*International Journal of Latest Engineering Research and Applications (IJLERA) ISSN: 2455-7137*

*Volume – 03, Issue – 05, May 2018, PP – 18-29*

# Simplified Geometric Models for Clarifying Skill-Based Manipulation

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**Abstract:** Dexterous and reliable manipulation plays an important role in working robots. Manipulator tasks such as assembly of objects and operation of tools can generally be divided into several motion primitives. We call these "skills" and explain how most manipulator tasks can be composed of skill sequences. Skills are also used to compensate for errors both in the geometric model and in manipulator motions. There are dispensable data in the shapes, positions and orientations of objects that are not required to achieve skill motions in a task. Therefore, we can simplify geometric models by considering the dispensable data in a given skill motion. This paper proposes a method using simplified geometric modeling to easily understand skill-based manipulation involving high-level techniques. The procedures can clarify which parts of objects change at each step of a manipulation task. This method can also be applied to error recovery techniques for the overall manipulation system, since when the scope to be observed at each step of a task becomes clear, reliability improves.

**Keywords:** Manipulation skill, Planning, Geometric model, Simplified model, Visual sensing, Error recovery

## I. INTRODUCTION

In recent years, attention has focused on technologies enabling work to be performed by robots instead of people. For robots with manipulators to be useful in several fields, it is necessary for them to be able to successfully perform various tasks using special techniques. By analyzing human motions in typical tasks such as assembly and disassembly, we found that movements consisted of several significant motion primitives. We call these "skills" and have shown that most tasks of a manipulator can be composed of sequences of skills [1]–[4]. We have demonstrated that robots are capable of performing various tasks substituting for a human using the concept of skills. We proposed a fine motion planning method for various tasks that were composed of several skills [5]–[7] and showed that general and skillful planning can be derived with ease.

There are very many kinds of manipulation skills with respect to the tasks performed by robots. However, skills in which the contact states vary during assembly and disassembly tasks are particularly significant. We selected three skills, "move-to-touch," "rotate-to-level" and "rotate-to-insert," all of which play an important part in such tasks [1]–[5]. Most assembly tasks are composed of these three skills.

Skill technique is also used to compensate for errors both in geometric modeling and in motion planning. The move-to-touch skill can cancel model errors in the direction of the transition. Similarly, the rotate-to-level skill and the rotate-to-insert skill can cancel model errors in the direction of rotation. Furthermore, we can derive simplified geometric models by allowing for a maximum error or margin in a task composed of skill motions [8], [9]. In skill-based manipulation to operate a grasped object, the modeling of an object, including the goal that the grasped object will reach, can have margins for the shape, position and orientation. Therefore, models can be constructed simply using only the data necessary in planning for manipulation and in visual sensing for model matching. Since less data with respect to shapes, positions and orientations of the objects is needed, planning and visual sensing is easier.

Our method involves a manipulation system based on sequences of skill primitives. Manipulation techniques based on component processes of a task have also been reported as a discrete-event system [10]–[12]. However, those studies are not related to the simplification of geometric models.

We have considered a method to facilitate planning and sensing by deriving a simplified model of part of an object including the goal in skill-based manipulation. In this paper, we propose simplified models for all parts of objects concerned in the manipulation task. Our development can clarify which parts of objects change at each step of skill-based manipulation. Therefore, it becomes easy to understand skill-based manipulation with complex and high-level techniques. Moreover, this method will be applied to error recovery techniques, which we have previously reported [13], [14], since the method clarifies the scope that must be observed at each step of a manipulation task. Therefore, our method will contribute to reliable manipulation.

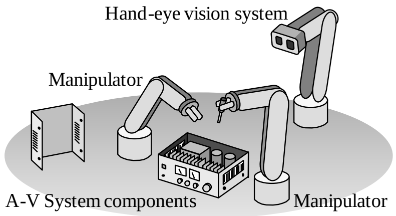



Fig. 1 Maintenance robot for audio-visual system components

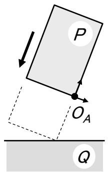



Fig. 2 Move-to-touch skill

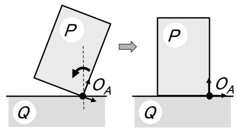



Fig. 3 Rotate-to-level skill

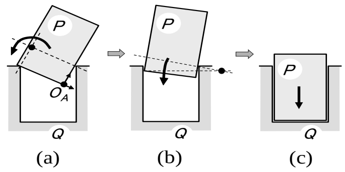



Fig. 4 Rotate-to-insert skill

The next section explains manipulation skills, the composition of skill sequences and the manner of arranging the visual sensing, geometric modeling, planning and execution of a task. Simplified models in planning and visual sensing with respect to an object including the goal are defined in section 3. The simplified model applied for every part of the objects in the working environment of the robot is shown in section 4. Additionally, an example of a task involving mechanical parts is shown in section 5. Our method assumes that a hand-eye vision system on a manipulator (Fig. 1) is used. With such a setup, it is possible to obtain the necessary data for constructing the simplified models.

