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In-Hand Precise Twisting and Positioning by a Novel Dexterous Robotic Gripper for Industrial High-Speed Assembly

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***Abstract*— In electronic manufacturing system, the design of the robotic hand with sufficient dexterity and configuration is important for the successful accomplishment of the assembly task. Due to the growing demand from high-mix manufacturing industry, it is difficult for the traditional robot to grasp a large number of assembly parts or tools having cylinder shapes with correct postures. In this research, a novel jaw like gripper with human-sized anthropomorphic features is designed for in-hand precise positioning and twisting online. It retains the simplicity feature of traditional industrial grippers and dexterity features of dexterous grippers. It can apply a constant gripping force on assembly parts and performs reliable twisting movement within limited time to meet the industrial requirements. Manipulating several cylindrical assembly parts by robot, as an experimental case in this paper, is studied to evaluate its performance. The effectiveness of proposed gripper design and mechanical analysis is proved by the simulation and experimental results.**

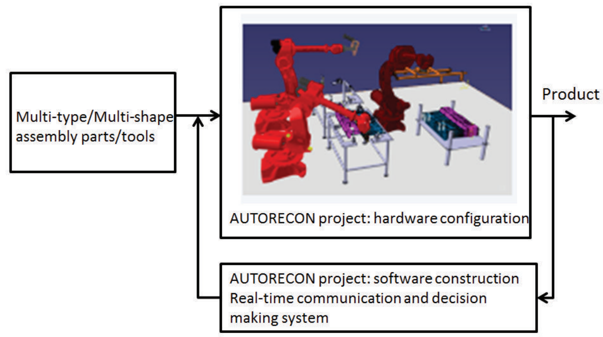

Fig. 1. Assembly scenario in this research under AUTORECON project [4]. The objective of AUTORECON project is to design a manufacturing system with reconfigurable robotic manipulator under the well controlled information flow. To design several reconfigurable robotic hands suitable for industrial implementation is one of its tasks.

I. INTRODUCTION

During the past tens of year, the development in manufacturing industry has been divided into three main streams: Massive Production, Medium Production and Small production. Small production, usually fully using robots, cannot keep in step with the growing social demanding for High-Mix, Low-Volume manufacturing. For the manufacturing fully with human workers, the labor cost is also increasing rapidly. When addressing this problem, it is important to build more flexible systems to improve the dexterity and reconfigurability of current manufacturing system by considering combining and coordinating the above two respects, considering their trade-off and improving the overall assembly effectiveness and efficiency [1]. From our research, if we can provide the robot with sufficient flexibility in reconfiguration, it can help the factory boosting the product quality and meanwhile reducing the cost [2].

Currently in robotic assembly cell for flexible manufacturing, there still remain many unsolved issues for robots. One is that the robot cannot work efficiently in dealing with assembly parts with complicated shapes. They often rely on external sensor systems to help with the assembly work [3]. On the other side, human workers are skilled in performing complicated tasks using their hands. In this case, it is essential that the conventional robotic manipulator is able to perform complicated manipulation like human worker does. During the past years of development in robotic manipulators, nevertheless, the basic appearance of the manipulator has seldom changed, and it is also difficult on the other hand to modify the basic architecture of robots. Therefore, people tend to improve the capacity of robots by designing various functional end-effectors (hands) for robots.

In order to meet industrial application requirements, the robotic hands must be inexpensive, compact, low weight and robust. It also must be capable of performing simple grasping and manipulation tasks, such as precision manipulation, in-hand grasp transitions, and sufficiently general to manipulate different objects and tools. Up to present, most robotic hands in both industrial and academic worlds are either few actuators powered jaws, or simplified human hand shape liked multi-fingered hands for certain grasping patterns. Lots of researchers have already paid much attention to develop such functional robotic end-effectors in the past 25 years. A robotic gripper could be of two fingers, like a jaw [3] with two fingers in our previous research, three fingers [5] or four fingers [6] or even more, the same with human's hand [7].

Parallel manipulator [8] has been already successfully implemented in industry. They can perform and demonstrate pick and place operations in really fast speed with high reliability [9]. Meanwhile, it is much cheaper and simpler than serial manipulators. It is widely adopted in high speed, high-accuracy positioning within only limited workspace, such as food packing and electronic parts placing.

