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Lightweight Underactuated Pneumatic Fingers Capable of Grasping Various Objects

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***Abstract*—This paper presents the design and implementation of a lightweight and powerful fingers actuator capable of grasping various shaped objects. The proposed fingers actuator is designed on the underactuated structure formed by a thumb and an index finger, which are composed of a zigzag tube with one chamber and a soft polyurethane foam with notch. When the inside of the tube is pressurized by pneumatics, each finger joint can be bent simultaneously performing one degree of freedom motion. Due to the compliance of pneumatic and the softness of the structure, it can automatically hold various types of objects. The design parameter of each joint is illustrated in order to base on distributed grasping force evenly against the objects. The developed fingers could not only perform wide range of grasping but also realize two and half times larger force/weight ratio than general fingers actuator with electric servo motor. Lastly, as the application of the proposed fingers, it is mounted on an aerial manipulator for the door opening mission, and its validity is experimentally verified.**

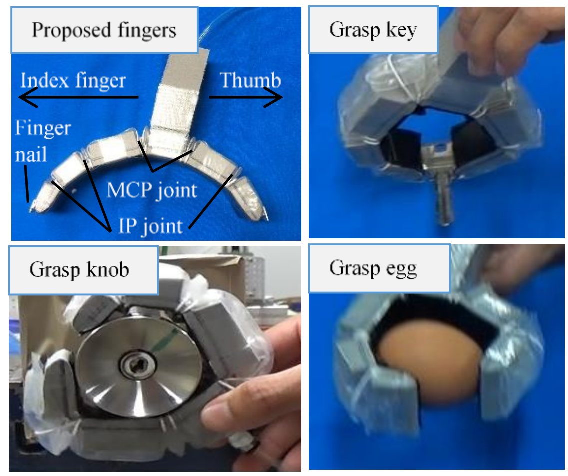

Figure 1. Proposed finger actuator

I. INTRODUCTION

The development of service robot with manipulation function had grown rapidly. For example we can see that the wheeled manipulator robot to open the door had been developed [1], [2]. We can also see that the robot performing door opening and surveillance mission at nuclear building had been demonstrated and the aspect to consider when implementing robot rescue at nuclear building had been discussed [3]. Aerial manipulator robot which aimed to grasp or hold some object also had been reported in [4], [5]. However if these robot directly ordered to grasp and twist the door knob, several issue will occur such as door reaction force. For that reason, we had introduced aerial manipulator robot which can twist bar-type knob and open the door by pushing motion [6]. However this robot cannot twist the round-type door knob due to lack of grasping ability.

Regarding finger robotics research for grasping some object or door knob, several design type had been proposed recently. For example rigid finger-type design as proposed in [7], [8] have advantages especially for producing high-speed and large grasping force because it use geared DC motor and the rigid structure serve to transfer the force thoroughly. However this design tends to make the total weight of the finger become heavy so that the force to weight ratio is low. Lightweight actuator is compulsory when we considering the manipulator to be mounted on aerial robot.

Another bending and grasping actuator with lightweight structure such as pneumatic rubber [9], plastic film [10], or elastomeric material [11], [12] including PneuNets [13] had been developed. This type of actuator have advantages especially lightweight structure. For small size actuator, it could produce large curling angle with low input pressure. However, when we enlarge the size of the actuator, the same input pressure cannot exert the same increasing linear factor of the grasping force due to the energy loss to deform the rubber itself. Also larger input pressure required to produce relatively small force can be seen from the example [9]. With the limited maximum pressure given by the motor pump installed on the aerial robot, we must avoid energy loss as possible. Small input pressure was used in [10]. However due to the structure, this actuator could not perform fingertip grasping. In [13], it could grasp objects with small pressure, however the force exerted is not enough to grasp the knob.

In this paper, we propose a new structure of fingers actuator to perform power grasping and fingertip grasping to hold various object including round-type door knob. Fig. 1 above shows the proposed fingers actuator grasping various object. The actuator use zigzag tube actuator with determined joint parameter so that it can produce uniformly distributed grasping force. Besides, the fingers utilize pneumatic power source mounted on the aerial robot for twisting the door knob as well as grasping actuator so that no additional actuator is installed which then the lightweight manipulator can be achieved.

