The Development of a Low Cost Pneumatic Air Muscle Actuated Anthropomorphic Robotic Hand

Chung Yik Lau*, Almon Chai
Swinburne University of Technology, 93350 Kuching, Sarawak, Malaysia

Abstract
This paper presents the design of an anthropomorphic robotic hand of low-budget, achieving basic grasps similar to the human hand. The hand has an anthropomorphic design with 16 degrees of freedom (DOFs). With 14 Mckibben style pneumatic air muscles (PAM) implemented as the power actuator of the tendon-driven fingers, the actuator offers the robotic hand a compliant, soft grasp for manipulating objects in open-loop control. Besides, this work reports the force transmission layout that enables underactuation which allowed the use of fewer actuators to control the DOFs of the hand. The performance of the hand was accessed through testings using power and precision grasps.

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Nomenclature

\[\text{DOF}\]\quad \text{degrees of freedom}

\[\text{PAM}\]\quad \text{Pneumatic air muscles (actuator)}

1. Introduction

A robotic hand is a multi-fingered object manipulation end effector that involves the integration of different engineering expertise like mechanical, electrical, and control. Motivated by the great potential robotic hands hold as a human substitution in difficult situations, scientists throughout the world have been researching in this field since the 1980s. The state-of-art of contemporary anthropomorphic dexterous robotic hands offers human kind assistance in tasks that are considered unachievable, ranging from tedious routine tasks to upper extremity prosthetics.

Nature has always been a source of inspiration for engineering designs. As it is desired to develop a robotic hand to mimic the appearance and grasps of the human hand, hence it is reasonable to choose the human hand as the basis of designing the robotic hand. Through literature reviews, numerous robotic hands have been developed based on hand anthropometry, at least in the MIT/Utah Hand [1], the Robonaut Hand [2], the Gifu Hands [3-4], the Shadow Hand [5], the Salford Hands [6], and the BIT Hand [7]. The hands listed are designed to be highly dexterous, with high number of degrees of freedom (DOF), and generally more than 15 DOFs. Although robotic hands with lesser fingers are able to handle objects as well, but the humanoid design offers greater dexterity in object manipulation.
Conventional power actuators for contemporary robotic actuation are either in the form of electronic, pneumatic or hydraulic. Of course, each of them has their own pros and cons serving as robotic actuators. An actuator that is appropriate for robotic applications should be lightweight, compact due to limited spaces, compliant for ease in control, safe due to possible human interactions, and low cost. Through reviews, the Mckibben style Pneumatic Air Muscle (PAM) is found to satisfy the requirements listed. Different names have being used for PAM in various works. For example, Pneumatic Muscle Actuators, Fluid Actuator, Axially Contractible Actuator, Fluid-Driven Tension Actuator, and Tension Actuator [9]. From literature, the PAM has been implemented in different robotic hands at least in the Shadow Hand [5], the Salford Hands [6], the BIT Hand [7], and Festo Airic’s Hand [8]. In this work, PAM was selected as the actuator due to the properties it offers as a robotic actuator.

In this preliminary work, we pursue the design and development of a humanoid robotic hand mainly focused on its anthropomorphism, dexterity, underactuation, and low cost. The structure of the anthropomorphic robotic hand ought to resemble the human hand in appearance and functionality. Therefore the number of fingers, the hand ratio, and the fingers/thumb position should be identical to the human hand. Besides, the robotic hand should have decent dexterity since the human hand has more than 26 DOFs which enables full dexterous manipulation of objects in different shapes and sizes. Hence, it is desired to develop a robotic hand that has sufficiently high amount of DOFs that can perform simple grasps such as power grasp or precision grasp. Moreover, it is desired to design an economical robotic hand that is low cost with materials that are easily accessible. This is also where underactuation of the hand comes into play - to control the DOFs with lesser actuators. The purpose of implementing this concept is to save cost on the total pneumatic valves required to power the pneumatic actuators. The knowledge and experience gained from this work can be applied on further studies in dexterous hands and relevant researches.

