Development of a Versatile Robotic Hand Toward Jig-Less Assembly of a Shaft-Shaped Part

Kohei Shibata and Hiroki Dobashi, *Member, IEEE*

***Abstract*—Jig-less assembly of a shaft-shaped part with a single versatile robotic hand requires several functions of the hand to achieve a series of operations such as alignment, picking, reorientation, and positioning of the part. In this research, we propose a novel robotic hand with these functions and corresponding finger mechanisms. Moreover, we propose a manipulation strategy for grasping shaft-shaped parts with the proposed hand, and experimentally verify the feasibility of desired operations with the proposed method as well as the versatility of the hand for several different parts.**

***Index Terms*—Multifingered hands, grasping, mechanism design.**

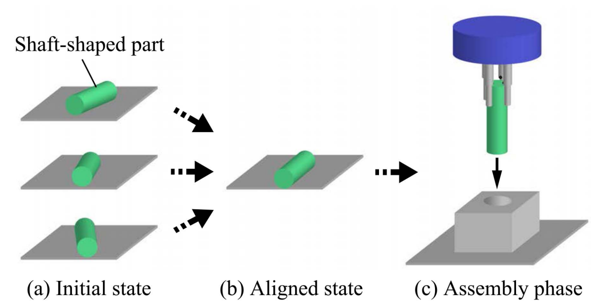

Fig. 1. Common sequence of handling a shaft-shaped part from the initial state toward the assembly phase.

I. Introduction

In the manufacturing industry, variable-mix, variable-volume production has become mainstream due to the diversification of customer needs, and robotic cells are being introduced to automate the manufacturing process [1].The current robotic cells require a number of special jigs and grippers each of which is customized for each target part to achieve high-precision assembly of parts in various shapes. However, this approach requires the development and exchange of these for each part to be handled, which is undesirable in terms of cost. Therefore, the development of a versatile robotic hand (i.e., a hand that can handle various part shapes) that can perform jig-less assembly of products consisting of various parts is required.

In assembly tasks, a shaft-shaped part is one of the most frequently handled parts. Shaft-shaped parts are generally supplied lying on the workbench as shown in Fig. 1(a), and their initial poses (positions and orientations) are uncertain in jig-less assembly tasks. Therefore, it is necessary to absorb the uncertainty in the initial pose of the parts before grasping and to make them aligned as shown in Fig. 1(b). In addition, when assembling the parts, it is necessary to grasp them in poses that align the longitudinal direction of the parts with the assembly direction, as shown in Fig. 1(c), which requires an appropriate reorientation from the initial supplied poses. It is often realized by using multiple robotic arms and hands to regrasp the target parts [2], but this method heightens the cost of installing them. The method of reorientation of shaft-shaped parts using a gripper with a shape and a mechanism specialized for them is also often used. However, such a special shape and mechanism causes the gripper to be less versatile and makes it difficult to apply to parts in various shapes. Moreover, as with reorientation, it is desirable that positioning of the parts can be done without using any jigs in order to reduce costs. For realizing this, it is necessary to be able to position the parts by hand only, regardless of their initial supplied poses. In our previous work [3], we proposed a grasping strategy for jig-less assembly of shaft-shaped parts using a parallel stick fingered hand with protrusions at the fingertips and developed the hand to realize it. However, this hand is large for the handled parts and cannot grasp small parts due to the large minimum finger opening width.

Based on the above background, we aim to develop a versatile robotic hand with parallel stick fingers that can perform the series of operations, i.e., alignment, picking, reorientation, and positioning of shaft-shaped parts with the single hand toward the realization of their jig-less assembly.

The organization of this paper is as follows. In Section II, related works are overviewed. In Section III, the problem setting is given. In Sections IV and V, the mechanisms of our proposed hand and its finger are described, respectively. In Section VI, the manipulation strategy for shaft-shaped parts using the hand is presented. Experimental verification of the proposed method is conducted in Section VII, and finally the conclusion is given in Section VIII.

II. Related Works

A typical example of a versatile robotic hand is a human-like one designed to imitate a human hand. Shadow Robot [4] developed a highly dexterous humanoid hand with 24 joints and 20 degrees of freedom (DOFs). Gao et al. [5] developed a five-finger anthropomorphic hand and achieved dexterous manipulation and robust grasping of multiple types of objects. Although these hands are versatile and dexterous, their high installing costs,

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Kohei Shibata is with the Graduate School of Systems Engineering, Wakayama University, Wakayama 640-8510, Japan (e-mail: s236128@wakayama-u.ac.jp).

Hiroki Dobashi is with the Faculty of Systems Engineering, Wakayama University, Wakayama 640-8510, Japan (e-mail: dobashi@wakayama-u.ac.jp).

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redundant DOFs, and control complexity make them unsuitable for industrial applications that require only minimal DOFs.

