Development of anthropomorphic robotic hand driven by Pneumatic Artificial Muscles for robotic applications

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Abstract. This paper presents the design and fabrication of a three-fingered anthropomorphic robotic hand. The fingers are driven by tendons and actuated by human muscle-like actuators known as Pneumatic Artificial Muscle (PAM). The proposed design allows the actuators to be mounted outside the hand where each finger can be driven by one PAM actuator and six indirectly interlinked tendons. With this design, the three-fingered hand has a compact size and a lightweight with a mass of 150.25 grams imitating the human being hand in terms of size and weight. The hand also successfully grasped objects with different shapes and weights up to 500 g. Even though the number of PAM actuators equals the number of Degrees of Freedom (DOF), the design guarantees driving of three joints by only one actuator reducing the number of required actuators from 3 to 1. Therefore, this hand is suitable for researches of robotic applications in terms of design, cost and ability to be equipped with several types of sensors.

1. Introduction

In robotics, an end effector is the device at the end of a robotic arm, designed to perform certain tasks depending on the application. A robotic hand refers to a particular kind of end-effector with an anthropomorphic inspiration. Numerous researchers have attempted to create robotic end-effectors that can match the human hand in terms of performance and abilities. [1–3]. Naturally, the human hand contains more than 19 muscles, 17 joints, 19 bones, not counting ligaments, nerves, and thousands of various sensors [4]. Therefore, the development a robotic hand that matches the performance of the human hand is a highly challenging task.

Robotic hand actuators can drive the joints either directly or indirectly. So, the mechanisms of robotic hand can be categorized into direct-driven and wire-driven joint. The former contains an actuator in every active joint which means mismatching with human hand in terms of size and weight. In contrast, the wire-driven structure enables the actuators to be mounted outside of the hand which in turn reduces the hand’s size and weight [2]. By comparing the two mentioned mechanisms, it can be seen that even there are some of limitations in the wire-driven joint mechanism, such as mechanical design and the driving force, it is still the right choice for anthropomorphic hand design in terms of size and weight. For example, Ishihara et al. (2011) developed a motorized anthropomorphic hand using wire-driven joints. However, some problems such as friction between a wire and its guide made its motion unstable [2]. Pneumatic FRH-4 hand developed by Gaiser et al. (2008) is actuated by flexible fluidic
Artificial Muscle (PAM) actuators are widely used as fluidic pneumatic actuators in the robotic and industrial fields due to their characteristics such as high power to weight and power to volume ratios, identical behaviour with human muscles, easy implementation, uncomplicated design, flexible architecture, simple working principle, an efficient performance and safe usage [1,3,6–8]. The PAMs are also known as McKibben actuators that were developed by McKibben and Gaylord in the 1950s [5]. PAM actuator contracts when it is activated by pressurized air like the biological muscle. Typically, PAMs can contract up to 25% of their initial length. Even though some recent prototypes of the robotic hands are overdesigned [4], a trend toward simplifying the hardware design based on application requirements is noted in the art of robot hands [9,10]. In addition, the implementation of simple control approaches causes a lack of robustness in terms of position control. Therefore, the approach of a simple hand design with an advanced control strategy can be adopted where this hand might be used.

A three-fingered pneumatic anthropomorphic hand has been developed in this research. Three wire driven joints are actuated by one PAM actuator for each finger. This design allows the actuators to be mounted outside the hand to achieve the anthropomorphic concept in terms of size, weight and shape. The hand can grasp objects with different shapes and weights up to 500 g and can be used in robotic applications in terms of design, cost and ability to be equipped with several types of sensor.

