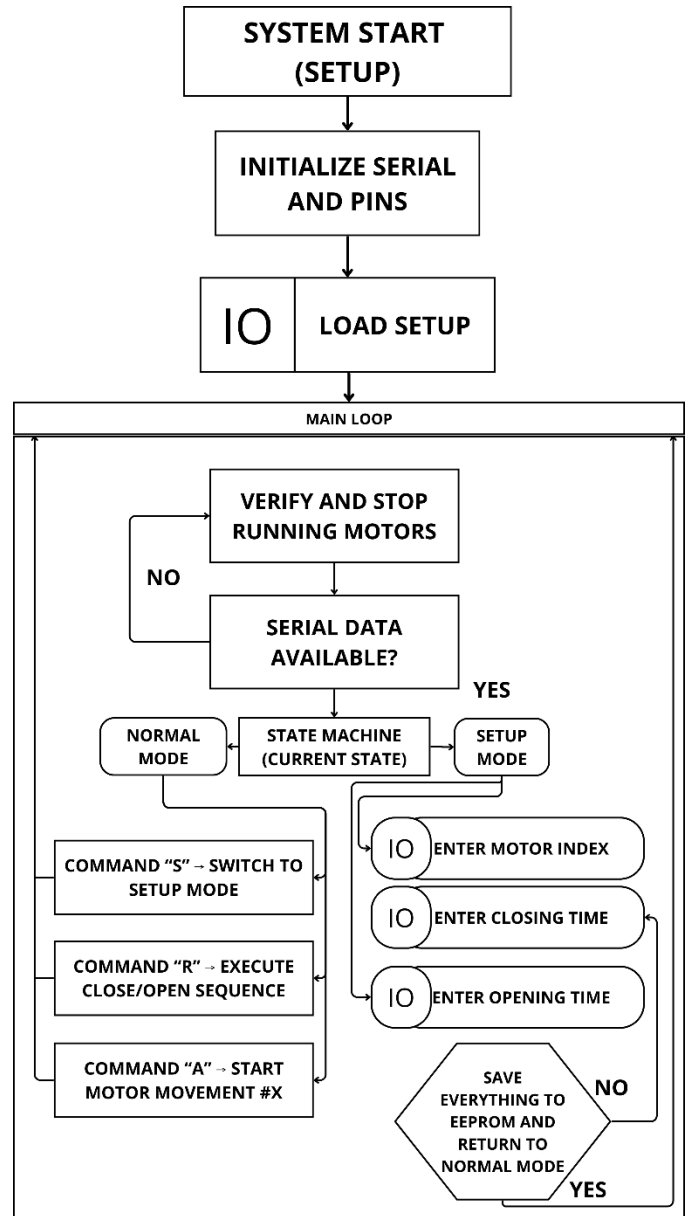


Fig. 3 Programming algorithm for time-based motor calibration.