On the other hand, versatile robotic hands with low DOFs and simple structures also exist. The representative one is a hand with parallel stick fingers (i.e., relatively thin cylindrical fingers). GLORY [6] developed a hand with three parallel stick fingers that can be commonly used in the process of handling various parts, and it is actually used in the manufacturing site. OnRobot [7] developed the same type of hand, especially for grasping cylindrical parts in various sizes. Tennomi et al. [8] developed a high-speed, three parallel stick fingered hand with a quick-return mechanism. Introducing the load-sensitive continuously variable transmission (LS-CVT) [9] into the hand in [8], Nishimura et al. [10] developed a three parallel stick fingered hand realizing grasping of a wide range of parts with a high speed and a high grasping force. Balan and Bone [11] proposed an algorithm to automatically design a versatile gripper with three parallel stick fingers suitable for grasping given three-dimensional parts. Bone and Capson [12] developed two programmable grippers with three parallel stick fingers and achieved vision-guided jig-less assembly of automotive body parts with these grippers. Li et al. [13] developed a gripper with four parallel stick fingers for stable grasps of target objects in planar form-closure [14], and Rui et al. [15] improved the design of the gripper with an additional DOF for dealing with wider range of objects. However, reorientation of target parts is addressed in none of the above works. Dobashi et al. [16] studied a robust grasping strategy to align a three-dimensional part on a workbench surface against its initial pose uncertainty with a versatile hand with four parallel stick fingers, and showed its usefulness in a jig-less assembly task of a soma cube. For a more challenging task with this hand, Fukuda et al. [18] realized jig-less assembly of the gear unit, which is a target product to be assembled in the Manufacturing Track of IORS 2017 Robotic Grasping and Manipulation Competition (RGMC) [17]. In the assembly task, the hand performed reorientation of two shafts in a certain way as mentioned later. However, the hand is remarkably large (with a horizontal length of 477 mm) due to the usage of off-the-shelf ball screw units and may easily collide with the environment.

The hand to be proposed in this research is required to have a function to reorient shaft-shaped parts. For reorienting a part with a robotic hand, pivoting of the gripped part by fingertip manipulation is often adopted, and various grippers have been developed to realize this. Carlisle et al. [19] developed a gripper with bearings at the fingertips that allow rotation around the pivot axis when pivoting a part. Taylor et al. [20] and Chavan-Dafle et al. [21] developed grippers that can use different gripping forms such as pivoting and firm grasping by using pneumatic mechanisms at the fingertips, and the grippers realized reorientation of shaft-shaped parts. Hou et al. [22] developed a gripper with a fingertip mechanism that can switch between pivoting and firm grasping. Zhao et al. [23] developed specially designed fingertips for a two-fingered gripper that can actively control the orientation of the grasped object, and demonstrated the reorientation of a screw. Endo et al. [24] developed a hand that reorients a disk-shaped object by rotating the fingertip of stick fingers from vertical to horizontal. All of these grippers effectively use fingertips to reorient target parts with a single hand and a few steps. On the other hand, there are some issues such as low versatility due to the specialized mechanism and difficulty in both vertical and horizontal positioning.

As another approach, a method of reorientation of parts by multiple pick-and-place operations with a robotic hand has been studied. Wan and Harada [25] and Fukuda et al. [18] adopted reorientation strategies of parts by multiple pick-and-place operations using workbench/table surfaces and hands. In particular, Fukuda et al. applied this method to each shaft of the gear unit, which was supplied lying on the workbench, to reorient it via temporary placement toward the assembly phase in [18]. However, this method assumes that the target parts can be freestanding on the workbench/table surfaces in desired orientations and cannot handle parts with shapes that do not satisfy this assumption. By contrast, Cao et al. [26] introduced a vertical pin on the workbench and extended the reorientation capability of a pick-and-place regrasp, using the pin as the intermediate location for regrasping target parts. While this approach eliminates the need for parts to stand by themselves at the temporary placement, the additional equipment, the pin, other than a hand is necessary.

Moreover, Savarimuthu et al. [27] showed a manipulation strategy to reorient a lying object by grasping it from an angle and rotating the hand, instead of grasping it directly from above. However, this method requires advanced sensing for assembly because parts cannot be positioned sufficiently, which is concerned about an increasing cost.

The hand proposed in this paper differs from the above conventional hands or grippers in that it has a novel finger mechanism presented later in Section V and can realize desired accurate grasps of shaft-shaped parts toward their jig-less assembly with the single hand without losing the versatility of the hand with parallel stick fingers.

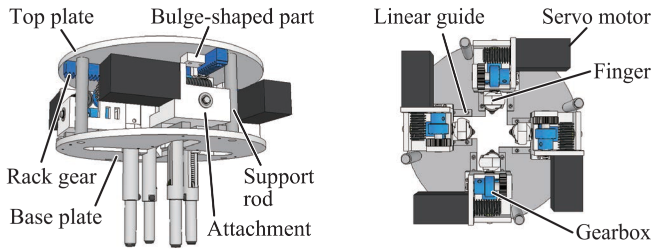
III. Problem Setting

A. Objective Operation

The hand proposed in this research aims to grasp a lying shaft-shaped part in a positioned state with the single hand as shown in Fig. 1 and to carry out an assembly task without using any jigs. In general, positioning means constraining all the translational and rotational degrees of freedom in a given pose. However, in principle, the rotation of targeted shaft-shaped parts around their longitudinal axes cannot be constrained. So, here we consider ‘positioning’ as constraining the translational and the other rotational degrees of freedom of a target part.