2. Design of Robotic Hand

2.1. Working Principle of the Robotic Finger

The schematic drawing of the robotic finger is shown in Figure 1. The way in which the pulleys and links are attached is based on M. Tatsumi et. al. work where only one finger was driven by PAM actuator using miniaturized unconstrained valves. In this research, the number of fingers is increased to build a full robotic hand to perform grasping tasks of weight-varying objects. The working principle of the robotic finger is described as follows. The free end of the PAM is connected to Pulley 3 in the finger by an inextensible string made up of stainless steel. Since the string can only pull and not push, the PAM actuator is able to bend the finger in a unidirectional motion. The passive extension spring is attached to the opposite side of Pulley 3 allowing it to expand the finger. Link 4 and Pulley 2 are connected by red and blue tendons while Link 3 and Pulley 1 are connected by brown and green tendons. Pulleys 1, 2 and 3 are fixed onto Links 1, 2 and 3 respectively. This mechanism allows the finger to bend under the contraction force $F_m$ produced by PAM actuator and to expand under the spring restoration force $F_s$. When the PAM actuator is activated, Pulley 3 rotates anticlockwise under the contraction force $F_m$ and Pulleys 1 and 2 rotate in the same direction under pulling forces of brown and red tendons respectively. As a result, the three pulleys revolve with the same angle $\theta$ and the finger bends. When the PAM actuator is deactivated, Pulley 3 rotates clockwise under the spring restoration force $F_s$. Pulleys 1 and 2 rotate in the same direction under pulling forces of green and blue tendons respectively, and the finger expands. This mechanism introduces the advantages of a small number of the required actuators, uncomplicated design, compact size and ability to grasp diverse sizes of objects. However, the grasp force produced at the fingertip is smaller than the contraction force produced by PAM actuator.
2.2. Robotic Hand Prototype
The three-fingered robotic hand prototype has been designed using computer aided design software and has been fabricated using 3D print technology and CNC milling machine as shown in Figure 2. The dimensions of the finger and the palm have been chosen to be close to human’s as shown in Figures 3 and 4 respectively. The angles between middle, index and thumb fingers are shown in Figure 5. In design perspective, the thumb is given an initial angle of 49.53° with the palm surface to allow it bending across the palm and to give more power grasping. As the object’s weight is our concern in this research rather than its shape, this design allows the robotic hand to perform a power grasping of objects with varying weights.

Figure 1. Schematic diagram of the robotic finger.

Figure 2. Robotic hand prototype (a) mechanical drawing, (b) fabricated hand.
Figure 3. Mechanical dimensions of the robotic finger, (a) top view, (b) side view.

The finger is composed of 19 parts as shown in Figure 6. This design enables the modification of any hand’s part to be made easily during assembling progress. The fingers are installed onto the palm shown in Figure 7. The tendons pass through tiny paths in the palm to be linked to Pulley 3 as illustrated in Figure 1. The pulley fixing point, shown in Figure 8, is located on $\phi = 111^\circ$ and this value has been determined experimentally. This location allows a bigger rotation angle $\theta$ for the pulleys producing a power grasping by the robotic hand [11]. Table 1 summarizes the links and pulleys that represent the finger’s parts in the schematic diagram shown in Figure 1.
Two types of material have been used to fabricate the hand in two different manufacturing processes which are the Acrylonitrile Butadiene Styrene (ABS) plastic using 3D printing technology and aluminum using CNC milling machine. Table 2 shows the manufactured material and its quantity. Referring to the table, seventy-six parts should be assembled to build the complete hand. After assembling the three fingers, the pulleys and the pins are linked tightly based on Figure 1. Then, the robotic hand can be actuated by human hand to test the motion of the fingers. Finally, the hand is ready to be installed on the experiment setup and perform grasping task.

**Figure 5.** Angles between the robotic fingers, (a) middle finger, index finger and the thumb (b) the thumb’s initial angle.

**Figure 6.** Robotic fingers parts, (a) middle and index fingers, (b) thumb.
Figure 7. Robotic palm, (a) tiny paths of the tendons and the fingers bases, (b) thumb tendons passing through the tiny paths.

Figure 8. Pulley-fixing point, (a) back view, (b) real view of the pulley.