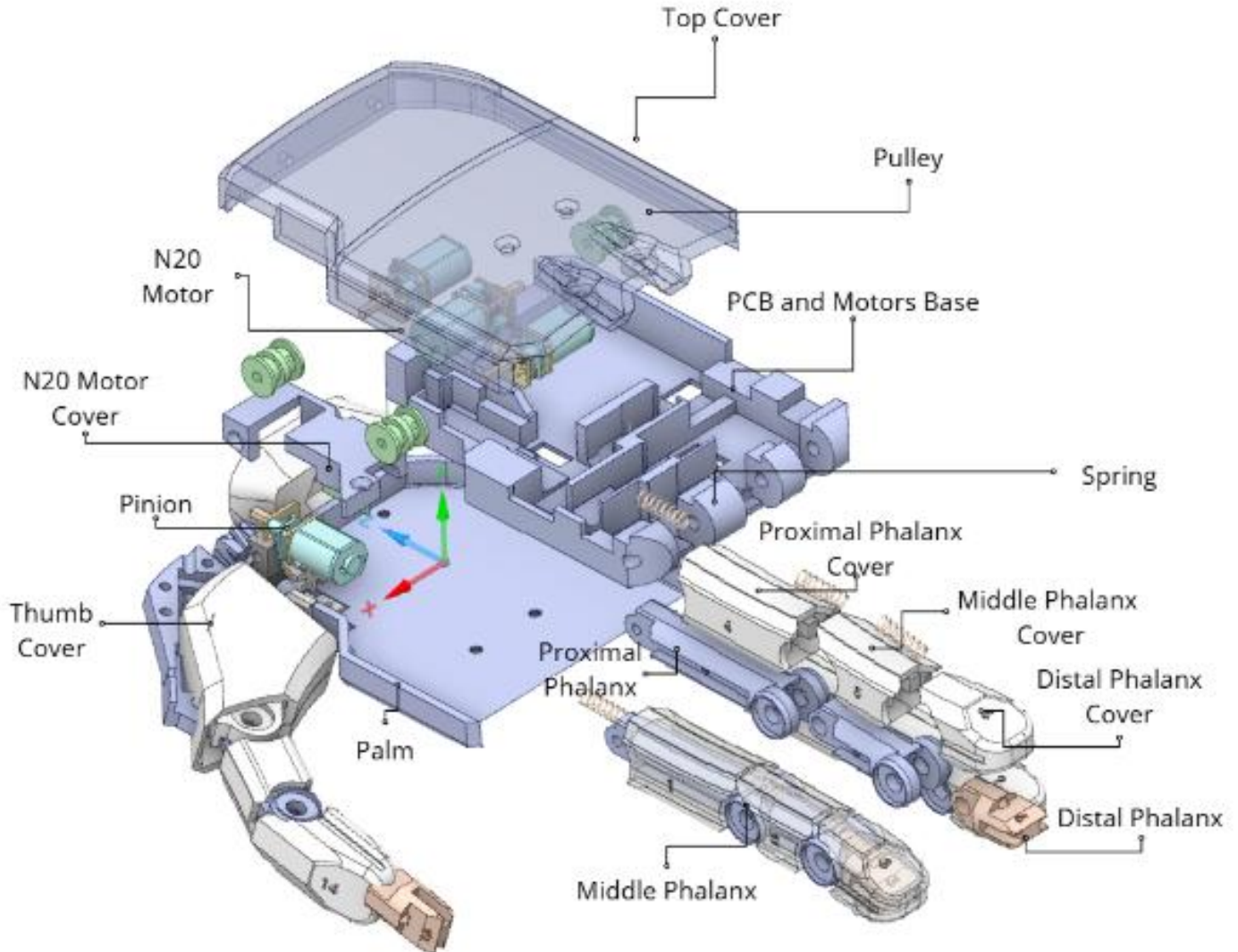


Fig. 4 Exploded view of SpaceClaim with description.

D. Structural Performance and Material Selection

the 3D printing process with carbon fiber PLA, the tensile strength of moving components was improved. Recent studies confirm that carbon fiber in PLA increases tensile strength compared to basic PLA [13]. After testing the components by forcing them to close against rigid objects, the print showed no bending or fractures, validating the significant improvement provided by the material. Compared to basic PLA, the components could not withstand the iterations performed, and they didn't even manage to achieve a correct print due to the complexity of the geometry for this material. On the other hand, the TPU 95 HF covers showed improvements when performing grip tests with smooth-surfaced objects. TPU deforms slightly under pressure. This property increases friction when coming into contact with the surface. By allowing objects to require less

force to be grasped, this strategy is used in robotic grippers to save costs [14][15]. The time-based control system proved capable of absorbing certain tolerances, allowing the hand to perform basic manipulation tasks without requiring a closed-loop control system [16].

E. Motor Calibration

The calibration was done individually for each motor (M1-M4), and the time was adjusted in milliseconds according to the length of the satin cord on each finger. This method compensated for voltage variations between three and twelve volts, and the pulley geometry, reducing the accuracy of the final position.

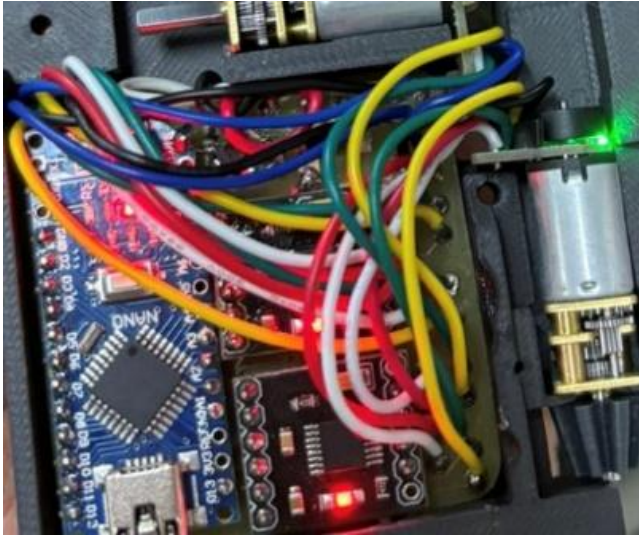


Fig. 5 PCB operating in the final prototype

The final PCB connection primarily consisted of Schottky diodes integrated into the power supply. The input pins of the DRV8833 drivers were connected to the analog pins of the Arduino Nano, while the output pins of the DRV8833 were connected to the motors.

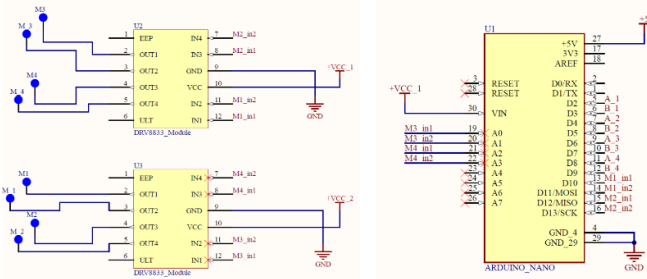


Fig. 6 Detailed schematic of final connections between components on the PCB.

