Research article

Design of a Robotic Arm Based on a 4-DOF SCARA Configuration with a 2 m Reach and a 5 kg Load Capacity

Diseño de un brazo robótico basado en una configuración SCARA de 4 GDL con un alcance de 2 m y una capacidad de carga de 5 kg

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Abstract: In this work we present the design of a four-degree-of-freedom robotic arm based on a SCARA-type configuration, with an approximate reach of 2.22 m and a load capacity of 5 kg, intended for the positioning and orientation of a projection system. The development of the system was carried out following Karl Ulrich's product design methodology, ranging from the definition of requirements to the validation of the prototype. The mechanical design of the manipulator was carried out using CAD tools, as well as kinematic modeling using the Denavit–Hartenberg method to determine the position and orientation of the end effector. Additionally, a structural analysis was carried out using finite element simulation in the Fusion 360 software, obtaining a minimum safety factor of 4.8 and maximum displacements of 4.464 mm, which validates the structural integrity of the system. The actuation system was designed based on the required torque analysis, implementing NEMA 24 stepper motors with timing-belt transmission that allows amplifying the torque up to 15 Nm. Finally, the Arduino-based electronic control system was developed in conjunction with the DM542 driver, allowing manual operation of the manipulator. The results obtained show the viability of the proposed design and its potential application in different environments.

Keywords: Robotic arm; SCARA; Denavit–Hartenberg; Finite elements

Resumen: En este trabajo se presenta el diseño de un brazo robótico de cuatro grados de libertad basado en una configuración tipo SCARA, con un alcance aproximado de 2.22 m y una capacidad de carga de 5 kg, destinado al posicionamiento y orientación de un sistema de proyección. El desarrollo del sistema se llevó a cabo siguiendo la metodología de diseño de producto de Karl Ulrich, desde la definición de requerimientos hasta la validación del prototipo. El diseño mecánico del manipulador se realizó mediante herramientas CAD, así como el modelado cinemático mediante el método de Denavit–Hartenberg para determinar la posición y orientación del efector final. Adicionalmente, se realizó un análisis estructural mediante simulación por elementos finitos en el software Fusion 360, obteniendo un factor de seguridad mínimo de 4.8 y desplazamientos máximos de 4.464 mm, lo que valida la integridad estructural del sistema. El sistema de actuación se diseñó a partir del análisis del torque requerido, implementando motores paso a paso NEMA 24 con transmisión por correa dentada que permite amplificar el torque hasta 15 Nm. Finalmente, se desarrolló el sistema electrónico de control basado en Arduino junto con el driver DM542, permitiendo la operación manual del manipulador. Los resultados obtenidos muestran la viabilidad del diseño propuesto y su potencial aplicación en distintos entornos.

Palabras clave: Brazo robótico; SCARA; Denavit–Hartenberg; Elementos finitos

1. Introduction

The development of robotics projects is a highly integrating training scenario, in which knowledge of mechanics, electronics, control and programming converges [6;9;11]. One of the main challenges when tackling this type of project is to achieve an effective integration of the different stages of the design process within a complete and functional development, from the definition of requirements to the implementation and validation of the system [7]. In particular, the design of robotic manipulators constitutes an opportunity for the applied understanding of concepts such as kinematic modeling, the analysis of strain and stress in a mechanical structure, the selection of actuators and the integration of control systems [3].

In this context, the purpose of this work is to describe the design, development and construction of a robotic arm based on a SCARA configuration of four degrees of freedom, with the ability to position and orient a projection system. The development of the system is based on Karl Ulrich's product design methodology [4], which provides a structured approach to systematically address the different stages of the process, from planning to testing and adjustments of the system.

This article describes in detail the design process of the robotic arm, starting with the definition of the functional requirements and operating constraints that guide the design. Next, the mechanical design of the manipulator is addressed, considering the structural configuration, the selection of materials and the geometry of the joints and links. Subsequently, kinematic modeling is developed using the Denavit–Hartenberg method [1] to establish the relationship between the articular variables and the position and orientation of the end effector. In the same way, the evaluation of the structural behavior of the system is carried out through simulations of stresses and load conditions, which allows verifying the strength and rigidity of the design [8]. Likewise, the process of selection and sizing of the actuation system is presented, including the choice of motors and transmission mechanisms. Finally, connection drawings and a base code of the electronic control system are presented.

The remainder of this article is organized as follows: section 2 summarizes the main contributions of the work. Section 3 reviews related works on the design of robotic manipulators. Section 4 describes the materials and methods, including the design methodology, the mechanical structure, the kinematic modeling and the actuation system. Section 5 presents the results obtained for the mechanical structure, the structural analysis, the direct kinematics and the electronic control system. Section 6 discusses these results in the context of previous studies, and Section 7 presents the main conclusions and future work.

2. Contributions

The main contributions of this work are the following:

i. An integrated design of a 4-DOF SCARA-type robotic arm for positioning and orienting a projection system, developed under Karl Ulrich's structured product design methodology.
ii. The kinematic modeling of the manipulator using the Denavit–Hartenberg method, which establishes the forward-kinematics relationship between the joint variables and the pose of the end effector.
iii. The structural validation of the design through finite element simulation, obtaining a minimum safety factor of 4.8 and maximum displacements on the order of millimetres.
iv. The sizing of the actuation system from a torque-requirement analysis, selecting NEMA 24 stepper motors with a timing-belt transmission that amplifies the torque up to 15 Nm.

v. The implementation of an Arduino-based electronic control system with DM542 drivers that enables manual operation of the manipulator.

