Selecting and Designing Grippers for an Assembly Task in a Structured Approach

Jingren Xu[1,2], Weiwei Wan[1], Keisuke Koyama[1], Yukiyasu Domae[2], and Kensuke Harada[1,2]

arXiv:2003.04087v2 [cs.RO] 27 Jul 2020

***Abstract*— In this paper, we present a structured approach to selecting and designing a set of grippers for an assembly task. Compared to current experience-based gripper design method, our approach accelerates the design process by automatically generating a set of initial design options on gripper type and parameters according to the CAD models of assembly components. We use mesh segmentation techniques to segment the assembly components and fit the segmented parts with shape primitives, according to the predefined correspondence between primitive shape and gripper type, suitable gripper types and parameters can be selected and extracted from the fitted shape primitives. Moreover, we incorporate the assembly constraints in the further evaluation of the initially obtained gripper types and parameters. Considering the affordance of the segmented parts and the collision avoidance between the gripper and the subassemblies, applicable gripper types and parameters can be filtered from the initial options. Among the applicable gripper configurations, we further optimize number of grippers for performing the assembly task, by exploring the gripper that is able to handle multiple assembly components during the assembly. Finally, the feasibility of the designed grippers is experimentally verified by assembling a part of an industrial product.**

I. Introduction

Robots have been increasing engaged in industrial applications such as robotic assembly, where a set of mechanical components are handled and manipulated by robotic grippers. The gripper plays a pivotal role for the robot interacting with the environment, the performance of the gripper grasping an assembly component is strongly influenced by how well the chosen gripper and its characteristics coincide with the characteristics needed for grasping a specific part [1]. Therefore, designing reliable grippers is one of the key issues for applying robots in industrial environment.

However, robotic grippers are manually designed in most of the cases, the manual design process is time-consuming and requires a lot of experience and expertise, which makes it extremely challenging to design grippers, especially for an assembly task. In a general robotic assembly task, a set of specialized grippers are required to firmly grasp all the assembly components with different shapes and properties, in addition, the grippers have to satisfy the assembly constraints, such as avoiding collision with other subassemblies. Moreover, there is a trend in High-Mix Low-Volume production, which refers to producing a large variety of products in small quantities, the fast changing manufacturing routines propose great challenges for applying robot in such agile manufacturing. In terms of the grippers used in the assembly tasks, a more efficient approach of designing grippers is highly demanded in order to quickly adapt to the frequently changing assembly tasks.

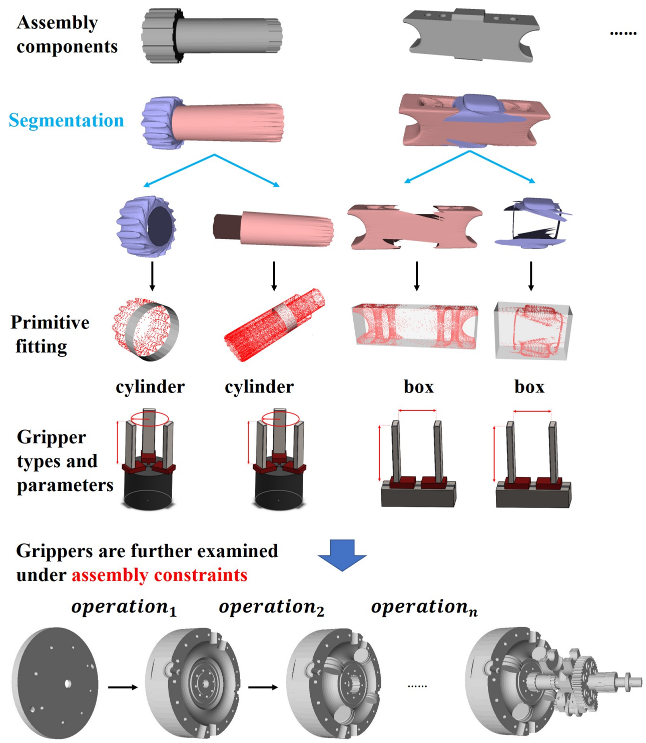


Fig. 1: Overview of the proposed approach of selecting and designing grippers for an assembly task. In the first stage, suitable gripper types (2-finger or 3-finger gripper) and parameter constraint (opening width) can determined by mesh segmentation and primitive fitting. Then the segments and grippers of such configurations are further evaluated under the assembly constraints, such as affordance and collision avoidance. Finally, we optimize the number of grippers to cut down the cost.

To efficiently design grippers satisfying the assembly constraints, we propose a structured approach of selecting and designing the grippers based on the shape analysis and assembly constraints. The insight is that the industrial products are usually comprised of many regular shape primitives, such as cylinder and cuboid, each of the shape primitives can be firmly grasped by a suitable type of gripper. Therefore, we pre-define the rules for selecting suitable gripper types,

[1]Graduate School of Engineering Science, Osaka University { xu@hlab., harada@, wan@ }sys.es.osaka-u.ac.jp
[2]Automation Research Team, Artificial Intelligence Research Center, National Institute of Advanced Industrial Science and Technology (AIST) domae.yukiyasu@aist.go.jp

which reduces the space for searching possible gripper configurations and significantly accelerates the design process. Through mesh segmentation techniques, we can uncover the underlying shape primitives and assign predefined gripper types to them. The gripper parameters, such as the max/min opening widths, can be further extracted from the dimensions of the fitted primitives. These steps are automatically processed and provide reduced gripper configurations for further selection and evaluation. These gripper configurations work well in terms of grasping, however, robotic assembly is a much more complex task, where the grippers have to not only firmly grasp the assembly components, but also avoid the collision with the subassemblies. Furthermore, some segments are not suitable for grasping considering their affordance, and they are excluded from the selection of graspable segments. After the evaluation under assembly constraints, some of the remaining segments can be commonly grasped by the same gripper, therefore, the number of grippers can be optimized to reduce the total cost.

A few researches were performed on the design of grippers for assembly tasks. However these researches are limited to designing the local shape of the fingertip [2] and general suggestions for designing the gripper systems. There has been no attempt on the structured approach of selecting and designing grippers according to the assembly constraints, as well as minimizing the number of grippers, for a sequence of assembly tasks.

The rest of the paper is organized as follows: Section II reviews the related work. Section III introduces the segmentation of the assembly components. Section IV exacts the initial set of gripper configurations by primitive fitting. In section V, we evaluate these gripper configurations under the assembly constraints and optimize the number of grippers. The feasibility of the designed grippers are confirmed by an assembly experiment in section VI. Finally, we draw the conclusions and provide the prospect for future work in section VII.

II. Related Work

There have been a lot of research on gripper design [3], [4], however, very few of them consider the assembly constraints and design for an assembly task. Another line of work that is related to our work is part/model/primitive based grasp planning [5], [6], [7], [8], [9], in this sense, our work can be called shape primitive based gripper design, considering assembly constraints and optimization of number of grippers.

