Development of a Pneumatic Muscle Actuator System for a Robotic Hand

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***Abstract*—The purpose of this project is to develop a Pneumatic Muscle Actuator (PMA) system for a robotic hand that can accurately imitate the motion and function of a human muscle. The project consists of several different areas of design which include: a mechanical component, an electrical component, a programming component, a pneumatic component, and a control systems component. The mechanical components are designed to be simple, and they consist of a mechanical hand and a testing station or panel. The mechanical hand structure was designed to have a total of three, independently operated limbs, each of which contained a Single Degree of Freedom (SDOF). The electrical system consists of an Arduino Mega 2560 micro-controller, six linear potentiometers and a power supply. The micro-controller is used to produce three Pulse Width Modulation (PWM) output signals which are varied in accordance with the analogue inputs of the potentiometers. The programming component for the project involves the programming of the micro-controller. The pneumatic component of the project consisted of three PMA's, three rapid switching valves and an air purifier. The PWM outputs from the micro-controller are then used to control the rapid switching valves which in turn will control three PMA's. Controlling the pressure and positioning of the PMA's proved to be problematic and thus several control systems will be considered.**

***Index Terms*—pneumatic, muscle actuator system, robotic hand.**

I. Introduction

Mother Nature has consistently been the root of inspiration for most engineering innovations. A robotic hand is a result of attempts to imitate the functionality of the human hand. The efficient function of a robotic system hinges on the effectiveness of the actuation system. The following factors make Pneumatic Muscle Actuator Systems ideal for robotic hand control: compactness, high power to weight ratio, relative low cost, and operation conveniency. Robotic hands have been of service to humans in routine and monotonous tasks.

Traditional robotic action systems have been in the following forms: hydraulic, pneumatic and electronic [1]. The pneumatic muscle actuation system has been implemented in several designs. Kumar et. al. [2] have designed a Fast, strong and compliant pneumatic actuation for dexterous tendon-driven hands. Their design was inspired by the desire to upgrade the Shadow Hand system. The designed actuation system could control the Shadow Hand skeleton at high speed and with greater precision. In a separate study, Shin et. al. [3] utilized a hybrid actuation approach for the control of a human-friendly robot. In the design, merging of pneumatic and electrical actuators was successfully carried out. The study results demonstrated that the designed hybrid actuation system was superior to a system with either pneumatic or electrical actuators separately.

An original pneumatic system has been successfully designed for controlling an anthropomorphic arm [4]. To guarantee stability and flexibility of the anthropomorphic arm in motion, an adaptive fuzzy backstepping control system was incorporated. Validation of the design was achieved using numerical simulations. The obtained results are a testimony of the efficiency and robustness of the designed pneumatic control system. Numerous other designs have successfully developed and utilized pneumatic control systems for robot control [5-7].

This study presents the development of a Pneumatic Muscle Actuator (PMA) system that can accurately imitate the motion and function of a human hand muscle. The designed PMA system must have the following attributes: low cost, good operation conveniency and a high power to weight ratio. The expertise acquired during the study is valuable in developing robot actuation systems for similar and related applications. Furthermore, the study adds on the already available literature on pneumatic control of robots. The ultimate benefit is the reduction in cost of robot control systems through use of readily available materials and trimming of pneumatic valves.

II. System Requirements

Current servo controlled robotic applications are relatively complex and expensive. This project aims to reduce the complexity of servo control by making use of PMAs. However, the basic control mechanism of the PMAs will still be developed to an optimal level. The top-level system requirements include the following:

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- Precise control of the position of the PMAs with respect to some desired input position.
- Perform tasks such as a tight grasp and precision grasp.
- Provide useful results and conclusions that can be used for further studies in the development of PMA servo-controlled applications.
- Linearization of the expansion and contraction of the PMAs.
- Quick response time with minimal overshoot.
- Counter feedback error between the ideal and actual position of the PMA.

III Concept Generation and Selection

Since all concepts considered for this project are restricted to the use of PMAs and will be used to control the same mechanical system, only the pressure control methods for each concept will be compared.