Another novel universal grippers is developed, which is able to pick up unfamiliar objects of widely varying

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shape and surface properties [10]. Different with traditional grippers, the individual fingers are replaced by a single mass of granular material that, when pressed onto a target object, flows around it and conforms to its shape. Upon application of a vacuum the granular material contracts and hardens quickly to pinch and hold the object without requiring sensory feedback. However, neither parallel manipulator nor this universal hand is able to do in-hand dexterous manipulation.

When addressing the dexterous robotic hands, DLR hand [11], Barrett hand [12] and i-HY hand [13], which are all human-sized anthropomorphic robotic hand, are the most representative. Both DLR hand and Barrett hand have the dexterity to secure target objects of different sizes, shapes, and orientations. Furthermore, i-HY is specially designed for passive adaptive grasp. It has also demonstrated a good ability in in-hand object transition, such as pinch grasp to power grasp gesture transition.

Although various grippers are designed and built for precise picking and placing, seldom attention has been paid to the in-hand transition problem for potential industrial application, particularly in lots of assembly case within electronic manufacturing industry. In such industry, the assembly parts are usually well shaped rigid ones, and therefore, the parallel jaw like gripper is widely adopted. However, there still remains a large number of assembly parts or tools which are cylinder shaped made by either rigid or soft materials [14](Fig. 2). If these parts are not fixed to some positions as people in industry always do, but are just naturally lying on the conveyor (Fig. 2-(e)), there could be lots of possible postures available for the robot to choose before they are successfully grasped. Usually in such situation, the robotic manipulator has to carefully examine them by utilizing sensor system, and choose an appropriate gesture to pick it up. This method is straight but not effective. It has increased the complexity of the whole system. It also costs the robot lots of time to search and decide proper gesture. If the gripper picks up it and adjusts its posture in-hand, it will save a huge amount of time. As a consequence, it is essential to design a jaw like gripper combining the advantages of both conventional industrial gripper and dexterous robotic hands, which can not only be used for general picking and placing usage, but also for in-hand transition. It also needs to be able to work under very extreme working conditions, including high velocity and acceleration, little time consumption but high accuracy requirements, and so on.

The main contribution of this research is that we develop a novel jaw gripper with human-sized anthropomorphic features especially suitable for precise in-hand posture transitions, such as twisting and re-positioning (TP). The advantages of this grippers, compared with traditional robotic gripper, is that it can apply a constant gripping force on cylinder shaped assembly parts with various surface material (Table I) and can perform positioning and twisting with relatively high speed. Therefore, it can guarantee a trade-off between the effectiveness of parallel manipulator and dexterity of human-sized anthropomorphic robotic hands. It makes the robot applicable for more advanced assembly tasks while maintaining the reliability with industrial manufacturing requirements.

Fig. 2. A category of assembly parts that are generously cylinder shaped. A brief introduction to the common feature extraction of these objects is presented in Table I.

TABLE I
ASSEMBLY PARTS CATEGORY

Category	External Appearance	Surface Material	Feature
a	Straight	Plastic	Rigid
b	Irregular	Rubber	Deformable
c	Straight	Plastic	Rigid
d	Bending	Rubber	Deformable
e	Straight	Metal	Rigid

This paper is organized as follows. In Section II, after a brief introduction of the design requirements and assumptions, mechanical design of TP gripper is discussed. In Section III, the mechanical behavior study is carried out. Also an initial task analysis is presented. In Section IV, we carry out the simulation according to the mechanical analysis, and test the gripper under practical industrial environment. Conclusions and future works are presented in Section V.

II. Mechanical Design

A. Problems, Requirements and Assumptions

Small production has to keep step with the growing social demanding for High-Mix, Low-Volume manufacturing, it has to adopt various robotic manipulators with different end-effectors to carry out different assembly tasks. A typical small production shown in Fig. 1 can be divided into three parts: 1) Feeding system. It is usually constructed by conveyors. 2) Robotic manipulators. The key point for this part is to design various functional end-effectors, or grippers. 3) The assembly zone. The basic assembly action is: picking, fixing, placing, mating, and so on.

