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Robot Operating System (ROS) Controlled Anthropomorphic Robot Hand

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This paper presents a new design of a dexterous robot hand by incorporating human hand factors. The robotic hand is a Robot Operating System (ROS) controlled standalone unit that can perform key tasks and work independently. Hardware such as actuators, electronics, sensors, pulleys etc. are embedded within or on the hand itself. Raspberry Pi, a single board computer which runs ROS and is used to control the hand movements as well as process the sensor signals is placed outside of the hand. It supports peripheral devices such as screen display, keyboard and mouse. The hand prototype is designed in Solid Works and 3D printed/built using aluminum sheet. The prototype is similar to the human hand in terms of shape and possesses key functionalities and abilities of the human hand, especially to imitate key movements of the human hand and be as dexterous as possible whilst keeping a low cost. Other important factors considered while prototyping the model were that the hand should be reliable, have a durable construction, and should be built using widely available off-the-shelf components and an open-source software. Though the prototype hand only has 6 degrees-of-freedom (DOF) compared to the 22 DOF of the human hand, it is able to perform most grasps effectively. The proposed model will allow other researchers to build similar robotic hands and perform specialized research.

Keywords: Grasp, Mechanical design, Robotic hand, Robot operating system, SolidWorks

Introduction

The human hand has been studied for centuries with an aim to build robotic hands for assistive purposes.[1] Human hands can perform a wide range of challenging complex tasks and this is due to the advanced biological anatomy and sensing features. When compared with the human hand, the robotic hand consists of fewer parts and segments.[2] The human hand has 27 major bones (8 carpals, 5 metacarpals and 14 phalanges) and at least 18 joint articulations with 22 degrees-of-freedom (DOF) driven by about 40 muscles.[3] A human hand grasp involves all 5 fingers that can exert up to about 400N force.[4,5] Phalanges are the key parts of each finger which consists of a proximal, middle and distal phalanges while the thumb only has a proximal and distal phalanges. Each of the joints of the fingers is capable of exercising flexion and extension, however, it is only the proximal phalanges that are capable of exercising abduction and adduction. As for the thumb, it can be characterized as consisting of the most complex structure i.e., flexion and extension as well as abduction and adduction. Moreover, the thumb can also rotate around the axis of the metacarpal joint on the metacarpal phalanx. In addition, the thumb is capable of exercising opposition and reposition motions which makes the thumb even more complex and dexterous than the fingers.[6]

Most medical literatures in empirical studies have outlined six types of grasps: cylindrical, fingertip, hook, palmar, spherical and lateral.[6–9] These grasps are associated with the shapes of the objects to be manipulated. However, Napier (1956) noticed that grasps should be categorized according to their functionality rather than appearance.[10] While conducting his research, Napier observed that the type of grasp chosen to make a particular movement is determined by the task that needs to be performed rather than the shape and size of the object. Therefore, Napier's scheme explores only two categories of grasps; power grasps and precision grasps. The first category of the grasp is characterized by stability and security to enable for e.g., getting a jar lid unstuck or holding a heavy tool. Another important characteristic is that there is a substantially large area of contact between the human hand and the object while performing a power grasp. As for the second category of precision grasps, considerations of sensitivity and dexterity are paramount for e.g., when writing with a pencil. To perform a precision grasp, it is the thumb and the tips of the fingers that are used to hold an

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object. Based on the exploration of the above presented categories Cutkosky and Wright conducted a study where they observed single-handed operations by machinists working with metal parts and hand tools. Subsequently the scientists presented a partial taxonomy of manufacturing grasps in 1986.[(11)] The study of grasp and manipulation can comprise elements of experimental and analytical research.[6] The experimental elements relate to the exploration of grasping by human beings and animals that are thus able to learn from the natural systems of how to construct and repeat a similar mechatronic structure. The analytical elements reveal how interactions between the hand and the grasped object can be modelled using the laws of physics. There are primarily three different approaches to designing the mechanical structure of a robotic hand, which depends on a number of factors including the number of actuators and the DOF[4],

- Under-actuated system (Fewer actuators than the DOFs)
- Fully actuated system (Equal number of actuators and the DOF)
- Redundantly actuated system (Fewer DOFs than the number of actuators)

Under-actuated and Fully actuated systems are used more widely due to their efficiency and simplicity while reducing the overall cost. Redundantly actuated systems are not used commonly as it is costly, complex and bulky.