A. Gripper Design and Robotic Assembly

Generally, the grippers are specially designed according to the task to be performed [4], [3], in this case, the design process takes many iterations to obtain a satisfactory design. There have been very few attempts to design grippers for assembly tasks and improve the design efficiency. Pham et al. [10] surveyed the design methods to achieve versatile and cost-effective gripping and proposed a strategy for minimizing the number of grippers through part-family grouping, and later Pham et al. [11] proposed a system to determine the configuration of grippers for assembly tasks. However, none of the above work proposed a framework of automated gripper selection and design, including model processing, parameter extraction, evaluation and optimization of the number of grippers, moreover, none of them explicitly incorporate the assembly constraints into the gripper design.

In addition to the gripper configuration, the contact between the finger and object plays an important role on grasp stability, therefore, the contact model has been studied extensively [12], [13], [14], [15]. Early research mainly used point contact model [16], later on, soft finger model was developed to model the contact in a more realistic way [13], [12]. Some researchers studied the finger design to change the contact characteristics and improve the performance of the gripper. Honarpardaz et al. [17], [2] proposed generic optimized finger design (GOFD) to automate the finger design process, the fingertip shape was designed to mimic the workpiece, thus the contact area was increased. Song et al. [18] noticed that most grasp contacts share a few local geometries, they proposed a uniform cost algorithm to cluster a set of example grasp contacts into several contact primitives, and designed the finger shape to match the local geometry in order to increase the contact area.

Rodriguez et al. [19] explored the effector form design for 1 DoF planar actuation, the mechanical function of a product is formulated as the product of the effector's shape and motion. Taylor el al. [20] investigated the role of shape and motion in the contact interaction, and proposed a framework to optimize the shape and motion of a planar rigid body end-effector to achieve a manipulation task. Chavan-Dafle et al. [21] proposed a two-phase gripper for passively reorient the objects while pick them up. Birglen et al. [22] extensively reviewed the characteristics of industrial grippers, the stroke, weight, force and weight, as well as performance, are investigated in details. Hermann et al. [23] designed a gripper that can switch between two modes, including grasping mode and high precision fully actuated mode.

For an assembly task, usually more than one gripper is required to grasp all the assembly components. Kramberger et al. [24] proposed a flexible and cost-effective grasping solution to quickly develop and test custom fingertips to handle multiple parts. Harada et al. [25] incorporated the tool changer into the assembly planner and proposed an assembly planner that is able to automatically select a suitable gripper to assemble parts. Nakayama et al. [26] designed grasping tools for assembly tasks based on shape analysis of parts, however, the assembly constraints are not considered in the evaluation of graspable segments and suitable gripper configurations, additionally we optimize the number of grippers for the assembly task.

B. Shape Approximation Based Grasping

Grasp planning is difficult due to the large number of possible gripper configurations, but grasping planning can be simplified if considering the shape of the object and the grasping strategy are closely related. Miller et al. modeled the object as a set of simple shape primitives [5], then the grasp location and preshape can be determined. Goldfeder et. al [27] used decomposition tree of the object to prune the large space of possible grasps into a subspace that is likely to contain many good grasps. Huebner et al. [7] approximated the object by box primitives and select grasps based on the approximated boxes. However, the error of approximating by primitives may result in low-quality grasps, to counteract this problem, Przybylski et al. [6] proposed the grid of spheres for grasp planning, which effectively reduce the search space for grasps without sacrificing potential high-quality grasps.

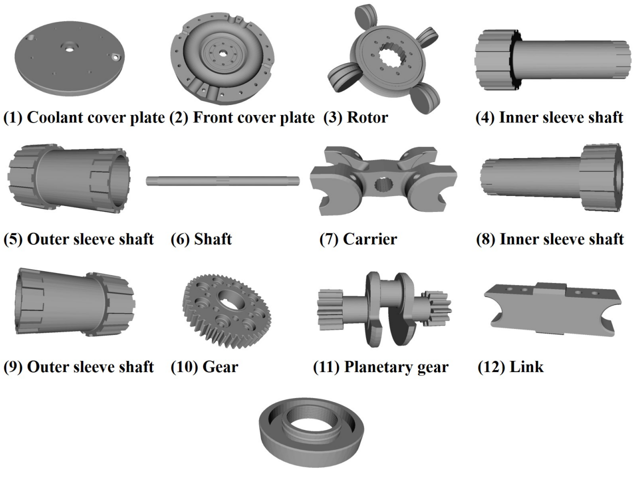
These researches **passively** plan grasps given the object model, we can also **actively** design the gripper configurations according the shape of target object in order to easily obtain high-quality grasps. This idea is somewhat related to the taxonomy of grasps proposed in [28], where the grasps are classified based on task-related and geometric considerations, each type of grasp is corresponding to one category of task and object geometry. For grasping the assembly components, we select suitable grasping postures according to the shape of the assembly components, since we do not use dexterous robot hand to realize these grasps, instead we abstract a simple gripper configuration from the grasping postures of dexterous hand.

Our main contributions are summarized as follows:

- We proposed a structured approach of configuring the gripper types and parameters based on mesh segmentation, primitive fitting and assembly constraints.
- The assembly constraints are explicitly taken into account in the evaluation of the feasible gripper configurations. The number of grippers required for the assembly task is optimized to reduce the cost.
- The proposed method is experimentally verified by assembling a part of an industrial product.

III. Mesh Segmentation

Mechanical products are usually comprised of many regular shapes such as cylinders and cuboids, which makes the proposed method feasible and promising in industrial applications. We use mesh segmentation to find the underlying shape primitives of an assembly component, then suitable gripper types are determined according to the predefined rules. The mesh models of the assembly components (Fig. 2) are segmented based on Shape Diameter Function (SDF) [29], which is a consistent function measuring the neighborhood diameter of an object at each point on the surface. To obtain the SDF value at a point P on the surface, we use a cone centered around the inward-normal direction of P, as sketched in black dashed lines in Fig. 3 (a), from P we shoot a set of rays (red lines) inside the cone and stop at the intersections on another side of the mesh. The SDF value is calculated as the weighted average lengths of the rays. We shoot 30 rays per point and set the cone angle to $120°$, as a result, Fig. 3 (b)&(c) show two examples of SDF distribution on the model. The segmentation process is comprised of soft clustering and hard clustering. Soft clustering is a Gaussian mixture model that fits a set of Gaussian distributions to



(1) Coolant cover plate **(2) Front cover plate** **(3) Rotor** **(4) Inner sleeve shaft**
(5) Outer sleeve shaft **(6) Shaft** **(7) Carrier** **(8) Inner sleeve shaft**
(9) Outer sleeve shaft **(10) Gear** **(11) Planetary gear** **(12) Link**
(13) Main seal

Fig. 2: Models of all the assembly components before processing, they are displayed in the order of the assembly sequence.

the distribution of the SDF values, this step outputs the probability matrix for each face to belong to each cluster, note that a cluster may contain multiple segments. Hard clustering yields the final segmentation of the mesh by minimizing an energy function combining the probability matrix and geometric surface features [29], [30]. Readers are referred to [31] for other mesh segmentation methods.

