2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)
Beijing, China, November 6-9, 2018

Gripper with Thumb Adduction/Abduction Joint for Enhanced In-hand Orientation Manipulation

Seungyeon Kim and Jaeheung Park

***Abstract*— A new gripper with a *Thumb Adduction/Abduction joint (TAA joint)* is presented in this study. The purpose of the proposed gripper is to enable the orientation control of an object along all axes using in-hand manipulation and the last wrist joint. Using TAA joint motion, it was possible to achieve not only stable grasping but also in-hand orientation control. The gripper can produce 13 out of 16 human grasp motions according to hand taxonomy, including four of the most used hand postures [1][2].**

The grasping performance was evaluated using various objects. Some of them were tools for specific tasks such as electric drill, screwdriver, and hammer. The others were objects in daily life such as ball, CD, pen, cup, wallet, and card. To evaluate the capability of in-hand orientation control, the maximum ranges of rotations were also estimated using circular cross-sectional objects. The gripper can consecutively rotate the object along the roll and yaw directions, and this was demonstrated using a spherical object.

I. INTRODUCTION

In humanoid robots, the role of the end effector is not simply to pick up objects, but also to provide a pathway for direct interaction with the environment. The development of robotic hands has continued to progress, but its size, weight, dexterity, and output power still include limitations. Thus, a gripper that simplifies the function of the hands is used as an end effector for various manipulators, including humanoids.

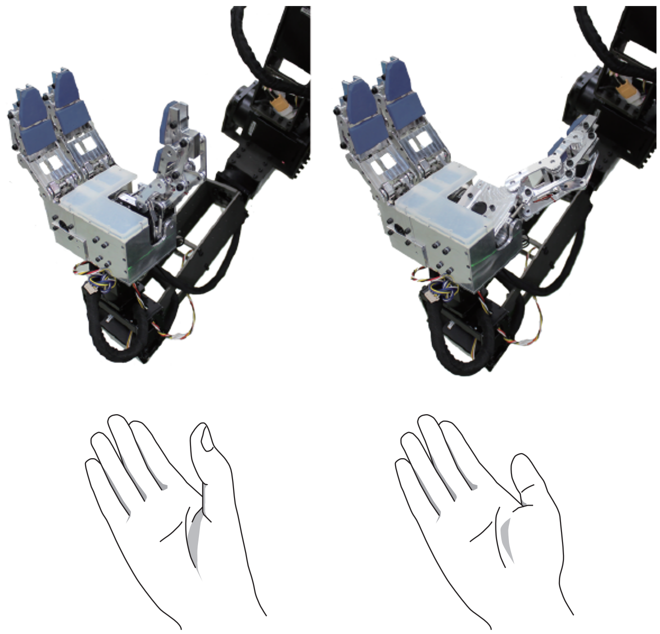
The majority of grippers are designed specifically considering their application because they use a few motors to reduce complexity. Simultaneously, various grasping strategies have been developed in accordance with the shape of grippers to grasp different objects stably [3][4][5][6].

Conversely, there are robotic hands that express all the degrees of freedom of the human hand [7][8][9]. These robotic hands that use more than 20 motors can implement human-like hand motions. However, due to the high degrees of freedom, they require very complex and sophisticated control technology. A thumb carpometacarpal joint constitutes the main difference between robotic hands and grippers. This joint has three degrees of freedom and controls the thumb opposition to enable various hand movements as well as the orientation control of an object.

Unlike a robotic hand, when a gripper grasps an object the position and orientation of the object equal the position and orientation of the gripper. Since the joints of the manipulator,

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. NRF-2015R1A2A1A10055798)

The authors are with DYROS Lab, Graduate School of Convergence Science and Technology, Seoul National University, Seoul, Republic of Korea. Jaeheung Park is the corresponding author. {ksy0711, park73}@snu.ac.kr



(a) Thumb Abduction (b) Thumb Adduction

Fig. 1. Gripper with Thumb Adduction/Abduction joint

to which the gripper is attached, are larger and heavier than those of the gripper, the total load of manipulation will be reduced using in-hand manipulation which is implemented by small motors in the gripper [10].

