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Design of a Flexible Articulated Robotic Hand for a Humanoid Robot*

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Abstract— For humanoid robots, it is desirable to have dexterous hands and human-like grasps. Traditionally, researchers employ firm materials to design and fabricate robotic hands for robotic systems. However, natural systems have deformable body parts which are superior to rigid robotic hands in terms of grasping. Recently, the advancement of 3D printing technology makes printing with flexible resin materials¹ possible. In this paper, inspired by the human hand anatomy, we propose a method of designing a new 3D printable, flexible surface robotic hand for a humanoid robot (i.e. Nadine social robot). We acquire the 3D hand base model by 3D scanning and generate the final 3D articulated robotic hand model using standard shape objects such as cuboids, spheres and cylinders. The whole process of 3D modelling is handled by script codes with landmarks of the hand as variables. Compared with other works, we provide a rapid way of producing a customizable six DOFs (Degree of Freedom) articulated robotic hand. Experimental results have verified that the robotic hand is capable of grasping a variety of objects with different shapes.

Keywords: Flexible material, Anthropomorphic, Customized model, 3D printing, 3D scanning

I. INTRODUCTION

Since the world's first dexterous hand (i.e. Stanford/JPL hand [1]) was created in 1983, researchers and engineers have been pursuing replicating the mechanisms of the human hand through mechanical designs. However, there are still gaps between the mechanical structure of the designed robotic hands and the anatomy of the human hand. The human hand consists of 27 pieces of bones [2], where 14 bones are in the fingers, five bones in the palm region, and the rest are in the wrist. In addition, the human hand has 15 movable joints and in all 27 DOFs. Each finger has three joints. The motion of the fingers is controlled by a natural evolutionary complex system. In this system, muscles actuate the bones through the tendons. Ligaments, synovial cavities and bursae constitute the finger joints and regulate the motion range and speed of the joints passively. The joints are surrounded by the soft skin and tissues.

The human hand has inspired various designs of robotic hands [3]. However, the conventional robotic hands hardly duplicate the human hand as the mechanical properties of the rigid materials that are chosen differ from those of the human hand. Recently, engineers have been exploring the design and control of soft-bodied robots that are composed of soft or flexible materials [4]. Young's modulus is a mechanical property that measures the stiffness of a solid material. It

defines the relationship between stress (force per unit area) and strain (proportional deformation) in a material in the linear elasticity regime of a uniaxial deformation. It is also a useful way of measuring the hardness of materials employed in the robotic systems [5]. Figure 1 demonstrates that the traditional robotic hands that are made from metals and 3D printable hard plastic have high order moduli (10^9 - 10^{12} Pa), whereas the elements of the human hand (skin, tissue and muscle) have low moduli in the order of 10^4 - 10^9 Pa. In [4], they defined soft robots as the systems capable of autonomous behaviour that is primarily composed of materials with moduli in the range of the moduli of soft biological materials.

Figure 1 Young's modulus for various materials and two 3D printing material we are using for our robotic hand (Red arrow) Adapted from [4]

The application of soft materials will enhance safe interaction between robots and human beings, which has been proven by rigid robots with compliant joints in [6]. A robotic hand made of compliant materials can grasp objects stabler and more efficiently in comparison to a robotic hand with a hard surface[7]. For example, a robotic hand made by metal or rigid 3D printing material is difficult to pinch a coin. The flexible substrates can improve the way of movement as well [8]. The deformable structure could store elastic energy and smooth the movement.

We propose a method to create a customized 3D printable flexible robotic hand. The pipeline is, first, we use a 3D scanner to capture the shape of a physical hand. A 3D scanned model with triangle meshes is created, which contains the geometric shape information of the scanned hand[9]. Then, we extract the hand model from the scanned model and hollow the hand model by setting the thickness to 1.5mm. Hollowing out the hand model not only reduces the weight of the robotic hand but also provides space to add joints inside the hand. Next, we run the python script we code on the model and transfer it into an articulated 3D model. We divide the hand into segments based on hand bones location and add hinge or ball joints to link these segments. Our joints have target motion ranges the same as a real human hand. To remove the collision part caused by the finger motion, we simulate the motion in MAYA and remove the possible collision part from the 3D model. Finally, we add a palm's bones skeleton. We 3D print the palm bones and the surface part using firm and flexible material (rs-f2-gpcl-04² and rs-f2-flgr-02³) respectively with the "Form2" 3D printer. Form 2 is a

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¹ <https://formlabs.com/3d-printers/form-2/>

² <https://formlabs.com/store/form-2/materials/clear-resin/>

³ <https://formlabs.com/store/form-2/materials/flexible-resin/>

stereolithography (SLA) 3D printer provided by “Formlabs”. It supports more than 10 different types of 3D printing materials. Compared to the traditional robotic hands which mentioned in part II.B, our method retains 90 percent geometry information (estimated base on surface area) of the 3D scan target, which calculates by the surface area. In the experiments, we analyse the trajectory of three fingers and provide a grasp plan to a basic grasp gesture. In the experiment part, we have compared the trajectories of our hand with other robotic hands and proved that the soft surface robotic hand have similar trajectories to the rigid robotic hand. Figure 2 shows our robotic hand’s internal structure and the final product.