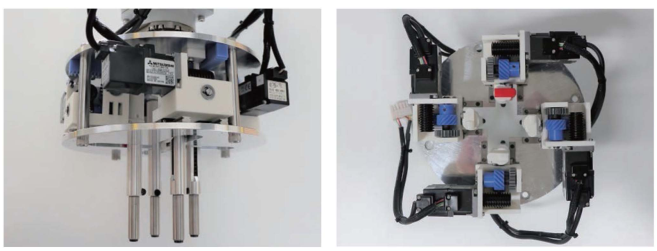
B. Assumption

As in general assembly tasks of the manufacturing industry, we assume that the properties of target shaft-shaped parts such as shapes, dimensions, masses, and centers of gravity are known. This is reasonable because CAD models with these properties of most industrial parts are available. Also, we assume that the parts are supplied lying on a horizontal workbench surface as shown in Fig. 1(a). Note that there is some uncertainty in the initial pose of the parts. We suppose that external sensors such as visual sensors are used only to detect approximate initial poses of the parts, and all subsequent operations are performed without using the external sensors. This eliminates the need for external sensors with high specifications and could restrain the cost of the whole robotic assembly system. In addition, the proposed hand is attached to a conventional industrial robotic arm.



(a) Overall view (b) Top view

Fig. 2. CAD model of the designed robotic hand.



(a) Overall view (b) Top view

Fig. 3. Overview of the fabricated robotic hand.

IV. Proposed Robotic Hand Mechanism

A. Outline of the Proposed Hand

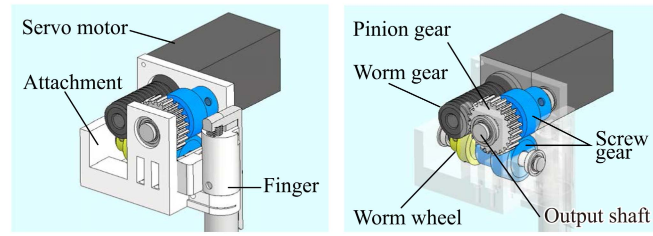
The CAD model of the proposed robotic hand is shown in Fig. 2. As can be seen in Fig. 2(a), the hand has a structure in which the opening and closing mechanism of the fingers is sandwiched between two metal plates (the top and base plates) and has four parallel stick fingers protruding from the base plate. Note that the top plate is omitted in Fig. 2(b) for visibility.

Each of the four fingers is equipped with a servo motor, allowing all the fingers to move independently in cross-shaped trajectories. This and the symmetry of each finger make it possible to align and grasp parts in various shapes accurately by moving the fingers toward form-closure configurations in the horizontal plane, according to the part shapes. It is the same approach as the one adopted in [16].

B. Main Body of the Hand

The overview of the fabricated hand is shown in Fig. 3. Note that the top plate is removed in the top view of the hand shown in Fig. 3(b). The hand body mainly consists of the top and base plates mentioned in the previous section and the four equally spaced support rods that connect these plates. The base plate, to which the opening and closing mechanism of the fingers is attached, has a cross-shaped hole along the finger trajectories.

Our previous hand [3] has a horizontal length of 510 mm, a height including fingers of 178 mm, a mass of 3.54 kg, and a range of the diameter of a graspable part of 50–80 mm. In contrast, as for the hand proposed in this research, the horizontal length of the hand in the fully opened/closed states are 288 mm and 210 mm, respectively, the height including the fingers is 162 mm, the mass is 2.32 kg, and the range of the diameter of a graspable part is 15–100 mm. Compared to our previous hand, the horizontal length is less than half, and smaller parts can be grasped. Moreover, the proposed hand is even smaller than the hand used in [18] and thus less likely to collide with the environment.



(a) Overall view (b) Driving mechanism

Fig. 4. Finger unit.

C. Opening and Closing Mechanism of the Fingers

The hand has four finger units shown in Fig. 4(a), each of which integrates the finger, attachment, gearbox, and servo motor (Mitsubishi Electric, HC-AQ135D). The finger unit integrates each component via a plastic attachment made with a 3D printer (Raise3D, R-E2), and is attached to two miniature linear guides on the base plate. A rack-and-pinion mechanism is adopted as the driving system to move each finger unit linearly on the linear guides. Note that the two opposing fingers travel in the same straight line.

The gearbox consists of a worm gear, a worm wheel, screw gears, and a pinion gear as shown in Fig. 4(b). The reduction ratio between the motor and the output shaft is 1:20. Rack gears are fixed to the back of the top plate of the hand as shown in Fig. 2(a), and the pinion gear attached to the output shaft travels on each of them by transmitting the motor torque to the pinion gear via the gearbox. This results in the opening/closing motion of the finger. The minimum and maximum opening widths of the fingers are 8.65 mm and 124 mm, respectively. The rated torque of the servo motors is 0.0318 Nm, and the rated rotation speed is 3000 r/min. The amount of finger translation is about 3.6 mm per rotation of the motor shaft, and the theoretical fingertip force is about 14 N. The theoretical maximum speed of the finger motion is about 250 mm/s.