Table 1. Finger parts presenting schematic links and pulleys.

| Link / Pulley in Figure 1 | Finger’s part in Figure 6 |
|---------------------------|---------------------------|
| Link 1                    | Distal right / left tip   |
| Link 2                    | Middle link               |
| Link 3                    | Proximal link             |
| Link 4                    | Right / Left base         |
| Pulley 1                  | Middle pulley             |
| Pulley 2                  | Middle pulley             |
| Pulley 3                  | Proximal pulley           |
Table 2. Manufacturing material of hand parts.

| Material       | ABS | QTY | Aluminium | QTY |
|----------------|-----|-----|-----------|-----|
| Palm           |     | 1   | Right base| 2   |
| Middle Link    | 6   |     | Left base | 2   |
| Proximal Link  | 6   |     | Thumb right base | 1 |
| Axis locker    | 18  |     | Thumb left base | 1 |
| Distal right tip| 3  |     | Proximal pulley | 3 |
| Distal left tip| 3  |     | Middle pulley | 6 |
| Steel          |     | QTY | Base pin  | 3   |
| Heelless screw | 18  |     | Proximal pin | 3 |

The anthropomorphic robotic hand is equipped with two position sensors attached to PAM actuators and two Force Sensing Resistor (FSR) sensors to measure grasping force. The position sensor is a spring return and a linear actuation potentiometer. It converts the mechanical travelling of the PAM actuator into a DC voltage signal in range of 0-5V. First FSR sensor is located on the palm, for middle and index fingers, and the second one is located on the side of the thumb’s tip. Table 3 summarizes the mechanical properties of the robotic hand and the dimensions of the fingers. The complete set of anthropomorphic robotic hand is shown in Figure 9.
Table 3. Mechanical properties of the robotic hand

| Description                     | Value  | unit  |
|---------------------------------|--------|-------|
| Mass of the hand                | 150.25 | g     |
| Volume of the hand              | 82940.73 | mm³  |
| Finger’s Moment of inertia     | 2.246e-5 | Kg.m² |
| Length of Link 1                | 26.189 | mm   |
| Length of Link 2                | 16.957 | mm   |
| Length of Link 3                | 26.866 | mm   |
| Length of Link 4                | 15.902 | mm   |
| Finger’s length                | 70.012 | mm   |
| Finger’s width                  | 19.000 | mm   |
| Finger’s thickness              | 10.656 | mm   |
| Pulley diameter                 | 8.000  | mm   |

Figure 9. The complete set of anthropomorphic robotic hand.

3. Results and Discussion

Figure 10 shows the experiment results of grasping multiple shape objects with different weight where the force response can be detected using FSR sensors while the position of finger can be detected by position sensors. The maximum weight that the hand can grasp without slipping is 500 g. However, by increasing or decreasing the weight the grasping force can be changed accordingly. The robotic fingers driven by tendons are capable to grasp cylindrical-shaped objects with different diameters. The PAM actuator and the mechanical design have allowed the robotic hand to possess a light weight and a compact size imitating the human being hand and implementing the anthropomorphic concept.
In terms of the anthropomorphism concept, the size of the developed hand is closer to human hand size compared to the hand developed by Maeda et al. (2011) where 13 PAMs actuators have been used causing the large size of this hand [3]. In addition, using PAM actuators makes the developed hand more commercialized compared to pneumatic FRH-4 hand developed by Gaiser et al. (2008) where uncommercialized FFA actuators have been used [5].

4. Conclusion
In this work, a three-fingered anthropomorphic robotic hand driven by two PAM actuators has been developed. Based on the results it can be concluded that the proposed design allows the actuators to be mounted outside the hand where each finger can be driven by one PAM actuator and six indirectly interlinked tendons. With this design, the three-fingered hand has a compact size and a lightweight with a mass of 150.25 grams imitating the human being hand in terms of size and weight. The hand also successfully grasped objects with different shapes and weights up to 500 g. In addition, the hand can avoid the object from dropping by detecting the slip signal generated by FSR sensors when the weight is increased. Therefore, the hand can maintain grasping objects with changing weights up to 500 g. Therefore, this hand is suitable for researches of robotic applications in terms of design, cost and ability to be equipped with several types of sensors.

Acknowledgements
The authors would like to thank Ministry of Education Malaysia for supporting this research under the Research Acculturation Grant Scheme (RAGS13-025-0088).

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