## II. MANIPULATION SKILLS AND CONSTRUCTION OF TASKS

This section explains our concept of skills and the processes to perform tasks composed of skills. See References [1]–[4] for more details.

### 2.1 Skill primitives

In assembly and disassembly tasks, skills in which the contact states vary are particularly significant. In References [5]–[7], we considered three skills, "move-to-touch," "rotate-to-level" and "rotate-to-insert," all of which play an important part in such tasks. For simplicity, we assume that the grasped object, another object and the hole are rectangular parallelepipeds. Furthermore, we view these skill motions as occurring in a two-dimensional environment to easily explain them, though the same skills can be defined in a three-dimensional environment.

**(1) Move-to-touch Skill**

The move-to-touch skill is defined as the transition of a grasped object *P* in a constant direction that continues until contact with another object *Q* occurs (Fig. 2). This skill is performed in a velocity control mode. This skill includes not only transition in free space, but also sliding while maintaining contact in a different direction of motion. The achievement of this skill can be detected by instantaneously increased resistance in the direction of the transition.

**(2) Rotate-to-level Skill**

The rotate-to-level skill is defined as rotation around either a contact point or a contact edge to match the face of the grasped object *P* with the face of another object *Q* (Fig. 3). This skill is performed with a pushing force. The achievement of this skill can be detected by the change of the instantaneous center position.

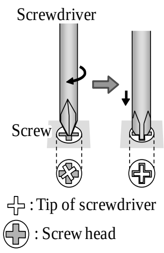



Fig. 5 Rotate-to-bite skill

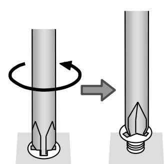


Fig. 6 Rotate-to-loosen skill

**(3) Rotate-to-insert Skill**

In an insertion task it is generally difficult to directly achieve the state in Fig. 4(b) when the clearance is small. The state in Fig. 4(a) is achieved first by using other skills, such as a skill sequence composed of move-to-touch skills. The state in Fig. 4(b) is accomplished next by gradually raising the object while maintaining contact as in Fig. 4(a). The rotate-to-insert skill is the motion of rotating the object $P$ obliquely into a hole in another object $Q$ to insert it accurately. In our study, we assume that the rotate-to-insert skill also includes the pressing motion required to achieve the goal of the insertion task (Fig. 4(c)). The achievement of the rotate-to-insert skill is detected by the change of the instantaneous enter position.

We will also consider two other skills related to the tasks in the examples described later. In these two skills, we use a crosshead screwdriver and screw as examples.

**(4) Rotate-to-bite Skill**

This skill is a rotation around the axis of the screwdriver to fit the tip of the screwdriver into the flutes of the screw head (Fig. 5). This skill is performed with pushing force.

**(5) Rotate-to-loosen Skill**

This skill is defined as a rotation to loosen the screw (Fig. 6). This is performed by matching the axes of rotation of the part (screw) to be loosened and the tool (screwdriver) used. If these axes do not correspond, the tool is moved to the position before the rotation was executed. In this paper, we assume that this skill also includes the transition to remove an error before rotating.

### 2.2 Composition of Skill Sequence

A specific assembly task is composed of sequences of skill primitives such as move-to-touch, rotate-to-level and rotate-to-insert skills. The skill sequences can be decided by several methods. We have previously demonstrated a method using variations of the number of contact points in skill primitives [5]. Many other researchers have generated skill sequences by taking geometric constraints into account [15]–[17] and derived the appropriate sequence using Petri nets [18], [19]. In most of these studies, however, assembly performed by manipulation robots is not taken into account. It is necessary to compose the skill sequences using motion primitives that can be performed by a manipulator.

### 2.3 Process of Sensing, Modeling, Planning and Execution

To accurately execute a task based on skills, it is important to clarify the processes of sensing, modeling, planning and execution [8], [9]. If range data acquired by a vision system is obtained correctly and the environment model is constructed accurately, overall manipulation planning could be performed only by initial visual sensing. In reality, however, visual sensing errors cannot be ignored. Therefore, visual sensing and modeling should be performed at each step just before planning the task and skills. The procedures for sensing, modeling, planning and execution are shown in Fig. 7. In this scheme, the planning of the task level is first performed, and then the executions of the skill level are performed according to sequences derived from the task planning.