A. Concept 1

This concept makes use of a pressure regulator, together with two high-speed on/off, 2/2-way valves to control the pressure in the PMA. The block diagram for concept 1 is presented by Fig. 1. Movement of the position control device produces an analogue voltage signal that is sent to the Micro-Controller Unit (MCU), after which it is amplified and converted to a digital Pulse Width Modulated (PWM) voltage with a fixed frequency and varying duty cycle. With the assistance of a pressure sensor in the PWM digital signal is used to control two valves that either increase or decrease PMA pressure. The purpose of the potentiometer feedback device is to account for load disturbance. Any load disturbance applied to the PMA will render the pre-scaled values between the control device and the pressure regulator insufficient, since these values only apply under no load conditions. Thus, in a load disturbance situation, the outer closed loop control circuit will take preference. This process is executed continually depending on the position of the input control device.

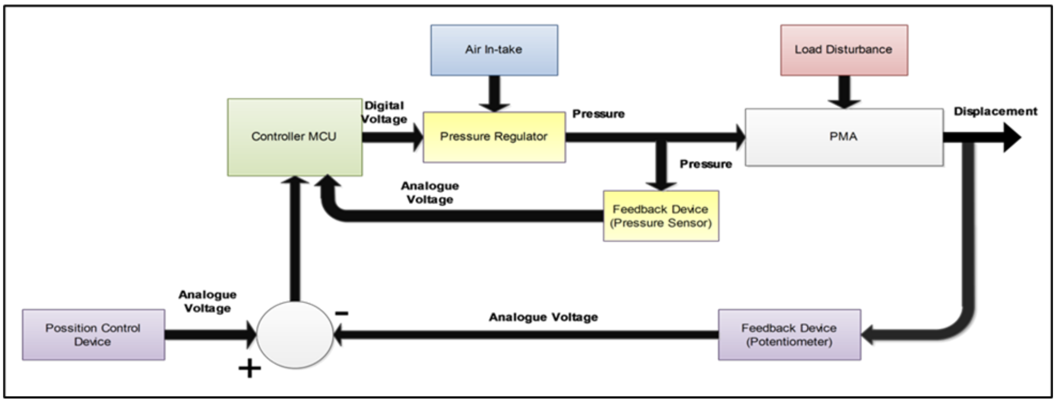

Figure 1. Concept 1 block diagram.

B. Concept 2

The block diagram for concept 2 is presented by Fig. 2. Movement of the position control device produces an analogue voltage that is sent to the MCU for further amplification and conversion to a corresponding digital PWM voltage before being sent to the rapid switching valve. Once the valve is turned on, the PMA will contract until the output analogue voltages of the feedback potentiometer and the position control potentiometer are approximately equal. The pressure in the PMA is controlled by adjusting the duty cycle of the output PWM of the MCU. For a larger duty cycle the valve remains open for a longer period, allowing for a higher-pressure buildup in the PMA. To allow for smooth displacement of the PMA, the rapid switching valve will be required to operate in the millisecond range and the non-linear characteristic of the PMA must be linearized.

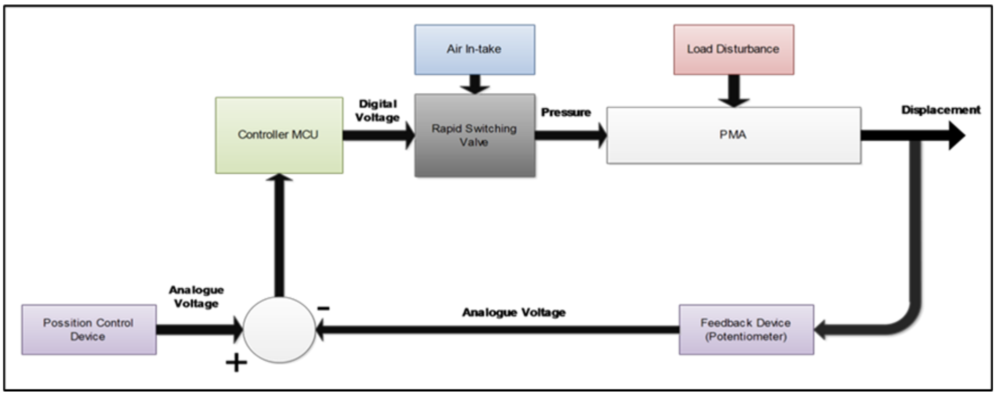

Figure 2. Concept 2 block diagram.