3. Related Works

Various works have addressed the design and development of robotic manipulators from complementary perspectives. In [5] the design and development of a 4-DOF SCARA robot aimed at educational purposes is presented, integrating the definition of specifications, conceptual design, finite element stress analysis, kinematic modeling and the implementation of the electronic control system. Similarly, [2] report the design and simulation of a robotic arm for manufacturing operations, showing that finite element analysis under different load conditions allows verifying structural strength, as well as estimating deformations and displacements. For its part, [10] propose a modified SCARA manipulator for pick-and-place applications, combining CAD modeling, structural analysis, motion simulation and kinematic modeling using the Denavit–Hartenberg method to extend the functionality of the system. Likewise, [13] highlight the importance of kinematic analysis and motion control in industrial robots, using homogeneous transformation matrices to determine the position and orientation of the end effector. Taken together, this background shows that the development of robotic arms requires the integration of mechanical design, kinematic modeling, structural analysis, and control strategies to achieve functional and reliable systems.

4. Materials and Methods

To design the robotic arm, Karl Ulrich's product development methodology, renowned for its systematic and structured approach, was applied. Five stages were addressed: planning, concept development, system-level design, detail design, and testing and adjustments. These stages allow the design to be approached in an orderly manner, starting from the collection of requirements and needs, until reaching the detailed design of the components and the construction of the system. In the planning stage, the functional requirements and the constraints of the operating environment were established. This laid the foundations for the development of the concept, where different alternatives were explored and the most suitable one was selected through a comparative analysis. Subsequently, in the system-level design, the mechanical structure was modeled and analyzed using CAD software and load-analysis simulations to make design improvements using Fusion 360 software. In the detailed design stage, the design of the joints and the selection of the actuators, the electronic control system and the direct kinematics of the robot were addressed.

4.1. Mechanical structure and configuration of the robotic arm

In this work, the design and construction of a robotic arm capable of positioning a videobeam for the projection of images and video on a vertical surface is proposed. Figure 1 presents the scenario where the robotic arm will be installed and the projection surface, from which the requirements for the development of the robotic arm were established; these are presented in Table 1.

Table 1. Project requirements.

No.	Requirement	Importance (1–5)
1	The robotic arm must be easy to operate	4
2	The robotic arm must be a safe structure for users and passers-by	5
3	The robotic arm must have the ability to position and orient itself flexibly	5
4	The robotic arm must operate semi-automatically	2
5	The robotic arm must have weather-resistant elements	4
6	The robotic arm must have safety devices such as limit switches	5
7	The robotic arm must have an emergency stop option available to the user	4
8	The robotic arm must move at a safe and consistent speed while waiting for the user	3
9	The robotic arm must have a load capacity of 5 kg	5
10	The robotic arm must have a reach of 2 m	5

Source: The authors.

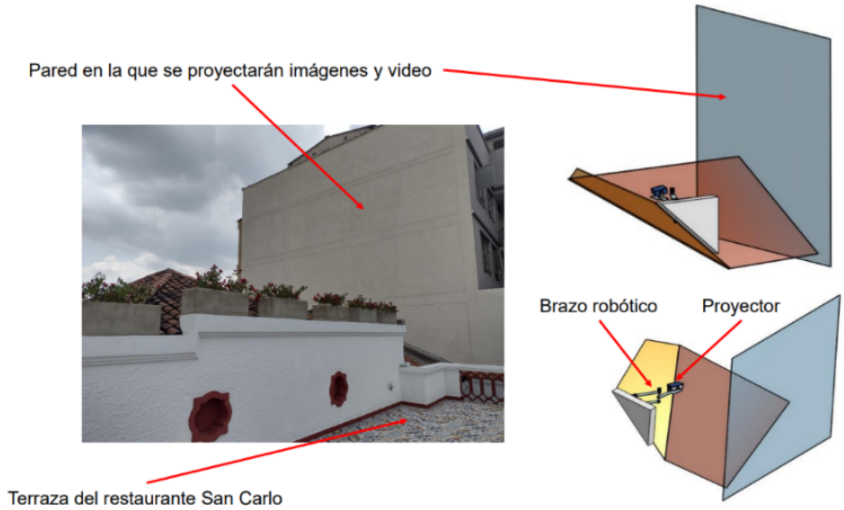

Figure 1. Stage where the robotic arm and projection surface will be installed.
Source: The authors.

To translate the needs of the project into measurable technical parameters that guide the design process, metrics associated with the identified requirements were defined. These metrics allow quantifiable criteria to be established to evaluate the performance of the system during the design, implementation and validation stages of the robotic arm. They also facilitate traceability between the user's needs and the technical specifications of the system, ensuring that each requirement is considered within the engineering process. Table 2 presents the defined metrics, the units in which they will be evaluated, and their relationship with the needs of the project described above. In this way, a basis is established for design decision-making and verification of compliance with system requirements.

Table 2. Metrics and units.

No.	Metric	Units	Relationship
1	Number of movements under keyboard command	Quantity	1
2	Structural safety factor	Dimensionless	2
3	Number of degrees of freedom	Quantity	3
4	Number of automatic or pre-programmed actions	Quantity	4
5	Material characteristics	List	5
6	Number of safety devices	Quantity	6–7
7	Movement speed	m/s	9
8	Maximum load capacity	kg	10
9	Maximum reach of the robotic arm	m	10

Source: The authors.

Onshape was used for the design of the manipulator arm. This is a cloud-based computer-aided design (CAD) platform that allows collaborative creation, editing, and management of 3D models from a web browser.

4.2. Direct kinematics

The direct kinematics of the robotic arm was developed with the aim of establishing the mathematical relationship between the joint variables and the position and orientation of the end effector. To do this, the Denavit–Hartenberg (D–H) method was used, which allows the systematic modeling of kinematic chains by assigning reference frames to each joint. From this formulation, the matrix of D–H parameters of the system was defined and the homogeneous transformation matrices between consecutive links were constructed.