Characteristics of Existing Robot Hands

Electric, hydraulic and pneumatic actuators are most commonly used to build robotic hands and assist in performing rotational as well as translational movement. Electric actuators are considered the most efficient (usually 90% or more), are easy to install, control and power, and are most frequently used in the robotic industry. However, electric actuators could be noisy and the achieved torque is insignificant in comparison to their weight and size. Hydraulic actuators are around 60% efficient, and produce very low noise and a significant force. However, they are susceptible to contamination, viscosity changes and high temperature. Pneumatic actuators are only about 30% efficient, non-flammable, and easy to install/maintain. Pneumatic actuators produce lower force compared to hydraulic actuators, but also have lesser weight and are cheaper to manufacture.

Sensors used in robotic hands depend on the environment where the hand will be used and the type of tasks that will be performed. Sensors can read many different parameters such as joint torque, applied pressure, position etc. and can also measure environmental parameters like surface roughness, humidity, temperature etc. The sensor value is used to control the actuator.

Robotic hands have evolved significantly over the past few decades. [4,12–14] The first robotic hands were mainly based on the mechanical structure and then they would gradually be upgraded with the advent of complex electronic components. However, a noticeable improvement can also be observed in software development, advanced algorithms and artificial intelligence. Recently, Computer Aided Design (CAD) and 3D printing technologies have a significant influence on the process of designing robotic hands while reducing the prototype development cost.[15–18] Below are presented some significant robotic hands which have had a bit of an impact on the design proposed in this paper.

Barrett Hand

The first Barrett Hand was designed in 1993 based on patents from the University of Pennsylvania[19], and is one of the few robotic hands used for commercial purposes. Barrett hand can grasp objects of different shapes, sizes and weight. The main applications of this hand includes component assembly, food handling, remote manipulation, nuclear-waste management and bomb disposal. All the components are built-in and the complete hand weighs 980 grams only The Barrett hand can be connected through industry-standard serial communication or USB port. These parameters enable easy and simple installation which makes the hand compatible with different types of robotic arms. [20]

The Barrett hand consists of eight joints in total, and controlled using four brushless DC servomotors. Each of three fingers has two rotational joints which are mechanically coupled (moving one joint makes the other joint move as well). All five microprocessors, communication electronics, signal processing electronics, current amplifiers, sensors and servomotors are embedded within the base of the hand. When grasping an object, three articulated fingers close and make six contact points with the object on two links of each finger. The full grasp could be achieved with one more contact point located on the hand's base. Three servomotors, one for each finger are responsible for bending the fingers. The fourth servomotor controls the spread movement of fingers F1 and F2. This allows to rotate these fingers simultaneously by 180 degree. The third finger F3 does not rotate, it can only bend. The servomotors can close and open each finger fully in less than one second. The maximum force measured at the end of each fingertip is 2 Kg. Once the grasp is completed, the joints in each finger are locked. This allows to switch off all servomotors and save electric power. Each of the three fingers has two joints driven by patented mechanism called Torque Switch. The Torque Switch automatically redirects torque to the joint requiring an active power. If the fingertip touches a grasping object first and it reaches the torque threshold, it will switch off the servomotor and lock the finger joints. The finger will stay in this position and wait for the next instruction. However, when the inner link contacts the object first, the Torque Switch locks that link against the object and redirects that finger's motor torque to the outer joint. The outer link then continues under microprocessor control to secure the target object.

The switching of power from inner link to the other link is quite instantaneous and difficult to notice with the naked eye. The threshold torque is adjustable so the Barrett hand can grasp from light to heavy objects and also from soft or fragile to hard objects.

The bending joints of inner and outer links in each finger are anthropomorphic. The spread movements of the first and second finger are not anthropomorphic. However, these fingers could be compared to the human thumb because in the fully spread position they function similarly to the human thumb.

UTAH/MIT Robotic Hand

The Utah/MIT robotic hand was designed by University of Utah and Massachusetts Institute of Technology.[6,21] This project was developed as a general tool for researching dexterity of machines. Initially, it was intended to build an anthropomorphic robotic hand for testing, control and sensing as well as to compare human hand operations with the robotic hand. However, the final version consists of four fingers (only three main fingers and one thumb) and is not fully anthropomorphic. This hand is also an example of a redundantly actuated system in which there are a less number of DOF than the actuators.

Robonaut Hand

The Robonaut hand was developed as part of NASA Robonaut Humanoid Space Robot by the Johnson Space Centre.[6,22] This robot was designed to help astronauts on International Space Station perform Extra Vehicular Activity (EVA). The Robonaut Hand has fourteen DOFs (twelve in fingers and two in the wrist) which are driven by fourteen DC motors. The hand and wrist are at a high anthropomorphic level, however there is ample scope to embed AI-based/Robot Operating System (ROS) based intelligent control. The Robonaut hand's kinematics, size and strength are very similar to the human hand.