Due to the above reason, many studies have been conducted on implementing in-hand manipulation using a simple gripper. Ma et al. reproduced the sliding motion of the hand using a gripper with a fixed thumb and a finger actuated by two motors [4]. In addition, Ward-Cherrier et al. implemented rolling motion of a cylinder object using the feedback from a tactile sensor mounted on the surface of a fixed thumb [11]. Ma and Dollar developed a gripper using the thumb with an active sliding surface to overcome the limitations of existing grippers. The gripper implemented the continuous sliding and rolling motion of various objects [12].

There are various studies that have performed in-hand manipulation using additional motions or interaction with the environment including gravity. Cruciani and Simth rotated a long rod-shaped object using the angular velocity of the object generated by the motion of a robotic arm [13]. Chavan Dafle et al. experimentally presented 12 regrasp methods for changing the position and orientation of an object using the

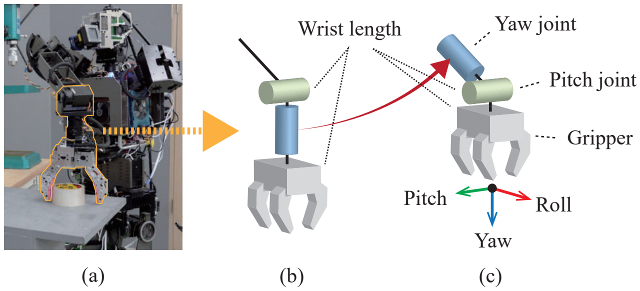


Fig. 2. (a) DYROS JET: picking an object, (b) Abnormally long wrist length, (c) Relocating yaw joint

motion of the gripper [14]. However, the use of additional motions of the manipulator requires more energy and causes discontinuity in the overall task.

The grippers presented in the previous studies were commonly designed with locating a thumb facing other fingers like Fig. 1(a) [3][4][5][15]. It is a reasonable design based on the use of thumb opposition when human grasp an object [1].

DYROS JET, one of our humanoid robots, has a yaw joint at the end of its arm. Using this joint, the yaw orientation of the grasped object can be controlled easily. However, this creates an abnormally long wrist due to the length of the actuator. Fig. 2 shows different kinematic structures for the arm when picking up an object, whereby Fig. 2(c) that possesses a short wrist shows a more natural kinematic structure than Fig. 2(b) with a long wrist.

To produce human-like grasping motions and enhance in-hand manipulation capability (particularly orientation control), a new gripper (Fig. 1) with *Thumb Adduction/Abduction joint (TAA joint)* is developed. The new gripper has three fingers and four modular actuators called Dynamixel X. Each finger is actuated by one motor, while an additional motor is used to control the TAA joint motion by rotating the thumb along pitch axis (Fig. 3(a)). Using TAA joint motion, the gripper can produce 13 out of 16 human grasp motions according to hand taxonomy [2]. Although the new gripper uses only four motors, the combination of three fingers and TAA joint motions achieve stable grasping and orientation control along two axes.

In Section II, the role of the TAA joint is introduced. Section III describes the structure of the proposed gripper. To demonstrate the performance of the gripper, experimental results related to grasping and in-hand orientation control using various objects are shown in Section IV. Finally, the conclusions are presented in Section V.

II. ORIENTATION CONTROL USING TAA JOINT

Fig. 3(a) shows notations of parts of the gripper and the rotation axis. The purpose of the new gripper is to enable orientation control along all axes using in-hand manipulation together with the last wrist joints. Since the pitch joint is located at the end of the wrist (Fig. 3(c)), rotation along the pitch axis can be controlled by the last pitch joint. Therefore, the rotations along the roll and yaw directions should be controlled by the gripper.