Before mesh segmentation, smoothing is applied on the mesh to eliminate the sharp edges of the screw thread, otherwise it may result in undesirable segments [32]. Fig. 4 shows the mesh after smoothing is applied. Then all the assembly components are segmented based on SDF values. The segmentation results are visualized as Fig. 5, different segments are colored differently, each of the segments is regarded as a candidate for grasping[1].

IV. Gripper Selection and Dimensioning

Through mesh segmentation, the assembly component with complex shape is decomposed into segments with simpler shapes. Obviously, some shape primitives can be easily grasped by some common types of gripper, e.g. cylinders can be easily grasped by the 3-finger centric gripper. Therefore, we attempt to fit the segments with shape primitives and then determine the suitable gripper types according to the predefined rules. In this section, we obtain the initial decisions on gripper types and parameters based on previous segmentation result.

A. Rules for Gripper Type Selection

In this paper, we consider using two common types of gripper[2]: 2-finger parallel jaw gripper and 3-finger centric gripper as shown in Fig. 6 (a) and (b). 2-finger grippers are suitable for grasping parts with (nearly) parallel surfaces,

[1]Grasping multiple segments are not considered in this paper.

[2]More gripper types and shape primitives can be used to cope with more complex shapes.

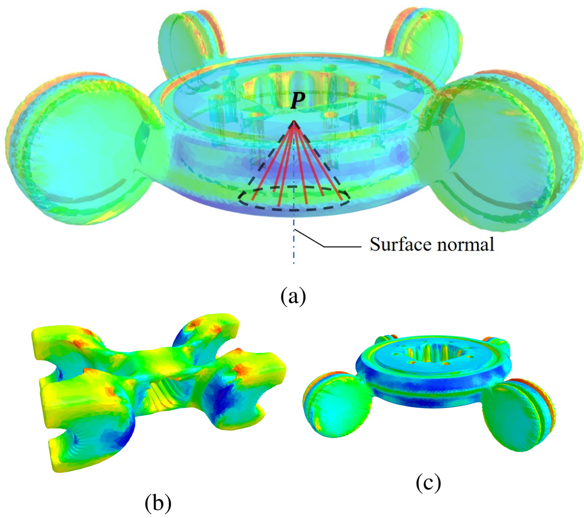


Fig. 3: (a) The Shape Diameter Function (SDF) is the weighted average length of the rays (red lines). (b)&(c) SDF distribution of the carrier and the rotor.

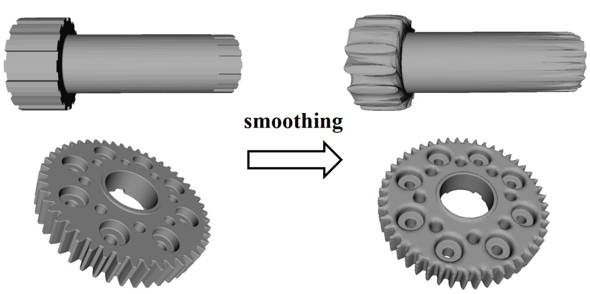


Fig. 4: Two examples of models before and after smoothing.

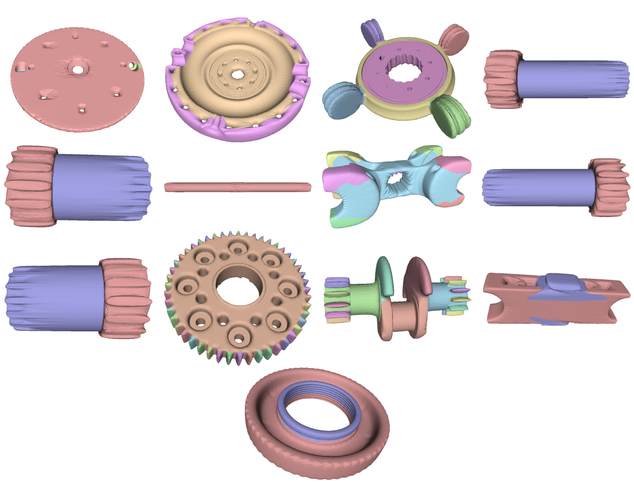


Fig. 5: After mesh segmentation, an assembly component is decomposed into several segments, different segments are marked with different colors. The original component with complex shape is decomposed into segments with simpler shapes, which are suitable for further primitive fitting.

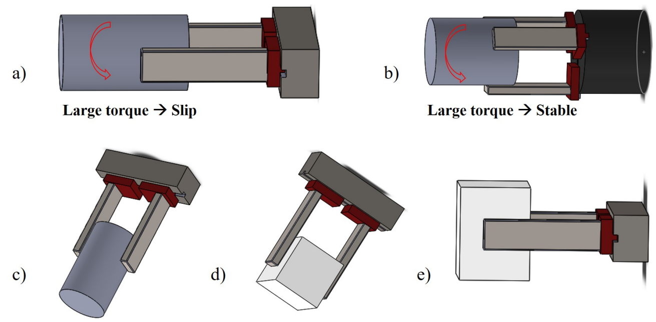


Fig. 6: (a) & (c) Grasping a cylinder by a 2-finger gripper is not stable under external torque, the object may slip around the contact normal. (b) Grasping a cylinder by a 3-finger gripper is stable in the radial direction. (d) & (e) Grasping a box shape by a 2-finger gripper is appropriate.

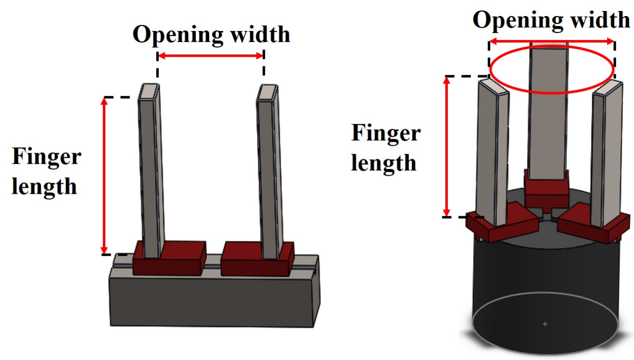


Fig. 7: The opening width and finger length of the 2-finger and 3-finger grippers.