RIC Arm

The Rehabilitation Institute of Chicago (RIC) developed the RIC arm.[23] The arm has 5 DOFs (2 DOFs in the hand, 2 DOFs in the wrist, and 1 DOF in the elbow). The size of the arm is similar to a female arm and includes a battery and a control system. It was designed as a small anthropomorphic trans humeral prosthesis which could help amputees in their daily activities for tasks such as pick up every-day objects and achieve a wrap-around stable grasp.

The fingers design of RIC arm is based on the four-bar linkage mechanism connecting metacarpophalangeal joint (MCP) with proximal interphalangeal joint (PIP). There is a slightly different design of index/middle fingers and annular/pinkie fingers. One motor actuates all four fingers simultaneously. Since each finger is equipped with a spring, this mechanism is under-actuated. Torque is transmitted through an integrated 4:1 planetary gear head, a spur gear and a satellite roller screw. When the grasp is completed, a non-back-drivable clutch locks the fingers' positions and further motor activity is not required, which reduces power consumption. The thumb has a separate brushless motor with another 16:1 non-back-drivable planetary gear and a helical gear set. A tilt angle of the thumb was determined with clinicians through a number of experiments and testing prototypes. One noticeable characteristic of the fingers' design is that the distal and intermediate phalanges of the human hand are represented as one part in this robotic hand. The same design approach applies to the thumb's distal and proximal phalanges. This simplified design results in a lower weight and fewer number of moving parts making the robotic hand more reliable and easier to control.

This work presents a method to produce a modular, scalable and easily reproducible robot hand with five dexterous fingers. The system is remotely controlled through ROS, which is flexible in doing a range of grasping tasks. The main objectives of this paper are as follows:

1. Implement the defacto industry standard ROS framework to control the gripper operation, making it convenient to interface with other robot parts.
2. To design a gripper (with 5 mini servos to control 6 DoF) that simulates the human grasp.
3. A dexterous and flexible biomimetic shaped gripper can be inexpensively designed.
4. To enable pre-defined grips for pick/place daily use items thereby offering flexibility in pre-set tasks.
5. To have designed source files as open source for easy reproduction.

The next section "Materials and Methods" presents the proposed robotic hand with discussions around its hardware and software configurations.

Materials and Methods

The process of designing the proposed robotic hand started from analyzing the designs of robotic hands discussed in the previous section. Several aspects such as the prototype manufacturing method, material availability, different kinds of actuators, force sensors, mechanical coupling of moving parts, time required to build the hand, cost of parts etc. were considered. The decisions and choices made were to achieve an inexpensive robotic hand with the functionality and shape similar to a human hand. The proposed robotic hand is presented in

Kinematic Model

The robotic hand is a fully actuated and open kinematic chain model with 6 DOFs. The location of joints and size of phalanges, fingers, thumb and wrist were intended to mimic the human hand, while also providing with anthropomorphic characteristics. However, the proposed robotic hand has far fewer DOFs and moving parts compared to the human hand, but the most important joints and their functions were replicated. Kinematic model of the designed robotic hand is shown in Fig. 2.

To simplify and reduce the complexity of the design, the distal and middle phalanges of the fingers were merged together (similar to the RIC and Barrett hand). Also, for the same reason, distal and proximal phalanges of the thumb were also merged. As the thumb of the human hand is complex and has more DOF than the other fingers [24], it was decided to reflect this characteristic in the proposed robotic hand. Therefore, the thumb of the robotic hand has 2 DOFs and each finger has 1 DOF. Thus, the thumb is capable of flexion/extension and abduction/ adduction movements while each finger is capable of

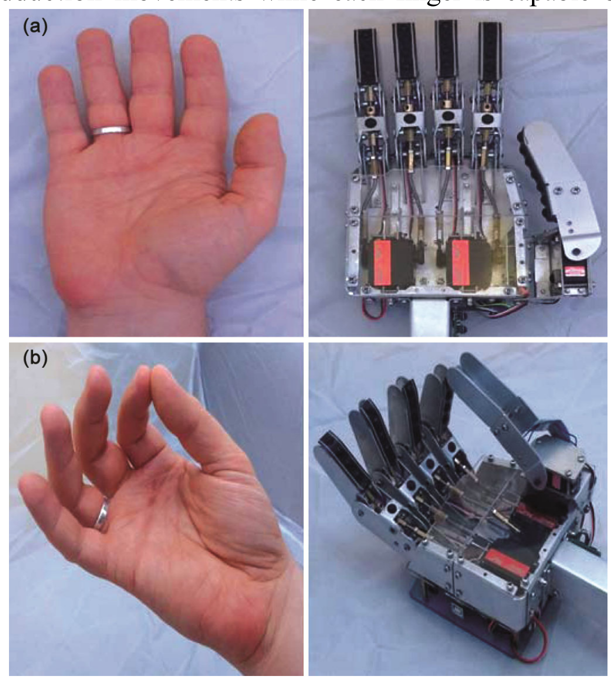

Fig. 1 (a) — Top view of the human hand and robotic hand; (b) Side view of the human hand and robotic hand