Subsequently, the total transformation matrix of the system was obtained, which describes the position and orientation of the end effector with respect to the base frame. This representation allows extracting directly both the position vector and the rotation matrix of the end of the manipulator.

4.3. Actuation system

The actuation system was designed based on the analysis of torque requirements and loading conditions of the robotic arm. Initially, a calculation of the required torque was made by means of a diagram of forces and torques present in the system, considering the total length of the extended arm and the mass of the system, including the projector, which allowed the selection of the actuators and the sizing of the power transmission elements. Based on this analysis, the use of stepper motors was chosen. For the first three joints, NEMA 24 motors were selected, which, together with a belt drive system and toothed pulleys, allow amplifying the torque in the joint. This transmission was designed with a ratio that increases the torque of the motor, ensuring that the minimum torque required for movement is exceeded. Additionally, axial and radial bearings were incorporated to support the loads present and reduce friction in the joints, improving the efficiency of the system. In the case of the fourth degree of freedom, a smaller motor with direct coupling was used, since its main function is the orientation of the end effector and requires less torque.

5. Results

5.1. Mechanical structure and configuration of the robotic arm

The final design of the robotic arm corresponds to a 4-degree-of-freedom (DOF) structure based on a SCARA configuration, with an R–R–R–R type kinematic architecture, where each degree of freedom is associated with a rotational joint. The articular variables of the system are denoted as $\theta_1, \theta_2, \theta_3$ and θ_4. The arm is made up of two rigid links that connect the first three joints ($\theta_1, \theta_2, \theta_3$). Each link is constructed from a pair of 50 mm $\times$ 50 mm $\times$ 1.5 mm square stainless steel tubes, arranged in such a way that one face of the tube is located on the side of the other and joined by specialized welding, ensuring adequate structural rigidity and mechanical strength. The fourth joint (θ_4), mounted on the third joint (θ_3), allows the projector to be tilted, extending the orientation capacity of the end effector and facilitating the adaptation of the system to different operating conditions (see Figure 2).

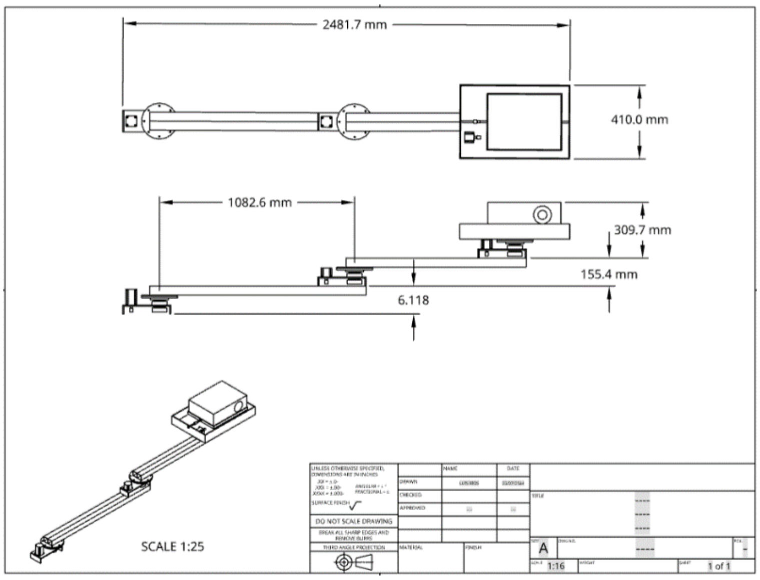

Figure 2. Robotic arm design blueprint.

Source: The authors.

5.1.1. Structural analysis

Figure 3 presents the structural analysis of the system under load conditions, including the visualization of the three-dimensional model and the distribution of stresses along the structure. It is observed that the minimum safety factor obtained is 4.8, indicating that the system operates within a safe range.

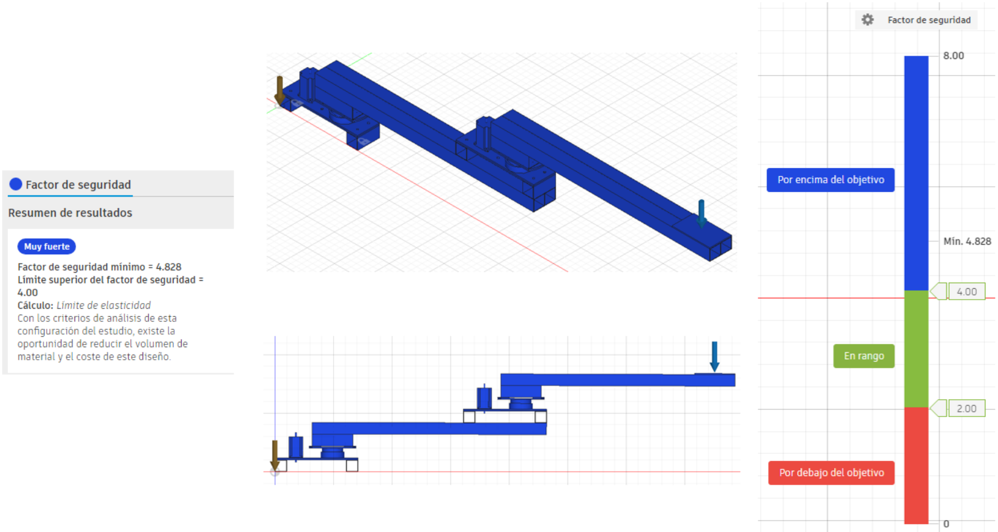

Figure 3. Structural analysis of the robotic arm - safety factor.
Source: The authors.