V. Proposed Finger Mechanism

A. Finger Functions Toward Assembly of Shaft-Shaped Parts

As described in Section I, jig-less assembly of a shaft-shaped part supplied in a lying pose requires appropriate reorientation and positioning of the part only with the hand. In addition, the hand is required to perform a series of operations that include alignment and picking as well as these two operations.

To realize the above operations, the finger mechanism of the hand requires the following three major functions.

- (F1) The passive rotation of each finger around its longitudinal axis is allowed.
- (F2) Protrusions are provided to enable appropriate reorientation of a target part by pivoting operation.
- (F3) Functions (F1) and (F2) can be used separately.

Function (F1) induces the slippage between the target part and the fingers, which effectively absorbs the errors in the pose of the target part on the workbench surface in the same way as in [16]. This potentially enables to plan alignment strategies that are more robust to the initial pose error of the target part,

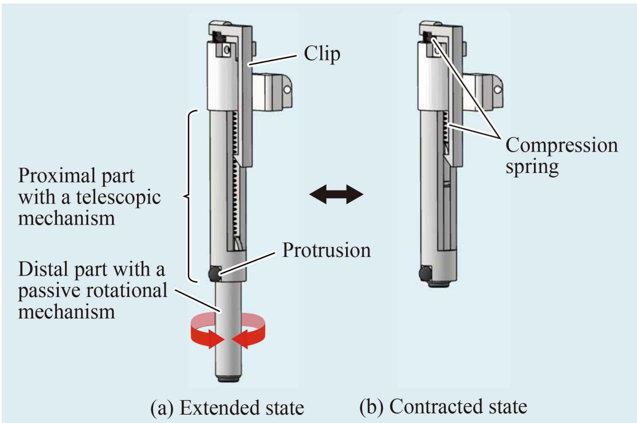


Fig. 5. Finger mechanism.

such as the two-step alignment strategy for the shaft-shaped part shown in [18]. Function (F2) enables to realize reorientation of the target part by utilizing the rotation caused by its own weight around the grasping points through lifting the lying target part with the protrusions of the two opposing fingers. Function (F3) is necessary because the protrusions are effective during reorientation but may interfere with the target part in alignment and positioning phases and limit the functions of the hand unless functions (F1) and (F2) can be used separately.

B. Finger Mechanism

The proposed finger mechanism is shown in Fig. 5. It is like the mechanism of a ballpoint pen with a clip. The finger is divided into four major parts: a distal part with a passive rotational mechanism, a protrusion, a proximal part with a telescopic mechanism, and a clip for a locking/unlocking mechanism. The mechanisms of the first and third parts provide the finger with a total of passive 2 DOFs.

The above three mechanisms and the protrusion are equipped to realize functions (F1) to (F3) required toward the assembly of shaft-shaped parts with no additional active actuators. In the following, the details of these are described.

1) Passive Rotational Mechanism: As a mechanism corresponding to (F1), the distal part of the finger has a passive rotational mechanism. It is equipped at the tip of the finger mechanism. It consists of a cylinder sandwiched between two bearings from above and below, and a shaft passing through the cylinder. The length of the cylinder is 37 mm, and the diameter is 10 mm. The material of the cylinder is stainless steel. The cylinder passively rotates along the shape of the target part when manipulating it, which enables efficient manipulation by eliminating the effect of friction between the fingers and the part. This mechanism is similar to the one used in [16] and [18]. We utilize it as well since its usefulness has been shown in the literature.

2) Protrusion: As an element corresponding to (F2), the proximal part of the finger has a protrusion at its tip. The protrusion is made of urethane rubber, which facilitates a stable pivoting operation without dropping a target part, and has a hemispherical shape with a diameter of 6 mm in order to grasp the target part in the state similar to point contact when pivoting. The pivoting operation using the protrusion can realize appropriate reorientation of the target part. Note that the proposed hand

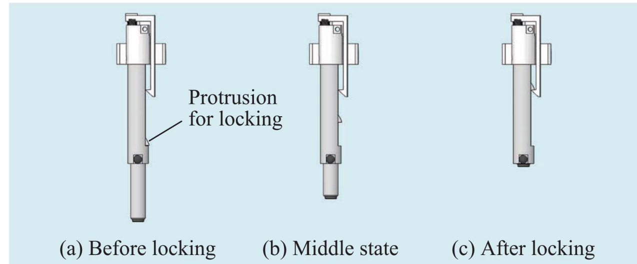


Fig. 6. Finger locking process.

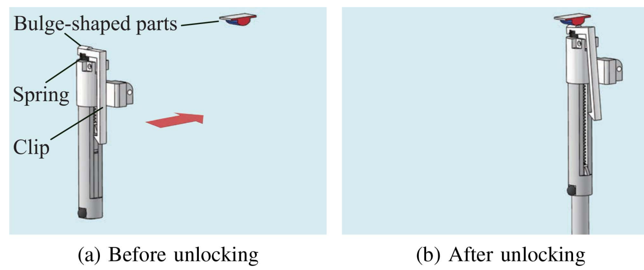


Fig. 7. Finger unlocking process.

has protrusions on all the four fingers because the manipulation strategy described later in Section VI requires transferring the target part from the two fingers used for pivoting to the other two free fingers.