C. Concept 3

This concept makes use of a pressure regulator together with six high-speed on/off, 2/2-way valves to control the pressure in the PMA. This concept operates in a similar manner to that of concept 1 but allows for a much smoother movement of the actuator. Each valve is controlled using PWM via an MCU, after amplification. The usage of six valves, in parallel, provides a higher flow rate to the PMA as well as a higher resolution of flow rate control. Fig. 3 is a presentation of the basic layout of the system.

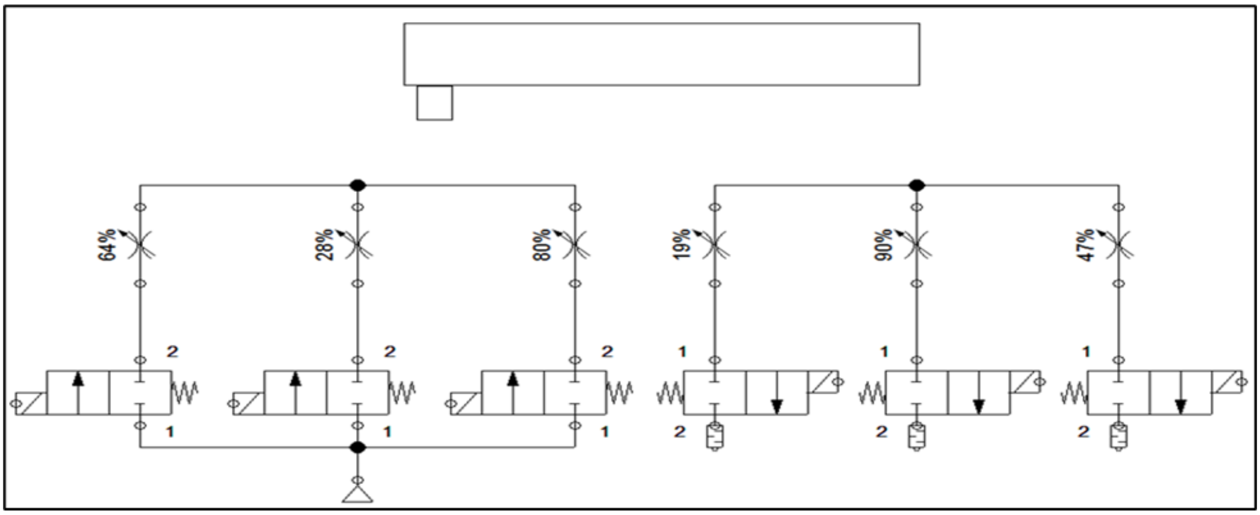

Figure 3. Basic electro-pneumatic circuit for concept 3.

D. Comparison Matrix

The total scores for the comparison matrix were calculated using Equation (1) and presented in Table I. The totals row is a presentation of the level of satisfaction by each concept. Concept 2 has the highest satisfaction level of 0.6732, followed by concept 1 (0.5763), and lastly concept 3 (0.46). Hence, concept 2 is the superior solution and has been selected and developed in this study.

TABLE I. THE TOTAL SCORES FOR THE COMPARISON MATRIX

	Weight	**Concept 1**	**Concept 2**	**Concept 3**
System Cost	0.3	0.3544	0.8439	0.0
System Complexity	0.3	0.8	0.6	0.7
System Noise Level	0.1	0.6	0.8	0.5
Weight (mass)	0.1	0.5	0.8	0.2
Level of Control	0.2	0.6	0.4	0.9
Total		**0.5763**	**0.6732**	**0.46**

IV. DOMAIN SPECIFIC DEVELOPMENT

The following section contains a detailed description of the procedure followed in the development of the final design as well as the design specifications and overall operation.