Figure 4 shows the analysis of displacements of the structural system under the action of the applied load. In the three-dimensional representation and its lateral view, the distribution of displacement is observed; this simulation presents a maximum displacement of approximately 4.464 mm at the free end of the structure. The results allow evaluating the stiffness of the system and verifying that the deformations are kept within acceptable limits for its operation.

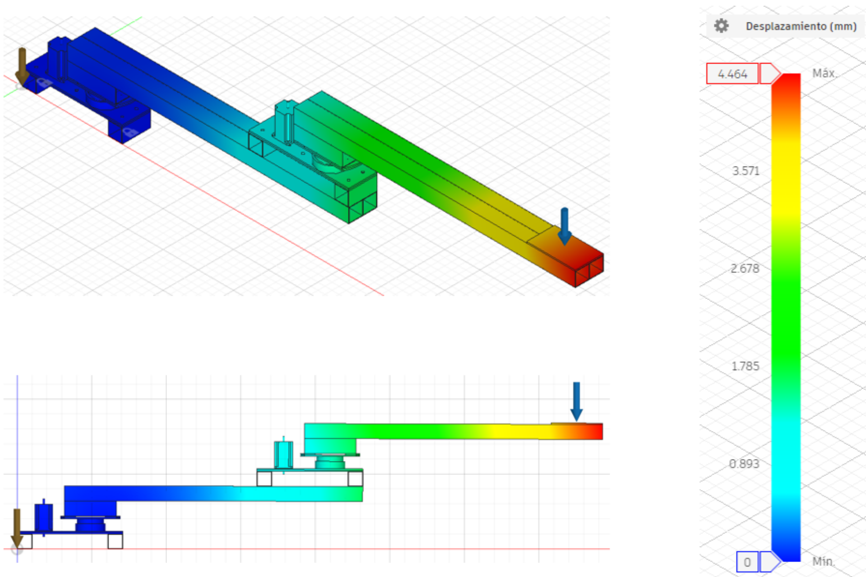

Figure 4. Structural analysis of the robotic arm - displacements.
Source: The authors.

5.2. Direct kinematics

The Denavit–Hartenberg parameter matrix of the robotic arm is presented in Table 3. The system of reference frames used to obtain it is illustrated in Figure 5.

Table 3. Denavit–Hartenberg parameters of the robotic arm.

i	a_i	α_i	d_i	θ_i
1	a_1	0	d_0	θ_1
2	a_2	0	d_1	θ_2
3	0	-90	d_2	θ_3
4	0	0	0	θ_4

Source: The authors.

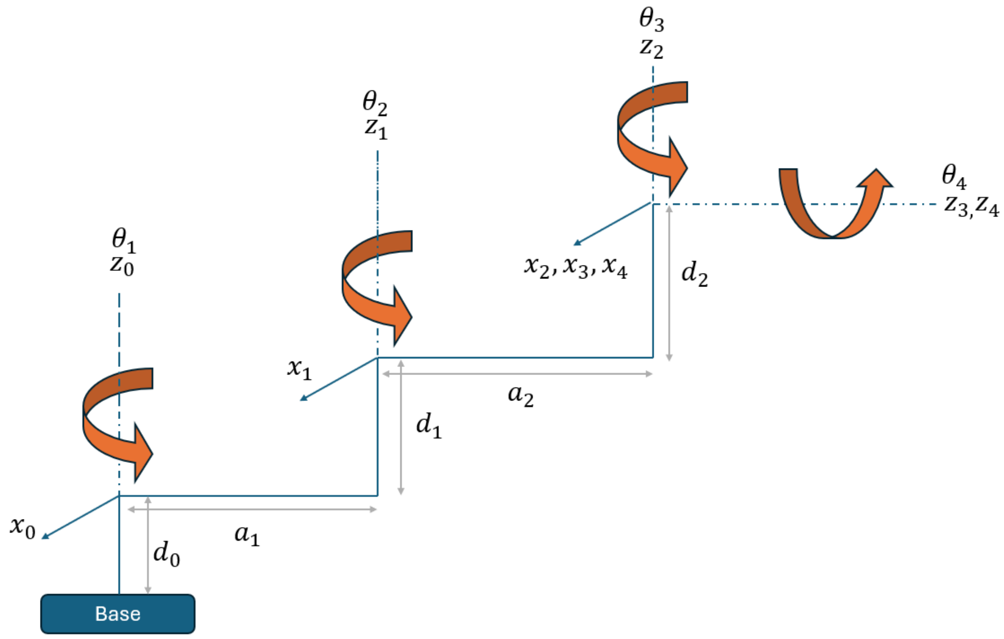

Figure 5. Reference frames for obtaining the Denavit–Hartenberg parameters of the robotic arm.
Source: The authors.