3) Telescopic Mechanism: The proximal part of the finger has a telescopic mechanism as one of the most important features. It can eject or retract the distal part with the passive rotational mechanism from/into the proximal part. In addition, a compression spring (Misumi, WY8-70) with a spring constant of 0.1 N/mm is equipped inside the proximal part, and the entire distal part can be retracted by applying a force of about 4 N in the longitudinal direction. The distal part can be used for alignment and positioning when the finger is extended as shown in Fig. 5(a) whereas the protrusion is at the fingertip and is used for reorientation of the target part when the finger is contracted as shown in Fig. 5(b). In this way, (F3) is realized by using this extension and contraction of the finger.

Telescopic mechanisms have been introduced to a few robotic hands, specifically to the palm of a hand for assisting grasping [28], [29] or the fingers for grasping a wider range of objects in size and shape [30]. To our best knowledge, however, the introduction and use of a telescopic finger to switch finger functions is a new attempt that differentiates our proposed hand from the conventional ones.

4) Locking/Unlocking Mechanism: As a mechanism contributing to (F3), the finger has a locking/unlocking mechanism. A plastic clip made with the 3D printer mentioned in Section IV-C is installed at the top of the finger as shown in Fig. 5. The finger can be kept in a contracted state by shrinking it and hooking the protrusion attached on the top of the distal part to the clip as shown in Fig. 6. The process of unlocking is shown in Fig. 7. By moving the finger in the direction of the arrow illustrated in Fig. 7(a), the bulge-shaped parts on both the clip and the top plate interfere with each other and open the clip to unlock the finger as shown in Fig. 7(b). The bulge-shaped part on the top plate is fixed at a position such that the interference occurs when the finger is opened to the maximum.

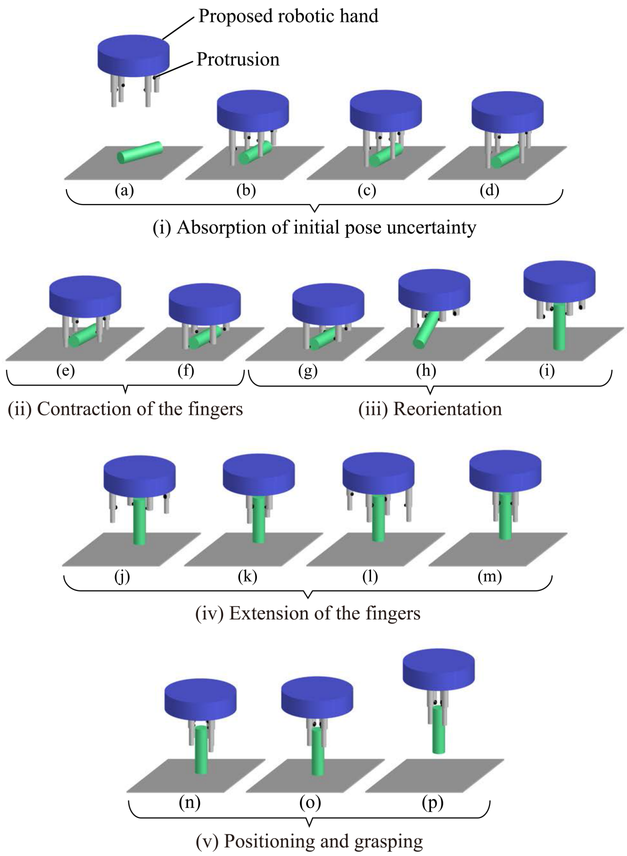


Fig. 8. Example of a manipulation strategy.

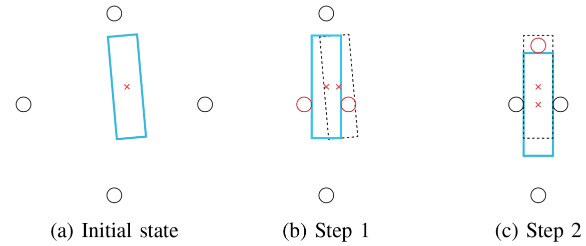


Fig. 9. Alignment strategy.

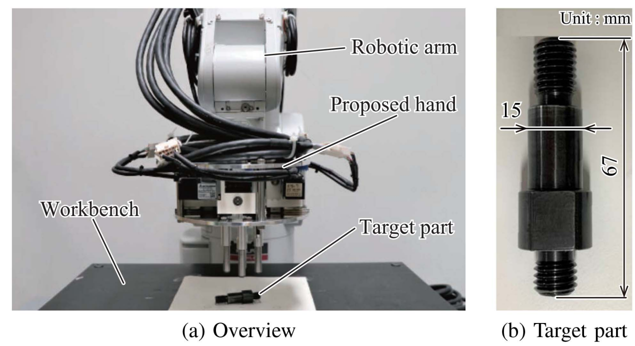


Fig. 10. Experimental setup.

This mechanism allows the finger to transition to the contracted state by pressing the finger against the workbench surface when the finger is in the extended state. Conversely, when the finger is in the contracted state, the unlocking mechanism can work by opening the finger to the maximum, and it can be extended by the restoring force of the compression spring in the proximal part. Thus, by combining the locking/unlocking mechanism with the telescopic mechanism, it is possible to transition between the extended and contracted states of the finger without using additional actuators.