2. Overview of system design

The complete robot hand system is illustrated in Fig. 1. Overall, the system is consisted of 4 main parts. Namely, the five fingered humanoid robot hand, the forearm (actuators and sensors), the pneumatic system, and the system controller. In term of size, the hand is marginally larger than the average hand of an adult male. Dexterity wise, the hand has a total of 16 joints with 16 DOFs. Besides, 14 PAM have been installed at the forearm with nylon tendons as the power transmission connecting the actuators with the coupled joints. Due to the properties of PAM, it grants the hand open loop finger position control without the use of force feedback sensors on the hand. Despite of not having tactile feedback sensors, linear potentiometers were attached to the pneumatic actuators to keep track the position. The pneumatic system consists of electrical solenoid valves and a pneumatic regulator was used to control and regulate the compressed gas into the pneumatic actuators. Moreover, a Master-Slave control was developed to access the performance of the hand. The controller would be a custom made control glove that synchronizes the human controller’s hand gesture with the robotic hand. A simple control algorithm similar to fuzzy logic was developed for the experiment.

Fig. 1. Illustration of the system overview
3. Robotic hand design

3.1. Mechanical profile

The design of the robotic hand resembles the anthropomorphic structure of the human’s right hand. It has 4 fingers, 1 thumb, and a palm. As shown in Fig. 2(a), the index finger and middle finger are installed onto the solid metacarpal of the hand. On the other hand, the ring finger and the little finger are connected to the solid metacarpal through a flexible metacarpal. This additional DOF on the palm enhances the grasping capability especially when dealing with cylindrical shaped objects. Besides, the thumb is installed at the lower part of the solid metacarpal which forms the opposability of the thumb with the fingers. The dexterity of a robotic hand in object manipulation is closely dependant to the efficiency of the thumb [3]. Overall, the robotic hand is consisted of 16 DOFs, whereby the joints and DOFs can be distributed as: 3 joints and 3 DOFs on each finger which contributed to 12 DOFs, 3 joints and 3 DOFs on the thumb, and 1 joint and 1 DOF connecting the flexible metacarpal with the solid metacarpal. Since the wrist is non-functional so the hand is not capable of wrist actions such as roll, pitch, and yaw. Moreover, the hand was mainly fabricated with aluminum with each part assembled together with screws and nuts. Hence the hand is lightweight and low cost.

Fig. 2. Illustrations of the robotic hand in (a) computer generated image, (b) the DOFs, and (c) the actual prototype
3.2. Power transmission

Tendons are implemented as the power transmission between the tendon-coupled phalanges and the actuators. The nylon tendons chosen are 0.52mm in diameter and have a maximum tensile strength of 227.0N. Due to its compactness, flexibility, and lightweight, the tendons can fit in the hand without major obstructions. Besides, plastic pins are used to guide the tendons to the designated joints. Moreover, the concept of underactuation has been implemented for actuating the number of DOFs that outnumbers the actuators. Underactuation is achieved through careful arrangement of tendons within the finger phalanges which functions like static pulleys and sliding pulleys. As shown in Fig. 3, the distal phalanges and the middle phalanges of the 4 fingers shared the same actuators whereas the proximal phalanges were actuated by their own actuators. Although underactuation causes the fingers to decrease in active DOFs, but the amount of valves required to operate the actuators can be reduced for the purpose of cost saving. Moreover, passive springs have been installed at the back of each fingers serving as return mechanisms. Therefore, the contraction of an actuator causes flexion to the DOF the tendon is coupled, whereas the springs are installed to the backside of the fingers which leads to extension of the DOF.

4. Actuator

4.1. Concept and operation

A McKibben style PAM consists of an internal inflatable bladder, covered with an outer braided nylon mesh, and enclosed with gas closure fittings [11]. PAM as its name suggests, operates with compressed gas which involves energy conversion from pneumatic energy to mechanical energy. The actuator contracts as pressurized gas is added into it and extends back as gas is extracted out. As the inner inflatable bladder is pressurized by gas, PAM undergoes an increment in volume which leads to radial expansion and axial contraction. The outer braided nylon mesh limits the internal inflatable bladder as it pushes outwards. As a result of the axial contraction, PAM generates tension force that can be utilized for hoisting mechanical loads [11]. With proper control, a PAM is capable of producing jerk free and smooth motion which is suitable for robotic applications in delicate objects manipulation [9].