Figure 2 our robotic hand 3D model and the final product

The rest of the paper is organized as follows. In Section II we review recent developments in the robotics hand area, especially with soft material. In section III, we then present our design and fabrication process in details. Section IV shows our experiments of evaluating the performance of the design in terms of grasping objects, followed by our conclusion and future work in Section V.

II. RELATED WORK

A. Robotics made by soft material

Natural rubber and silicon rubber are two commonly used soft materials in our daily life. Silicon rubber is applied in most of the soft body robots as it has better plasticity. To actuate the soft body made of silicon rubber, variable length tendons are used. In [10], a silicone arm with embedded tension cables to replicate the muscle functions of an octopus’ arm was built. The arm is capable of pushing-based locomotion and object grasping. Shape Memory Alloys (SMA) is another solution to driving the soft body robotics. Laschi et al. created a prototype that presents the morphology of the biological model and the broad arrangement of longitudinal and transverse muscles. Actuation is obtained with cables for longitudinally move muscles, and with shape memory, alloy springs for transversally move muscles [11].

Pneumatic actuation is another commonly used approach to inflate the soft material to get the motion. Pneumatic artificial muscles (PAMs) and Fluidic elastomer actuators (FEAs) are two soft actuators, which have been used recently. RBO Hand 2 uses a highly compliant, pneumatic continuum actuator design, called “PneuFlex” which was invented by Deimel and Brock[7]. FEAs also can work with hydraulic pressure [12].

For all of these designs, the soft body has close properties like human fingers. However, as the internal structure of these robotic hands consist of soft segments, the trajectories of these fingers are not human-like.

B. Cable-driven robotic hand

Prosthetic hands account for a large proportion in robotic hands [13]. However, due to the robustness and mass production requirement, most traditional prosthetic hands use gears or linkage bar to actuate the fingers[14]. Compared to the widely distributed prosthetic robotic hands, the research-oriented robotic hands have less design restriction. They have relatively less limitation on the weight, size and control method. Therefore, they can focus on simulating one or more certain aspects of the human hand and make it closer to nature. Cable-driven or tendon-driven is a widely-used actuation method of robotic hand as it is similar to human muscle-tendon-bones driven system [2].

Underactuate, which means the number of actuator is less than the number of DOFs, is a popular method to actuate robotic hand. Prior researches have proven that underactuated robotic hands are also capable for simple grasping [15, 16]. The Shadow hand has 20 DOFs, which almost duplicate all DOFs of the human hand. It is compatible with two control systems which have 20 or 40 actuators. Each actuator actuates the corresponding finger through the driven cable[17]. Dextrus hand is a 3D printable low-cost prosthetic robotic hand actuated by six actuators with 15 joints[18]. All Dextrus hand’s fingers have three joints and controlled by six tendons. Z. Xu and his colleagues have designed two cable-driven robotic hands, which are based on the bones structure of a hand [19, 20]. In 2013, they designed a low-cost modular, 20-DOF anthropomorphic robotic hand [19]. In 2016, a highly biomimetic robotic hand which simulates finger ligaments soft tissues and bones [20]. More previous work of robotic hands can be found in [21].

Most robotic hands simulate the human hand using the fifteen joints or sixteen joints (two joints to simulate the trapeziometacarpal joint of the thumb). Therefore, they have similar finger working space such as the human hand. However, the unsolved problem lies in that the rigid body is hard to reproduce the natural compliant grasp of the human hand.

C. Customised the 3D model of a robotic hand

All of the robotic hands mentioned above is modelling by their creators based on their skills and experiments. Manually 3D model the parts will consume a lot of time as well as not easy to duplicate by others. Some existing studies investigate automatic generate of a 3D printable articulated hand. In [22], they proposed a new method to convert 3D models into functional, non-assembly and printable models with internal friction. It will add joints and provides an interface for specifying rotational constraints. In [23], a shell mesh is taken as an input, and the output is an interlocked articulated 3D printable model.