A. Mechanical Domain

The mechanical system for this project consists of a single mechanical hand and a metallic frame to house the hand, electronics, and pneumatic components. Fig. 4 is a CAD design of the metallic housing frame and the single mechanical hand. The inspiration the design of the mechanical hand was taken from SLSA 3D [8]. The mechanical structure of the hand and housing frame are made up of three types of aluminium profiles. These profiles include a 3 mm and 5 mm plate, 15.88 x 15.88 x 1.6mm channel and 28 mm diameter round tubing. The various members of the hand and housing frame are constrained together using a range of fasteners. This is advantageous since the entire mechanical system can be assembled and disassembled with relative ease and thus worn or damaged components can be replaced with minimal effort. Originally, the various members of the hand and housing frame were going to be assembled using an aluminum welding process. However, since the aluminum profiles used in the construction of the hand and housing frame are relatively thin, the heat produced by the welding process caused the profiles to distort and buckle. Thus, the welding process proved to be problematic and unnecessarily complicated.

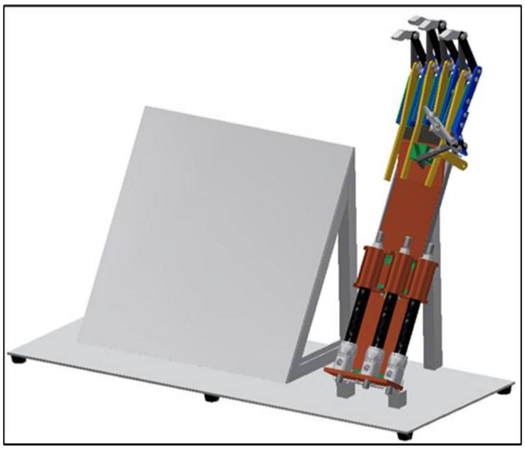

Figure 4. CAD design of housing frame with hand.

B. Electrical Domain

The electrical system for this project consists of three main stages; these include the input, processing, and amplification stage. Fig. 5 shows a simple block diagram of the electronic system. The input stage makes use of six slide potentiometers, three of which are used to indicate the desired output position and the remaining three are used to indicate the actual output position of the fingers. The processing stage consists of a single MCU which reads in analogue input signals from all the potentiometers, calculates the resulting error and duty cycle and then produces three separate PWM signals. The amplification stage is used to increase the output voltage signals generated by the MCU, from 5 to 24 volts.

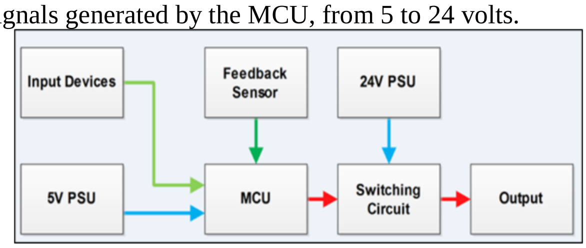

Figure 5. Block diagram of the electronic system.

The purpose of the electrical switching circuit is to switch the PWM signals generated by the MCU from a 5-volt signal to a 24-volt signal. The amplification of this signal must be done in such a way that the output signal can provide sufficient power to run the required pneumatic valves. Fig. 6 shows the proposed layout of the switching circuit with a 5-volt variable PWM input signal and the resulting 24-volt output PWM signal.

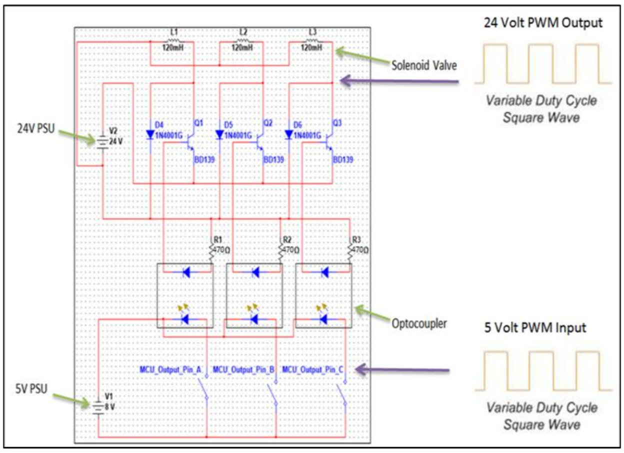

Figure 6. Electrical schematic of the switching circuit.

C. Pneumatic Domain

The PMA's to be used for this assignment had to meet the following constraints:

- Must provide a minimum contraction displacement of 15 mm.
- Must not be too large.
- Should operate at relatively low flow rates.
- Must be durable.