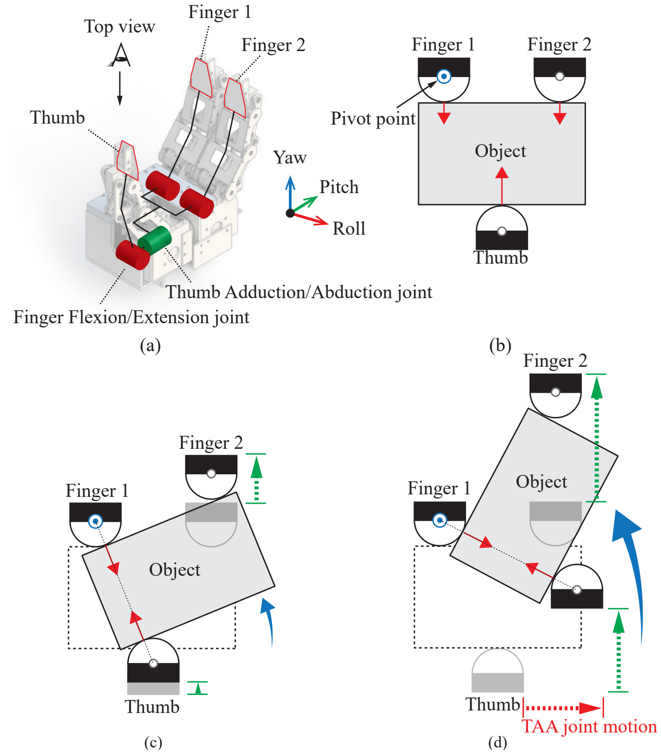


Fig. 3. (a) Fingers and view point notation, (b) Configuration before yaw rotation, (c) Yaw rotation without TAA joint motion, (d) Yaw rotation with TAA joint motion

A. Roll Rotation

Roll rotation can be realized through the motion of two independent fingers [4][10]. The gripper introduced in this paper follows a similar method to control roll rotation. Cylinder-shaped objects, as well as box and thin plate-shaped objects, can be controlled using the same method. The details will be described later through experiments (Section IV-*B*).

B. Yaw Rotation

Fig. 3 shows yaw rotation when using three finger gripper. Fig. 3(b), (c), and (d) show top view of an object being manipulated. The contacts between fingers and the object are assumed as a point contacts and are indicated by red arrows. The cross section of the fingertip is assumed to be circular to simplify explanations.

Fig. 3(b) shows a state of static equilibrium when grasping an object using three fingers. In this case, if the contact force produced by finger2 is reduced by controlling its motion, rotation in the yaw direction occurs naturally. The object is rotated along the pivot point of finger1 and position of thumb should be controlled appropriately to maintain the contact. The rotation of the object continues until the contact forces of two fingers(finger1, thumb) are on the same direction (Fig. 3(c)), and the new configuration is stable along the yaw direction.

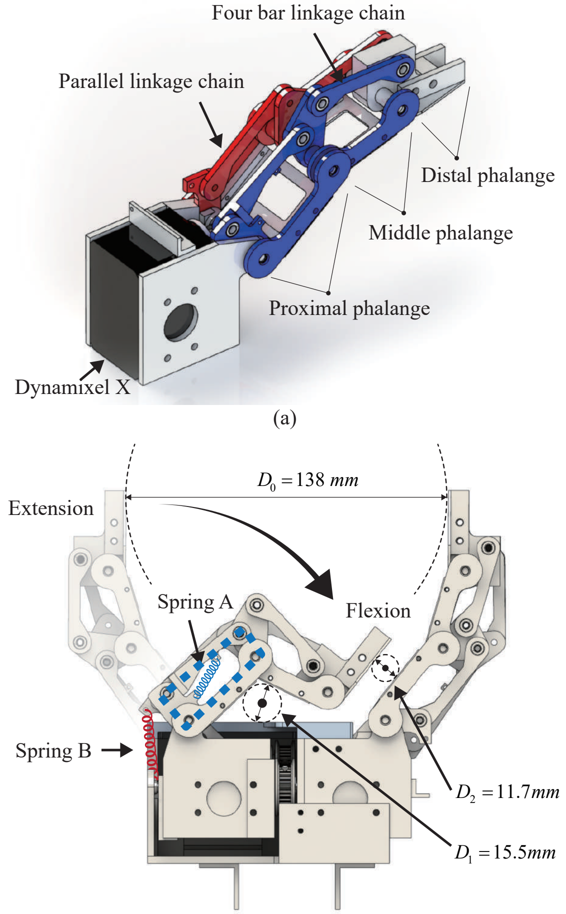


Fig. 4. (a) Finger structure using two types of four bar linkages, (b) Lateral view of the gripper

A comparison of Fig. 3(c) and Fig. 3(d) shows the effect of TAA joint motion on the yaw rotation of the object. Larger rotation can be achieved using a TAA joint. The method that does not have a TAA joint can rotate objects along the yaw axis. However, as the width of the object increases, the range of rotation becomes smaller. In contrast, the method of Fig. 3(d) that uses a the TAA joint can maintain yaw rotation in a wider range of object and can control box-shaped as well as circle-shaped objects.