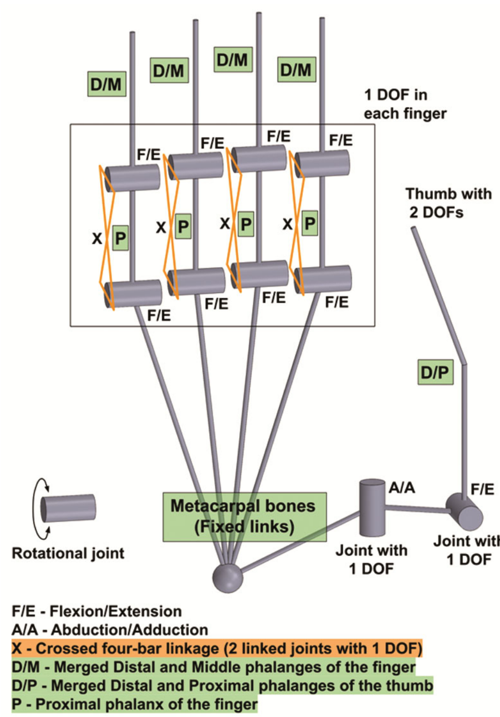

Fig. 2 — Kinematic model of the designed robotic hand; the colors in legend correspond to the parts

flexion/extension movements only. Each finger consists of two rotational joints and links which are coupled together into crossed four-bar linkages giving 1 DOF to each finger. The thumb has 2 DOFs and is able to move on 2 perpendicular planes.

Design and Simulation (SolidWorks)

The robotic hand was designed in SolidWorks – 3D CAD software. This software was chosen because it allows to make a virtual model of the robotic hand and also evaluate collision between moving parts. SolidWorks was also chosen because it can export DXF files to the manufacturing machines for e.g., CNC cutter or 3D printer to make physical components of the robotic hand, and also export files to MATLAB for designing future control algorithms.[25–27] The 3D model of the robotic hand designed in SolidWorks are shown in Fig. 3 and Fig. 4 There are two different design approaches in SolidWorks: the top-down and bottom-up design approach. The first one allows to design parts right inside the assembly, the second one allows to make parts outside assembly and import them to the assembly later. Since the robotic hand design consists of many moving parts which are connected together, the top-down approach was chosen. Thus all parts were designed inside the assembly as it was easier to determine their shapes and dimensions. Also it was easier to find collision and correlation between the moving parts.

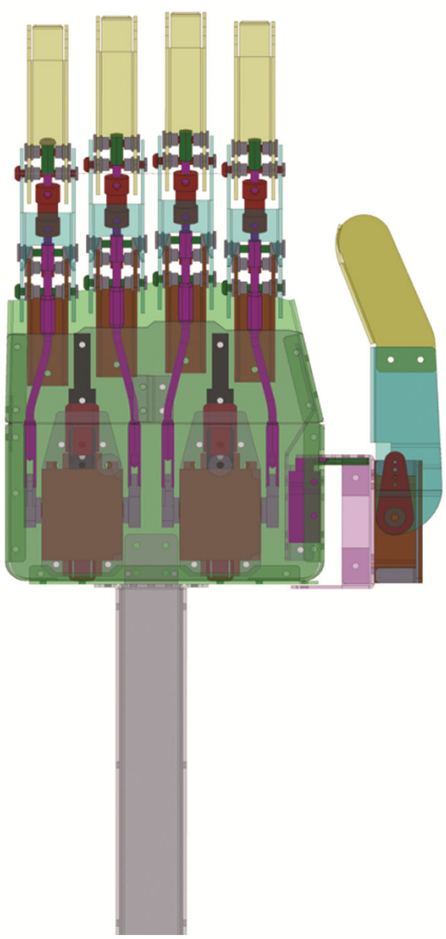

Fig. 3 — The top view of the proposed robotic hand 3D model designed in Solid Works

The first step was to import off-the-shelf purchased components such as servomotors, brass shaft couplings, flat head threaded rivets etc. into the assembly. It was required to have these parts in assembly first because other custom-made parts were designed to fit these off-the-shelf parts. As the servomotor has a moving horn, therefore the motor was designed in another assembly. Servomotor body and its horn were designed as separate parts. Then both parts were joined together using Solid Works Mates (a tool for applying correlation between parts).

