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DESIGN AND IMPLEMENTATION OF A 3 DEGREES OF FREEDOM ROBOTIC ARM POWERED BY PNEUMATIC ARTIFICIAL MUSCLE

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ABSTRACT

The development of a 3-DOF robotic arm powered by pneumatic artificial muscles is represented as an innovative approach in the field of robotics, with the advantages of lightweight and flexible design being combined with the power and control benefits of pneumatic actuation. The design process, challenges, and solutions that were encountered in the development of the robotic arm are outlined in this paper, with an emphasis on its potential applications in industrial and research settings being highlighted. Experimental results demonstrated that the arm can handle loads up to 250 grams, maintain precise horizontal positioning, achieve a 90° rotation at each joint, and operate within a minimum workspace radius of 250 mm. Advanced control algorithms, including sliding mode control, were implemented to optimize the arm's performance. The control system successfully maintained the set angles within a tolerance range, achieving a minimum angular error of approximately 0.7°. Additionally, the robotic arm's modular design is enabled to allow easy customization and scalability, making it possible for the arm to be tailored to a wide range of tasks, from precise laboratory work to more robust industrial applications.

Keywords: Pneumatic Artificial Muscle; Robotic Arm; Sliding Mode Control; Collaborative Robot

1. INTRODUCTION

Industrial robots are used in various fields, ranging from the automotive industry to metal and machinery, electronics, and even the food industry [1]. One of the strongest principles in selecting processes for robotization is to comply with the called "3D" rule, which states that robots should perform Dull, Dangerous, and Dirty tasks [2,3]. The current generation of workers has a significant demand for jobs where their contribution adds considerable value. Additionally, there is growing interest in people working alongside robots in a shared workspace with the highest possible safety [4]. The drive systems of robotic arms are located on or near the rotational or translational joints of the arms. These joints are connected by segments, forming a closed kinematic chain where the forces and torques generated in the joints are counterbalanced by motors or actuators [5]. The most common type of motor used for their movement is the electric motor, which includes several options for application on robotic arms. Both direct current (DC) and alternating current (AC) motors can be used, but the most commonly employed types are DC servo and stepper motors [6]. Electropneumatic [7] or purely pneumatic actuation is also used in robots, either with pneumatic cylinders or pneumatic stepper motors [8,9]. This category includes so-called soft machines, one component of which can be the pneumatic artificial muscle [10,11]. A robotic arm actuated with pneumatic muscles (Figure 1) is a manipulator whose motor consists of artificial muscles that contract when pressure is applied and expand under counterforce when the pressure is released [12].

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Figure 1. Pneumatic Artificial Muscle [11]

Such mechanisms are typically part of humanoid robots or so-called "exoskeletons," and their application in industrial robotic arms is rare. In these cases, pneumatic artificial muscles are used as motors, positioned farther away from the robotic arm with the force transmission solved using Bowden cables [13].

2. DESIGN OF A ROBOTIC ARM WITH THREE DEGREES OF FREEDOM

2.1. Mechanical design

Since the goal is to implement a complex device, it is essential to define the threshold criteria that the robotic arm must meet at the beginning of the design process. Before the design process, the main parameters were specified in the specification to determine the criteria the system must meet.

The requirements for the robotic arm were defined as follows:

- The first criterion is that the force required for movement should be provided by pneumatic muscles, which are placed separately from the robotic arm. Minimum force required 200 N.
- Additionally, the arm should have at least three degrees of freedom, and the end effector should always be in a horizontal position at all reachable points within the workspace. Each joint should be capable of at least 90° rotation, reach a minimum usable workspace radius of 250 mm, and be able to move at least 250 grams of load besides its own weight.
- Furthermore, it was specified that the end effector should be a vacuum gripper. It should be positionable and controllable within a realistic time frame.

The segment of the kinematic diagram marked in red always remains horizontal. This is achieved by fitting an auxiliary frame (joints 5, 6, 7, and 8) around the segments of the robot and fixing the joints at a constant distance from each other. This geometrically ensures the horizontality of the end effector (Figure 2).