This method can be implemented by only two fingers including a TAA joint. However, in three-dimensional spaces, other fingers are required to generate one or more additional contact forces to prevent rotation along other directions.

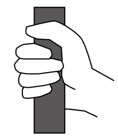
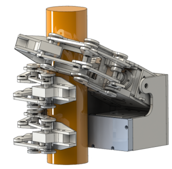
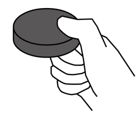
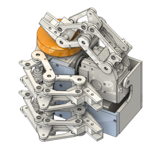
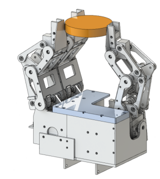
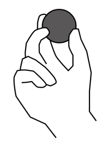
III. GRIPPER DESIGN

A. *Finger Structure*

Each finger has the same structure, and Fig. 4 shows one finger of the gripper. The range of motion of fingers is from 0° to 81°. The finger has three joints but is driven by one Dynamixel X. To compensate this, a four bar linkage chain and a parallel linkage chain are used simultaneously that are often used in grippers and robotic hands [16][17][18][19]. In Fig. 4, the blue and red parts represent four bar linkages and parallel linkages, respectively.

TABLE I

FOUR MAIN GRASPING POSTURES [2] - HAND AND GRIPPER

	Human motion	Gripper motion
Medium wrap		
Lateral pinch		
Precision disk		
Tripod		

Two springs are used on one finger and installed in the areas that do not restrict the movement of the finger. Springs assist in the operation of linkage chains. Before contact take place between the fingers and an object, the spring contracts and creates the dependency of joints of the finger [20]. Spring A (blue), shown in Fig. 4(b), is attached to the four bar linkage to maintain the shape of the first four bar linkage (blue dot box) and transfer the movement of the proximal phalange to the middle and distal phalanges. Simultaneously, spring B(red) is applied to the parallel linkage to keep the fingertip perpendicular to the palm during the finger flexion and extension ($0 \sim 60^\circ$) without contact. This fingertip motion increases the stability of pinch grasping. In the other range of motion ($60 \sim 81^\circ$), the spring is extended due to the structural limitation, and fingertip starts rotating. With this motion, pinch grasping between different phalanges can be achieved using the distal phalange of the thumb and the proximal phalange of the finger, as shown in Fig. 4(b).

Adaptive grasping is implemented using the contact force and tension of springs in the process of grasping objects. While contact forces are applied to the proximal phalange, spring A is extended resulting in an additional motion of the middle and distal phalanges. And extension of spring B results in the rotation of the distal phalange while contact forces are applied to the proximal, middle, and some areas of the distal phalanges.