VI. Manipulation Strategy for the Hand

An example of a manipulation strategy of the proposed hand for grasping a shaft-shaped part is shown in Fig. 8. The proposed strategy consists of five processes (i) to (v) shown in the figure. Note that it does not include an assembly strategy since we focus on the series of operations prior to the assembly phase in this paper. The assembly phase will be addressed in our ongoing research.

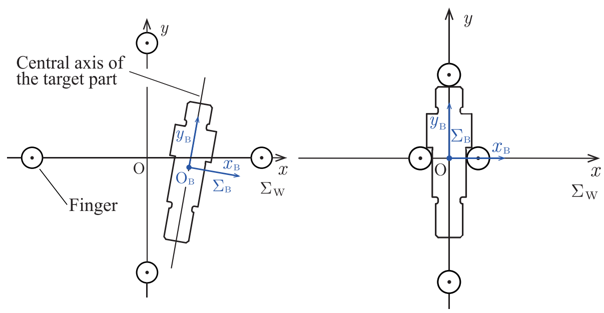
In the first process through (a) to (d) in the figure, the hand approaches the target part with the fingers extended, and absorbs the uncertainty of the initial part pose by alignment operation utilizing the passive rotational fingertips. The top view of the alignment process is shown in Fig. 9. First, a pair of opposing fingers are closed to absorb the error in the width direction of the part, and then the remaining fingers are closed to absorb the rest of the error. Because this two-step alignment method has been shown to be useful in [18], it is used in this research as well. Next, through (e) to (f), the hand presses the fingers down on the workbench surface in their longitudinal direction, and makes the fingers transition to the contracted state utilizing the telescopic mechanisms and the locking mechanisms. When this process is completed, the protrusions become available for the next process. Then, through (g) to (i), the hand reorients the part by pivoting operation utilizing the protrusions. After that, through (j) to (m), the hand unlocks each of the two pairs of opposing fingers in turn by opening the fingers to the maximum, and makes the fingers transition to the extended state again. Finally, through (n) to (p), the hand opens the fingers slightly enough to keep it caged (i.e., to prevent the part from falling down through the gap between the fingers), and regrasps the part with the distal passive rotational parts of the fingers. Note that we assume that the bottom of the part contacts the workbench surface when opening the fingers slightly, and thus there is no uncertainty in the vertical position of the part. As for the other directional positions and orientations (except for that around the longitudinal direction) of the part, possible uncertainty is absorbed through the regrasping process. This enables the positioning of the part, and thus the desired, accurate grasp for assembly can be achieved.

Note that unlike previous studies [18], [25], this manipulation strategy is applicable to even parts with sharp tips because it does not require the parts to stand by themselves on the workbench through the whole process in the strategy.

VII. Experimental Verification

A. Manipulation Experiment

The feasibility of the desired manipulation of a shaft-shaped part is experimentally verified with the fabricated robotic hand. As an experimental setup, the 6-DOF industrial robotic arm (Mitsubishi Electric, RV-7FL-D) with the proposed hand is used as shown in Fig. 10(a). Both the arm and the hand are position-controlled, and their predefined motions according to the manipulation strategy are pre-programmed. Note that, in a



(a) Initial state (b) Desired aligned state

Fig. 11. Initial and aligned state of the target part.

strict sense, each of the servo motors of the hand is controlled in the combination of an upper-level position control system with a PC and a lower-level velocity control system with a servo amplifier (Mitsubishi Electric, MR-J2-03A5) in the velocity control mode. The upper one determines the angular velocity command combining the feedforward of the desired velocity and the feedback of the displacement of each motor, and inputs it into the lower one by analog voltage. The overview of the target part in this experiment is shown in Fig. 10(b). As an example of a shaft-shaped part, the iron shaft (Misumi, FXNAC15-15-F22-N22-MA12) with a length of 67 mm, a diameter of 15 mm, and a mass of 8.45×10^{-2} kg is used. It is one of the components of the gear unit that was targeted in the RGMC.

In addition, as uncertainty in the initial pose of the target part, we add a pose error as shown in Fig. 11. In the figure, Σ_{W} and Σ_{B} are coordinate frames fixed on the workbench surface and the target part in a plane parallel to the workbench, respectively. The origin of Σ_{B}, $\mathrm{O_B}$, coincides with the center of the hand at the completion of alignment, and its y-axis, y_{B}, is parallel to the longitudinal axis of the target part. The initial pose error of the part is set in such a way which $\mathrm{O_B}$ is at $(20, -5)$ mm and the orientational angle of Σ_{B} is -10 deg with respect to Σ_{W}.

The snapshots of the conducted experiment are shown in Fig. 12, where (a)–(p) in the figure correspond to those in Fig. 8, respectively. The experimental results show that the series of operations (alignment, picking, reorientation, and positioning of the target part) can be achieved with the proposed hand according to the proposed strategy.