Fig. 6 (d) and (e) show a 2-finger gripper grasping a box with parallel surfaces, the gripper fingers coincide well with the object surfaces and they have large contact area, thus the grasp is robust. However, it may not be suitable to grasp a cylinder using a 2-finger gripper, as shown in Fig. 6 (a), small external torque can be balanced by assuming soft-finger contact, but in some assembly operations the gripper may have to exert large force/torque on the assembly components, which may lead to slip around the contact normal. Therefore, we select 3-finger centric grippers over 2-finger grippers for grasping cylindrical objects, which is guaranteed to be stable against the force in the radial direction, as shown in Fig. 6 (b). Another merit of grasping cylindrical objects using 3-finger grippers is that the grasp stability is independent of the radius of the cylinder, however, the stability of grasping a cylindrical object using a 2-finger gripper depends on the relative curvature of the finger and object surface, that is, grasping a cylinder with larger radius is more stable since the contact area is larger[3].

B. Gripper Type

Each segment of an assembly component shown in Fig. 5 is a candidate for grasping, in order to determine suitable

[3]Assume soft finger contact and constant external force.

gripper type for grasping the segment, we fit every segment with cylinder and bounding box. If the volume of cylinder is closer to the volume of the segment, then a 3-finger centric gripper is selected for this segment, otherwise, the 2-finger jaw gripper is used. Since the segments of a surface mesh are usually not closed surface, the volume of the such segments are obtained by calculating the volume of their convex hulls.

Fig. 8 shows two examples of fitting the segmented part with primitives. The rotor in Fig. 8 (b) is segmented into 6 parts, we fit all of them with cylinders and bounding boxes, by comparing the volume of the segmented part and the fitted primitives, the appropriate fitting for every segment can be determined. As a result, five of them can be closely fitted by cylinders and the other one is fitted by its bounding box. The fitted cylinders are represented by gray belts, the height of the cylinder is manually set as $1cm$ for visualization, but it can also be calculated from the maximum distance along the cylinder's axis between the points on the segment. Notice that the third segment looks cylindrical but it is empty on the cylindrical surface, therefore it is actually better fitted by the bounding box. Then the corresponding gripper type can be selected for every segment based on the predefined rules. In order to grasp a mechanical component, at least one of its segmented parts should be graspable by the designed grippers, e.g. the gripper for grasping the rotor should be capable of grasping at least one of the 6 segments in Fig. 8(b).

C. Gripper Parameters

The maximum and minimum opening widths and finger length are important parameters for the grippers. In order to grasp a segment, the characteristic length of the shape primitives, which are the diameter for a cylinder primitive and side length for a box primitive, must be within the stroke of the gripper. The capability of grasping a segment does not directly impose constraints on the finger length, however, the finger length has to fulfill some requirements in order to satisfy the assembly constraints, for example, the finger should be long enough to avoid collision with the shaft when inserting the shaft sleeve to the shaft. And the constraints on the finger length is described in section V-B. In addition, the gripper approach direction can be extracted from the fitted primitives. The 3-finger centric gripper should approach the part along the axial direction, and the 2-finger gripper can approach the part as long as the finger surfaces are parallel to the non-empty surfaces of the bounding box.

V. Evaluation under Constraints

Through mesh segmentation and shape primitive fitting, we have obtained the initial candidate gripper type and parameters for every segmented part of the assembly components, however, some of them are not applicable considering the assembly constraints. In this section, we take into account the assembly constraints and finalize the minimum number of grippers for the given assembly task.

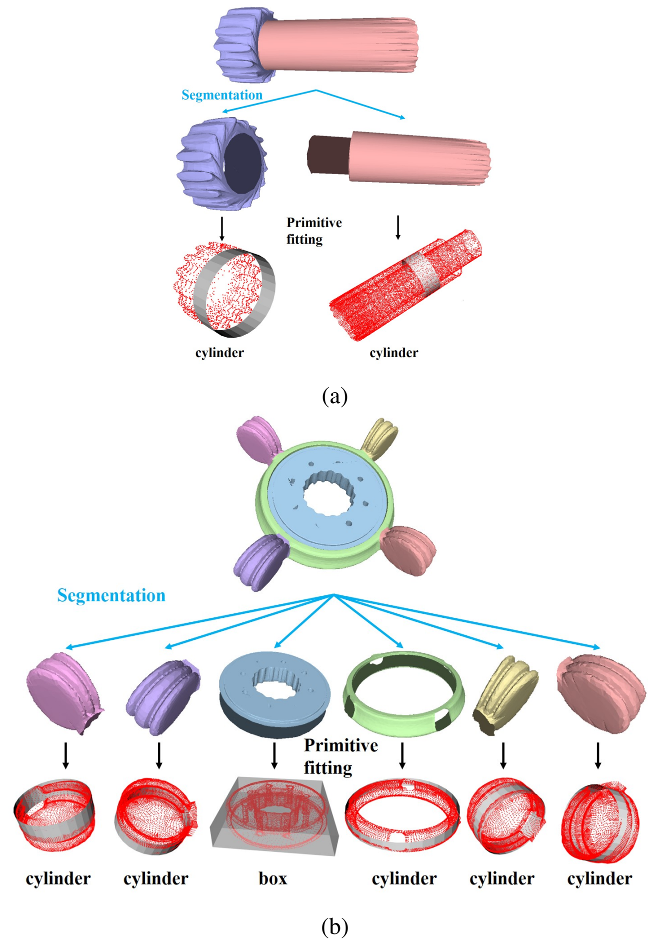


Fig. 8: Two examples of fitting the segmented parts with shape primitives. (a) The inner sleeve shaft is segmented into two parts, both of the two parts are fitted appropriately by cylinders. (b) Five segments of the rotor are more closely fitted by cylinders and the other one is fitted its bounding box, notice that the third segment looks cylindrical but it is empty on the cylindrical surface.

A. Assembly Task Specification

Referring to the assembly task decomposition method proposed by Mosemann et al. [33], an assembly task can be represented as a sequence of assembly operations, in each assembly $operation_i$, a new assembly component is added to the existing subassembly. We assume the assembly sequence is already given, then the assembly task is denoted as $Assembly = \{operation_1, operation_2, \ldots, operation_n\}$. each assembly operation can be represented as $\langle c_a, c_p, {}^aT_p, {}^{a'}T_p\rangle$, where c_a and c_p are the active and passive subassemblies being manipulated in the operation, ${}^aT_p$ and ${}^{a'}T_p$ are spatial transformations between active and passive assembly components before and after the assembly operation, respectively.

B. Assembly Constraints

In an assembly operation $operation_i$, the gripper has to grasp one segment of c_a and change the spatial relationship

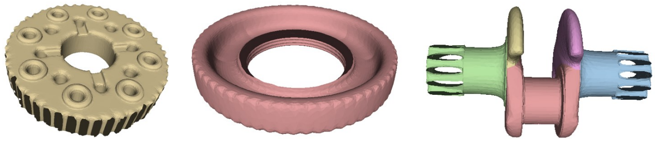


Fig. 9: Gear teeth and screw thread do not afford grasping, thus removed from the candidate graspable segments.