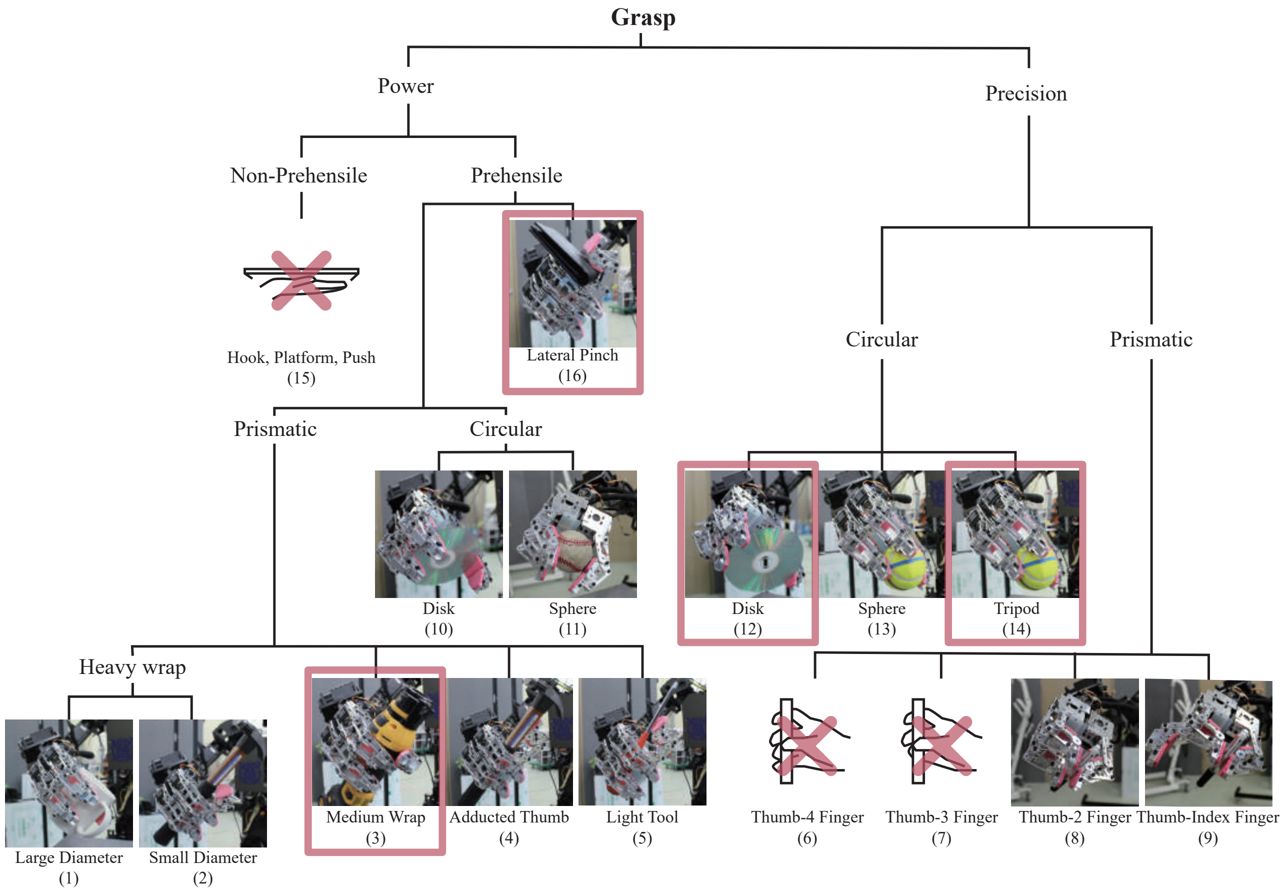


Fig. 5. Hand taxonomy[1] implemented by the new gripper. Red box indicates four most used hand postures[2] and red X means impossible postures

B. Thumb Adduction/Abduction joint (TAA joint)

Unlike other animals, humans have opposable thumbs. *Thumb Opposition* is the motion that the thumb rotates to make contact with the fingertip of the other fingers. According to hand taxonomy [1], thumb opposition plays a crucial role in various human hand movements including grasping and manipulating various objects, and it must be controlled to maintain stable grasping during in-hand manipulation.

The grippers introduced earlier are fixed in thumb opposition configuration because the thumb and the other fingers are always facing each other during grasping motions. This design is a result of focusing on stable grasping without considering in-hand manipulation at the design stage. Some grippers use one additional motors to rotate or tilt fingers, but it is also for stable grasping [15][21].

Another reason for applying a TAA joint is that the gripper can produce human-like grasping motions. Bullock et al. recorded the hand motion of four subjects through a camera and studied the frequency of hand movements used in daily household and machine shop [2]. The four most used hand movements are the medium wrap, precision disk, lateral pinch, and the tripod. Precision disks and tripods can be achieved using grippers with thumb opposition, but medium wrap and lateral pinch cannot be implemented without a separate thumb joint (Table. I). Precision disk and tripod grasps are conducted by the same configuration because the gripper has three fingers.

C. Graspable Object Size

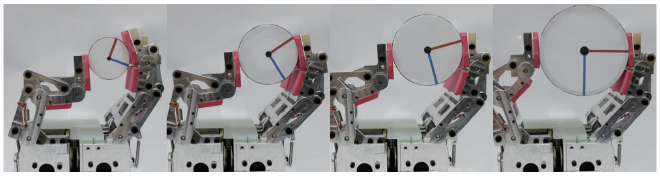
Graspable object size can be categorized according to the part of the gripper used. In Fig. 4(b), D_0, D_1, and D_2 represent the diameters of objects. D_0 is maximum diameter achieved when grasping with two fingertips, and D_1 is minimum diameter of the object using proximal and middle phalanges of the finger and the palm. Similarly, D_2 is minimum diameter of the object when grasping with the distal phalange of one finger and the proximal phalange of the other finger. The values are 138 mm, 15.5 mm and 11.7 mm, respectively.