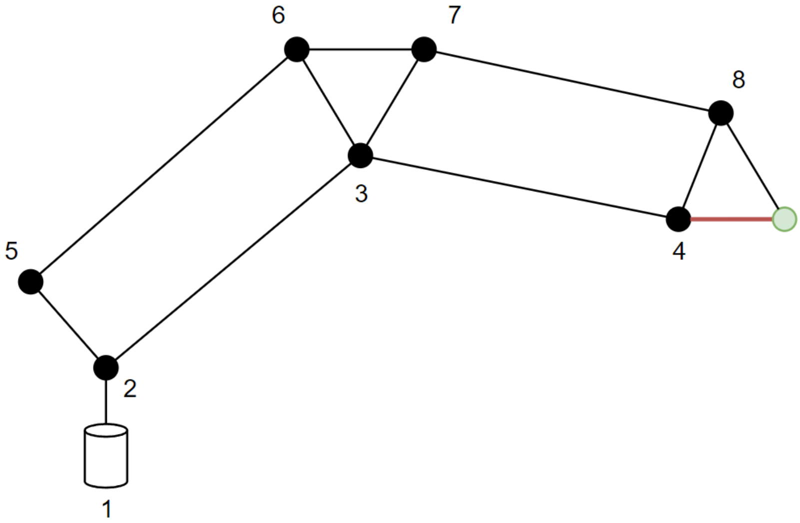

Figure 2. Kinematic Diagram

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The system is designed so that each joint is offset by 50 mm along both the x and y axes. For example, joint 5 is offset by 50 mm along both the x and y axes relative to joint 2. The overall dimensions of the robotic arm are illustrated in Figure 3.

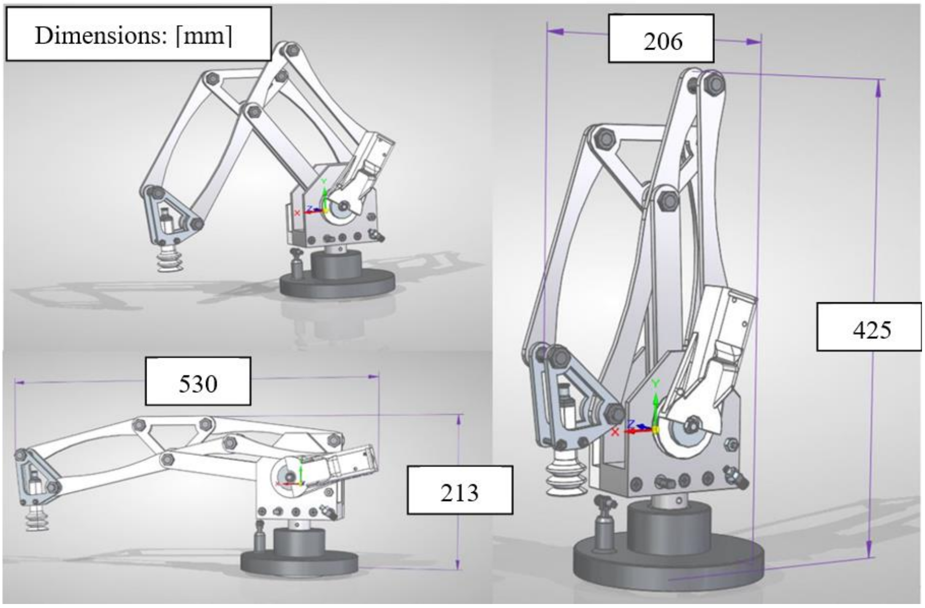

Figure 3. Dimensions of the Robotic Arm

The other main unit comprising the robot is the control housing, which includes the pneumatic and electrical components. The dimensions of the housing are 475 mm x 420 mm x 180 mm, providing sufficient space for the necessary elements.