The same experiment was conducted fifty times, and the success rate was exactly 90%. Two of the five failures were due to overloading during opening and closing of the fingers. This could be attributed to deteriorated lubrication of the worm gear and the worm wheel. Another one was a failure of grasping with the protrusions, and the other two were failures of the final grasp. Both these failures were caused by incomplete grasp where the fingers were not closed to the desired positions. The above results show that the proposed method is feasible with a good success rate.

B. Alignment Precision in the Vertical Direction

After grasping the target part shown in Fig. 10(b) with the proposed hand and strategy, the height of the part was measured with a height gauge five times as shown in Fig. 13 to check the vertical positioning accuracy. The measurement results are shown in Table I, and the maximum error from the desired height is 0.08 mm. Since this error is smaller than the dimensional tolerance of the target part, vertical positioning is sufficient for the assembly task of the part.

TABLE I
ERROR IN THE VERTICAL DIRECTION IN THE FINAL ALIGNMENT OF THE TARGET PART.

Trial	#1	#2	#3	#4	#5
Error [mm]	0.00	0.04	0.04	0.08	0.02

C. Scope of Applicability of the Proposed Method

As fundamental investigation on the scope of applicability of the proposed method to the target part, the permissible initial pose error region (PIPER) of the part is confirmed. This region is the set of initial poses of the part resulting in a successful desired alignment and represents the robustness of an assumed alignment strategy [3]. In our proposed method, this region can be regarded as the necessary condition to achieve the subsequent operations including pivoting. In previous research [18], the PIPER of the part shown in Fig. 10(b) was obtained by simulation when the alignment strategy shown in Fig. 9 was used for the part, but the validity of the region in the real environment was not confirmed. In this research, we experimentally confirm whether the desired alignment is achieved for the initial pose errors for which the simulation results indicated that alignment was possible.

The PIPER obtained as a result of the investigation is shown in Fig. 14. The x and y coordinates in the figure correspond to those of Σ_{W} in Fig. 11, and θ is the orientational angle of Σ_{B} with respect to Σ_{W} in Fig. 11. In addition, the red points in the figure indicate successful alignment, and the coordinates (x [mm], y [mm], θ [deg]) of some representative points P_1–P_8 are given on the right side of the figure. Note that the region is shown as a convex hull including all the red points as an approximation to make the region easier to understand. Therefore, when the initial pose error of the shaft-shaped part shown in Fig. 10(b) is within the region shown in Fig. 14, the proposed method is applicable. Moreover, it was confirmed that the simulation results were approximately correct in the real environment although the alignment failed for some of the initial poses such that the y-coordinate with respect to Σ_{W} was negative.

D. Confirmation of the Versatility of the Hand

In order to confirm the versatility of the proposed hand, we conduct grasping experiments of some other parts than the shaft targeted in Section VII-A. As other examples of industrial parts, we use five parts: the geared motor (Pololu, 37D-GEARMOTOR-50-70), the spur gear (Misumi, GEABDM2.0-40-20), the bearing holder (Misumi, SBARB6200ZZ-30), the L-shaped plate, and the nut (Misumi, LBNR12) shown in Figs. 15(a)–(e) with the size information. Note that the L-shaped plate is one of the components of the belt drive unit developed for the World Robot Summit 2018 [31]. The mass of each part is 1.90×10^{-1} kg for the motor, 1.42×10^{-1} kg for the gear, 1.19×10^{-1} kg for the bearing holder, 7.25×10^{-2} kg for the L-shaped plate, and 1.52×10^{-2} kg for the nut. Note that the motor shown in Fig. 15(a) is a kind of shaft-shaped part, and thus the proposed strategy described in Section VI should be

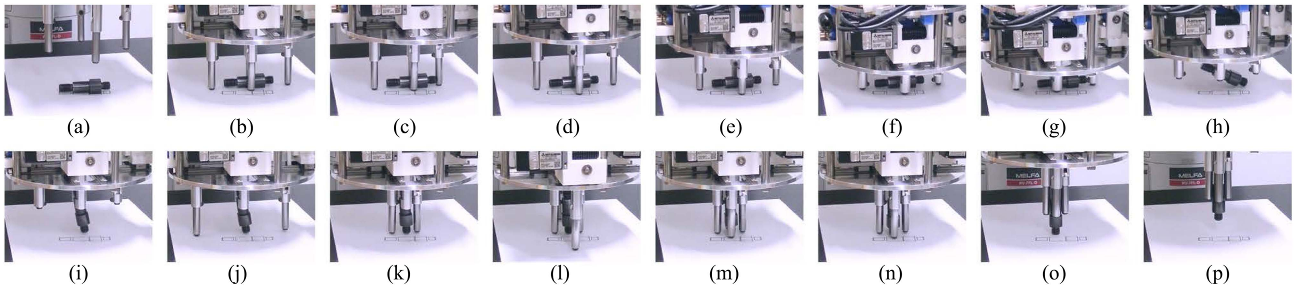


Fig. 12. Snapshots of the manipulation experiment of the shaft-shaped part.