The transformation matrix T_0^4 that relates the orientation and position of the reference frame of the end of the robotic arm (x_4, y_4, z_4) with respect to the base reference frame (x_0, y_0, z_0) is presented in Equation (1).

$$T_0^4 = \begin{bmatrix} \cos\phi\cos\theta_4 & -\cos\phi\sin\theta_4 & -\sin\phi & a_1\cos\theta_1 + a_2\cos(\theta_1+\theta_2) \\ \sin\phi\cos\theta_4 & -\sin\phi\sin\theta_4 & \cos\phi & a_1\sin\theta_1 + a_2\sin(\theta_1+\theta_2) \\ -\sin\theta_4 & -\cos\theta_4 & 0 & d_0+d_1+d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

From this, the orientation R_0^4 of the frame (x_4, y_4, z_4) with respect to the reference frame (x_0, y_0, z_0) is obtained, as shown in Equation (2).

$$R_0^4 = \begin{bmatrix} \cos\phi\cos\theta_4 & -\cos\phi\sin\theta_4 & -\sin\phi \\ \sin\phi\cos\theta_4 & -\sin\phi\sin\theta_4 & \cos\phi \\ -\sin\theta_4 & -\cos\theta_4 & 0 \end{bmatrix} \tag{2}$$

The position P_0^4 of the frame (x_4, y_4, z_4) with respect to the reference frame (x_0, y_0, z_0) is given by Equation (3).

$$P_0^4 = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} a_1 \cos\theta_1 + a_2 \cos(\theta_1 + \theta_2) \\ a_1 \sin\theta_1 + a_2 \sin(\theta_1 + \theta_2) \\ d_0 + d_1 + d_2 \end{bmatrix} \tag{3}$$

5.3. Actuation system

5.3.1. Motor selection

The selection of motors was made based on the analysis of forces and torques shown in Figure 6.

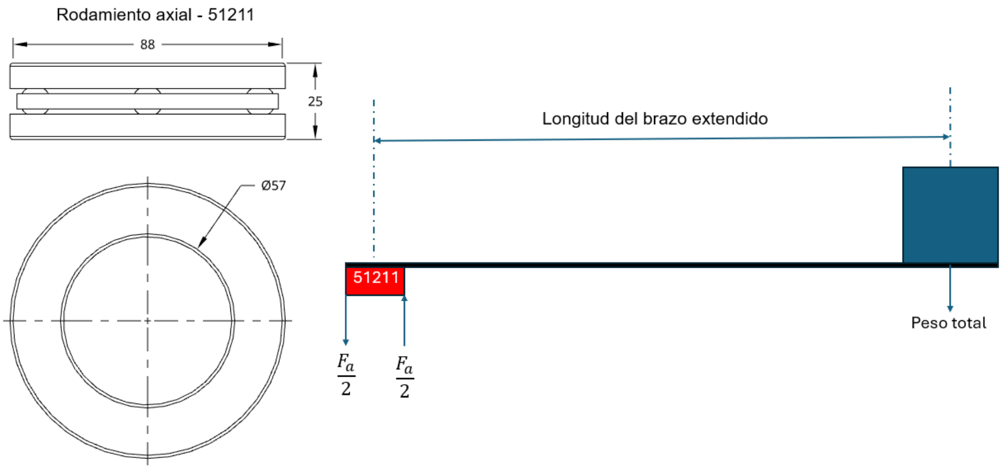

Figure 6. Diagram of forces and torques for selecting the actuators.
Source: The authors.

Considering an extended arm length of 2.4817 m and a total mass of 30 kg including the projector, a torque $T = 729.62$ Nm is generated. That torque must be counteracted by bearing 51211 with a force $F_a = \frac{T}{d_e} = 8291.1$ N. The contact between the structure and the bearing is obtained from the ratio of its inner and outer radii as $r = \frac{r_i + r_e}{2} = \frac{d_i + d_e}{4} = 0.0362$ m. The torque of the joint required to generate movement must be greater than $\mu F_a r = 6$ Nm, considering a friction coefficient $\mu = 0.02$, which can be significantly lower in a bearing [12].

For the transmission of the movement, a belt mechanism and toothed pulleys were chosen; these transmissions allow rotary movement and torque to be transferred between axles smoothly and quietly, and require reduced maintenance. Taking into account that the torque necessary for the joint to rotate must be greater than 6 Nm, two toothed pulleys of 12 (drive pulley) and 60 (driven pulley) teeth respectively were chosen, which implies a multiplication of the motor torque by a factor of five. A 3 Nm NEMA 24 stepper motor was chosen so that, together with the belt drive, the joint has a torque of 15 Nm.

5.3.2. Joint configuration

The first three degrees of freedom of the robotic arm correspond to rotational joints, each made up of:

- 1 × NEMA 24 3 Nm stepper motor
- 1 synchronous pulley drive system
  - 1 × P-60-5M15 pulley
  - 1 × P-12-5M15 pulley
  - 1 × HTD 520-5M belt
- 1 × 51110 axial bearing
- 1 × 51210 axial bearing
- 1 × 6206 radial bearing
- 1 coupling bushing for bearings

- 1 joint base
- 1 × 30 mm diameter shaft

The NEMA 24 stepper motor shaft is coupled to the P-12-5M15 pulley, which transmits motion to the P-60-5M15 pulley via an HTD 520-5M belt (see Figure 7).