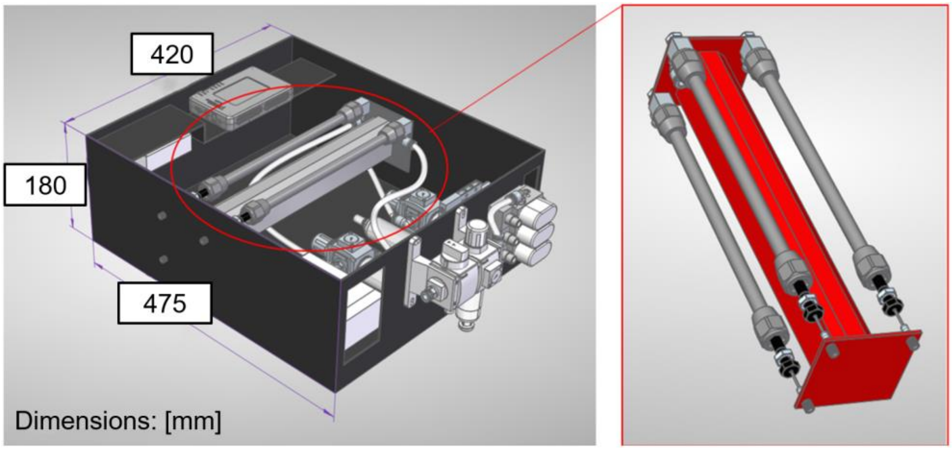

Figure 4. Control housing

The elements marked in red in Figures 4 are intended to reinforce the muscles within the machine housing. This reinforcement is necessary because the housing wall is a 1.5 mm thick sheet, which cannot withstand the forces arising from the attachment of the Bowden cables due to the muscle contraction, introducing an

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additional uncertainty factor into the system. To eliminate this, a 60 mm x 40 mm aluminum profile was placed between 3 mm thick steel plates as a stiffener.

The muscle is open at both ends, with an M10x1.25 thread, so it was necessary to design a component that not only secures the muscle but also provides sealing. At the Bowden end of the muscle, a screw with a Teflon seal was required, which was drilled to allow the Bowden cable to pass through, and then secured with a nut (Figure 5).

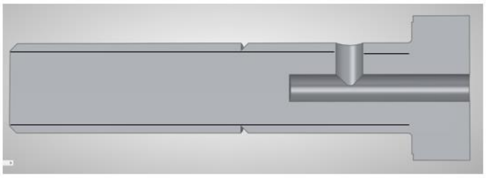


Figure 5. Muscle Mounting - Bowden Securing Screw

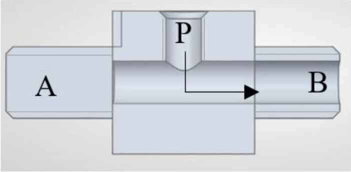
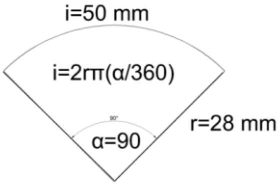


Figure 6. Muscle Connector Screw with Air Supply

A custom-designed connector was placed at the other open end of the muscle. As shown in Figure 6, the connection point marked "P" provides the air supply, where a ¼” pneumatic connector can be attached. The threaded part "A" secures the muscle to the machine housing, while part "B" is sealed into the muscle.

The force transmission between the arm and the housing is facilitated by Bowden cables, with the counterforce provided by rubber bands mounted on the robotic arm. High-precision Bowden cables with a diameter of 1.6 mm and Bowden housings with a diameter of 4 mm, typically used in high-precision gearboxes, were employed. To secure these, a Bowden securing/support screw was designed, highlighted in red in Figure 7. The Bowden ends are fixed on the segments so that the Bowden cable is 28 mm from the center of the joint. This ensures that the muscle's maximum contraction of 50 mm results in a 90° rotation of the segment, based on the following relationship (1).