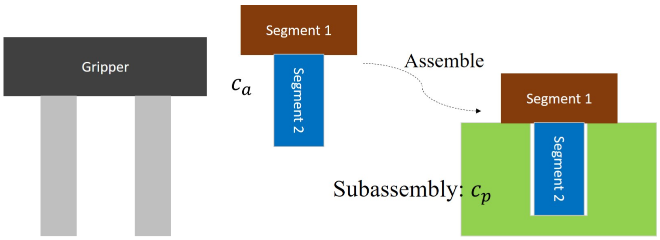


Fig. 10: The gripper has to avoid collision with the subassemblies in the assembly task.

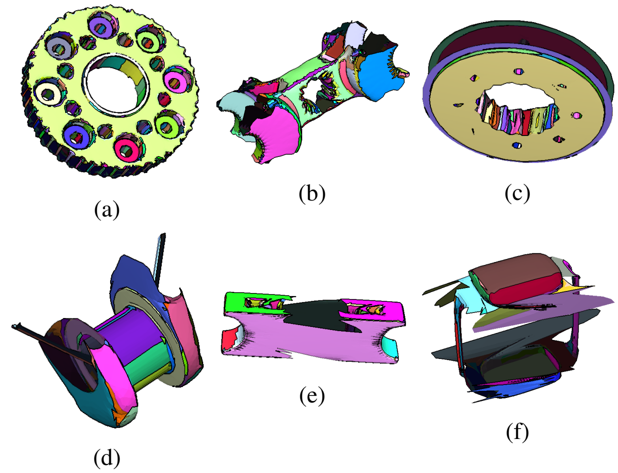


Fig. 11: Planar clustering of the segments to be grasped by 2-finger grippers.

from ${}^{a}T_p$ to ${}^{a'}T_p$. When grasping c_a, not every segment of c_a is suitable for grasping, the affordance of different segments should be taken into account in selecting graspable segments. Moreover, the gripper must avoid the collision with the subassemblies during the assembly.

1) Affordance: Affordance is defined as the possible action on an object or environment [34]. In an assembly operation, not all the segments of an assembly components afford grasping. For example, screw thread and gear teeth are mainly used for fastening and transmission, they may be damaged and lose their main affordance if they are directly grasped by the gripper. As illustrated in Fig. 9, some segments are removed from the candidate segments for grasping considering their major affordance.

2) Collision Avoidance: The gripper has to avoid collision with the subassemblies during the assembly, Fig. 10 shows that the gripper will collide with the subassembly if segment 2 is grasped in this assembly operation, thus segment 1 is selected as the graspable segment. A segment is graspable only if there exists a collision-free grasping pose for the gripper to assemble c_a to c_p. To get the graspable segments satisfying the collision avoidance constraint, we plan a set of grasps for each segment and check the collision between the gripper and the subassemblies, the segment is graspable if there is at least one collision-free grasp.

C. Grasp planning

After removing ungraspable segments according to their affordance, grasp planning is performed on the remaining segments to determine if there are collision-free grasps for the segments. For the segments to be grasped by two-finger parallel grippers, we first use planar clustering [35] to cluster the mesh into a set of nearly planar facets, and then search for nearly parallel facets to be in contact the fingers of the gripper, and rotate the gripper around the contact normal to obtain more grasps. Fig. 11 shows the some examples of the planar clustering, every color denotes the a clustered facet. By searching nearly parallel facets from the clustered model, pairs of facets and contact points for grasping are obtained, as shown in Fig. 12. In terms of the segments to be grasped 3-finger gripper, the grasp can be easily extracted from the fitted cylinder, the axis of the gripper should align with the axis of the cylinder.

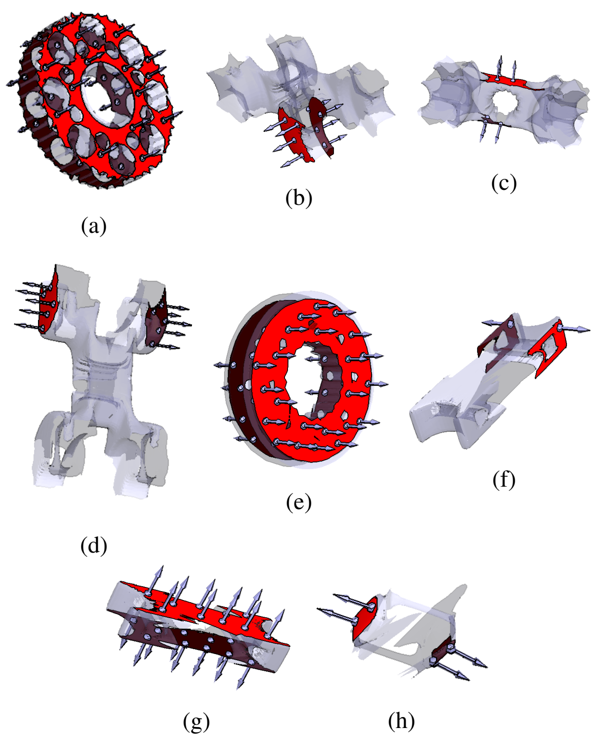


Fig. 12: Pairs of facets and contact points for grasping by 2-finger grippers.

The planned grasps are then examined by checking the collision between the gripper and the subassemblies. We take the rotor shown in Fig. 8 (b) as an example, Fig. 13 (a)&(b) are the planned grasps at a pair of contact points on the segment, Fig. 13 (c) shows all the grasps and the sub-

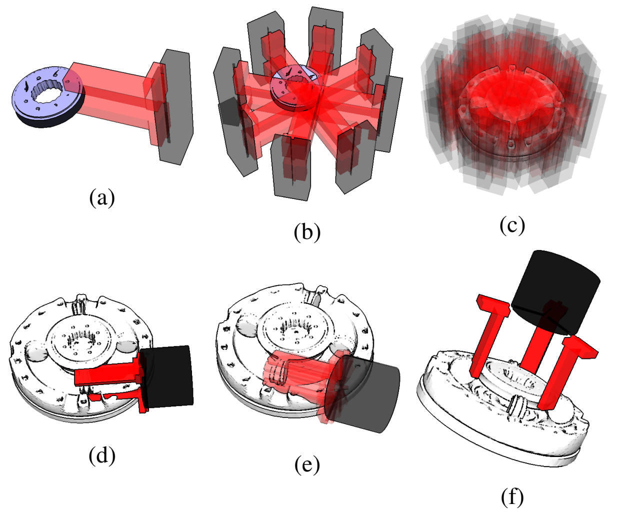


Fig. 13: (a) A planned grasp at a pair of contact points. (b) Planned grasps and collision check will the subassemblies.

assemblies, however, all the grasps are in collision with the subassemblies, which means this segment is not graspable. Similarly, grasping the segment like Fig. 13 (d)&(e) is not feasible due to collision, the only graspable segment and its grasp are shown in Fig. 13 (f). After the evaluation under the assembly constraints following such process, the remaining graspable segments of every assembly component are listed in Fig. 14, alongside the segments are the constraints on gripper types and parameters for grasping the segments.