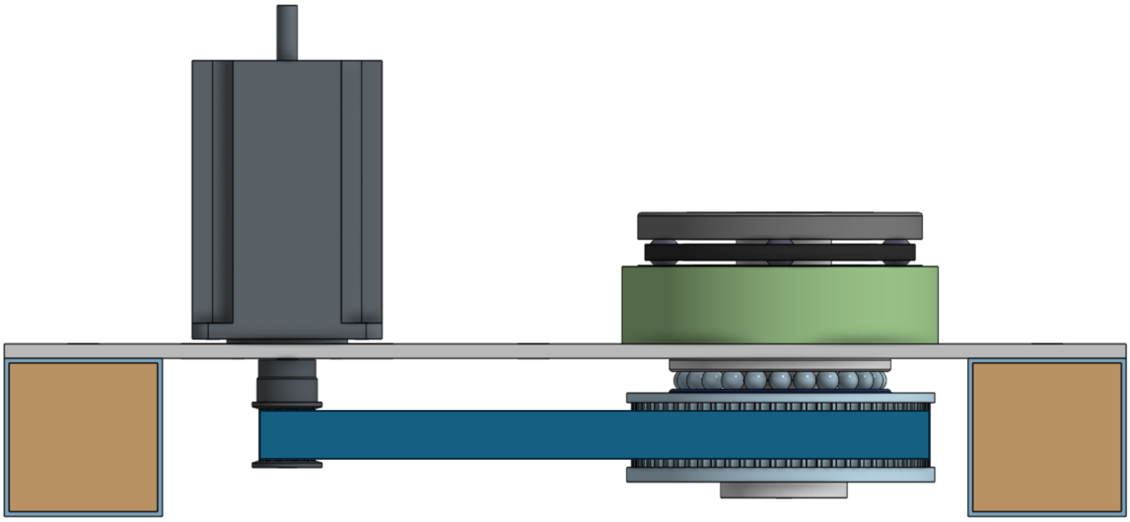

Figure 7. Robotic arm joint configuration.

Source: The authors.

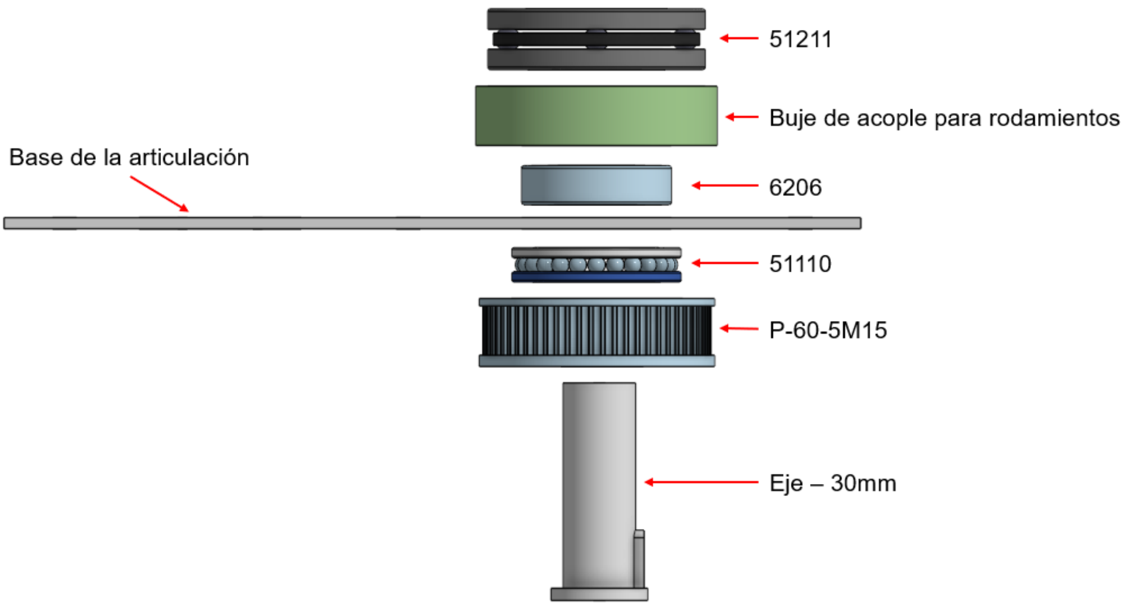

Figure 8. Exploded view of the rotational joint.

Source: The authors.

An exploded view of the components that make up the joint, as well as their arrangement, is presented in Figure 8. The fourth degree of freedom, which is mounted on the third joint, uses a 100 oz-in NEMA 23 stepper motor with direct coupling to the axis of rotation to generate the tilt of the projector.

5.3.3. Electronic control system

The control of the stepper motors that activate the joints is done with an Arduino Uno board, a DM542 driver for each stepper motor, and a keypad to manually activate the movement of the joints (see Figure 9). The keypad allows controlling the direction of rotation and regulating the angular velocity of each joint (see Figure 10).

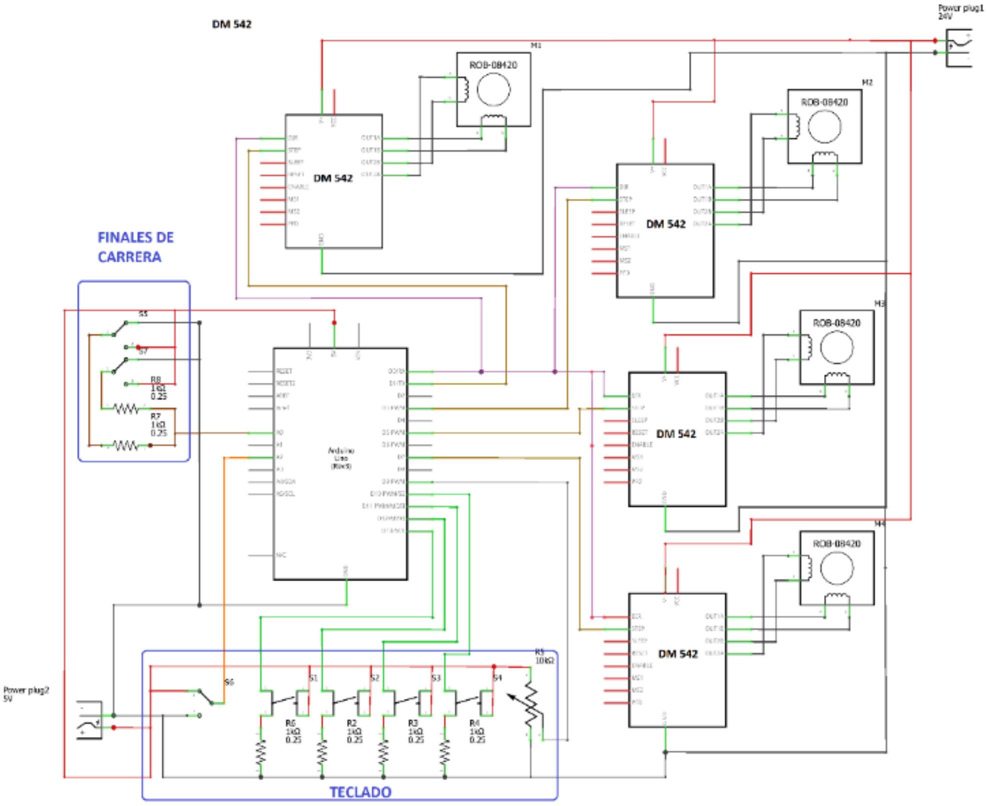

Figure 9. Electronic plan of the control system.