This paper is organized as follow: Current research regarding door opening robot, finger grasping actuator, and soft finger robotics presented in section I. Following the explanation of human finger structure and proposed finger structure in section II. Section III describe the parameter selection before fabricate the designed finger. In section IV,

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the experimental result of the finger grasping analyzed and the application to aerial manipulator is demonstrated. Lastly, conclusion and future plan for the finger improvement is presented in section V.

II. FINGER DESIGN

A. Human Hand Design

Fig. 2 shows the structure of human hand. Basic motion of the finger can be divided by flexion-extension motion, abduction-adduction motion, and rotating motion of the thumb. Finger motion is actuated by muscle that located at the forearm by pulling the tendon at finger segment joint at once so that the flexion-extension movement can be performed. This motion acted together with several finger which then we know as grasping. From fig. 2, the finger composed of proximal, intermediate, and distal phalanges which connected by IP joint and MCP joint. Metacarpals connect the finger to the wrist inside the palm. Aside from four finger, thumbs only composed by proximal and distal phalanges. From here [14] we know the average size of each phalanges of the human finger so that we can build anthropomorphic hand. We also know that human finger is underactuated in which the number of joint is larger than the muscle to actuate the joint. For example, at index finger, one muscle was used to pull the tendon which connected to each interphalangeal (IP) joint. Underactuated finger have advantages such as reducing the number of actuator while it could compliantly grasp the object. The example of underactuated finger actuator can be seen in these example [15], [16].

Human finger could grasp in many form, but we could conclude that the grasping action can be divided in two major form. The first form is power grasping and the second form is fingertip grasping [17]. Power grasping refer to grasp in which most of the finger surface contact the object (including the palm). This grasp main characteristic is the stability and security since it envelop most of the object surface inside the hand. Fingertip grasping refer to grasping which tip of the finger contact the object without touching the other surface of the hand. Dexterity and sensitivity is the main characteristic of fingertip grasping. Precision works using finger was perform with fingertip grasping.

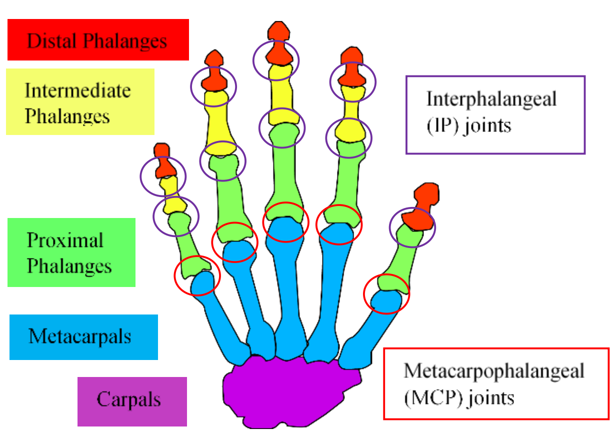

Figure 2. Structure of human hand

B. Proposed Finger Design

Based on human finger, we proposed underactuated fingers with lightweight structure and produce large grasping force by utilizing pneumatic micro pump as energy source. We simplified our finger design with only thumb, index finger, and small portion of palm to minimize the complexity, but without reducing the capability of both power and fingertip grasping. Fig. 3 shows the illustration of the driving mechanism of the fingers actuator.

Each finger actuator consist of phalanges and joints made from soft materials which is lightweight and easy to obtain. The phalanges which acted as finger pad fabricated from polyurethane foam that compliant with the object shape when grasping. The surface of the finger was affixed with the rubber material to increase the friction coefficient. We also put finger nail to slip on the object especially for fingertip grasping. The palm was designed to increase the contact area as well as connecting both of the finger.