D. Minimize the Number of Grippers

Some of the assembly components can be commonly grasped by the same gripper, thus the total cost of grippers can be cut down by reducing the number of grippers for the assembly task. From the previous analysis, we have obtained the graspable segments from all the assembly components, every assembly component c_i imposes a set of constraints on the gripper, such as the number of fingers F_i, opening width W_i, minimum finger length L_i^- and maximum finger length L_i^+. We denote the constraints for assembly component c_i as $\mathcal{C}_i : \{F_i, W_i, L_i^-, L_i^+\}$, $i = 1, 2, \ldots, M$, M is the number of assembly components, if an assembly component c_i has m graspable segments $\{c_{i1}, c_{i2}, \ldots, c_{im}\}$, then $\mathcal{C}_i = \mathcal{C}_{i1} \cup \mathcal{C}_{i2} \cup \cdots \cup \mathcal{C}_{im}$, where $\mathcal{C}_{ij}$ is the constraints imposed by segment c_{ij} of c_i. We can sample N sets of gripper parameters $x_j : \{F_j, W_j^-, W_j^+, L_j\}$ covering the minimum and maximmum gripper parameters and minimize the set of gripper parameters, the problem is formulated as follows,

$$\min \sum_{j=1}^{j=N} x_j \tag{1}$$

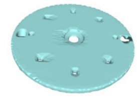
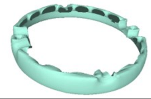
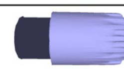
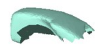
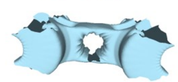
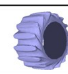
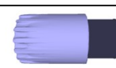
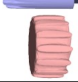
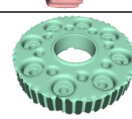
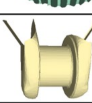
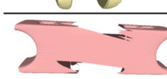
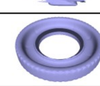
No.	Graspable segments	Gripper type	Opening width	Finger length
1		3-finger	227 mm	> 0mm
2		3-finger	227 mm	> 0mm
3		3-finger	110 mm	> 0mm
4		3-finger	25 mm	> 0mm
5		3-finger	32 mm	> 0mm
		3-finger	40 mm	> 41mm
6		3-finger	18 mm	> 0mm
7		2-finger	16.7 mm	> 0mm
		2-finger	19.1 mm	> 0mm
		2-finger	17.2 mm	> 0mm
		2-finger	15.9 mm	> 0mm
		2-finger	16.5 mm	> 0mm
		2-finger	15.8 mm	> 0mm
		2-finger	16.9 mm	> 0mm
		2-finger	18.5 mm	> 0mm
		2-finger	60 mm	> 0mm
8		3-finger	40 mm	> 50mm
9		3-finger	32 mm	> 0mm
		3-finger	40 mm	> 41mm
10		2-finger	17 mm	> 4.5mm
11		3-finger	20 mm	> 0mm
12		2-finger	15 mm	> 0mm
		2-finger	32.8 mm	> 0mm
13		3-finger	37.5 mm	> 22.7mm

Fig. 14: The remaining graspable segments after checking the assembly constraints.

$$
\text{s.t.}\begin{cases} x_j \in \{0,1\} \\ \forall i, \exists j \begin{pmatrix} F_j = F_i \\ L_i^- < L_j < L_i^+ \\ W_j^- < W_i < W_j^+ \end{pmatrix} \\ i \in 1,2,\ldots,M, j \in 1,2,\ldots,N \end{cases} \tag{2}
$$

where M is the number of assembly components, N is the number of gripper parameter samples, x_j is 1 if j-th gripper parameter sample is used and is 0 otherwise.

E. Discussion and limitation

In this research, we assume that the target assembly components can decomposed into boxes and cylinders, and we only use two types of grippers, which are 2-finger parallel gripper and 3-finger jaw gripper. To cope with more complex shapes, we have to use more shape primitives, such as cone and pyramid. In addition to affordance and collision avoidance described above, there are other aspects to be considered for further improvement.

1) Stability of Grasping Different Segments: In an assembly operation, grasping different segments may result in different force/torque distribution. Consider assembling the carrier to the shaft in Fig. 2, if the grasping contact positions are not symmetric about the shaft, it will lead to uneven normal force between shaft and hole, which may result in insertion failure, or even damage the components. Therefore, it is necessary to analyze the contact force distribution when selecting suitable segment for grasping during the assembly.

2) Finer Finger Design: The assembly components must be stably grasped without slipping during the assembly, in which the external forces include gravity, assembly force, etc. It is necessary to fine-tune the shape of the finger surface to increase the contact area with the object, especially when the object surface is curved. Assuming the soft-finger contact model, we can calculate the contact area from the relative curvature between fingertip and object surface, then appropriate fingertip curvature that ensures the grasp stability can be determined. Fig. 6 (a) illustrates the situation of the maximum torque caused by gravity, and it should be balanced by the torsional friction exerted by the soft finger contact.

VI. Experiment

In this section, the effectiveness and feasibility of our approach are verified by assembling a part of an industrial product using the designed grippers. Considering the limit of our 3D printer, the product is scaled to 55% of its original size and printed out as shown in Fig. 15 (Left). The grippers are constructed by attaching fingers to air chunks, the stroke of an air chunk determines the difference between the maximum and minimum opening widths $(W_j^+ - W_j^-)$, and it is referred in the sampling of gripper configurations. According to the strokes of air chunks we use, one 2-finger gripper with maximum opening of 33mm, and three 3-finger grippers with maximum opening of 22mm, 60.5mm and 124.9mm are required. The finger of the 2-finger gripper should be longer than 2.5mm in order to grasping segment surrounded by gear teeth, the 3-finger gripper with stroke of 22mm should have fingers longer than 27.5mm, in order to avoid collision with the shaft. We model and print out the fingers and attach them to the air chucks, the 2-finger gripper is constructed by attaching 2 fingers on SMC MHF2-12D2 air chuck (stroke: 48mm, 0mm to 48 mm), the 3-finger gripper is constructed by attaching 3 fingers on SMC MHSL3-32D air chuck (stroke: 8mm, 34 mm to 42 mm). As shown in Fig. 15, the actual opening widths are slightly larger than the calculation results to account for the uncertainties.