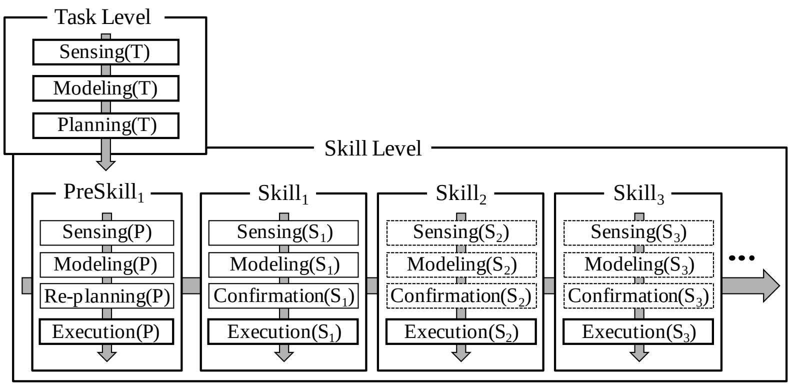



Fig. 7 Process flow

**(Step 1) Task Level**

At the task level, the skill sequence composing the task is decided. First, visual sensing of the working environment of the manipulation robot is performed using a vision system and geometric modeling is done. Next, motion planning of the robot follows, and the skill command sequences and the initial position and orientation of the grasped object are derived.

Measurement and modeling at this level decide the global arrangement of objects in the working environment of the robot. Since rough global data are used, the environment model often has some uncertainty. The motion planning derived at this task level may likewise have some uncertainty.

**(Step 2) Skill Level**

At the skill level, each skill in the command sequence $\{Skill_1, Skill_2, \ldots\}$ is executed successively. Before this sequence is performed, the transition of the grasped object $P$ to the initial state is done. We represent the transition as $PreSkill_1$.

**(2.1) $PreSkill_1$**

First, visual sensing of the object $Q$ including the goal is performed as close as possible from the direction of motion of the grasped object $P$ in $Skill_1$. Second, geometric modeling of the object $Q$ is performed. Third, planning is performed. Since precise local data is used, planning can be performed more precisely. During this re-planning, the exact start state is derived. Next, the transition to the initial state is executed. In addition, $PreSkill_1$ may often be expressed as $Skill_0$ for a unified notation to the following $Skill_i \{i = 1, 2, \ldots\}$.

**(2.2) $Skill_i \{i = 1, 2, \ldots\}$**

In this step, the sensing, modeling and execution of each skill in the command sequence are performed. Next, the same processes are performed for each $Skill_i \{i = 2, 3, \ldots\}$. Sensing, modeling and confirmation with respect to $Skill_i$ can be omitted if the grasped object $P$ is always in the initial state of $Skill_i \{i = 2, 3, \ldots\}$ when $Skill_{i-1}$ is achieved.

## III. SIMPLIFIED MODELS BASED ON SKILLS

This section explains simplified models in planning and in visual sensing and model matching, with respect to the objects $Q$ including the goal. Additionally, examples of simplified models of screws are shown in the task of loosening a screw using a screwdriver.

### 3.1 Concept of Simplified Models Based on Skills

It is possible to compensate for errors both in the geometric modeling and in the manipulator planning by using the concept of skills. For example, in the move-to-touch skill, errors in the direction of the transition can be canceled. Similarly, in the rotate-to-level skill and the rotate-to-insert skill, errors in the direction of rotation can be canceled. Furthermore, simplified geometric models can be derived by allowing for a maximum error or margin in most skill motions.

In planning for manipulation and visual sensing for model matching, it is not necessary to use geometric models that express real objects completely. By constructing geometric models using only the data necessary for planning and visual sensing, it is possible to facilitate these processes. We have shown how to simplify the processes of planning and visual sensing by using simplified models *(SM)* of the objects $Q$ in [8], [9]. (The *SM* we use in this paper is similar to what is called *FM* in [8], [9].) Simplified models in planning and in visual sensing are defined as follows.

**(1) Simplified models for planning**

Simplified models for planning *(SMP)* are geometric models composed only of the necessary and minimum data for shape, position and orientation to perform skill-based planning.

**(2) Simplified models for visual sensing and model matching**

Simplified models for visual sensing and model matching *(SMV)* are geometric models composed only of the necessary and minimum data for shape, position and orientation to perform model matching. Simplified models in planning *(SMP)* are constructed from the data of simplified models in visual sensing and model matching *(SMV)*.

Simplified models *SMP*, *SMV* can be obtained for object $Q$ in each skill primitive $Skill_i \{i = 0, 1, 2, \ldots\}$. We will often express simplified models for planning in $Skill_i$ using $SMP(Q)_i$. Similarly, we will express the simplified models for visual sensing and model matching in $Skill_i$ using $SMV(Q)_i$.

## 3.2 Simplified Model of a Part in a Task of Loosening a Screw Using a Screwdriver

We will consider the task of loosening a screw using a screwdriver [8], [9]. Although there are many kinds of screws and screwdrivers as shown in the left columns of Table 1 [20], we will consider this task by unifying the skill sequences in the following examples.

We assume that the task of loosening a screw using a screwdriver is composed of the following skills.