The joints made by flat tube pleated into zigzag structure and connected together to all the joint (IP and MCP joints) in one chamber of tube so that it could produce one degree of freedom flexion motion of grasping. Joints generate bending motion when pressurize with pneumatic energy source by expanding the zigzag tube into hemisphere-like structure which then transfer the force to bend the finger phalange. Flat tube and the application was introduced here [18], [19]. However, our proposed joint structure based on pleated flat tube fabricated using urethane sheet welded into zigzag structure. With this method, we can generate lighter and thinner flat tube but strong enough with the maximum pressure given by the motor pump. The zigzag tube joint then tied to the finger phalange. Inside the tube chamber, thread was pinned and connecting to each edge with determined diameter at each joint so that it could control the air flow and set the grasping phase. Grasping phase is important to be considered because it determine the sequence of each finger motion. In this case, we set the sequence which both MCP joint move first followed by middle IP joint and the last distal IP joint. As a result, a fingertip grasping can be performed while power grasping could also be

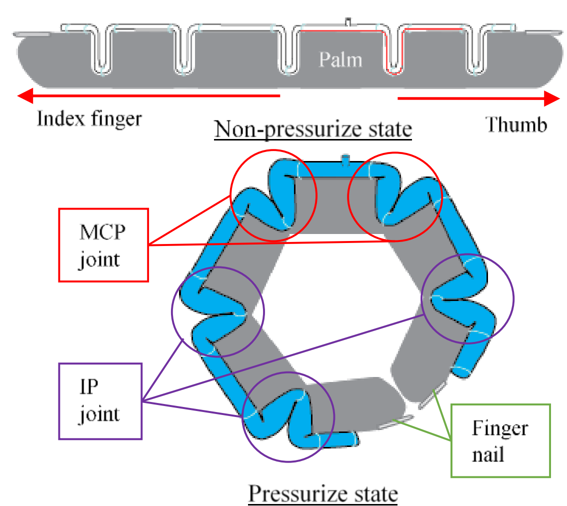

Figure 3. Driving mechanism of finger grasping

achieved for object with size larger than fingers circumference.

III. Parameter Selection

In this section, we will describe about the parameter selection to be implemented in our proposed fingers structure. First we will consider the force to be uniformly distributed in the whole fingers grasping surface. This will be expressed in distributed torque at each joint finger. After we know the required torque at each joint, then we will calculate the parameter of the zigzag tube to produce that torque so that it will follow the torque distribution function. After we know the parameter then we can fabricate the fingers and perform the experiment.

A. Uniformly Distributed Grasping Force

The uniformly distributed grasping force is important to produce softly and gently conform to any shape of object [20]. This also significant to transfer the force equally at any surface so that it could prevent the damage of the object. By distributing the force, we increase the contact area so that the power grasping can be perform much stably and prevent the damage to the object such as egg and another soft object. The resultant of the distributed force will also resulting higher output force. This is useful especially to grasp heavier object such as round-type knob.

Torque diagram for uniformly distributed grasping force can be approach with the model of cantilever beam which given by uniformly distributed force and expressed in (1). The length of the beam can be assume same with finger length (length of phalange), while the moment generated by the beam equal with the torque need to be generated by the finger joint (IP and MCP). Fig. 4 shows the torque diagram for uniformly distributed force.

$$\tau = 0.5F_u x^2 - F_u L x + 0.5F_u L^2 \quad (1)$$

The parameter τ express the torque that need to be generated by the finger joint at each location of the finger phalanges. The value of F_u is the value of single point force (F) per unit length. L is the maximum length of the finger. In our design finger, we know the length of each phalange for thumb and index finger, we also know the location of each IP and MCP joint so that we choose the location as x and we can determine the torque required value. This value will be used for designing the zigzag tube structure.

B. Joint Angle-Torque Formulation

After we know the required torque need to be generated at each location of the finger joint, then we need to calculate the parameter of the zigzag tube to get the desired value. The model of the zigzag tube and explanation of each parameter can be simplified with single pleated flat tube as can be seen in fig. 5.

The flat tube first at non-pressurize state. After given the pressure P, since one side is fixed to the wall of the foam inside the notch, then the deformation of the tube goes to other side and make the finger phalange bend at angle θ. The