IV. PERFORMANCE OF THE GRIPPER

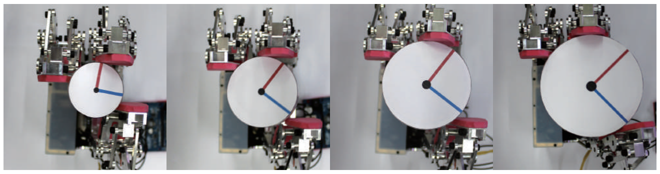
In this section, we present experimental results to evaluate the performance of the newly designed gripper. First, the grasping capability for various objects was investigated including the four desired hand motion mentioned in Section III. Second, we evaluate the enhanced in-hand manipulation using a TAA joint.

A. Object Grasping

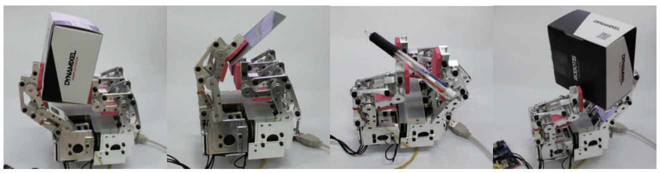
The new gripper with a TAA joint is an intermediate form of simple grippers and robotic hands. To evaluate



(a)



(b)



(c)

Fig. 6. Initially, the blue lines in the circular objects were vertical and downward. Thereafter, the objects were rotated in the counter-clockwise direction. (a) Roll direction maximum rotation (top view), (b) Yaw direction maximum rotation (lateral view). From left to right, the diameters are 40, 57, 67, and 85 mm. (c) Roll and Yaw rotation of various objects

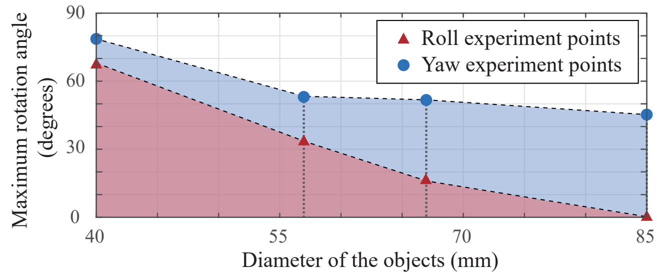


Fig. 7. Maximum rotation angles along the roll and yaw direction with circular objects

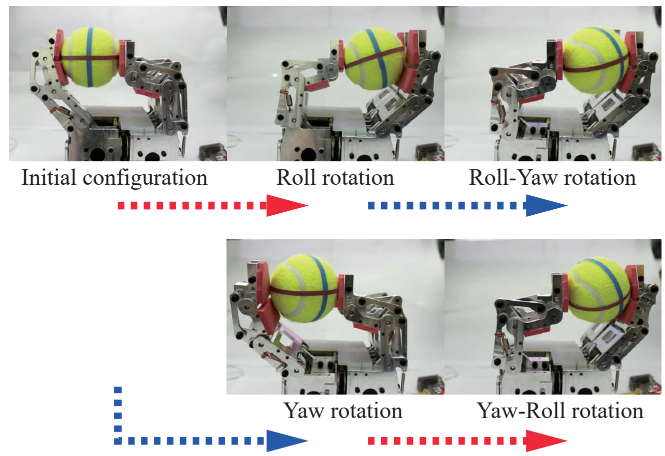


Fig. 8. Consecutive Roll-Yaw and Yaw-Roll rotation

the grasping performance extended by a TAA joint, we implemented the hand postures of grasp taxonomy, as shown in Fig. 5. According to Cutkosky, grasping postures of a human hand are classified into 16 postures [1]. The gripper with a TAA joint is able to perform 13 out of the 16 postures. Possible postures include medium wrap, precision disk, tripod, and lateral pinch, as shown in the red box in Fig. 5.