F. Electronic Considerations

The PCB design required certain calculations and considerations to make it functional. In battery-powered systems, every tenth of a volt is critical. A conventional diode (such as the 1N4007) exhibits a voltage drop between 0.7 V and 1.1 V, whereas the SSR34 (Schottky) diode has a drop of only 0.4 V to 0.5 V. The minimum operating voltage of the N20 motors is 3 V. With a conventional diode, the effective voltage is reduced to approximately 1.9 V, resulting in a loss of nearly 40% of motor power. In SSR34 reduces the voltage by 0.5 V, effectively operating at 2.5 V. This allows the motor to retain approximately 83% of its operational power. Due to these properties, the Schottky diode was chosen as the final component; it is capable of minimizing voltage loss and ensuring good performance in the actuators.

- Total current estimated:

$$300mA \times 4 = 1,200 mA$$

- SSR34 diode capacity: It's designed to manage 3A continuously.
- Heat calculation (Power dissipated):

$$P_d = \frac{0.5 V}{1.2 A} = 0.6 W$$

G. Operation Repeatability Evaluation

Hand subjected to consecutive open-close cycles. Initially precise and repeatable, but accuracy degraded over time. Better grip observed on larger objects. Tests divided into:

1. Individual finger and full-hand tests without objects.
2. Grip test medium, lightweight case, Object A.
3. Grip test with egg (small, fragile, oval object), Object B.

TABLE 2

STATISTICAL SUMMARY OF THE EXPERIMENTAL TESTS

Test type	Cycles	Successes	Failures	Success (%)	Main causes of failure
No object	15	13	2	86.70	Middle finger misalignment, tendon adjustment.
Object A	10	7	3	70.00	Motor mismatch, tendon object misalignment.
Object B	6	1	5	16.70	Oval geometry, improper orientation, object pushing.
Total	31	21	10	67.70	Mechanical and control limitations.

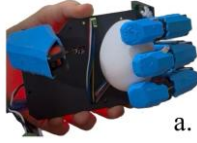
It can be concluded that, in general, the prototype can perform the opening and closing tasks and can grasp different objects. However, it is necessary to assist the prototype with orientation regarding its structure and the object it is handling for it to achieve these functions.

V. CONCLUSION

Underactuated robotic finger achieves adaptive grasping through passive mechanical dynamics rather than individual joint control. Both the dynamic model and experiments showed that each joint settles at different times under the same tendon tension, producing a natural progressive closing motion. The actuator therefore supplies energy only, while the final posture emerges from stiffness, inertia, and tendon geometry. This approach reduces sensing and control complexity, making it suitable for simple and low-cost robotic or prosthetic applications. The redesign from vertical to horizontal orientation was essential; it eliminated friction and tangling by properly aligning the tendon with the pulley. The independent springs allowed for a better return system, surpassing the elastic bands that degraded quickly. Time-based programming proved to be less precise than encoder feedback, but it ensured a compact prototype capable of opening and closing in each iteration.

TABLE 3

EXPERIMENTAL EVALUATION OF THE ROBOTIC HAND UNDER THREE CONDITIONS: NO OBJECT, CYLINDRICAL OBJECT (A), AND SPHERICAL OBJECT (B).

No Object		Object A		Object B	
Image	Description	Image	Description	Image	Description
 a.	In test A, the closing motion was evaluated without an object before mounting the hand on the base.	 a.	In the following tests, a case was introduced due to its size. It is important to note that the case had to be positioned close to the hand to facilitate grasping. Successful closing.	 a.	A malfunction occurred with the thumb, where the distal phalanx was lost; nevertheless, testing continued. The object was replaced with another of slightly different size, which facilitated successful trials.
 b.	Index finger closing.	 b.	Successful closing.	 b.	As with the lightweight object, it was necessary to position the egg near the proximal phalanges to assist the prototype in completing the grasp.
 c.	Closing test with the index finger. The finger could achieve a greater closing range by adjusting the programming timing.	 c.	All tests with the case were performed in a vertical position. At this stage, it became noticeable that the index and middle fingers did not achieve the same closing performance as in previous tests. This was due to desynchronization between the motors and the tendon thread.	 c.	In the vertical configuration, the hand was unable to grasp the object.
 d.	Simultaneous closing of three fingers. Again, the middle finger showed lower precision, so the internal structure was inspected for calibration.	 d.	Successful closing; however, one of the distal phalanx covers detached. The cycle had to be stopped to verify that the tendon thread had not over-wound.	 d.	In some instances, the fingers pushed the object, preventing full closure.

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