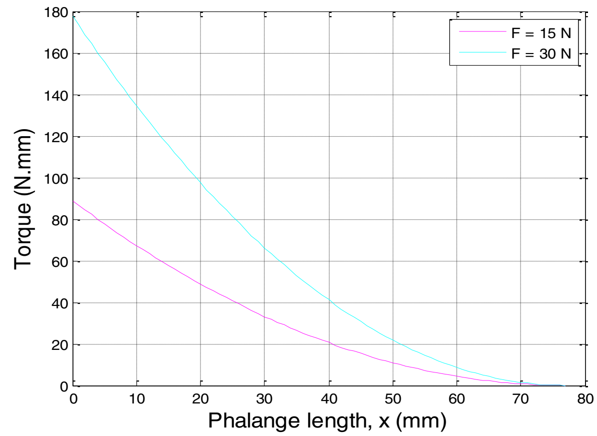

Figure 4. Torque diagram for uniform distributed force

angle generated by the pleated flat tube is expressed as in (2) and torque generated by it express in (3).

$$\theta = 0.5a\pi n/w \quad (2)$$

$$\tau = 0.5Pwda\sin(\theta) \quad (3)$$

Bending angle θ stands for the angle generated by the pleated flat tube from horizontal to inclination angle. Parameter a stands for the height of the pleated flat tube. Parameter w stands for the width of the flat tube seen from anterior direction. Parameter n stands for the number of pleated flat tube becoming zigzag tube. Parameter d stands for the distance from the center of rotation.

This equation then simulated and we got the characteristics of the finger parameter to the torque generated as shown in fig. 6. In this graph, by choosing the parameter w and a at each location of joint x, then we can get the torque that will be generated by the zigzag tube. The shape of the single flat tube when pressurized assume as a near-hemispherical shape with diameter a and w, and the shape affect the force generated by the expansion of the tube. In fig. 6, we can see that in case of w = 10 mm the maximum torque can be generated is at a = 13 mm. This is because even if we increase the parameter a, the shape won't increase the force as we can intuitively imagine that the ballooning

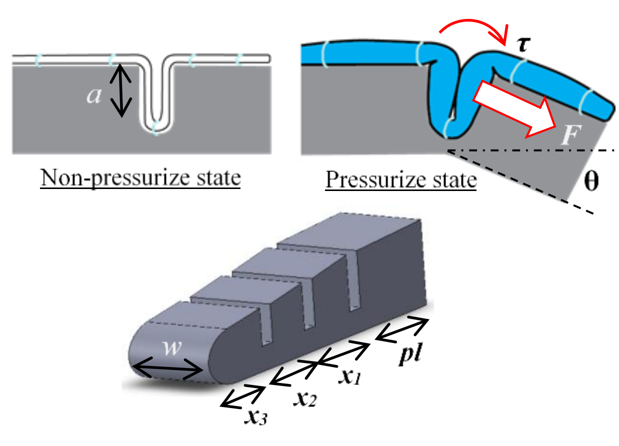

Figure 5. Design parameter

tube shape is reaching maximum expansion until a = 13 mm and then the expansion reduce as the parameter a increase. This also applied to w = 20 mm, and any other value of w.

C. Parameter Selection for the Finger

After we know the torque diagram for uniform distributed force and the torque that can produced by the zigzag tube, then we can select the parameter to fabricate the fingers. The parameter selection basically choosing the related parameter from fig. 4 and fig. 6 so that the fabricated fingers can grasp any shape of object. As for the phalange length, it had been explained in [14]. The resume of the parameter selection can be seen in table 1.

From fig. 4, we can see the required torque at the location of the joint. In this case, the location of each MCP joint and IP joints selected at parameter x. After that, using the value of this torque, we select the related torque generated by parameter a and w at fig. 6. In this simulation, we assume the pressure at 75 kPa which is lower than the actual maximum pressure that the motor pump could produce. We also choose the number of pleated zigzag tube n by 2. The size of the palm measure from average human palm size at flexion and extension choosen at constant value for simplification. With this, we can select the parameter of each joint and expecting that the fabricated joint will follow the torque distribution diagram.

IV. Experimental Result

After we simulate the torque generated by the zigzag tube deformation and select the appropriate parameter, then we can fabricate the finger. Torque generated by the zigzag tube is then measured and analyzed, the performance of grasping random object also demonstrated, and the application to be mounted on aerial manipulator for door opening mission was presented.