(1)

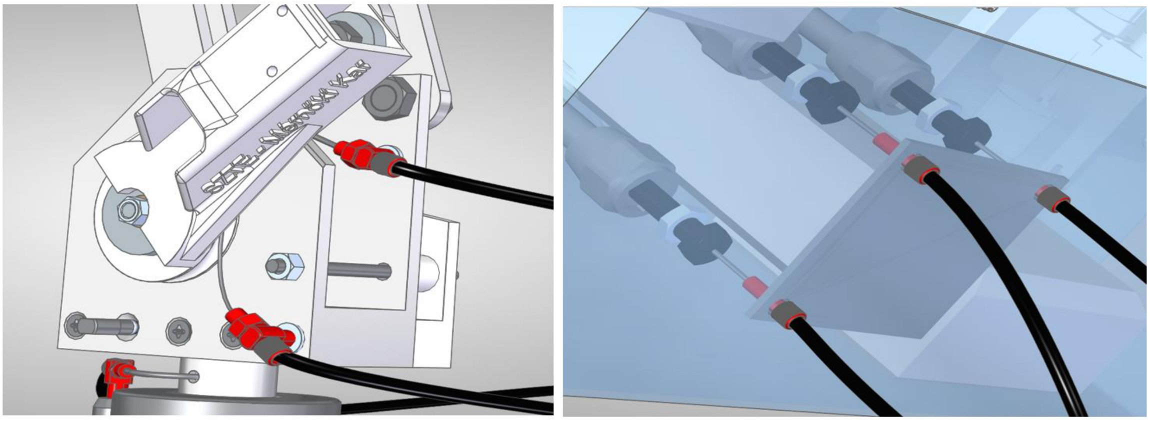


Figure 7. Bowden Housing Attachment

Due to its dimensions, it can be used for manipulating smaller objects and performing pick-and-place tasks where the always horizontal gripper is an advantage. Additionally, by using a control system without feedback, the designed robot can be potentially used in explosive environments and underwater. The flexibility of the pneumatic artificial muscles allows for smooth and precise movements, making it suitable for delicate operations. The modular design also facilitates easy maintenance and upgrades, ensuring long-term usability. Furthermore, its lightweight structure makes it easy to transport and deploy in various locations.

2.2. Pneumatic and Electrical Design

The first step is to select the pneumatic muscle. The "MAS-10-250N-AA-MO-O" type was chosen, which is a manually assembled version with a 10 mm diameter, allowing it to be cut to the appropriate size of 250 mm. This muscle can exert a force of 480N at an operating pressure of 6 bar. The maximum contraction is 25% of the nominal length. Thus, in the case of 250 mm, it can contract by 50 mm, which, by properly choosing the attachment points of the Bowden cables, is converted into rotational motion. Therefore, the muscle can exert a torque of 13.4 Nm on a 28 mm lever arm, while the required 250 g load at a 376 mm lever arm, which is the farthest point in the workspace from the center, generates a torque of 0.94 Nm, so the muscle is capable of performing the task.

The entire system starts with an air preparation unit with a pressure regulator, through which the air supply is conducted. The individual components are connected with an 8 mm diameter hose, except for the ejector, which has a 4 mm connection.

An E/P pressure regulator valve is installed for the air supply to the muscles. This type has a pressure regulation range of 0-6 bar, which can be controlled with an input voltage of 0-10 V. Its airflow capacity is approximately 250 l/min, which is sufficient for supplying the muscles.

An air filter is placed between the muscle and the pressure regulator valve because the minimal particle size in the transported medium for the pressure regulator is micron-sized, so it is advisable to avoid potential contamination, such as sealing material.

A "EBS-ET-07-NC-N-N" type vacuum switch ejector is used to generate vacuum, which can create an 84% vacuum at optimal pressure and has a maximum suction capacity of 7.5 l/min. It also includes a pressure sensor capable of providing a 5V signal at two set pressure values.