These two methods mentioned provide two automatic ways to generate an articulated 3D hand model. The final models, however, are both rigid and not compatible with actuators. The method we propose in the next section introduces a way to construct the articulated robotic hand by adding joints.

III. OUR METHOD

In this part, we first present the biomechanical features of the human hand. We also show the making process of our

robotic hand, including 3D modelling, 3D printing, fabrication and integration of the actuation system.

A. Human hand anatomy

Figure 3(A) and (B) below show the bones and joints of a human hand. Figure 3(C) shows the details on how the tendons and muscles drive the finger bones with the help of ligament and hood. The flexion of fingers is controlled by two tendons called Flexor Digitorum Superficialis(FDS) Tendon and Flexor Digitorum Profundus(FDP) Tendon while the finger's long extensor tendon controls the extension of the fingers. The muscles pull the bones through the tendons. The ligaments wrap the joints and tendons to regulate the motion when the bones are rotating based on the corresponding joints. The cable-driven actuation mimics this natural system closely compare to other actuation methods such as gears or linkage bar.

Figure 3(A) X-ray of a human hand, (B) The definition of the bones and joints of the human left hand [20], (C) Anatomy of a middle finger

B. Scan and Segment the hand

Compared to manually 3D modelling, we used a 3D scanner to quickly and precisely get the 3D model of a real target. We 3D scanned a human hand to get a 3D mesh model in STL (stereolithography) format. Based on our previous research [24], we segmented all five fingers apart from the palm according to the 3D coordinates of the landmarks. (Figure 4C). The final hand model after segmentation is shown in figure 4D.

Figure 4(A) 3D scanned hand model, (B) 1.5mm thick Shelled hand model (C) hand landmarks and (D) segmented 3D hand model

C. Finger and thumb design

Figure 5 3D modelling of the finger

Figure 6 3D modelling of the thumb

We use the python script to add the pin joints to each finger and ball joint to the thumb. The script has 12 steps:

1. Use a slight block and "Boolean-difference function" to separate the finger into three knuckles and remove the collision part.
2. Use suitable size blocks and "Boolean-difference function" to remove the collision parts caused by horizontal

linkage bars.

3. Use suitable size cylinders and “Boolean-difference function” to make holes for joints bars.

4. Use suitable size blocks and “Boolean-difference function” to remove the collision parts caused by neighbour knuckles.

5. Use suitable size cylinders and “Boolean-difference function” to make a hole in the tip of the finger for the driven cable.

6. Create a suitable size sphere.

7. Create a suitable size block to cove the top 25% of the sphere.

8. Use the block and “Boolean-difference function” to remove the top 25% of the sphere.

9. Add one more suitable size sphere in the same place as the first one but 20% smaller.

10. Use these two objects and “Boolean-difference function” to create the ball joint base.

11. Add the third sphere in the same position but 25% smaller than the first one.

12. Add two suitable size cylinder as linkage bars.

13. Move the ball joint to the TM joint of the thumb.

All the dimensions of standard objects above are set as variables which depend on the geometry information of the hand. All the positions are based on the landmarks of the human hand.

The three finger parts are printed by form 2 printer using flexible Resin (rs-f2-flgr-02). After remove the 3D printing support, they can snap on together easily by hand. Flexible Resin is an elastomer that allows bendable/compressible parts to be printed on a 3D printer.

Figure 7 3D printed index finger and the thumb

As the human hand has soft skin and tissues in the fingers and palm, an obvious deformation of the hand occurs during the grasping action. This deformation increases the contact area to the grasping object, thus improves the quality of the grasping. Prior research on grasping deformation can be found in [25-27].

Figure 8 The contact areas for a 5 N normal force (left) and a 25 N normal force (right) from within a transparent cube. The vertices of the convex boundary of the contact area are marked with the thin cylinders[25].

Our robotic hand is deformable in a human-like way when exerted an external force. This deformation can help hold the solid object with various grasping gestures (Refer to Figure 9 below for pinch coin).

Figure 9 Deformation of our robotic hand

D. Palm design

Figure 3 Palm's structure

The palm has two separate parts. The inside part is 3D printed with a rigid material (rs-f2-gpcl-04). It is composed of four palm bones and eight wrist bones. Besides the bones, it has one ball joint holder for the thumb and four pin-joint holders for four other fingers. It also has a connector at the bottom part, which allows connection to the forearm of the humanoid robot. The flexible material (rs-f2-flgr-02) for 3D printing the palm skin is the same as that for other robotic fingers (Figure 10). The layer height for both 3D printing is 0.1mm. There is no post-processing required and “Form2” will automatic add support for the printings. All parts can be manually linked, and the final product is shown in Figure 2.