A. Measured Data Analysis

The finger is fixed in experimental setup and the torque generated by the joint is measured using digital force gauge sensor. The finger given the pressure around 75 kPa which is equal with the simulation. The torque generated by each joint is measured and we can plot the torque distribution of the

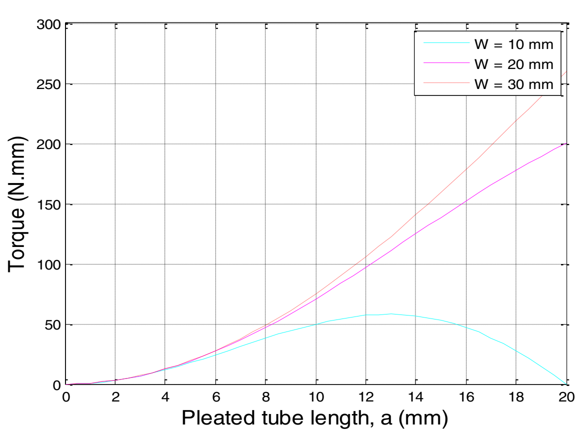

Figure 6. Finger parameter characteristics

TABLE I. FINGER PARAMETER

Finger Part	**Phalange/Joint Size**		
	Proximal	***Intermediate***	***Distal***
Index finger	x = 35 mm	x = 22 mm	x = 20 mm
Thumb	x = 31 mm	-	x = 30 mm
	MCP	***Intermediate IP***	***Distal IP***
Index Joint	a = 16 mm	a = 10 mm	a = 6 mm
Thumb Joint	a = 16 mm	-	a = 10 mm
Other	Finger width w = 20 mm, Palm length pl = 25 mm		

finger. The actual force distribution is also measured at each phalange of the finger, which both sown in fig. 7.

Fig. 7 shows that the torque distribution generated by the finger actuator tried to follow the exponential curve of uniformly distributed force, even though we see that the actual force distribution is not exactly uniform. From this graph we can expect that the finger should be able to grasp any shape of object and gently grasp by transferring the force equally in any finger surface. We can also see from the graph that the torque increase as the size of grasped object increase because the contact area of the deformation of zigzag tube related to the size of the object as the finger. When the object is large (which is object circumference far larger than finger circumference, then performing power grasping) regardless of weight, the angle generated by the joint is smaller so that the contact area of zigzag tube increase which lead to larger torque. As the object size is smaller (which perform fingertip grasping), the angle generated by the joint is larger make the contact area of zigzag tube lowered, then the torque reduced. We also see from the force distribution that at finger length location less than 27 mm (which is proximal phalange), the force exerted is much larger compare to at other phalanges. This effect is expected as we know the characteristic of tube deformation is not constant and have larger effect as the location closer to the base of the finger and because of the fabrication process.

Table 2 shows the comparison of proposed finger actuator with existing fingers actuator [15]. This fingers actuator have a similar structure of two underactuated fingers but using electric servo motor. We can see that our proposed fingers actuator could generate force by weight ratio around 2.5 times larger than the existing finger actuator. This is because the actuation was generated by only one pneumatic motor pump and the structure of the finger was made with lightweight material. Besides, the weight of the proposed fingers actuator (finger only 32 gr, valve 13 gr) already counting the weight of valve driver (50 gr), and micro pump (42 gr), which used not only for fingers but also for all the pneumatic system in our aerial manipulator robot, therefore the average weight of the fingers system itself is much lighter than the value shows on the table.

B. Grasping Performance

Fig. 8 above shown the performance of the fingers grasping various object from hard and fragile object until