4.2. Advantages in robotic actuation

PAM is deemed feasible as an actuator for robotic applications due to some of its desired properties, as reported in [10]. Firstly, the operation of PAM resembles biological muscles. Therefore, PAMs can be implemented as actuators to produce flexion and extension motions in robotic applications that is identical to it’s humanly counterpart. Secondly, PAM has a high power to weight ratio that is capable of producing high axial tension in spite of its lightweight. Besides, PAM is naturally damped due to the compressibility of air that causes the actuator to have a spring-like behavior which makes open-loop control possible for robotic applications. Moreover, it is physically compact and flexible, which allows the actuator to fit into tight spaces which eventually would simplify sophisticated engineering problems such as gear backlash in gear
transmissions. A PAM powered robotic hand is rather safe to be deployed to function in contact with human due to its natural damping characteristic. Furthermore, pneumatic devices have its benefits in eliminating possible risks such as fire outbreaks, short-circuit or instability in supply voltage. Lastly, PAM has a low cost and can be manufacture with ease.

5. Experimental results

Experiments were carried out to test the grasping performance of the robotic hand. Qualitative evaluations were made through observation on the power grasp, precision grasp, and the design of the mechanical hand.

5.1. Power grasp

First of all, the hand was capable of mimicking hand gestures that is desired by the user. As shown in Fig. 4(a), the hand had successfully performed a power grasp on an empty drinking bottle. This implies that sufficient force has been transmitted from the power actuators to the fingers. Besides, the dexterity of the hand in the manipulation of cylindrical objects was demonstrated in Fig. 4(a) as well. Through observation, it can be noticed that the bottle was tilted at an angle. This signified that the palm has adequate DOFs to allow the hand to mold around the round surface of the cylindrical bottle which increased the firmness of the power grasp. Furthermore, different objects such as power drill and cups have been experimented as well. The results were satisfying except that additional friction on the surface of the hand is required to assure a steady grasp.

5.2. Precision grasp

Fig. 4(b) illustrates the hand holding a tennis ball with the index finger and the thumb. This experiment was meant to access the precision grasp of the hand. Currently, the hand could hold onto the tennis ball but with lower precision. The first possible reason was the lack of opposability of the thumb with all the four fingers. The thumb could only meet with the finger tip of the index finger and the middle finger. Therefore the thumb was not opposable to the ring finger and the little finger which reduced the hand’s liberty in precision grasp. In order to tackle this problem, the design of the thumb could be revised and improved with an addition of a DOF to the base of the thumb. Secondly, the underactuation of the fingers has led to complexity in precision grasp. Due to the use of only one actuator on both distal phalanges and the middle phalanges, the fingers have lost one active DOF. Difficulty arose when it comes to precisely the control either of the distal or the middle phalanges. Since both of them would flex together when actuated. Hence, underactuation of the fingers has to be reconsidered if an exact mimic of precision grasp is desired.

![Fig. 4. Illustration of grasping types for (a) power grasp on a cylindrical bottle and (b) precision grasp on a tennis ball](image-url)
6. Conclusion

Currently at this preliminary stage, an anthropomorphic robotic hand actuated by pneumatic air muscles was developed. The cost of the entire project has met with the objective of creating a low cost robotic hand, with a minimum budget. Besides, qualitative evaluations of the design were made through observations via simple experiments. Overall, the hand is still at its primitive phase, there are rooms for potential improvement for the work which would further enhance the performance of the robotic hand. The dexterity of the robotic hand can be improved by increasing the DOFs which includes the addition of a wrist. Moreover, the design of the thumb can be revised in order to perform manipulation tasks with higher complexity. Further work such data collection on grip and grasp force is to be performed during work performing by the hand. This data can lead to future improvement such as better actuator selection or possible redesign of flange structure.

References