The robotic hand is primarily made of aluminum sheet bent across specific lines to achieve desired shape. However, bending a metal sheet is a complex task because the overall length of the bending sheet changes. The outside bend curve of the metal sheet becomes longer while the inside bend curve shrinks. Moreover, the type of metal, its thickness and the bend radius also play an important role in this process. Therefore, Solid Works software is needed to calculate the initial length of a sheet before bending so as to achieve the desired shape after bending. To deal with this challenge, a Sheet Metal module of Solid Works was used, which required the user to provide three parameters; thickness, bend radius and K-Factor1F. [28,29] The 1.22 mm aluminum sheet was used and all the bends were at the angle of 90 degrees. Parameters required for the calculation of K-Factor are shown in Fig. 5.

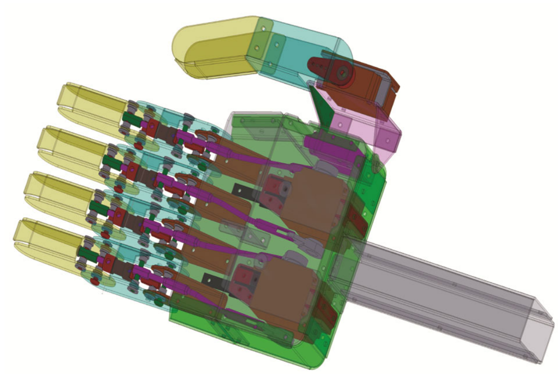

Fig. 4 — The angle view of the proposed robotic hand 3D model designed in Solid Works

The K-Factor calculation formula is shown below.

$$K\ factor = \frac{(360 * BA) - (2\pi * BAng * BR)}{2\pi * BAng * T}$$

where, BA - Bend Allowance (mm) BAng - Bend Angle (degrees) BR - Inside Bend Radius (mm) T – Sheet thickness (mm)

Bend Allowance (BA) was calculated using,

$$BA = Lf - L1 - L2 + 2 * BR + 2 * T$$

where,

Lf - Length of flattened sheet before bending (mm) L1 - Length of one side after bending (mm) L2 - Length of second side after bending (mm)

To find out Lf, L1, L2 and BR several bending tests were carried out on small pieces of aluminum sheets. Then these parameters were measured and the average values were calculated for each of them. Subsequently K-Factor was calculated with the value of 0.35. After entering this value into SolidWorks Sheet Metal module, it was possible to determine the length of each aluminum sheet before bending. Then sheets bent in SolidWorks were compared with the manually bent aluminum pieces. All measurements in SolidWorks were equal to the actual (physical) pieces meaning that the K-Factor was calculated correctly.

Reducing the Number of Joints and Merging Phalanges

Most of the anthropomorphic robotic hands are equipped with three separate movable sections in each finger representing three phalanges of the human hand[4]. However, some hands or grippers only have two movable sections in each finger for e.g., RIC hand and Barrett gripper. In addition, the distal and middle phalanges of RIC hand are merged together into one section (green colored part) which mimics the two human phalanges. Similar approach was used for the thumb of the RIC hand (blue colored part) which is a large single section with 1 DOF. Its shape reflects the distal and proximal phalanges and the metacarpal bone of the human thumb.

Based on the finger and thumb designs in the RIC and Barrett hand, a similar solution was implemented in the proposed design. The distal and middle phalanges of the finger were merged into one section and proximal phalanx was designed as the second moving section of each finger. As for the thumb, the distal and proximal phalanges were merged with metacarpal bone, creating one single section. All these simplifications made the design process and hand control easier. Designed finger and thumb are presented in Fig. 6 and Fig. 7.

To reduce the hand complexity even further, all four fingers were made exactly of the same size and shape. However, the fingers are not mounted across a straight line but across the curve, similarly to the fingers attached to a human wrist.

Electronic Components

The robotic hand hardware consists of servomotors , Arduino Uno board, Raspberry Pi 3 B+, Force Sensitive Resistors (FSRs), polarized capacitors, Resistors, cables, push buttons and breadboards. All electronic components were placed on the outside of the wrist and covered with a plexiglass sheet. When the hand performs the grasp and a force sensor touches a grasping object, the actuator will stop the finger or thumb which touched the object. Each finger of the robotic hand is powered with one servomotor for flexion and extension. The thumb is run by two