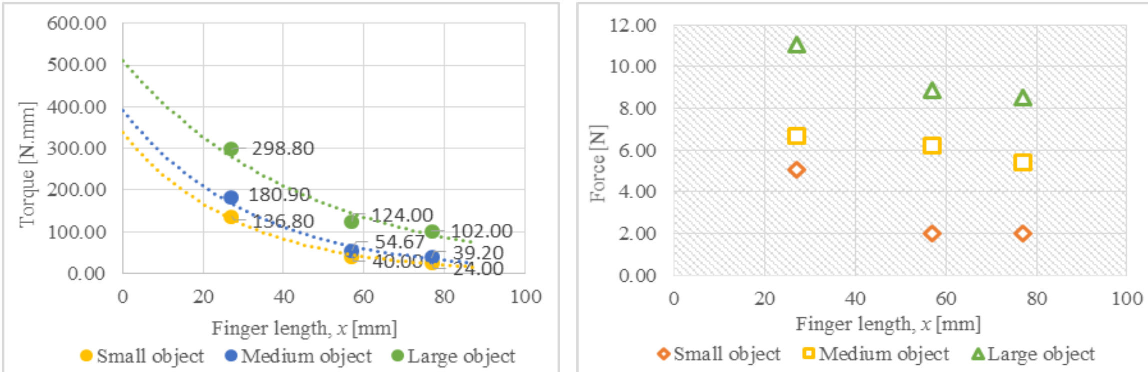

Figure 7. Finger torque and force distribution measurement

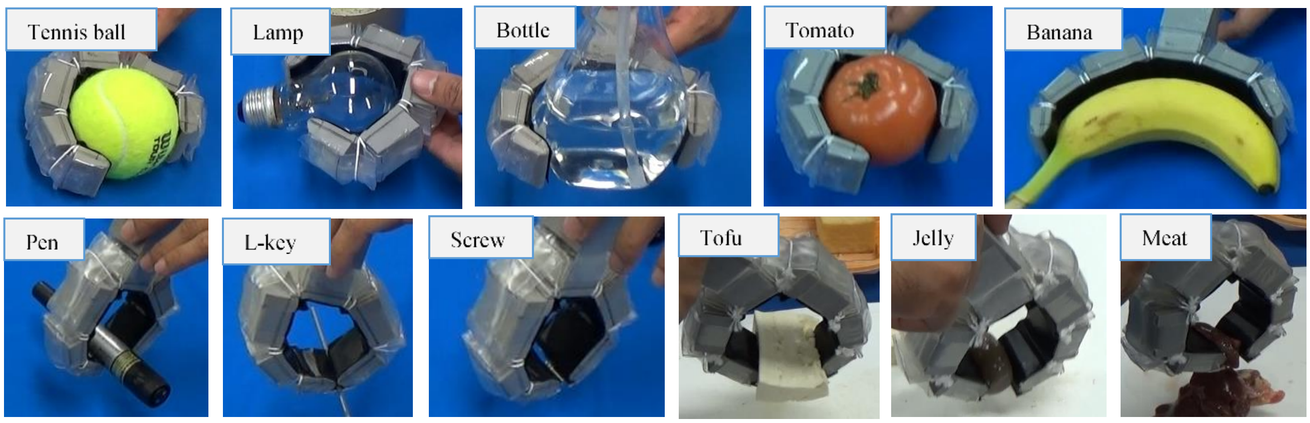

Figure 8. Performance of the proposed fingers actuator grasping various objects on table surface

soft object as also can be seen on the complementary video. The grasping capability can be divided into two form, power grasping and fingertip grasping. With one degree of freedom flexion-extension motion of grasping, we can make the control of finger much simpler without reducing the capability. The grasping force (flexion motion) increase as the input pressure is increase. The extension motion could simply be achieved by depressurizing the tube and the elastic material of polyurethane foam make the finger joint return to its initial position. This elastic restoring force also give a counter-productive effect to the grasping and we can see from the data that the actual force distribution (experimental data) generated by the actuator is less than 15 N as we had designed (simulated data). However even if it less than our designed, we can still achieve the knob twisting function by increasing the input pressure larger than we had simulated. The phase of grasping motion which affect by the thread diameter yield to desired grasping phase which prevent the object to move even if the object such as ball was put unconstrained. The pressure that used to grasp all the objects in the fig. 8 is 60-80 kPa, except round-type knob which need until 95 kPa. This pressure input satisfying the maximum pressure input 100 kPa of the micro pump.

In power grasping, the whole finger surface contact the object as we can see on the figure. With this grasping, we can distribute the force equally and hold the object stably. We can also see that it can grasp an egg securely without damaging it. In case of the object size smaller that the finger circumference, we perform fingertip grasping. It grasp the object on the tip of the finger and hold especially for small and thin object. The fingernail also help to slip into small and thin object so that it could be grasped by fingertip.