The basic assumption in this research is that the general shape of the assembly parts is cylinder, and with different surface materials. Usually when this kind of assembly parts lie on the conveyor, there could be several possible postures (Fig. 2-(e)). However, due to the design of the assembly system (Fig. 1), only limited number of postures are fitting for correctly assembly. If the posture is already fit enough, what leaves for the gripper is just to grasp it and perform the predesigned assembly action. If the posture is not fit, there remains some possible solutions: 1) change the posture of the assembly parts before they are grasped by the manipulator, or 2) adjust the posture of the assembly parts after they are grasped. There are a lot of related researches about how to estimate the postures of the assembly parts related

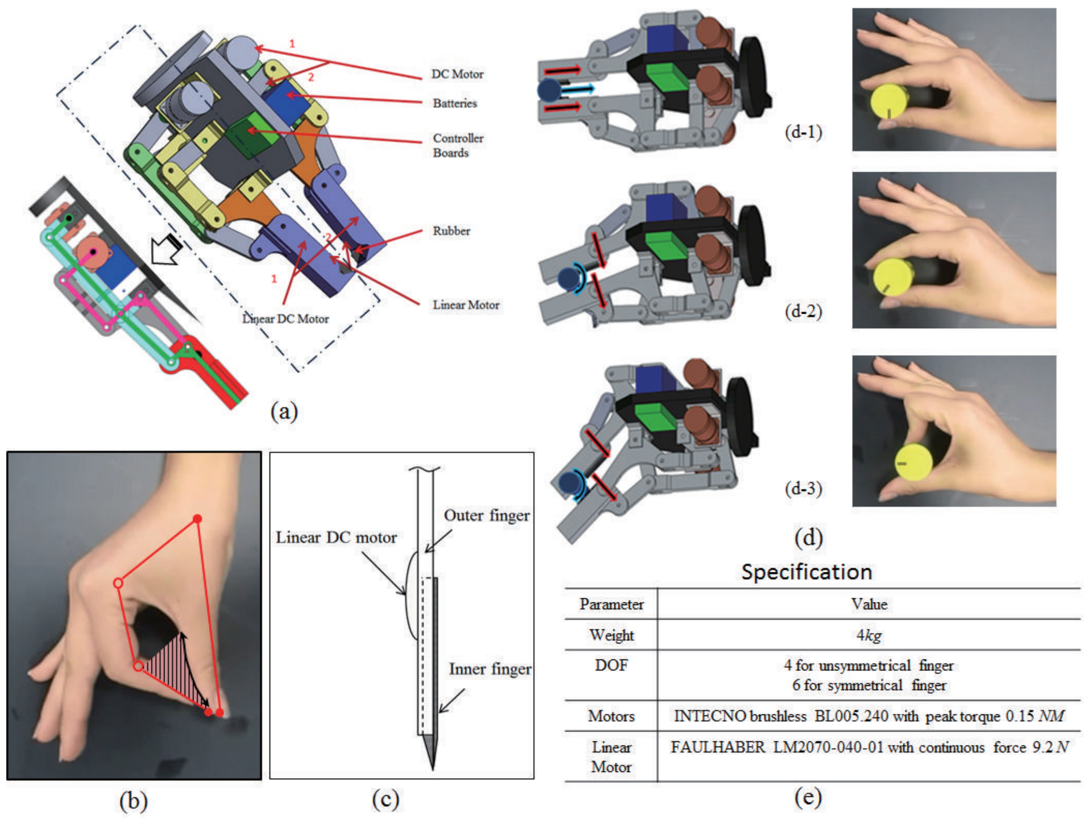


Fig. 3. A typical architecture of TP gripper. (a) Concept design of TP gripper. (b) Twisting action inspired by human. (c) Fingertip design for TP gripper. (d) Dexterity of TP gripper. (e) Specification of TP gripper.

TABLE II
FUNCTION OF DIFFERENT PARTS WITHIN TP GRIPPER SHOWN IN FIG. 3

Motor	Function
DC Motor 1	Control the stable contact on assembly parts between two inner grippers
DC Motor 2	Control the distance between two outer fingers
Linear DC Motor	Control the twisting movement in vertical direction using the inner fingers

with the first solution by using some specific sensor systems and estimation algorithms, and then robotic manipulator grasp them from appropriate direction. There are also special machines designed to support adjusting the posture of the assembly parts with external force, like using vibration. Due to some technical difficulties, seldom of these researches have ever considered adjusting the posture of the gripper online using the second solution. The second solution is very adaptive and reliable, and it can cope with more situations than the first solution.