$Skill_1$ : Move-to-touch skill
$Skill_2$ : Rotate-to-bite skill
$Skill_3$ : Rotate-to-loosen skill

Next, we will consider the simplified models of screws used in each skill primitive $Skill_i \{i = 0, 1, 2, 3\}$.

### 3.2.1 Case of a crosshead screw

The task for a crosshead screw (Table 1(a), (b)) is performed as shown in Fig. 8. $Skill_1$ is achieved if the tip of the screwdriver enters a groove near the center of the screw head. The simplified model for planning $SMP_1$ in $Skill_1$ is described by the shape of the groove (Table 1(a), (b)). The shape becomes a circle to eliminate any dependency on the relative orientations of the screw and the screwdriver. The radius in a rare Reed and Prince screw which has little clearance (Table (b)) is smaller than that in a typical Phillips screw (Table 1(a)). The region of the initial state of the move-to-touch skill of $Skill_1$ is obtained as a set of trajectories projected inversely from this circle. The simplified model for visual sensing and model matching $SMV_1$ in $Skill_1$ is described by the outside circle of the screw head (Table 1(a), (b)). The position and orientation of the circle of $SMP_1$ is derived from data of the circle of $SMV_1$ obtained by visual sensing. Simplified models $SMP_i$, $SMV_i$ in $Skill_i \{i = 2, 3\}$ are not needed since these can be executed continuously (Table 1(a), (b)). Additionally, simplified models $SMP_0$, $SMV_0$ in $PreSkill_1$ ($Skill_0$) are similar to the simplified models $SMP_1$, $SMV_1$ in $Skill_1$ since $Skill_0$ is the motion of transition to the initial region of $Skill_1$.

### 3.2.2 Case of a slotted screw

The task for a slotted screw (Table 1(c)) is performed as shown in Fig. 9. The simplified model $SMP_1$, $SMV_1$ in $Skill_1$ is described by a flute (Table 1(c)) since it is necessary to check the relative positions and orientations of both the screw and the screwdriver. There is a little leeway in the direction of the flute. The simplified model $SMP_2$, $SMV_2$ in $Skill_2$ is not needed (Table 1(c)) since $Skill_2$ is meaningless (Fig. 9). The axes of the rotations of the screw and the screwdriver must correspond for the achievement of $Skill_3$. Therefore, the simplified model for planning $SMP_3$ in $Skill_3$ can be described by the center of the circle (Table 1(c)). The position of the center is derived from the outside circle of the screw head, which means the simplified model for visual sensing and model matching $SMV_3$ in $Skill_3$ (Table 1(c)). Simplified models $SMP_0$, $SMV_0$ in $PreSkill_1$ ($Skill_0$) are similar to the simplified models $SMP_1$, $SMV_1$ in $Skill_1$.

### 3.2.3 Cases of Robertson, hex-drive, and two-hole screws

The procedure of the task for these screw types (Table 1 (d), (e), (f)) is the same as for a crosshead screw (Fig. 8). Simplified models $SMP_i$, $SMV_i$ in $Skill_i \{i = 0, 1\}$ take the shape of grooves since it is necessary to equalize the positions and orientations of both the screw and the screwdriver. Simplified models $SMP_i$, $SMV_i$ in $Skill_i \{i = 2, 3\}$ are not needed (Table 1 (d), (e), (f)).

### 3.2.4 Case of a cross and slotted screw

The cross and slotted screw (Table 1(g)) has two kinds of simplified models. Simplified models correspond to a crosshead screw when using a crosshead screwdriver, or to a slotted screw when using a slotted screwdriver (Table 1(g)).

# IV. SIMPLIFIED MODELS FOR EVERY PART IN THE WORKING ENVIRONMENT

We have considered a simplified model only with respect to the object $Q$ including the goal, which is the arrival region of the grasped object $P$. However, it is actually necessary to extend the processes explained in section 3 since many objects may be operated using various skill techniques in typical manipulation tasks. In this section, a simplified model will be considered for every part of the objects in the working environment of a manipulation robot. Going through the procedure can clarify which parts of which objects change at each step in which a given skill is performed. It becomes easy to understand it intuitively, since simplified models are expressed only in the information that is necessary for the process of transition.

Table 1 Simplified models in loosening a screw using a screwdriver

| Type of screw | | RO | Type of screwdriver used | PreSkill$_1$ (Skill$_0$) | | Skill$_1$ | | Skill$_2$ | | Skill$_3$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $SMP_0$ | $SMV_0$ | $SMP_1$ | $SMV_1$ | $SMP_2$ | $SMV_2$ | $SMP_3$ | $SMV_3$ |
| I | (a) Phillips | | | | | | | Not needed | Not needed | Not needed | Not needed |
| | (b) Reed and Prince | | | | | | | Not needed | Not needed | Not needed | Not needed |
| II | (c) Slotted | | | | | | | Not needed | Not needed | | |
| III | (d) Robertson | | | | | | | Not needed | Not needed | Not needed | Not needed |
| | (e) Hex-drive | | | | | | | Not needed | Not needed | Not needed | Not needed |
| | (f) Two-Hole | | | | | | | Not needed | Not needed | Not needed | Not needed |
| IV | (g) Cross & slotted | | | | | | | Not needed | Not needed | Not needed | Not needed |
| | | | or | | | | | Not needed | Not needed | | |