C. *Application to Aerial Manipulator Robot*

Build a lightweight and large grasping force finger actuator is important especially when the weight factor is crucial such as for aerial manipulator. Our previous research on aerial manipulator to open the door had been introduced here [6]. With this concept and our proposed lightweight finger actuator, we can expect the robot to perform door opening mission for both round and bar type knob. The performance of door opening function can be seen in fig. 9.

In order for the robot to be able twisting door knob, the robot must perch on the environment. In this robot, we use two-pair of suction pad for attaching the whole body of aerial manipulator on the door plane. By controlling the vacuum activation sequence, we can perform both perching and detaching behavior as had been explained in [6]. Lightweight manipulator is also important considering the payload limit of aerial robot. Built general manipulator

TABLE II. FINGER SPECIFICATION

Finger Aspect (from index to thumb)	**Specification**	
	Finger Actuator	***General Finger***
Weight	137 gr	400 gr
Length size (extension)	163 mm	277 mm
Fingertip (contact) Force	11.07 N	13.15 N

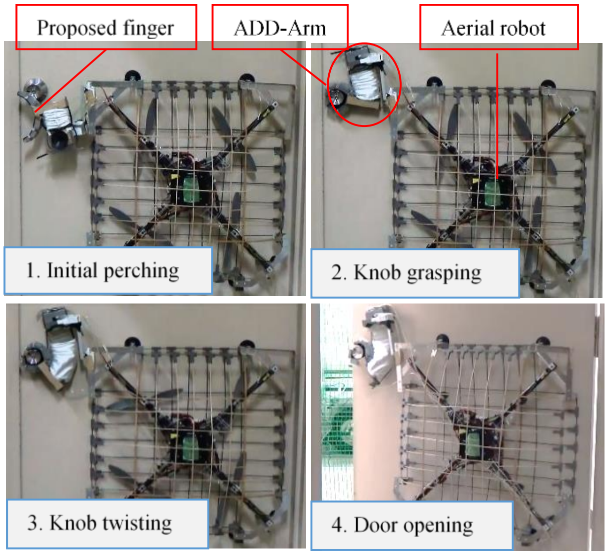

Figure 9. Aerial manipulator performing door opening mission

composed by servo motor and link is not enough to handle the weight limit. We introduce ADD-ARM which have weight 40% lighter compare with general manipulator [6]. It also transferred the force effectively while negate the knob torque spring when twisting. The end effector of the manipulator then installed with our finger actuator so it could grasp and twist the door knob. To open the door, after the robot perching, it push the door by using thrust force from the propeller.

V. Conclusion and Future Plan

In this paper, we proposed a new pneumatic fingers actuator based on underactuated structure performing power grasping and fingertip grasping with lightweight and large grasping force. The finger was able to grasp wide range of object, from ball, key, egg, fruits, meat, until tofu. The final weight of the finger is 137 gr including motor pump and it could twist general round-type knob with pressure input less than 100 kPa. With this fingers actuator specification, aerial manipulators with capability of twisting round-type knob can be achieved.

As we already know, simplified design also give defect to the capability of the finger. While it is true that ability of manipulating object is not really important for aerial manipulator robot to twist round-types knob, however when the door is locked, then the ability to manipulate the object such as key become important. We also know that pneumatic actuator had limitation for the force and speed control. Therefore the design of pneumatic finger with compliance to the increasing/decreasing of the input pressure with regard to the output finger performance would be promising for designing lightweight and robust finger control. For future plan, we would like to develop the finger much dexterous like human finger by installing tactile sensing so that we can grasp object/door knob although the visual system damaged or blocked.

References

[1] W. Chung, et al., "Door-Opening Control of a Service Robot Using the Multifingered Robot Hand," *IEEE Trans. Industrial Electronics,* vol. 56, no. 10, pp. 3975–3984, Oct. 2009.

[2] A. Jain and C. C. Kemp, "Pulling Open Doors and Drawers: Coordinating an Omni-Directional Base and a Compliant Arm with Equilibrium Point Control," *Proc. IEEE Int. Conf. Robotics and Automation*, Alaska, USA, May 2010, pp. 1807-1814.

[3] K. Nagatani, et al., "Emergency Response to the Nuclear Accident at the Fukushima Daiichi Nuclear Power Plant using Mobile Rescue Robot," *J. Field Robotics*, vol. 30, no. 1, pp. 44–63, 2013.