Because each finger has one actuated motor, Circular grasp of Power (10, 11) and Precision (12, 13, 14) are implemented by similar configurations. Sphere (13) and Tripod (14) are the same due to the absence of a finger adduction/abduction joint. However, all grasps are stable due to the adaptive grasping mechanism. The postures that cannot be implemented include Hook, platform, push (15), Thumb-4 finger (6), and Thumb-3 finger (7). The first one cannot be achieved due to hardware limitations that two fingers cannot be extended parallel to the palm, while the other two postures are impossible because there is no ring and little fingers.

The grasping performance was evaluated using various objects. Some of them were tools for specific tasks such as electric drill, screwdriver, and hammer. The others were the objects in daily life such as ball, CD, pen, cup, wallet, and card.

B. Roll & Yaw In-hand Orientation Control

To analyze orientation control capability along the roll and yaw directions, we used circular cross-sectional objects with four different diameters. The diameters of each object are 40, 57, 67, and 85 mm, respectively. The calculated ranges of rotation are averaged by five repeated experiments.

Fig. 6(a) shows the rotation of the roll direction according to the object diameters. The red area in Fig. 7 shows the range of roll rotation according to the size of objects.

The two pictures on the left side of Fig. 6(c) show that it is possible to rotate objects of thin plates and box shapes using similar motions. These shapes of objects are controlled by the relative motion of the fingers, as well as the rotation of the fingertip in the roll direction.

The rotation capability in the yaw direction was also evaluated in the similar manner. Fig. 6(b) shows the range of possible rotations in the yaw direction according to the diameter and the result is shown in Fig. 7. As the diameter of the object increases, the range of possible rotation decreases. It decreases less rapidly than that of the roll motion, with the rotation ability maintained.

All three fingers were utilized in the yaw rotation. As the distance between the thumb and finger2 become smaller, the grasp using only two fingers becomes unstable and the object cannot be grasped stably without the contact of finger1. The same method can be used for pen and box-shaped objects, and the results of stable yaw rotation control for these objects are shown in Fig. 6(c)(the two pictures on the right).

Finally, we tested the possibility of consecutive rotation control along the roll and yaw directions by combining the above methods. As shown in Fig. 8, consecutive rotation was conducted using a tennis ball. It was possible to control the orientation using only the step command without force feedback. However, there are differences between the results of roll-yaw and yaw-roll rotations due to the slip.

V. CONCLUSIONS

We have designed the gripper with a TAA joint as an intermediate shape between a gripper and a robotic hand to achieve various in-hand orientation control. The grasping performance and capability of in-hand orientation control were evaluated using various objects.

There are two advantages of using a TAA joint. First, yaw orientation control can be achieved using the motion of a TAA joint. Consecutive orientation control along the roll and yaw directions can extend in-hand orientation control. Second, by adopting TAA joint to the gripper rather than the robotic hand, high grasping performance can be achieved without sophisticated analysis of joint location that is essential for robotic hand design, particularly with underactuated fingers.

The new gripper has the joint configuration similar to that of the human hand. Therefore, it is expected that this gripper can be very effective in tele-manipulation using an operator's hand motions. Our future work will involve developing an intuitive tele-manipulation system using the proposed gripper in conjunction with our previous work on hand motion prediction using a motion capture system [22].

REFERENCES

[1] M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *IEEE Transactions on robotics and automation*, vol. 5, no. 3, pp. 269–279, 1989.

[2] I. M. Bullock, J. Z. Zheng, S. De La Rosa, C. Guertler, and A. M. Dollar, "Grasp frequency and usage in daily household and machine shop tasks," *IEEE transactions on haptics*, vol. 6, no. 3, pp. 296–308, 2013.

[3] A. G. Zisimatos, M. V. Liarokapis, C. I. Mavrogiannis, and K. J. Kyriakopoulos, "Open-source, affordable, modular, light-weight, underactuated robot hands," in *Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on*. IEEE, 2014, pp. 3207–3212.

[4] R. R. Ma, A. Spiers, and A. M. Dollar, "M 2 gripper: Extending the dexterity of a simple, underactuated gripper," in *Advances in reconfigurable mechanisms and robots II*. Springer, 2016, pp. 795–805.