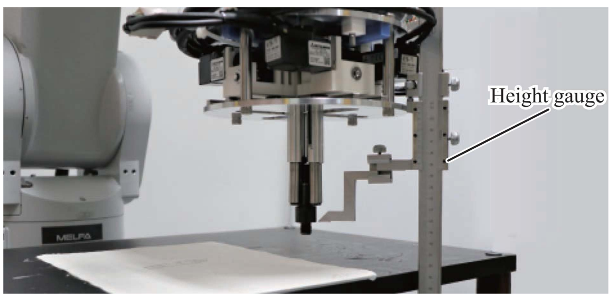


Fig. 13. Confirmation of the vertical positioning accuracy.

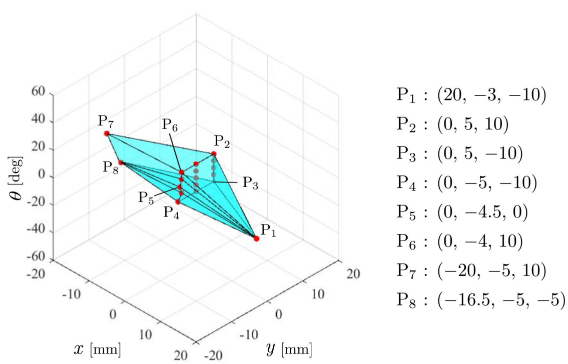


Fig. 14. Obtained permissible initial pose error region (PIPER).

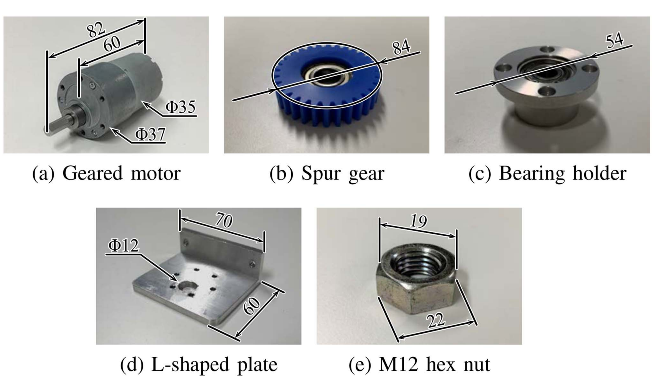


Fig. 15. Target industrial parts in the grasping experiments.

applicable to it as well as the shaft shown in Fig. 10(b). On the other hand, it is unnecessary to apply the manipulation strategy to the other parts shown in Figs. 15(b)–(e) because these parts can be assembled in the same grasping configurations as those applied to the parts in their initial states.

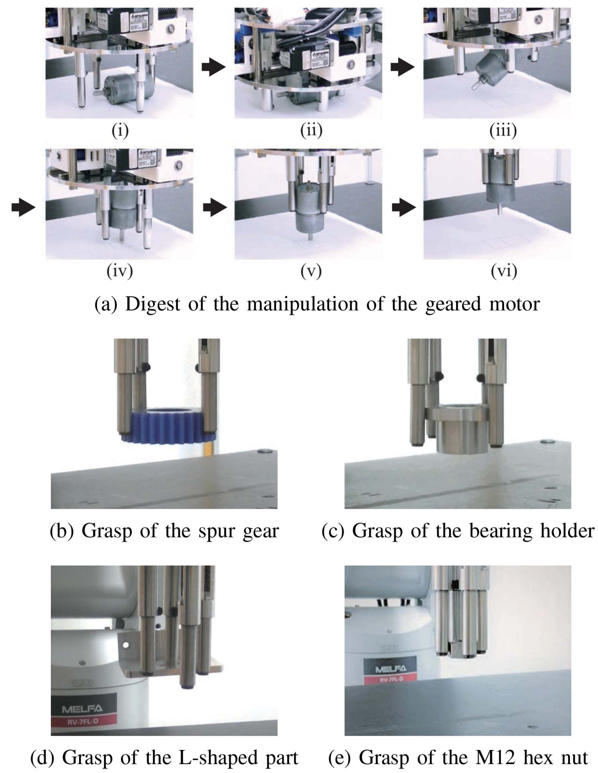


Fig. 16. Grasping experiments.

The experimental results are shown in Fig. 16. We confirmed that the proposed hand can grasp all the parts. In particular, the proposed strategy shown in Fig. 8 is effective even for the motor with a relatively large diameter and large mass, and the series of operations (alignment, picking, reorientation, and positioning) can be achieved.

VIII. Conclusion

In this paper, we developed a versatile low-DOF robotic hand with parallel stick fingers toward the realization of jig-less assembly of a shaft-shaped part with a single hand. Each finger has a novel telescopic mechanism with the passive rotational mechanism and a protrusion to realize the functions required for the series of operations, i.e., alignment, picking, reorientation, and positioning toward the assembly of shaft-shaped parts. In addition, we proposed an example of a manipulation strategy for the proposed hand, and confirmed that the desired manipulation can be achieved with a success rate of 90% and also that the target part is successfully positioned in the vertical direction with an error of less than 0.08 mm. Furthermore, we investigated the permissible initial pose errors for the initial alignment of the part and also confirmed the versatility of the proposed hand through the experiment of grasping different industrial parts.

In future work, we will conduct experiments to confirm the feasibility of the subsequent jig-less assembly of shaft-shaped parts with the proposed hand. Moreover, we need to discuss the efficiency of the proposed method and possibly improve the manipulation strategy.

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