Source: The authors.

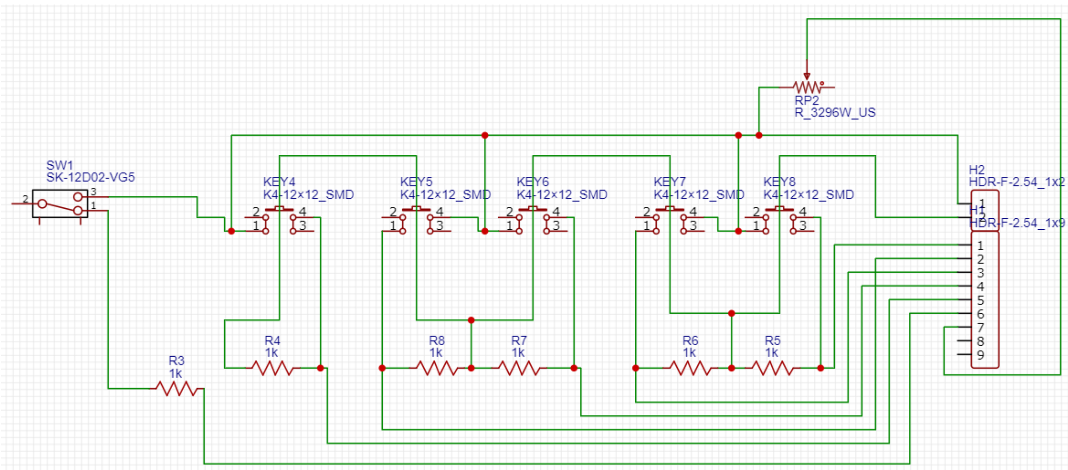

Figure 10. Electronic keypad plan for manual control of the robotic arm.

Source: The authors.

Code for Arduino

As a test of the system, code (see Figure 11) was written on the Arduino platform to control a NEMA 24 stepper motor via the DM542 driver, by generating digital pulses and defining the direction of rotation. To do this, two pins are configured as outputs: one for the pulse signal (PUL), which determines the advance of the motor, and another for the direction signal (DIR), which establishes the direction of rotation. In addition, two digital inputs are used to act as control commands, allowing the selection of the movement to the right or to the left in a mutually exclusive way. In the main cycle of the program, these inputs are continuously read and, depending on their status, the corresponding direction is set and 200 pulses are generated with a duration of 500 microseconds at high and 500 microseconds at low, which defines the operating speed of the motor.

```
int x;
int derecha = 11;
int izquierda = 12;
int derecha_ena = 0;
int izquierda_ena = 0;

void setup() {
    pinMode(9,OUTPUT);
    pinMode(8,OUTPUT);
    pinMode (derecha, INPUT);
    pinMode (izquierda, INPUT);
    Serial.begin(9600);}

void loop() {
    derecha_ena = digitalRead(derecha);
    izquierda_ena = digitalRead(izquierda);
    if (derecha_ena == HIGH && izquierda_ena == LOW){
        Serial.println ("Derecha");
        digitalWrite(8,HIGH);
        for(x = 0; x < 200; x++){
digitalWrite(9,HIGH);
        delayMicroseconds(500);
        digitalWrite(9,LOW);
        delayMicroseconds(500);
    }
  }

  if (derecha_ena == LOW && izquierda_ena == HIGH) {
      Serial.println ("Izquierda");
      digitalWrite(8,LOW);
      for(x = 0; x < 200; x++){
          digitalWrite(9,HIGH);
          delayMicroseconds(500);
          digitalWrite(9,LOW);
          delayMicroseconds(500);
      }
  }
}
```

Figure 11. Codebase for stepper motor control.

Source: The authors.

According to the datasheets of the electronic components used in the design of the robotic arm, it has a power consumption of 214.7 W when all motors are moved simultaneously, and 70 W when a single motor is activated. This value is obtained from the sum of the powers consumed by each of the active components as described in Table 4; this power is expressed as the multiplication of the amperage and nominal voltage of each component.

Table 4. Energy consumption of electronic components.

Item	Description of components	Number of items	Nominal voltage [V]	Amperage rating [A]
1	NEMA 24 3 Nm motor	3	24.00	2.80
2	NEMA 23 0.7 Nm motor	1	5.20	2.00
3	DM542 driver	4	5.00	0.01
4	Arduino UNO	1	5.00	0.50

Source: The authors.

The technical characteristics of the robotic arm are presented in Table 5.

Figure 12 presents a photo gallery of the progress in the construction of the robotic arm.

6. Discussion

The results obtained show that the proposed design complies with the established structural and functional requirements; in particular, the 2 m reach and the 5 kg load capacity place considerable demands on a manipulator. The minimum safety factor of 4.8 evidences an adequate structural margin under the load conditions considered in the simulation, although it also suggests a possible oversizing that could be adjusted in terms of weight and configuration of the structure. On the other hand, the maximum displacement at

Table 5. Technical characteristics of the robotic arm.