*RO* : Real objects
$SMP_i$ : Simplified models for planning in $Skill_i$
$SMV_i$ : Simplified models for visual sensing and model matching in $Skill_i$

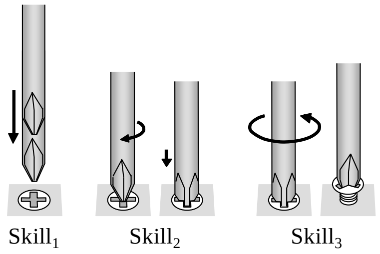



Fig. 8 Skill sequence of loosening with a crosshead screwdriver

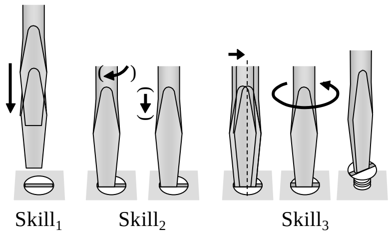



Fig. 9 Skill sequence of loosening with a slotted screwdriver

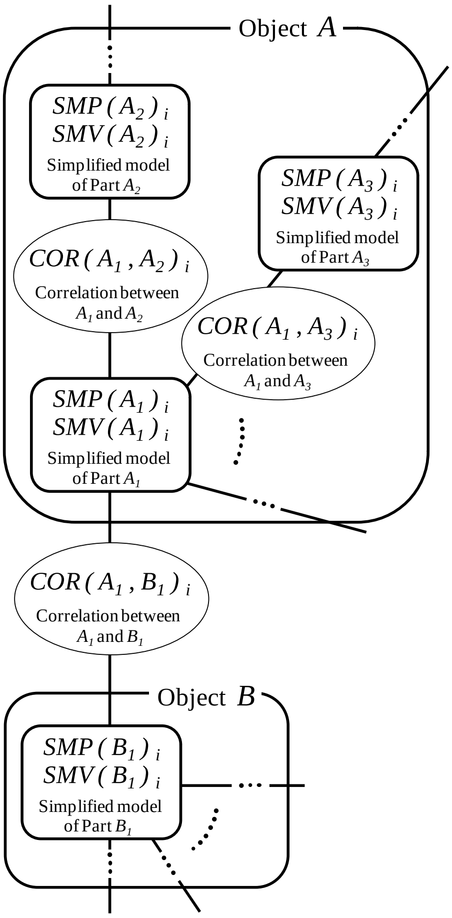
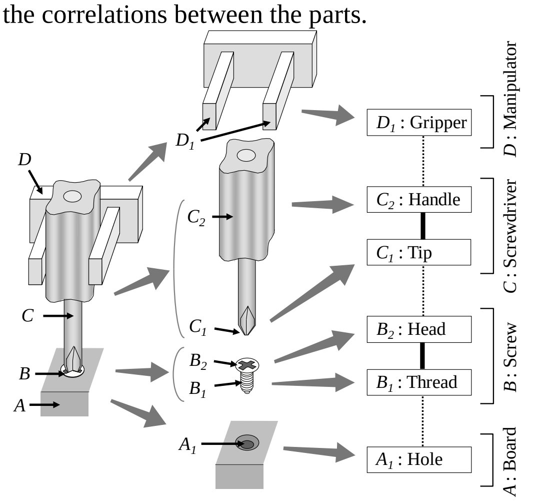



Fig. 10 Model expression based on parts of objects in $Skill_i$

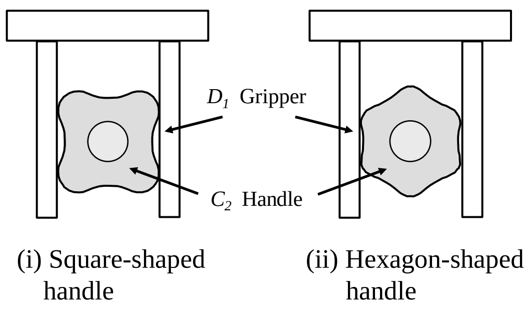
We will consider that there are objects $X \{X = A, B, C, \ldots\}$ in the working environment of the robot, where the objects $X$ consist of parts $X_j \{j = 1, 2, \ldots\}$. Fig. 10 shows that object $A$ consists of parts $A_j \{j = 1, 2, \ldots\}$ and object $B$ consists of parts $B_j \{j = 1, 2, \ldots\}$. There are various methods for dividing the parts of objects. In many methods, the division of objects into parts is performed based on changes of shapes [21]–[23]. The method of dividing based on function is also important [24]–[26] and is suitable for skill-based manipulation in which changes of states with movement are observed. For each part $X_j \{j = 1, 2, \ldots\}$ divided by such methods, a simplified model $SMP(X_j)_i$, $SMV(X_j)_i$ is derived in each skill primitive $Skill_i \{i = 0, 1, 2, \ldots\}$, by using the procedures explained in section 3.