Inspired by human being's hands (Fig. 3-(b)), it is better the traditional parallel jaw like gripper which can do the twist action by sliding one fingertip on the surface of another finger. A twisting action refers to the action grasp of an object in a human hand, which adjust its posture by twisting the fingers. It is easier to do so if a complete human-sized anthropomorphic robotic hand is built. It is difficult to apply this technology on hand shape like robotic hands, but it is relatively easier to make a jaw shape like robotic gripper to do so but only if it is equipped with additional movement freedom. Therefore, It is important to design a robotic gripper not only reserve the simplicity of jaw like gripper but also keep some feature like dexterous manipulation. One key issue in designing such a gripper is how to guarantee a constant and reliable twisting movement by the two fingers without dropping the gripped assembly parts.

B. TP Gripper Mechanical Design

In this paper, we design a robotic gripper for positioning and twisting to meet some industrial assembly requirements. The architecture of this TP gripper is shown in Fig. 3. A typical TP gripper (just half shown in Fig. 3-(a)) is driven by four motors (two DC motors and two linear DC motors). The functions of these motors are shown in Table II. Compare with the conventional gripper, this 4-DOF TP gripper can not only do open and close for positioning, but also do twisting for effective assemble cylindrical parts (Fig. 3-(d))).

A TP gripper also includes inner fingers and outer fingers (Fig. 3-(c))). With the help of DC motor 2, this TP gripper is suitable for almost every diameter of the cylindrical shaped electronic assembly parts by adjusting the distance between

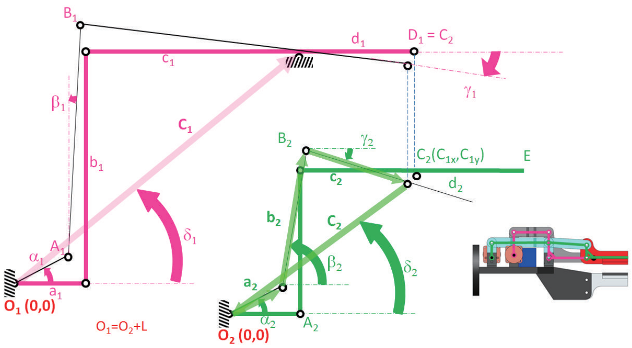


Fig. 4. Kinematic schema of a 4-DOF TP gripper. The first four bar link (pink solid line) deals with vertical movement of the point D_1. The rotation of the fingertip (point E) is given by the second four-bar-link (green solid line). The center of the motor can be considered coincident. The arrows (semi-transparent) represent the vectors for position analysis. In letter in caps are the joints, in bold the vectors and in Greek the angles.

its outer fingers. The inner fingers, driven by the linear motors, can slide on the track inside the outer fingers. DC motor 1 can adjust the contact point upon the object and guarantee a constant gripping force applied on the assembly parts. It provides sufficient friction force with which the cylinder assembly parts can be twisted by two inner gripper fingers. Both of the linear motors drive the inner finger movement with independent velocity. In this case, the rotation angle can be precisely controlled by both inner and outer fingers.

III. Kinematics Analysis

In order to control the position of the object precisely, it is necessary to know the precise fingertip position. As shown in Fig. 4, the finger structure is the composition of two four-bar-linkages. The analytical solution is to find out the point position D_1 (also same with C_2) and E.

A. Determine D_1

To determine D_1 position, it is necessary to compute γ_1. This parameter can be calculated by applying vector analysis to the first four-bar-linkage, as shown in semi-transparent light green in Fig. 4. So, we have

$$\vec{a_1} + \vec{b_1} + \vec{c_1} + \vec{C_1} = 0 \tag{1}$$

It is expanded into

$$\begin{aligned} &a_1 \cos\alpha_1 + b_1 \cos\beta_1 + c_1 \cos(-\gamma_1) + C_1 \cos(-\delta_1) = 0 \\ &a_1 \sin\alpha_1 + b_1 \sin\beta_1 + c_1 \sin(-\gamma_1) + C_1 \sin(-\delta_1) = 0 \end{aligned} \tag{2}$$