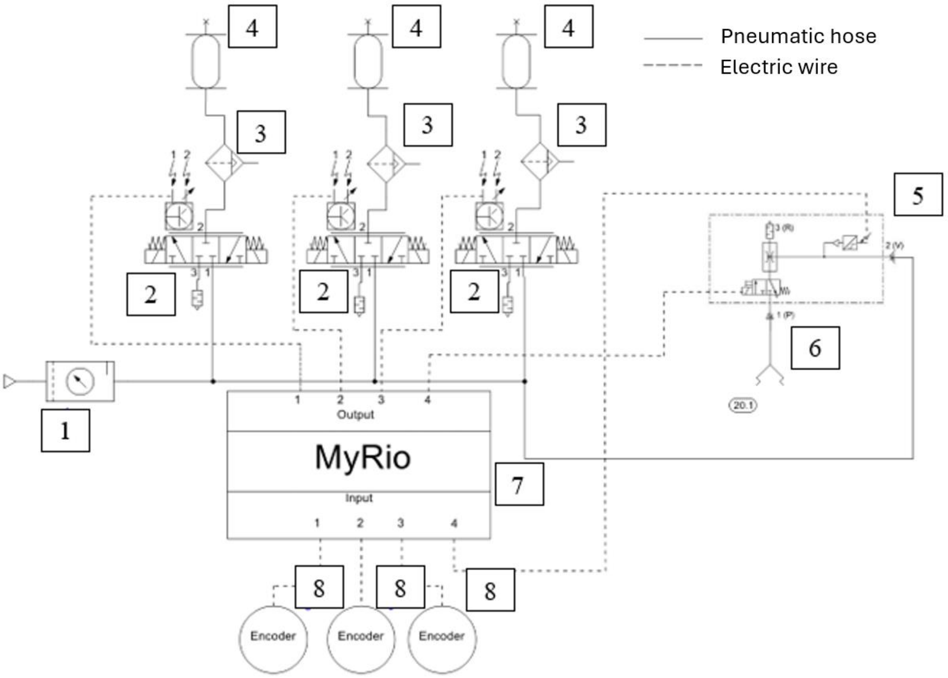


Figure 8. Electropneumatic Circuit

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The pneumatic elements marked in blue in Figure 8 are as follows:

1. Air preparation unit
2. Pressure regulator valve
3. Air filter
4. Pneumatic artificial muscle
5. Ejector
6. Gripper disc
7. MyRIO (Control unit)
8. Rotation sensor encoder

The electrical design is centered around a portable embedded device called myRIO, which can be programmed in the LabVIEW graphical programming environment, making it perfect for creating the user interface and control system. The valves and the ejector require 24V DC voltage, so a ~230/24V power supply unit is used to provide the necessary power for the system.

One of the key components of the electrical circuit is the AEAT-6600-T16 magnetic encoder IC. A custom circuit was built around the magnetic encoder.

In terms of its operating principle, the following can be said: By placing a cylindrical magnet with a diameter of 5 mm and a height of 3 mm, polarized around its perimeter, in front of the IC at a precisely specified distance and position, an absolute encoder is obtained that measures in 360°, achieving an accuracy of up to 0.005°. The position of the magnet can be read out as a bit stream using myRIO via the SPI protocol. In this case, I divide the 360° into 1024 parts, which translates to an accuracy of 0.35°. The IC can be programmed for the aforementioned accuracy; however, this is not used in my thesis. Furthermore, there is a risk of data loss due to signal noise. In terms of positioning, the mounting points on the PCB are designed so that, if we connect them with an imaginary line, the center of the magnet placed opposite should fall on the midpoint of the line connecting the two mounting points.

3. CONTROLLER DESIGN

The PID control was initially implemented on the robotic arm, but through empirical experience, as also confirmed by Lin's work, sliding mode control proved to be more suitable for this application [14]. Therefore, we decided to use sliding mode control. The simple linear sliding line control did not work well, as a large error resulted in a too large value on the output, leading to significant overshoot and undamped oscillation. Subsequently, the sliding line was replaced with an exponential curve, but unfortunately, this did not bring improvement either [15]. The controller regulates the angles of the robot segments relative to each other. Encoders located in the joints provide the feedback signal for the control. After processing, the signal is represented on a scale of 1024 elements for a full 360° rotation.