To account for both the size and mass flow rate constraints, PMAs with a diameter of 10 mm were considered. Now consider Fig. 3.1.1 which shows the basic force to displacement relationship for a 10 mm outer diameter PMA. To meet the minimum contraction displacement of 15 mm, it is required that the minimal length of the PMA be at least 60 mm in length (nominal length). However, to account for possible error, or lower operating pressures, a nominal length of 100 mm was chosen for the PMA.

D. Software Domain

The version of the Arduino software used to program the MCU is called "Arduino 1.5.2". Fig. 7 shows the logical processes the MCU executes under different conditions, where R1 and R2 represent the different resistances of the potentiometers.

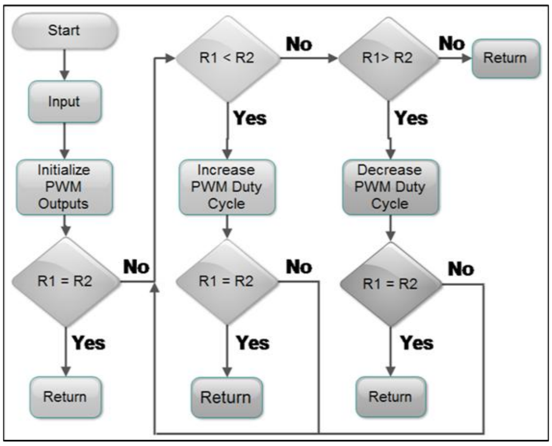

Figure 7. MCU logic block diagram.

V. Integration of Mechanical, Electrical, Pneumatics and Software Domains.

The hardware components were integrated, and tests were carried out to ascertain if the developed systems were confirming to the designs. Modular tests were done followed by system testing. Fig. 8 is a presentation of the assembled system design.

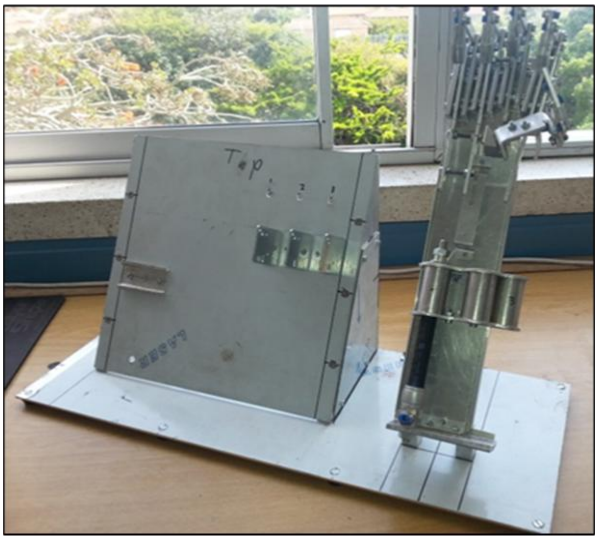

Figure 8. Assembled PMA system.

The overall system performance proved to be satisfactory since every component in the system preformed as intended and as a result most of the desired outcomes were met. These included:

- Precise control of the position of the PMAs with respect to some desired input position.
- Picking up an item using a tight grasp.
- Linearization of the expansion and contraction of the PMAs.
- Quick response time with minimal overshoot.
- To provide useful results and conclusions that can be used for further studies in the development of PMA servo-controlled applications.

VI. Conclusion

The development of a PMA system was investigated, and various concepts were considered to design an anthropomorphic robotic hand. The robotic had was required to make use of PMAs to move the various fingers in a similar manner to that of a human hand, except with less degrees of freedom. The PMAs were required to contract and expand incrementally based on some input value. Upon completing of the project, the following aspects were achieved: Incremental control of the PMAs with respect to some input value, the successful design and construction of a mechanical hand with the aid of Computer Aided Software, the successful implementation and integration of various engineering fields and the successful construction of an anthropomorphic robotic hand. Experiential knowledge was also gained regarding the implementation of pneumatic muscles, the usage of various manufacturing methods and tools, the advantages of using mechatronics systems in machine design and the importance of component calibration for the entire system to function effectively.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conception and design of the work, Benjamin Coetzee and Abou-El-Hossein. Manuscript preparation, Zvikomborero Hweju. Guiding the studies, revising the paper and managing laboratory resources, Abou-El-Hossein. All authors have read and agreed to the published version of the manuscript.

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