[5] R. Deimel and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *The International Journal of Robotics Research*, vol. 35, no. 1-3, pp. 161–185, 2016.

[6] M. Zhu, Z. Wang, S. Hirai, and S. Kawamura, "Design and fabrication of a soft-bodied gripper with integrated curvature sensors," in *Mechatronics and Machine Vision in Practice (M2VIP), 2017 24th International Conference on*. IEEE, 2017, pp. 1–6.

[7] H. Liu, K. Wu, P. Meusel, N. Seitz, G. Hirzinger, M. Jin, Y. Liu, S. Fan, T. Lan, and Z. Chen, "Multisensory five-finger dexterous hand: The dlr/hit hand ii," in *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*. IEEE, 2008, pp. 3692–3697.

[8] The shadow dextrous hand. [Online]. Available: http://www.shadow.org.uk/products/newhand.shtml

[9] G. Palli, C. Melchiorri, G. Vassura, U. Scarcia, L. Moriello, G. Berselli, A. Cavallo, G. De Maria, C. Natale, S. Pirozzi, *et al.*, "The dexmart hand: Mechatronic design and experimental evaluation of synergy-based control for human-like grasping," *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 799–824, 2014.

[10] M. Liarokapis and A. M. Dollar, "Post-contact, in-hand object motion compensation for compliant and underactuated hands," in *Robot and Human Interactive Communication (RO-MAN), 2016 25th IEEE International Symposium on*. IEEE, 2016, pp. 986–993.

[11] B. Ward-Cherrier, L. Cramphorn, and N. F. Lepora, "Tactile manipulation with a tacthumb integrated on the open-hand m2 gripper," *IEEE Robotics and Automation Letters*, vol. 1, no. 1, pp. 169–175, 2016.

[12] R. R. Ma and A. M. Dollar, "In-hand manipulation primitives for a minimal, underactuated gripper with active surfaces," in *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, 2016, pp. V05AT07A072–V05AT07A072.

[13] S. Cruciani and C. Smith, "In-hand manipulation using three-stages open loop pivoting," in *Intelligent Robots and Systems (IROS), 2017 IEEE/RSJ International Conference on*. IEEE, 2017, pp. 1244–1251.

[14] N. Chavan Dafle, A. Rodriguez, R. Paolini, B. Tang, S. S. Srinivasa, M. Erdmann, M. T. Mason, I. Lundberg, H. Staab, and T. Fuhlbrigge, "Extrinsic dexterity: In-hand manipulation with external forces," 2014.

[15] Robotiq 3-finger adaptive robot gripper. [Online]. Available: https://robotiq.com/products/3-finger-adaptive-robot-gripper

[16] A. Spiers, S. Baillie, T. Pipe, and R. Persad, "Experimentally driven design of a palpating gripper with minimally invasive surgery considerations," in *Haptics Symposium (HAPTICS), 2012 IEEE*. IEEE, 2012, pp. 261–266.

[17] Y. Tlegenov, K. Telegenov, and A. Shintemirov, "An open-source 3d printed underactuated robotic gripper," in *Mechatronic and Embedded Systems and Applications (MESA), 2014 IEEE/ASME 10th International Conference on*. IEEE, 2014, pp. 1–6.

[18] K. Y. Choi, A. Akhtar, and T. Bretl, "A compliant four-bar linkage mechanism that makes the fingers of a prosthetic hand more impact resistant," in *Robotics and Automation (ICRA), 2017 IEEE International Conference on*. IEEE, 2017, pp. 6694–6699.

[19] D. Yoon and Y. Choi, "Underactuated finger mechanism using contractible slider-cranks and stackable four-bar linkages," *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 5, pp. 2046–2057, 2017.

[20] L. Birglen and C. M. Gosselin, "Kinetostatic analysis of underactuated fingers," *IEEE Transactions on Robotics and Automation*, vol. 20, no. 2, pp. 211–221, 2004.

[21] Righthand robotics reflex plus. [Online]. Available: https://www.labs.righthandrobotics.com/reflexhand

[22] S. Kim, M. Kim, J. Lee, and J. Park, "Robot hand synergy mapping using multi-factor model and emg signal," in *Experimental Robotics*. Springer, 2016, pp. 671–683.