We also consider the correlations between the parts in a given object and between the parts of adjacent objects. We will express the correlation between two parts $A_j$, $A_k \{j, k = 1, 2, \ldots, j \neq k\}$ in an object $A$ using $COR(A_j, A_k)_i$ in each skill primitive $Skill_i \{i = 0, 1, 2, \ldots\}$, as shown on a link between the parts $A_j$ and $A_k$ in Fig. 10. Similarly, $COR(A_j, B_k)_i$ means a correlation between two parts $A_j$ and $B_k$ of adjacent objects $A$, $B$, as shown on a link between the objects $A$ and $B$ in Fig. 10. There are various states such as fixation, movable contact and non-contact, with respect to the correlation. For example, regarding the movable contact between two parts in the same object, we will be able to use the concept of a kinematic pair, such as a turning pair, screw pair, sliding pair and spherical pair [27], [28]. Furthermore, a change of state of the correlation in a skill can also occur, for example, the change of state from non-contact to contact in the move-to-touch skill. It becomes easier to understand which part changes and how it changes by considering not only the simplified models of parts but the correlations between the parts.



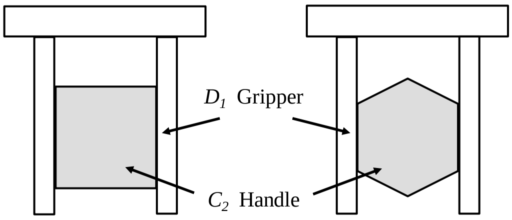

(a) Tools used in loosening task (b) Tools divided into parts (c) Correspondence between parts and tools

Fig. 11 Parts composing tools used in task of loosening a screw using a screwdriver




(i) Square-shaped handle (ii) Hexagon-shaped handle

(a) Relationships of real objects




(i) Square-shaped handle (ii) Hexagon-shaped handle

(b) Relation of simplified models

Fig. 12 Relation between $C_2$ Handle of screwdriver and $D_1$ Gripper of manipulator

## V. SIMPLIFIED MODEL OF EVERY OBJECT RELATED IN THE TASK OF LOOSENING A SCREW USING A SCREWDRIVER

### 5.1 Division into Parts of the Objects Related to Tasks

We will consider the task of loosening a screw using a screwdriver, while taking into account not only the screw but the gripper of the manipulator, the screwdriver, and the hole of the board (Fig. 11(a)). Fig. 11(b) shows the parts that are obtained by dividing every object related in the task by function. The screw is divided into a part which can be thrust into a hole by rotation and a part which can be connected to a screwdriver. The screwdriver is divided into a part which can be connected to a screw and a part which can be grasped by gripper. Fig. 11(c) shows the relationships between objects $X$ and parts $X_j$ $\{j = 1, 2, \ldots\}$.

There are various shapes of screwdriver handles depending also on the tool size and gripper. For example, a small screwdriver often has a square-shaped handle, and a large screwdriver typically has a hexagon-shaped handle. The relationship between the handle of the screwdriver and the gripper of the manipulator is illustrated in Fig. 12(a), and the simplified models of these handles *SMP*, *SMV* are shown in Fig. 12(b).

### 5.2 Simplified Model of Every Part Related in the Task of Loosening a Screw Using a Screwdriver

To show the above-mentioned content concretely, we will consider the simplified models of the parts of objects in each skill primitive of the task of loosening a screw using a crosshead screwdriver and a slotted screwdriver. The skill sequence consists of the move-to-touch skill ($Skill_1$), rotate-to-bite skill ($Skill_2$) and rotate-to-loosen skill ($Skill_3$), similarly to that described in section 3. Before $Skill_1$ is performed, the transition ($PreSkill_1$) of the screwdriver $C$ grasped by the manipulator $D$ to the initial state is performed. The skill sequence is illustrated in the upper row in Table 2 to Table 5. For the task using a crosshead screwdriver, Table 2 shows the simplified models for planning $SMP_i$, and Table 3 shows the simplified models in visual sensing and model matching $SMV_i$ in $Skill_i$ $\{i = 0, 1, 2, 3\}$. Likewise, for the task using a slotted screwdriver, Table 4 shows the same $SMP_i$ models, and Table 5 shows $SMV_i$ in $Skill_i$ $\{i = 0, 1, 2, 3\}$. The row of (a) in Table 1 corresponds to the rows of $SMP(B_2)_i$ in Table 2 and $SMV(B_2)_i$ in Table 3. Likewise, again, the row of (c) in Table 1 corresponds to the rows of $SMP(B_2)_i$ in Table 4 and $SMV(B_2)_i$ in Table 5. In these tables, $SMP(C_2)_i$, $SMV(C_2)_i$, $SMP(D_1)_i$ and $SMV(D_1)_i$ are omitted since these models do not change. Similarly, $COR(B_1, B_2)_i$, $COR(C_1, C_2)_i$ and $COR(C_2, D_1)_i$ are also omitted. Furthermore, simplified models are considered only with respect to a plane parallel to the screw head, since the task consists of transition that is parallel to the axis of the screwdriver and rotation around the axis of the screwdriver.