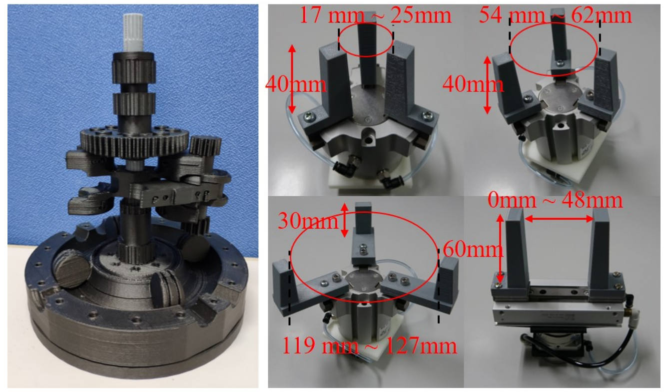


Fig. 15: (Left): The product to be assembled. (Right): The designed 4 grippers in their maximum opening state, the strokes are 8mm for 3-finger air chuck and 48mm for the 2-finger air chuck, respectively.

We performed the assembly experiment on a NEXTAGE robot from Kawada Robotics Inc., as shown in Fig. 16, all the 13 assembly components can be firmly grasped by using the designed 4 grippers. We assume the assembly sequence is known, the target segment of an assembly component for grasping can be obtained from the previous analysis, then the robot is able to successfully complete the task without collision with the subassemblies during the assembly, as shown in Fig. 17.

VII. Conclusions and Future Work

Tackling the challenges of designing grippers for an assembly task, we presented a structured approach of selecting and designing the grippers. The input for our approach are the assembly specification and the geometrical models of the assembly components. In the first phase, the assembly components with complex shape are segmented into simpler parts, then the segmented parts are fitted with shape primitives. By defining the correspondence between simple shape primitives and gripper types, suitable gripper types and parameters can be determined from the results of mesh segmentation and primitive fitting. In the second phase, the results in the first phase are examined under the assembly constraints, afterwards, the number of grippers is minimized by finding a set of gripper parameters that satisfy the constraints imposed by all the assembly components. Finally, the effectiveness of designed grippers is confirmed by the assembly experiment.

In the future, the current work can be improved from

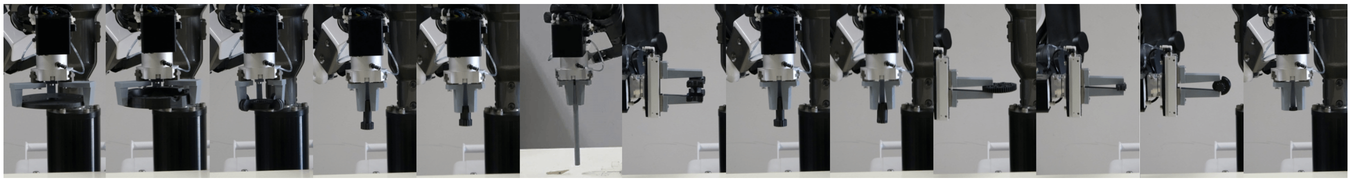


Fig. 16: Designed 4 grippers are able to firmly grasp all the 13 assembly components.

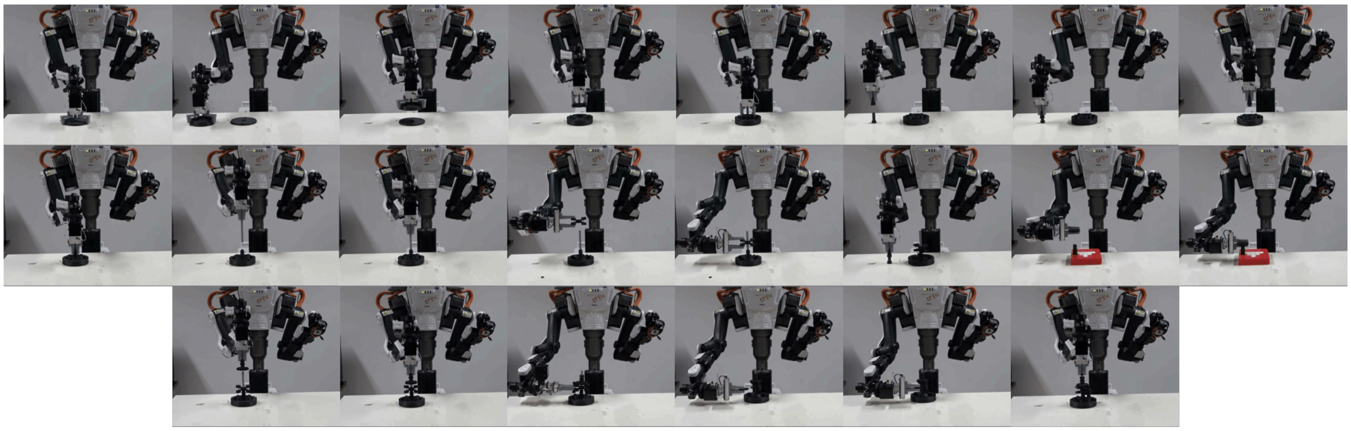


Fig. 17: The robot successfully assembled the product, there is no collision between the gripper and the subassembly.

several aspects: (1) We consider exploring more powerful mesh segmentation method [36] to decompose the assembly components, the affordance of the part will be taken into account in the segmentation. (2) More shape primitives such as cone and pyramid can be used to improve the ability of fitting more complex shapes. (3) The representation of the assembly task and constraints can be refined, and classifying the basic assembly operations (such as peg-in-hole) can further automate the design process. (4) The fingertip shape can be fine-tuned to increase the contact area and grasp stability.

REFERENCES

[1] J. Schmalz and G. Reinhart, "Automated selection and dimensioning of gripper systems," *Procedia CIRP*, vol. 23, pp. 212–216, 2014.

[2] M. Honarpardaz, J. Ölvander, and M. Tarkian, "Fast finger design automation for industrial robots," *Robotics and Autonomous Systems*, vol. 113, pp. 120–131, 2019.

[3] B. R. Cannon, T. D. Lillian, S. P. Magleby, L. L. Howell, and M. R. Linford, "A compliant end-effector for microscribing," *Precision engineering*, vol. 29, no. 1, pp. 86–94, 2005.

[4] K. Nie, W. Wan, and K. Harada, "An adaptive robotic gripper with l-shape fingers for peg-in-hole tasks," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 4022–4028, IEEE, 2018.

[5] A. T. Miller, S. Knoop, H. I. Christensen, and P. K. Allen, "Automatic grasp planning using shape primitives," in *2003 IEEE International Conference on Robotics and Automation (Cat. No. 03CH37422)*, vol. 2, pp. 1824–1829, IEEE, 2003.