From equation. 2, we can get,

$$\begin{aligned} b_1^2 = {} & a_1^2\cos^2\alpha_1 + c_1^2\cos^2\gamma_1 + C_1^2\cos^2\delta_1 \\ & + 2a_1c_1\cos\alpha_1\cos\gamma_1 - 2a_1C_1\cos\alpha_1\cos\delta_1 \\ & - 2c_1C_1\cos\gamma_1\cos\delta_1 + a_1^2\sin^2\alpha_1 + c_1^2\sin^2\gamma_1 \\ & + C_1^2\sin^2\delta_1 - 2a_1c_1\sin\alpha_1\sin\gamma_1 - 2a_1C_1\sin\alpha_1\sin\delta_1 \\ & + 2c_1C_1\sin\gamma_1\sin\delta_1 \end{aligned} \tag{3}$$

because we have the following relationship,

$$P_1\sin\gamma_1 + P_2\cos\gamma_1 = P_3 \tag{4}$$

P_1, P_2, P_3 are calculated by,

$$\begin{aligned} P_1 &= 2c_1(a_1\sin\alpha_1 - C_1\sin\delta_1) \\ P_2 &= 2c_1(a_1\cos\alpha_1 - C_1\cos\delta_1) \\ P_3 &= b_1^2 - a_1^2 - c_1^2 - C_1^2 + 2a_1C_1\cos\alpha_1\cos\delta_1 \\ &\quad + 2a_1C_1\sin\alpha_1\sin\delta_1 \end{aligned} \tag{5}$$

then γ_1 is determined by

$$\gamma_1 = \pm\sin^{-1}\left(\frac{P_1P_3 \pm P_2^2\sqrt{P_1^2 + P_2^2 - P_3^2}}{P_1^2 + P_2^2}\right) \tag{6}$$

Finally, we can calculate D_1 position by

$$\begin{aligned} D_{1x} &= C_1\cos\delta_1 + d_1\cos\gamma_1 \\ D_{1y} &= C_1\sin\delta_1 + d_1\sin\gamma_1 \end{aligned} \tag{7}$$

B. Determine E

The point E can be determined by studying the second four-bar-link like above one. Following the same law, we have,

$$\vec{a_2} + \vec{b_2} + \vec{c_2} + \vec{C_2} = 0 \tag{8}$$

It is expanded into

$$\begin{aligned} &a_2\cos(-\alpha_2) + b_2\cos\beta_2 + c_2\cos\gamma_2 + C_2\cos(-\delta_2) = 0 \\ &a_2\sin(-\alpha_2) + b_2\sin\beta_2 + c_2\sin\gamma_2 + C_2\sin(-\delta_1) = 0 \end{aligned} \tag{9}$$

From Equation. 9, we can get,

$$\begin{aligned} b_2^2 = {} & a_2^2\cos^2\alpha_2 + c_2^2\cos^2\gamma_2 + C_2^2\cos^2\delta_2 \\ & + 2a_2c_2\cos\alpha_2\cos\gamma_2 - 2a_2C_2\cos\alpha_2\cos\delta_2 \\ & - 2c_2C_2\cos\gamma_2\cos\delta_2 + a_2^2\sin^2\alpha_2 + c_2^2\sin^2\gamma_2 \\ & + C_2^2\sin^2\delta_2 - 2a_2c_2\sin\alpha_2\sin\gamma_2 + 2a_2C_2\sin\alpha_2\sin\delta_2 \\ & - 2c_2C_2\sin\gamma_2\sin\delta_2 \end{aligned} \tag{10}$$

Q_1, Q_2, Q_3 are calculated by,

$$\begin{aligned} Q_1 &= 2c_2(a_2\sin\alpha_2 - C_2\sin\delta_2) \\ Q_2 &= 2c_2(a_2\cos\alpha_2 - C_2\cos\delta_2) \\ Q_3 &= a_2^2 - b_2^2 + c_2^2 + C_2^2 - 2a_2C_2\cos\alpha_2\cos\delta_2 \\ &\quad + 2a_2C_2\sin\alpha_2\sin\delta_2 \end{aligned} \tag{11}$$

then γ_2 is determined by

$$\gamma_2 = \pm\sin^{-1}\left(\frac{Q_1Q_3 \pm Q_2^2\sqrt{Q_1^2 + Q_2^2 - Q_3^2}}{Q_1^2 + Q_2^2}\right) \tag{12}$$