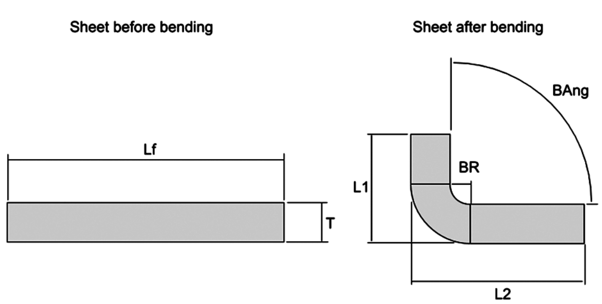

Fig. 5 — Parameters of aluminum sheet for K-Factor calculation

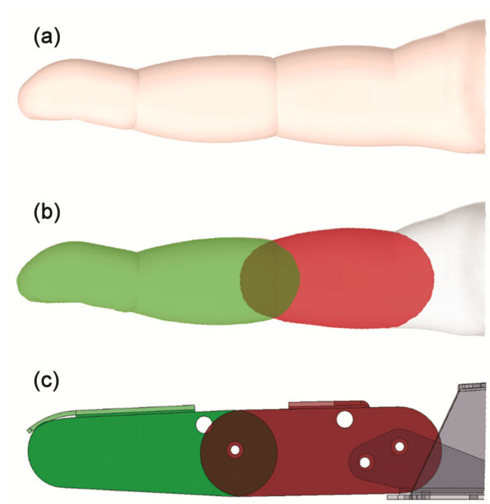

Fig. 6 — Finger design compared to the human hand

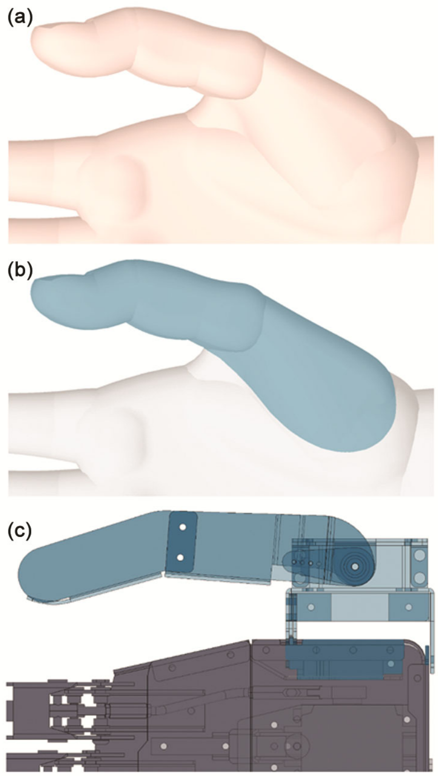

Fig. 7 — Thumb design compared to the human hand

servomotors and is capable of flexion/extension and abduction/adduction. Force sensors read the pressure applied on each finger and thumb. When the force exceeds the specified threshold, the finger or thumb stops. Raspberry Pi runs Robot Operating System (ROS) and calculates the positions of servomotors depending on the signals received from the force sensors. The electronic circuit of the robotic hand and connections between the components are shown in Fig. 8.

Raspberry Pi was chosen to run Linux system with ROS, as it is a popular and affordable small single-board computer. Also, it has a good software support and compatibility. However, it does not have a sufficient number of PWM pins to control servomotors and is not equipped with an analog-to-digital converter (ADC) for reading signals from the force sensors. Therefore, Arduino Uno microcontroller was connected to Raspberry Pi. There is also a wide range of libraries available for ROS communication.

Software: Robot Operating System (ROS)

The Robot Operating System (ROS) is a set of software libraries and tools that helps one build