[4] C. E. Doyle, et al., "An Avian-Inspired Passive Mechanism for Quadrotor Perching," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 2, pp. 506–517, Dec. 2012.

[5] J. Thomas, J. Polin, K. Sreenath, V. Kumar, "Avian-Inspired Grasping for Quadrotor Micro UAVs," *ASME Int. Design Engineering Technical Conference,* 2013.

[6] A. Dameitry, T. Hamada, M. Watanabe, R. Iizuka, and H. Tsukagoshi, "Aerial Manipulator with Door Opening Function," *Proc. The 9th JFPS Int. Symp. Fluid Power*, Matsue, Japan, Oct. 2014, pp. 195-200.

[7] Y. J. Shin, H. J. Lee, and K. S. Kim, "A Robot Finger Design Using a Dual-Mode Twisting Mechanism to Achieve High-Speed Motion and Large Grasping Force," *IEEE Trans. Robotics*, vol. 28, no. 6, pp. 1398–1405, Dec. 2012.

[8] R. Oshima, et al., "Assemblable Three-Fingered Nine-Degrees-of-Freedom Hand for Laparoscopic Surgery," *IEEE Trans. Mechatronics*, vol. 15, no. 6, pp. 862–870, Dec. 2010.

[9] A. A. M. Faudzi, et al., "Development of Bending Soft Actuator with Different Braided Angle," *Proc. IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics*, Kaoshiung, Taiwan, Jul. 2012, pp. 1093-1098.

[10] Y. Nishioka, M. Uesu, H. Tsuboi, and S. Kawamura, "Proposal of an Extremely Lightweight Soft Actuator using Plastic Films with a Pleated Structure," *Int. Conf. Mechatronics and Machine Vision in Practice*, Auckland, New-Zealand, Dec. 2012, pp. 474-479.

[11] S. Wakimoto, K. Ogura, K. Suzumori, and Y. Nishioka, "Miniature Soft Hand with Curling Rubber Pneumatic Actuator," *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Chicago, USA, Sep. 2014, pp. 28-33.

[12] R. Qi, T. L. Lam, and Y. Xu, "Design and Implementation of a Low-Cost and Lightweight Inflatable Robot Finger," *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Chicago, USA, Sep. 2014, pp. 28-33.

[13] P. Polygerinos, et al., "Towards a Soft Pneumatic Glove for Hand Rehabilitation," *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Tokyo, Japan, Nov. 2013, pp. 1512-1517.

[14] A. Buryanov and V. Kotiuk, "Proportions of Hand Segments" *Int. J. Morphol.*, 28(3), pp. 755–758, 2010.

[15] L. U. Odhner, R. R. Ma, A. M. Dollar, "Open Loop Precision Grasping with Underactuated Hands Inspired by a Human Manipulation Strategy," *IEEE Trans. Automation Science and Engineering*, vol. 10, no. 3, pp. 625-633, Jul. 2013. Available: http://www.eng.yale.edu/grablab/openhand/model_t42.html#about

[16] A. M. Dollar and R. D. Howe, "The Highly Adaptive SDM Hand: Design and Performance Evaluation," *Int. J. Robotics Research*, vol. 29, no. 5, pp. 585–597, Apr. 2010.

[17] M. R. Cutkosky, "On Grasp Choice, Grasp Model, and the Design of Hands for Manufacturing Tasks" *IEEE Trans. Robotics and Automation*, vol. 5, no. 3, pp. 269–279, Jun. 1989.

[18] H. Tsukagoshi, A. Kitagawa, and Y. Kamata, "Wearable Fluid Power Composed of Transformed Flat Tube Actuators," *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Lausanne, Switzerland, Oct. 2002, pp. 1178-1183.

[19] H. Tsukagoshi, Y. Mori, and A. Kitagawa, "Fast Accessible Rescue Device by Using a Flexible Sliding Actuator," *Proc. IEEE Int. Conf. Robotics and Automation*, Minnesota, USA, May. 2012, pp. 1175-1180.

[20] S. Hirose and Y. Umetani, "The Development of Soft Gripper for the Versatile Robot Hand," *Mechanism and Machine Theory*, vol. 13, pp. 351–359, 1978.