Finally, we can calculate E position by import Equation. 7, and get

$$\begin{aligned} E_{1x} &= C_1\cos\delta_1 + d_1\cos\gamma_1 + d_2\cos\gamma_2 \\ E_{1y} &= C_1\sin\delta_1 + d_1\sin\gamma_1 + d_2\sin\gamma_2 s \end{aligned} \tag{13}$$

Consider that $c_1 \gg d_1$, it follows that $\alpha_1 \gg \gamma_1$. The rotation range of the motor α_1 is $[-\frac{\pi}{2}, \frac{\pi}{2}]$. The range of γ_1 could be

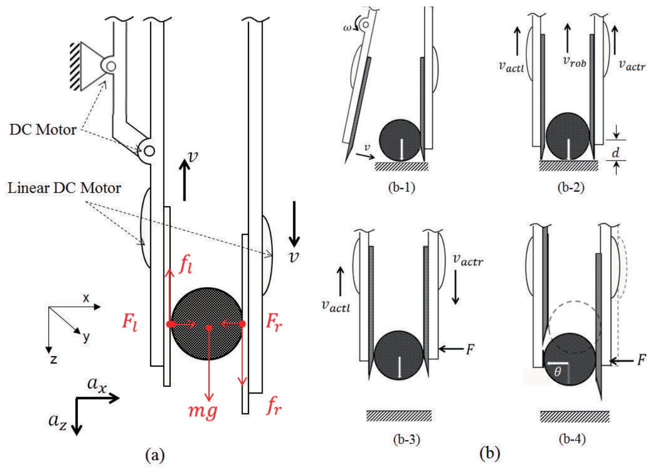


Fig. 5. Dynamic of twisting movement using TP gripper with 4-DOF configuration. (a) Dynamic analysis of twisting phase. (b) Four phases of a typical grasping manipulation, including approaching, grasping, picking up, and twisting with an angle θ.

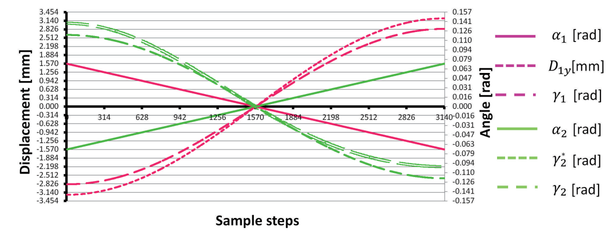


Fig. 6. Relationship of parameters

within $[-\frac{\pi}{16}, \frac{\pi}{16}]$, which is a very small angle. So $d_1 \cos\gamma_1 \cong d_1$. Based on this analysis, Equation 6 is derived into

$$\gamma_1 \cong \sin^{-1}\left(\frac{a_1}{c_1}\sin\alpha_1\right) \tag{14}$$

and Equation 12 is derived into

$$\gamma_2 \cong \sin^{-1}\left(\frac{a_2 - D_{1y}}{c_2}\sin\alpha_2\right) \tag{15}$$

so finally Equation 13 is reduced into

$$\begin{aligned} E_{1x} &= C_1 + d_1 + d_2 \\ E_{1y} &= C_1 \sin\delta_1 + d_1\left(\frac{a_1}{c_1}\sin\alpha_1\right) + d_2\left(\frac{a_2 - D_{1y}}{c_2}\sin\alpha_2\right) \end{aligned} \tag{16}$$

C. Task Analysis

It is assumed that the robot can always grasp the object at or close to the centre of gravity, so we do not have to consider the misalignment of the object along y-axis. A typical grasp with in-hand transition process is divided into four phase (Fig. 5-(b)): (1) approaching, (2) grasping, (3) picking up, and (4) twisting with an angle $theta$ or repositioning with a desired distance. During the second phase $(b-2)$, how in deep (d) the gripper can grasp the object will determine how the gripper will do the twisting. If d is very large, most of the twisting case will take place upon the inner fingers. If d is very small, which means the TP gripper only grasps the object close to the end of the fingertip $(b-3)$. In this case, if a large rotational angle θ is required, the TP gripper has to twist the objects upon the outer finger $(b-4)$.