E. Actuation system

Figure 4(A) Servo bed for Nadine robot (B) Servo bed from Inmoov robot[28]

To actuate the motion of the robotic hand and to imitate the human hand motion, six actuators are used to control 15 joints of our robotic hand. As an under-actuated system, three joints of each finger of the hand share one DOF. The thumb has an additional one DOF for the abduction/adduction movement. For each finger, the driven cable goes through the

inner part of the whole finger and the palm. We use cables (0.5 mm diameter Nylon cable) to link the actuators' horn and fingers' tips. The holes on each fingertip are used to hold the knots of the driven cable. We use two drive cables which linked to the two sides of thumb's MCP joints for move the ball joint in abduction and adduction directions. The horn of the motor is 42mm in length. The servo motion is modified to 180 degree turning which could drive the cable to a maximum 84 mm displacement. When the horn is moving, the linked driven cable will stall pull the finger curl. The finger will move to start from the DIP joint, which has the least resistance force of all finger joints.

Our robotic hand is compatible with different cable driven actuation systems. Figure 11A is the servo bed specially designed for the Nadine robot. HITEC HS-5070MH is chosen as actuators and it has 12.7g in weight. So our robotic hand weighs in all 225g (the robotic hand part weighs 135g). Table 1 shows our robotic hand is much lighter compared to other robotic hands. Our robotic hand is compatible with the robotic arm from the Inmoov robot as well (Figure 12B).

Table 1 Mass comparison of the robotic hands

Robotic Hand Name	Developer	Mass (g)
Our robotic hand (2019)	IMI NTU	225
InMoov Hand [29](2015)	Gael Langevin	400
Tact [30](2015)	University of Illinois	350
Dextrus [18](2013)	Open Hand Project	428
Bebionic [31](2014)	RSL steeper	550
i-Limb [14](2010)	Touch Bionic	460-465
Xu et al's hand [20](2016)	Xu et. al.	942

IV. EXPERIMENTS

A. Trajectories of the fingers

The finger trajectories are basic criterion of the robotic hand. In [32] and [20], researchers also provide the trajectory of their robotic hand. They captured the motion of the fingertips by a motion capture system. In another paper, Pitarch drew the workspace of thumb in 3D space[33].

Based on Landsmeer's model III [34], the basic equation for modelling the tendon displacement (L) can be simplified to a second order polynomial approximation [35]:

$$L = (b+h\theta) \theta \quad (1)$$

where b and h are constants determined by the mechanical structure and material, and θ is the corresponding angle rotation.

The servomotors have active pulse width modulation (PWM) range 0.75 ~ 2.25 millisecond. We sample the motion from 0.70 to 2.20 millisecond with 0.1-millisecond interval. During the motion test of our robotic hand, we record down the angle changed after each step of the motion and thus calculated the pose of the fingers. To simulate the grasping of our robotic hand virtually, we draw the four set sample data of trajectories obtaining from four endpoints of the middle finger in lines and show them in a 2D space with the help of Matlab (Fig. 12 left). It has similar trajectories as Xu Zhe's robotic hand[20]. We also show the ranges of motion of the index and thumb in a 3D space (Figure 12 right).

Figure 5(left) 2D workspace of the middle finger of our robotic hand (Right) 3D workspace of the middle finger, index finger and thumb of our robotic

B. Grasp Tests

The definition of grasping is "to a static posture with an object held firmly with a hand"[36]. Cutkosky first divided human grasps into 15 different postures [37] in 1989.

Figure 6 Test for grasp objects

In our experiments, we placed the objects at an ideal grasp place based on human hand grasping experiences, and then manually controlled the servo motors to drive each digit to approach the target according to the 15 different postures.

V. CONCLUSION

In this paper, we present a new method of designing a personalised, flexible robotic hand. Based on the biomechanical studies on the human hand, we aim to incorporate the important features of the human hand to the 3D hand model. Our robotic hand has six DOFs, 15 joints, and similar ranges of motion to the human hand. We calculated the trajectory of each finger in Cartesian space. The test results have shown that our robotic hand is capable of different grasping gestures. One problem we found is the flexible material we are using (rs-f2-flgr-02) cannot sustain heavy actuated pulling force larger than 3kg.cm. So the force during grasping is limited. Recently, the 3D printer is capable of printing with more types of flexible materials. So this problem could be solved by employing new 3D printable, flexible materials.

For future work, we plan to measure amount of deformation of the material with respect to applied force. We will design solid finger bones and more biometric joints for our robotic hand. We also plan to test our robotic hand with the humanoid robot Nadine for autonomous grasping in a

human-like way.

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