First, we will look at Table 2. In the planning of the task, Table 2 shows that only data of $SMP(B_2)_i$ and $SMP(C_1)_i$ in $Skill_i$ $\{i = 0, 1\}$ is important since we do not need to consider many models. If the planning is done correctly so that the tip of the screwdriver $C_1$ enters the groove on the screw head $B_2$ and if each skill is performed accurately, this task will succeed. Although there is little required model data, we can see the various motions in each skill using the outlines of the behaviors, such as the specific skill and concrete kinematic pair shown in the correlations $COR(A_1, B_1)_i$ and $COR(B_2, C_1)_i$, except for the cases of “Fixed”.

Secondly, we will consider Table 3 in which the simplified models for visual sensing and model matching are illustrated. Table 3 also shows that only data of $SMV(B_2)_i$ and $SMV(C_1)_i$ in $Skill_i$ $\{i = 0, 1\}$ is essential. The circles $SMV(B_2)_i$ and $SMV(C_1)_i$ $\{i = 0, 1\}$ obtained from the sensing data of the vision system are used to derive the position and orientation of the circles $SMP(B_2)_i$ and $SMP(C_1)_i$ $\{i = 0, 1\}$, respectively. The other elements in Table 3 are similar to those in Table 2.

Thirdly, we will look at Table 4 and Table 5. In the planning of the task, Table 4 shows that data of $SMP(B_2)_i$ and $SMP(C_1)_i$ in $Skill_i$ $\{i = 0, 1, 3\}$ is indispensable. If the planning is correctly done so that the tip of the screwdriver $C_1$ enters the slot on the screw head $B_2$ and that the center of the tip of the screwdriver coincides with the center of the screw head during rotation for loosening and if each skill is performed accurately, this task will succeed. The data of $SMV(B_2)_i$ and $SMV(C_1)_i$ $\{i = 0, 1, 3\}$ in Table 5 derived by visual sensing are used to decide the position and orientation of model of $SMP(B_2)_i$ and $SMP(C_1)_i$ $\{i = 0, 1, 3\}$, respectively. Therefore, the data can be used to image various motions in each skill with the aid of the behaviors shown in correlations $COR(A_1, B_1)_i$ and $COR(B_2, C_1)_i$, except for the cases of "Fixed".

## VI. CONCLUSION

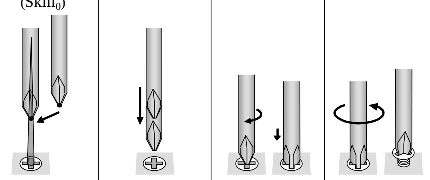
We have shown a method of using simplified models for every part of the objects in the working environment of a manipulation robot. Introduction of these procedures can clarify which parts of which objects change at each step in which a given manipulation skill is performed. The greatest advantage of our method is that it makes it easy to understand skill-based manipulation using high-level techniques. Furthermore, we considered not only simplification of models but also correlations between parts in objects, thus making it clearer to know which part changes and how it changes.

Simplified geometric models which we have explained in this paper can be constructed using only the data necessary in planning for manipulation and in visual sensing for model matching. Since less data with respect to shapes, positions and orientations of the objects is needed, planning and visual sensing becomes easier. Furthermore, we have shown an example of a simplified geometric model for every part in the task of loosening a screw using a screwdriver. In this example, we have represented that it's done easily to understand the skill-based manipulation task by using both models in planning and in visual sensing.

Our method also clarifies whether or not an execution result is correct in each manipulation skill. Another advantage of this method is that it can be applied to error recovery systems. The application to error recovery is important, since a recent manipulation task has become complicated. As such, our method will contribute to improving the reliability of manipulation tasks.

In the future, we will further study how to derive simplified models and the correlations between parts for various skill-based tasks. Other study themes include the division method of the model to parts which is most suitable for our technique. We must also attempt to apply our method to error recovery in real systems.