D. Twisting Dynamic

For simplicity, it is also assumed that the cross section of the gripped object is a perfect circle with a radius of R. So during the twisting phase, the dynamic analysis is shown in Fig. 5-(a). According to Newton law, we have

$$F_r - F_l = ma_x \tag{17}$$

During the assembly process, the object has to suffer from high acceleration via the horizonal direction. It also equals to the robotic end-effector movement acceleration. Because there is no sliding movement for the object when it is twisted by the gripper to roll a short distance, the friction forces upon both contact surfaces are all static friction forces.

$$\begin{aligned} f_l &= F_l\mu \\ f_r &= F_r\mu \end{aligned} \tag{18}$$

where μ is the friction coefficient, F_l and F_r are the gripping forces upon on both contact surfaces respectively. According to Newton-Euler law, we have

$$\begin{aligned} -ma_z &= f_l - f_r - mg \\ a_z &= RI\dot{\omega} = R(M_t + M_l) = R(f_rR + f_lR) \end{aligned} \tag{19}$$

where M is the rolling moment driven by friction force

IV. Experiments

A. Kinematics simulation

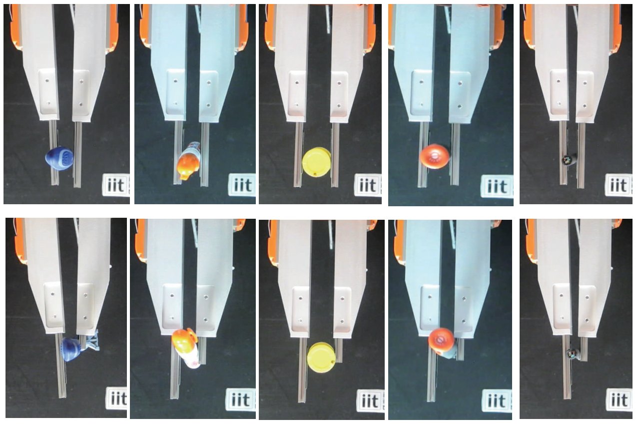
From Equation 16, we can control object position precisely by controlling rotation angels α_1 and α_2. The twisting movement is controlled by adjusting the value of parameters d_1 and d_2 by controlling the velocity of both linear motors. Fig. 6 shows the relationship of these parameters.

B. Gripper test for twisting and repositioning

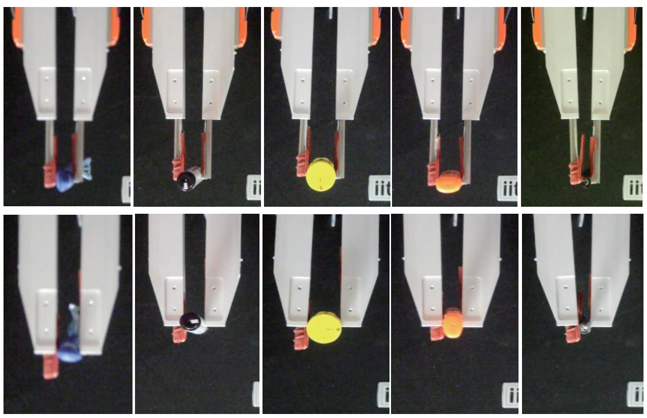
The generic application on different objects are carried out in Fig. 7. The twisting on inner fingers and outer fingers as described in Section III-C is also studied. One may notice that there is an alignment displacement on the two fingers after twisting, which may prevent the gripper from moving down towards the assembly area. The solutions are mainly two, 1) drop the assembly parts to the assembly slots when the gripper is getting close enough, or 2) adjust the posture of the robot gripper, and make one part of the assembly part touch the slot. The assembly part will slide into the slot due to its compliance structure when it is released.

C. Gripper test for high speed assembly

We also test the gripper performance within high acceleration and high speed movement by attaching it to an industrial robotic manipulator. Fig. 8 shows the basic three phases within a complete twisting movement. According to the experimental results (table III), it costs less than $0.6s$ to accomplish twisting by rotating within 180 degrees. The



(a)



(b)

Fig. 7. A test of TP Gripper for twisting on (a) inner fingers when d is large, and (b) outer fingers when d is small.