[6] M. Przybylski, T. Asfour, and R. Dillmann, "Planning grasps for robotic hands using a novel object representation based on the medial axis transform," in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1781–1788, IEEE, 2011.

[7] K. Huebner and D. Kragic, "Selection of robot pre-grasps using box-based shape approximation," in *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1765–1770, IEEE, 2008.

[8] N. Vahrenkamp, L. Westkamp, N. Yamanobe, E. E. Aksoy, and T. Asfour, "Part-based grasp planning for familiar objects," in *2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids)*, pp. 919–925, IEEE, 2016.

[9] J. Bohg, A. Morales, T. Asfour, and D. Kragic, "Data-driven grasp synthesisa survey," *IEEE Transactions on Robotics*, vol. 30, no. 2, pp. 289–309, 2013.

[10] D. Pham and S. Yeo, "Strategies for gripper design and selection in robotic assembly," *The International Journal of Production Research*, vol. 29, no. 2, pp. 303–316, 1991.

[11] D. T. Pham, N. S. Gourashi, and E. E. Eldukhri, "Automated configuration of gripper systems for assembly tasks," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 221, no. 11, pp. 1643–1649, 2007.

[12] K. Harada, T. Tsuji, S. Uto, N. Yamanobe, K. Nagata, and K. Kitagaki, "Stability of soft-finger grasp under gravity," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 883–888, IEEE, 2014.

[13] M. Ciocarlie, C. Lackner, and P. Allen, "Soft finger model with adaptive contact geometry for grasping and manipulation tasks," in *Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)*, pp. 219–224, IEEE, 2007.

[14] K. Harada, T. Tsuji, K. Nagata, N. Yamanobe, K. Maruyama, A. Nakamura, and Y. Kawai, "Grasp planning for parallel grippers with flexibility on its grasping surface," in *2011 IEEE International Conference on Robotics and Biomimetics*, pp. 1540–1546, IEEE, 2011.

[15] A. Bicchi and V. Kumar, "Robotic grasping and contact: A review," in *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No. 00CH37065)*, vol. 1, pp. 348–353, IEEE, 2000.

[16] R. M. Murray, *A mathematical introduction to robotic manipulation*. CRC press, 2017.

[17] M. Honarpardaz, M. Meier, and R. Haschke, "Fast grasp tool design: From force to form closure," in *2017 13th IEEE Conference on Automation Science and Engineering (CASE)*, pp. 782–788, IEEE, 2017.

[18] H. Song, M. Y. Wang, and K. Hang, "Fingertip surface optimization for robust grasping on contact primitives," *IEEE Robotics and Automation Letters*, vol. 3, no. 2, pp. 742–749, 2018.

[19] A. Rodriguez and M. T. Mason, "Effector form design for 1dof planar actuation," in *2013 IEEE International Conference on Robotics and Automation*, pp. 349–356, IEEE, 2013.

[20] O. Taylor and A. Rodriguez, "Optimal shape and motion planning for dynamic planar manipulation," *Autonomous Robots*, vol. 43, no. 2, pp. 327–344, 2019.

[21] N. Chavan-Dafle, M. T. Mason, H. Staab, G. Rossano, and A. Rodriguez, "A two-phase gripper to reorient and grasp," in *2015 IEEE International Conference on Automation Science and Engineering (CASE)*, pp. 1249–1255, IEEE, 2015.

[22] L. Birglen and T. Schlicht, "A statistical review of industrial robotic grippers," *Robotics and Computer-Integrated Manufacturing*, vol. 49, pp. 88–97, 2018.

[23] K. Hermann, R. Hostettler, M. Zimmermann, and A. V. Sureshbabu, "A joint-selective robotic gripper with actuation mode switching," in *2019 IEEE 15th International Conference on Automation Science and Engineering (CASE)*, pp. 1532–1539, IEEE, 2019.

[24] A. Kramberger, A. Wolniakowski, M. H. Rasmussen, M. Munih, A. Ude, and C. Schlette, "Automatic fingertip exchange system for robotic grasping in flexible production processes," in *2019 IEEE 15th International Conference on Automation Science and Engineering (CASE)*, pp. 1664–1669, IEEE, 2019.

[25] K. Harada, K. Nakayama, W. Wan, K. Nagata, N. Yamanobe, and I. G. Ramirez-Alpizar, "Tool exchangeable grasp/assembly planner," in *International Conference on Intelligent Autonomous Systems*, pp. 799–811, Springer, 2018.

[26] K. Nakayama, W. Wan, and K. Harada, "Designing grasping tools for robotic assembly based on shape analysis of parts," in *2019 IEEE-RAS 19th International Conference on Humanoid Robots (Humanoids)*, pp. 1–7, IEEE, 2019.

[27] C. Goldfeder, P. K. Allen, C. Lackner, and R. Pelossof, "Grasp planning via decomposition trees," in *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pp. 4679–4684, IEEE, 2007.

[28] M. R. Cutkosky *et al.*, "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.

[29] L. Shapira, A. Shamir, and D. Cohen-Or, "Consistent mesh partitioning and skeletonisation using the shape diameter function," *The Visual Computer*, vol. 24, no. 4, p. 249, 2008.

[30] The CGAL Project, *CGAL User and Reference Manual*. CGAL Editorial Board, 5.0.2 ed., 2020.

[31] A. Shamir, "A survey on mesh segmentation techniques," in *Computer graphics forum*, vol. 27, pp. 1539–1556, Wiley Online Library, 2008.

[32] P. Cignoni, M. Callieri, M. Corsini, M. Dellepiane, F. Ganovelli, and G. Ranzuglia, "MeshLab: an Open-Source Mesh Processing Tool," in *Eurographics Italian Chapter Conference* (V. Scarano, R. D. Chiara, and U. Erra, eds.), The Eurographics Association, 2008.

[33] H. Mosemann and F. M. Wahl, "Automatic decomposition of planned assembly sequences into skill primitives," *IEEE transactions on Robotics and Automation*, vol. 17, no. 5, pp. 709–718, 2001.

[34] N. Yamanobe, W. Wan, I. G. Ramirez-Alpizar, D. Petit, T. Tsuji, S. Akizuki, M. Hashimoto, K. Nagata, and K. Harada, "A brief review of affordance in robotic manipulation research," *Advanced Robotics*, vol. 31, no. 19-20, pp. 1086–1101, 2017.

[35] W. Wan, K. Harada, and F. Kanehiro, "Planning grasps for assembly tasks," *arXiv preprint arXiv:1903.01631*, 2019.

[36] T. Le and Y. Duan, "A primitive-based 3d segmentation algorithm for mechanical cad models," *Computer Aided Geometric Design*, vol. 52, pp. 231–246, 2017.