Table 2 Simplified models for planning in skill sequence of loosening with a crosshead screwdriver



| i | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| Skill $_i$ | Preskill$_1$ (Skill$_0$) | Skill$_1$ | Skill$_2$ | Skill$_3$ |
| ***SMP(C$_1$)$_i$*** Tip of Screwdriver | ○ | ○ | Not needed | Not needed |
| ***COR(B$_2$, C$_1$)$_i$*** Correlation between $B_2$ and $C_1$ | Transition | Transition Until touch | Rotating with pushing In contact | Fixed |
| ***SMP(B$_2$)$_i$*** Head of Screw | ○ | ○ | Not needed | Not needed |
| ***SMP(B$_1$)$_i$*** Thread of Screw | Not needed | Not needed | Not needed | Not needed |
| ***COR(A$_1$, B$_1$)$_i$*** Correlation between $A_1$ and $B_1$ | Fixed | Fixed | Fixed | *Screw pair* Rotating |
| ***SMP(A$_1$)$_i$*** Hole of Board | Not needed | Not needed | Not needed | Not needed |

Table 3 Simplified models for visual sensing and model matching in skill sequence of loosening with a cross-head screwdriver

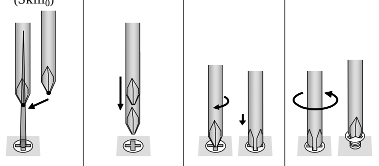
| i | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| Skill $_i$ | $Preskill_1$ ($Skill_0$)  | $Skill_1$ | $Skill_2$ | $Skill_3$ |
| ***SMV(C$_1$)$_i$*** Tip of Screwdriver | | | Not needed | Not needed |
| ***COR(B$_2$, C$_1$)$_i$*** Correlation between $B_2$ and $C_1$ | Translation | Translation, Until a touch | Rotating with pushing, In contact | Fixed |
| ***SMV(B$_2$)$_i$*** Head of Screw | | | Not needed | Not needed |
| ***SMV(B$_1$)$_i$*** Thread of Screw | Not needed | Not needed | Not needed | Not needed |
| ***COR(A$_1$, B$_1$)$_i$*** Correlation between $A_1$ and $B_1$ | Invisible, Fixed | Invisible, Fixed | Invisible, Fixed | *Screw pair*, Invisible, Rotating |
| ***SMV(A$_1$)$_i$*** Hole of Board | Not needed | Not needed | Not needed | Not needed |

Table 4 Simplified models for planning in skill sequence of loosening with a slotted screwdriver

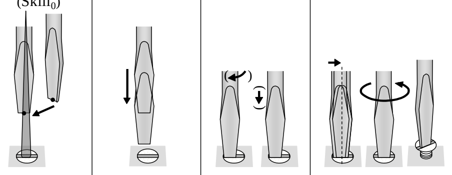
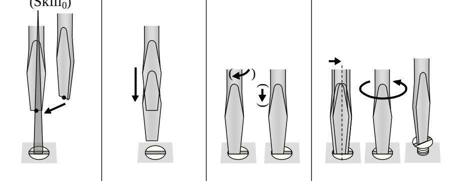
| i | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| Skill $_i$ | $Preskill_1$ ($Skill_0$)  | $Skill_1$ | $Skill_2$ | $Skill_3$ |
| ***SMP(C$_1$)$_i$*** Tip of Screwdriver | | | Not needed | |
| ***COR(B$_2$, C$_1$)$_i$*** Correlation between $B_2$ and $C_1$ | Transition, Rotating | Transition, Until touch | Rotating with pushing, In contact | Rotating after matching axes |
| ***SMP(B$_2$)$_i$*** Head of Screw | | | Not needed | |
| ***SMP(B$_1$)$_i$*** Thread of Screw | Not needed | Not needed | Not needed | Not needed |
| ***COR(A$_1$, B$_1$)$_i$*** Correlation between $A_1$ and $B_1$ | Fixed | Fixed | Fixed | *Screw pair*, Rotating |
| ***SMP(A$_1$)$_i$*** Hole of Board | Not needed | Not needed | Not needed | Not needed |

Table 5 Simplified models for visual sensing and model matching in skill sequence of loosening with a slotted screwdriver

| i | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| Skill $_i$ | Preskill$_1$ (Skill$_0$) | Skill$_1$ | Skill$_2$ | Skill$_3$ |
| |  | | | |
| ***SMV(C$_1$)$_i$*** Tip of Screwdriver | | | Not needed | |
| ***COR(B$_2$, C$_1$)$_i$*** Correlation between $B_2$ and $C_1$ | Transition Rotating | Transition Until touch | Rotating with pushing ( ) In contact | Rotating after matching axes |
| ***SMV(B$_2$)$_i$*** Head of Screw | | | Not needed | |
| ***SMV(B$_1$)$_i$*** Thread of Screw | Not needed | Not needed | Not needed | Not needed |
| ***COR(A$_1$, B$_1$)$_i$*** Correlation between $A_1$ and $B_1$ | Invisible Fixed | Invisible Fixed | Invisible Fixed | Invisible *Screw pair* Rotating |
| ***SMV(A$_1$)$_i$*** Hole of Board | Not needed | Not needed | Not needed | Not needed |

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