(a) (b) (c)

Fig. 8. A test of TP Gripper with three phases including (a) grasping, (b) picking up, and (c) twisting.

results show that this TP gripper can accomplish the twisting during high-speed and high-acceleration assembly.

V. Conclusion and Future Works

In this paper, a novel jaw like gripper for precise twisting and positioning is designed, analyzed, and demonstrated. It is significant to introduce this TP gripper for flexible assembly to small sized manufacturing. This mechanical design can guarantee both simplicity and dexterity, the effectiveness of which is proved by the experimental data.

Future work will focus on in deep analysis of some specific assembly case and improvement of the mechanical design.

TABLE III

Time cost for different stages within twisting (Fig. 8)

Rotational angle θ $[rad]$	(a)-(b) $[s]$	(b)-(c) $[s]$	Total time cost $[s]$	Rolling distance $[mm]$
$\pi/2$	0.12	0.22	0.34	24
π	0.13	0.40	0.53	48

At the same time, control algorithm for adaptive and reliable twisting is also should be designed.

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References

[1] G. Michalos, S. Makris, N. Papakostas, D. Mourtzis, and G. Chryssolouris, "Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach," *CIRP Journal of Manufacturing Science and Technology*, vol. 2, no. 2, pp. 81–91, 2010.

[2] F. Chen, K. Sekiyama, J. Huang, B. Sun, H. Sasaki, and T. Fukuda, "An assembly strategy scheduling method for human and robot coordinated cell manufacturing," *International Journal of Intelligent Computing and Cybernetics*, vol. 4, no. 4, pp. 487–510, 2011.

[3] F. Chen, K. Sekiyama, P. Di, J. Huang, and T. Fukuda, "i-hand: An intelligent robotic hand for fast and accurate assembly in electronic manufacturing," in *Robotics and Automation (ICRA), 2012 IEEE International Conference on*. IEEE, 2012, pp. 1976–1981.

[4] Autorecon, "Autorecon co-operative machines for highly reconfigurable assembly operations of the future," Available: http://www.autorecon.eu/, 2011-2014.

[5] M. Wagner, J. Morehouse, and S. Melkote, "Prediction of part orientation error tolerance of a robotic gripper," *Robotics and Computer-Integrated Manufacturing*, vol. 25, no. 2, pp. 449–459, 2009.

[6] S. Ragunathan and L. Karunamoorthy, "Modular reconfigurable robotic gripper for limp material handling in garment industries," *International Journal of Robotics and Automation 2008*, vol. 23, no. 6, pp. 213–219, 2008.

[7] Y. Yokokohji, J. San Martin, and M. Fujiwara, "Dynamic manipulability of multifingered grasping," *IEEE Transactions on Robotics*, vol. 25, no. 4, pp. 947–954, 2009.

[8] G. Gogu, *Structural synthesis of parallel robots: Methodology. Part 1*. Springer, 2008.

[9] I. Bonev, "Delta parallel robot-the story of success," *Newsletter*, 2001.

[10] E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. Zakin, H. Lipson, and H. Jaeger, "Universal robotic gripper based on the jamming of granular material," *Proceedings of the National Academy of Sciences*, vol. 107, no. 44, pp. 18 809–18 814, 2010.

[11] J. Butterfaß, M. Grebenstein, H. Liu, and G. Hirzinger, "Dlr-hand ii: Next generation of a dextrous robot hand," in *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, vol. 1. IEEE, 2001, pp. 109–114.

[12] W. Townsend, "The barrett hand grasper–programmably flexible part handling and assembly," *Industrial Robot: an international journal*, vol. 27, no. 3, pp. 181–188, 2000.

[13] L. U. Odhner and A. M. Dollar, "Dexterous manipulation with underactuated elastic hands," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*. IEEE, 2011, pp. 5254–5260.

[14] J. Huang, P. Di, T. Fukuda, and T. Matsuno, "Robust model-based online fault detection for mating process of electric connectors in robotic wiring harness assembly systems," *IEEE Transactions on Control Systems Technology*, vol. 18, no. 5, pp. 1207–1215, 2010.