Feature	Unit	Value
Maximum reach to the projector center	Metre	2.22
Load capacity	kg	5
Power rating	Watts	90.15
Maximum rotational speed in joints	Deg/s	5
Degrees of freedom	Unit	4
Maximum height without projector	Metre	0.501
Maximum structure length	Metre	2.48

Source: The authors.

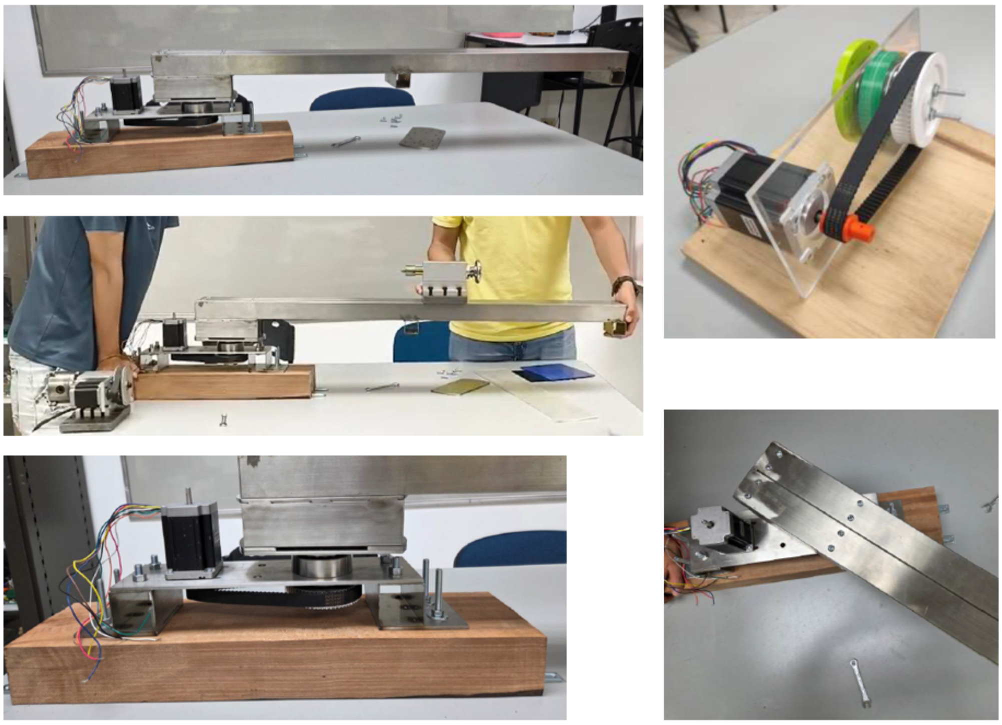

Figure 12. Photo gallery of the progress of the construction of the robotic arm.
Source: The authors.

the end of the manipulator, on the order of millimetres, is acceptable for projection applications, where positioning tolerances are relatively wide, but could represent a limitation in applications that demand high precision. As for the actuation system, the selection of stepper motors together with a toothed-belt transmission allows meeting the torque requirements, taking into account that speed is a factor that is not relevant in this type of application; however, this configuration has limitations associated with open-loop control and possible elasticity effects in the transmission. Additionally, the kinematic model developed using the Denavit–Hartenberg method adequately describes the relationship between joint variables and the position of the end effector, although it does not consider effects such as friction, clearance or structural deformations, which can influence the real performance of the system.

These results are consistent with previous works on SCARA-type manipulators. Mohamed Sahari et al. [5] similarly addressed the integration of mechanical design, structural analysis by finite elements, kinematic modeling and the electronic control system in a 4-DOF SCARA robot. Likewise, Daniyan et al. [2] demonstrated the usefulness of finite element analysis to verify structural strength and estimate the deformations of robotic arms, while Subhashini and Singh [10] integrated CAD design, structural analysis and Denavit–Hartenberg modeling in a modified SCARA manipulator. Compared with these developments, the present work applies these design elements in an integrated manner to a configuration specifically intended for the positioning and orientation of a projection system.

7. Conclusions

This work presented the design and development of a four-degree-of-freedom robotic arm with a configuration based on the SCARA type, meeting the established reach and load capacity requirements. The proper implementation of Karl Ulrich's product design methodology allowed the development process to be effectively structured, ensuring coherence between the needs and the solutions of the system. The integration of mechanical design, kinematic modeling using Denavit–Hartenberg and structural analysis allowed validating the viability of the system, evidenced by an adequate safety factor and deformations within acceptable limits. The sizing of the actuation system, based on torque analysis, together with the implementation of an Arduino-based control system, guarantees the functionality of the manipulator. Overall, the developed prototype represents a viable solution for positioning and orientation applications.

This type of development constitutes a high-impact training tool in engineering education, as it allows the practical integration of knowledge in mechanics, electronics, control and programming, strengthening project-based learning and the development of robotics skills.

As future work, the construction of the robotic arm will continue, and the implementation of automatic control strategies, the incorporation of sensors to improve positioning accuracy, and the development of more advanced user interfaces are proposed.

Author Contributions: **Luis Enrique Rios Benitez:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualization. **Jhon Edwar Vargas Vásquez:** Methodology, Formal analysis, Investigation, Software, Writing – review & editing. **Edgar Francisco Arcos Hurtado:** Conceptualization, Supervision, Project administration, Writing – review & editing.

All authors have read and agreed to the published version of the manuscript. Please refer to the CRediT taxonomy for the definitions of the terms. Authorship should be limited to those who have made substantial contributions to the reported work.

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