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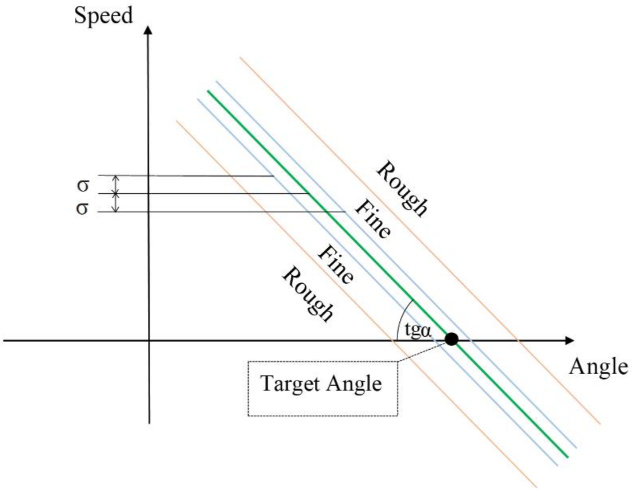

Figure 9. Sliding Mode Control

The applied control is illustrated in Figure 9. The x-axis represents the angle, while the y-axis represents the velocity. The black dot indicates the target angle, and the green line represents the sliding line. The blue lines indicate the minimum tolerance value, and the yellow lines indicate the maximum tolerance value. The control is designed so that there is a range where the output does not change, called "σ" This is necessary to stop oscillations, allowing the robotic arm to remain stationary. There are also two additional ranges: "Fine" and "Rough" If the current error is within the "Fine" range, a lower value is added to the output; if it is within the " Rough" range, a higher value is added to the output. The slope of the line is indicated by tgα. If the velocity error is denoted by x, the controller performs "Fine" and " Rough" adjustments based on the magnitude of the error.

At the three joints, essentially three different controls are implemented. Since each joint has different characteristics, individual tuning is justified. The "Fine" adjustment increases the output value by 0.005, while the "Rough" adjustment increases it by 0.02. By changing the value of tgα, the slope of the sliding line can be modified. The minimum and maximum values should be set such that minimum is not too low, as this would cause continuous oscillation, but not too high either, as it would affect accuracy. The maximum value impacts the speed of the robotic arm, and it is advisable to keep it as low as possible; if it is too high, the overshoot can be significant.

Lower limit of 0V and an upper limit of 5V are set to ensure the output remains within realistic boundaries. The "case" structure initiates the control if the automatic control for the joint is activated.

The control performs the necessary tasks and positions the robotic arm with adequate precision and speed. Experience shows that it maintains the set angle within the tolerance range. The minimum error achieved is 2 increments, which in reality means an angular error of approximately 0.7°. This value can be further improved in future developments by programming the magnetic encoder to 16 bits and fine-tuning the controller based on precise measurements.

In the design phase, various versions of the sliding mode controller were tested. Initially, a linear sliding surface was used, but it did not perform well under large errors due to significant overshoot and oscillations. Consequently, an exponential curve was adopted for the sliding surface, which improved performance. The final design regulates the angles between the robot segments using encoders that provide feedback signals. These signals are scaled and processed to ensure precise control within a defined range, minimizing angular errors and enhancing stability. The choice of a sliding mode controller over a traditional PID controller was driven by the nonlinear and variable dynamics of the pneumatic artificial muscles. Unlike PID controllers, which can struggle with overshoot and steady-state errors in such environments, sliding mode control effectively handles nonlinearities and ensures precise, stable control under varying conditions.

4. CONCLUSION

In conclusion, the development of the 3-DOF robotic arm powered by pneumatic artificial muscles represents a significant innovation in robotics, combining lightweight and flexible design with the power and control of pneumatic actuation. The modular design facilitates easy customization and scalability, broadening the arm's applicability from precise laboratory tasks to demanding industrial applications. The potential impact of this robotic arm in both industrial and research settings underscores its versatility and adaptability. It creates a good basis for conducting experiments. The use of pneumatic artificial muscles provides a unique combination of compliance and strength, allowing the robotic arm to perform delicate tasks as well as heavy-duty operations. This adaptability is enhanced by advanced control algorithms such as sliding mode control, ensuring optimized performance. High-precision sensors and feedback mechanisms allow for continuous monitoring and adjustment, ensuring consistent performance. The robotic arm's design also emphasizes robustness and reliability, essential for industrial environments. In research settings, the arm provides a versatile tool for exploring new methodologies in robotics and control systems. Its modular nature and compatibility with various experimental setups foster innovation and the development of new applications.

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