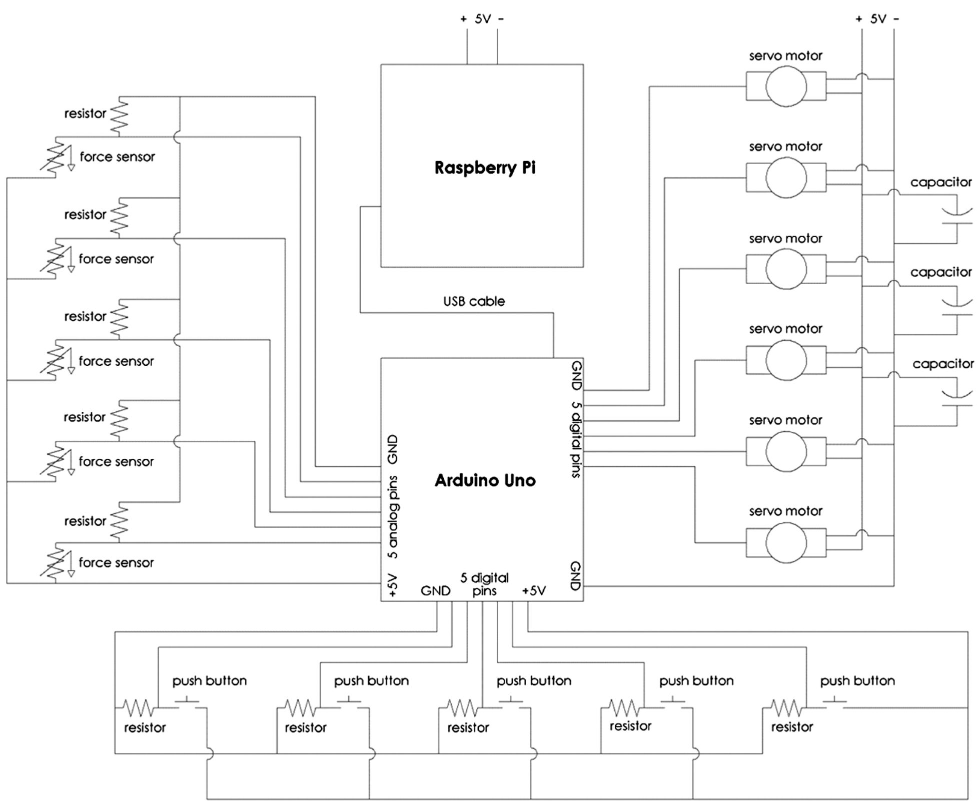

Fig. 8 — Electronic circuit of the robotic hand

robot applications. From drivers to state-of-the-art algorithms, and with powerful developer tools, ROS is also open source.[30] The software is based on ROS and written in Python language. Ubuntu 16.04.6 LTS and ROS Kinetic were installed and configured on Raspberry Pi. Subsequently the *catkin* workspace and source shell environment were set up. Firmata protocol is used for serial communication over USB cable between the two hardware components. Successively, Python script was written and ROS Master started. As the last step, the “Hand_Control” ROS node was launched to control movement of servomotors based on the feedback received from the force sensors and push buttons pressed by the subject. There are five push buttons on the handle of the robotic hand. By pressing the first

push button the robotic hand is initialized and moves to the rest position wherein all fingers and thumb are opened widely. The other four push buttons run different grasp patterns. Four grasp patterns have been coded, each one for a different kind of object to be grasped. The hand can perform two power grasps and two precision grasps:

- Power grasp 1: Large diameter grasp
- Power grasp 2: Small diameter grasp
- Precision grasp 1: Tip pinch
- Precision grasp 2: Lateral pinch

When the push button for a specific grasp is pressed for the first time, the fingers and thumb are initialized and move to the position relevant to the type of grasp. All fingers and thumb move individually as they are powered by separate servomotors.

When the push button is pressed the second time, the fingers and thumb start to move towards the object to perform a grasp. Signals from all force sensors are collected and compared with maximum threshold values and this process runs to achieve a closed-loop feedback control. When the finger touches the object and the force sensor value exceeds the maximum threshold, the relevant servomotor moves this finger backwards until the force sensor value reduces below this threshold. If the picked object starts to slip out, the force sensor value drops below the minimum threshold and the finger is actuated to move towards the object until it reaches the minimum threshold again. This process runs in the loop and is based on the feedback from force sensors. All force sensor values are kept within the threshold range between the minimum and the maximum value. A similar process controls the movements of the thumb. The grasp is held until the subject presses a push button again. Then all fingers and thumb release the object and they move back to the initial position.

Result and Discussion

The proposed gripper using aluminum is durable, provides stiffness to the complete hand structure and reduces friction in the joint and axes. This helps to minimalize any energy loss when transferring power from servomotors to the fingers and thumb. The force sensors detected a wide range of forces and provided good tactile feedback. ROS enabled calculating the servomotors’ positions based on the feedback from the force sensors. As ROS is designed for a wide variety of robotic platforms, it had no problem in controlling this simple system. The Firm at a protocol worked well and allowed a smooth communication between the two hardware components.

Four types of grasp patterns were tested on different objects. Each time the hand was initialized to the start position and the grasp was performed. In the next step, the object was picked up and moved to another location where it was released. Similar tests were conducted a few times to verify the action and repeatability movement. Also, the grasps at different angles against the object were performed to check the dexterity of the fingers and the thumb. The grasps performed by the robotic hand were compared with the grasps done by a human hand. The comparison of these experiments are shown in Fig. 9 – Fig. 12.

In a separate experiment, the tactile feedback from force sensors was tested by grasping heavy objects and trying to pick them up. It was observed how the fingers react when the object starts to slip out. The results of the experiments show that the hand met the expectations and requirements set at the beginning of the design process. Surprisingly, though the proposed hand only has 6 DOFs compared to 22 DOFs of the

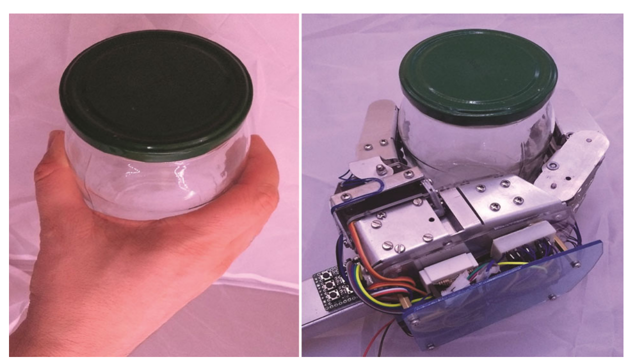

Fig. 9 — Comparison of the large diameter grasp \

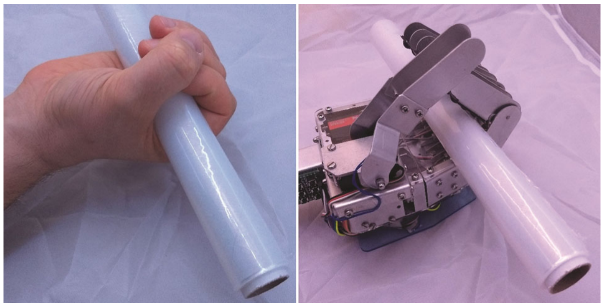

Fig. 10 — Comparison of the small diameter grasp

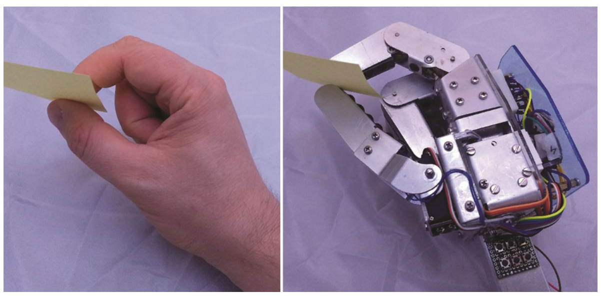

Fig. 11 — Comparison of the tip pinch

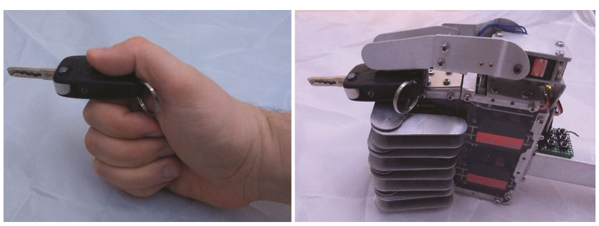

Fig. 12 — Comparison of the lateral pinch

human hand, it was able to perform all grasps quite effectively. However, advanced grasps and fingers manipulations would not be that effective or even possible at all due to the limited number of DOFs and the insufficient power of the servomotors.

Key contributions of the proposed work can be enlisted as below;

1 A dexterous robot hand shaped gripper is designed to demonstrate that making a flexible biomimetic device is not necessarily expensive.
2 The gripper has 5 mini servos to control 6 DoF on the device, simulating the human grasp actions quite closely.
3 The defacto industry standard ROS framework is used to control the gripper operation, making it convenient to interface or cooperate with other robot parts (which is also part of the future work on this project).
4 The design source files are open source for easy reproduction.
5 Pre-defined grips have been used for testing the protype and confirming it's working to pick/place daily use items and the flexibility it offers while doing major pre-set tasks. The authors understand that there are limitations in the gripper not being able to do everything, but that is not the purpose of this design.

The main limitations of pre-programmed grips are that both mechanical and control systems are usually designed for a fixed set of actions with no further flexibility. The presented design has enough flexibility so the gripper can easily interface with other robot parts, or manipulated by different control strategies, either the traditional PID control or the more biologically plausible spiking neuronal control.

Conclusions

The prototype of the proposed robotic hand has proved that it is possible to build an affordable and dexterous hand possessing anthropomorphic characteristics controlled by ROS. The four-bar linkages has been applied on the inside of the fingers which has allowed to reduce the number of actuators while still providing flexion and extension of each finger. It was found that these mechanisms were performed efficiently in both the joints of each finger. However, while performing some grasps (mainly with square or triangle shaped objects), the fingers did not make multiple contact points with the object, but this could be resolved by placing springs on the inside of the fingers. Placing two servo motors in the thumb allowed to perform a good range of movement required for most types of grasps, and enabled dexterity and performance. An improvement which could be done in the future is that the servomotor responsible for flexion and extension of the thumb could be more powerful as the thumb acts in the opposite direction to the four fingers during grasps.

Acknowledgment

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