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Disassembling Process Inference Using Positional Relations Matrix for Complicated Machines

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Abstract

Disassembling of a part is required for maintenance of machinery in case. However, the disassembling process is often not explained in the operation manual, or the explanation of the disassembling does not cover all the situations of all the individual parts, even though, such disassembling could be dealt with by operators that are not familiar with the mechanism of machine. Operators themselves have to determine the disassembly process in such a case. Therefore, it is crucial to develop a system that helps inexperienced operators to find out a proper disassembling process. We focus on the disassembling of a specific part referred to as a target part. The approach is based on the positional relation information among the parts. The positional relations matrix that obtained from the contact states of any two parts in all possible directions and can be generated from the ordinary CAD data. This study proposed a method to infer a disassembly process of a specific part based on the positional relation matrix. The method deduces the disassembly process of the target part with the shortest steps, in the condition of one-part-at-a-time manner. We also introduced an integration of disassembling parts based on the obtained process. A case study was conducted and the result confirmed the feasibility of the proposed method; the effectiveness of the integration approach was also demonstrated.

Keywords: disassembling process, inference, positional relations matrix, maintenance support

1. Introduction

Machine disassembling is required in various situations, such as maintenance, repair, abolishment, and so on of existing machines. Disassemble of machine is often a complex task; however, such disassembling could be dealt with by operators that are not familiar with the mechanism of the machine. An improper disassembling operation may cause severe damage on the machine, or may result in injuries of operators or customers in case. Owing to the shortage of skilled engineers, ‘installation, maintenance, and repair occupations’ had about 400 fatalities per year for the past 20 years (that is in the 5th worst of major occupational groups) (U.S. Bureau of Labor Statistics, 2022).

Assembling and disassembling process are reversal operations; however, disassembling of a machine is more difficult than assembling in general (Vongbunyong and Chen, 2015). This is because the disassembling process is often not explained in the operation manual, or because the explanation of the disassembling does not cover all the situations of all the individual parts. Operators themselves have to determine the disassembly process in such a case. Therefore, it is crucial to develop a system that helps inexperienced operators to find out a proper disassembling process.

This study aims to develop an approach of disassembling process inference. There are a number of studies that deal with disassembling process generation. Due to the growing awareness of environmental and economic sustainability, a development of computer aided disassembly planning system was reported (Santochi et al., 2002). Zhu et al. (2013) proposed an information modeling for disassembly and optimal disassembly sequence generation. The approach is based on a linear programming-based optimization model and has dynamic capabilities by means of state-dependent information model. Go et al. (2012) deal with a method to find an optimal disassembly sequence beforehand in the product design phase, to increase the reusability. Parsa and Saadat (2019) introduced new optimization parameters that evaluate disassemblability in order to consider the difficulty and feasibility of the disassembly operation as the main objective functions; the genetic algorithm is employed to optimize the process sequence. Computer vision and machine learning technologies are applied for supporting assembly/disassembly operations in recent research (Brogan et al., 2021; Guo et al., 2023; Nakamura et al., 2023). Most of these studies address to generate or optimize full disassembly process, where a product is to be completely disassembled.

In the current study, we focus on the disassembling of a specific part referred to as a target part; that is, the objective is to generate a disassembling process for the removal of the target part from the assembled product. The approach is based on the positional relation information among the parts. The positional relations matrix (Shinoda et al., 2009; Hashimoto et al., 2016) is adopted. The matrix denotes the contact states of any two parts in all possible directions and can be generated from the ordinary CAD data. On the basis of the proposed approach, a unification of multiple parts in disassembling process can also be available; the unified parts are dealt with as a single unit in this case. An optimization of disassembling process taking into account this unification and disassembling steps is also conducted. The proposed approach is demonstrated with an example assembled product.

2. Determining Disassemblability Using a Positional Relations Matrix

2.1 Positional Relations Matrix

A positional relations matrix describes the position of each part in a finished product and distances between any two parts in the six directions — the positives and negatives of the *X*, *Y*, and *Z* axes — on a design drawing (Hashimoto et al., 2016). In this study, the positional relations matrix is modified to focus on the positional relations state between two parts instead of the distance. By classifying the positional relations state into three types and arranging in a matrix form, the list of all parts that impede the removal of other parts is organized.

For any two parts of the assembled product, we can assume on one part to be fixed and the other to be moved relatively to the fixed part. From a generality point of view, we can assume any number of directions for a part to be moved; however, for the sake of simplicity, we assume $m = 6$ relative directions, that is, *X*+, *X*–, *Y*+, *Y*–, *Z*+, and *Z*–, the six directions of orthogonal three axes in space, in this study.

We assume that the final product is consisting of n parts. Take two parts i and j (i, j = 1, 2, …, n) and if we consider part i to be fixed part and part j to be moved, the condition that part i impedes the movement of part j in the kth direction or not is determined by their positional relation. We denote the condition as follows:

$$\boldsymbol{M}_{ijk} = \begin{cases} 0 & i \text{ does not impede } j \text{ in direction } k (j \text{ can move in direction } k) \\ 1 & i \text{ impedes } j \text{ in direction } k \ \ (j \text{ cannot move in direction } k) \end{cases} \tag{1}$$

Note that $M_{ijk} = 1$ does not necessary indicate that parts i and j are in immediate contact; this only indicates that part i is just in the position of impeding the motion of part j in the kth direction. This is the positional relation matrix adopted in this study.

Table 1 shows the positional relations matrix of a sample assembled product shown in Fig. 1. For example, the first row in the Table 1 describes the conditions that the motion of part 2 is impeded or not by part 1 in each of the six directions. Part 2 can move freely in both *X*+ and *X*– directions; however, it cannot move in *Y*– direction since the part 1 impedes the motion.

Table 1. Positional relations matrix of the sample product shown in Fig.1

Fixed	Moved	Directions *k*					
i	*j*	1 (*X*+)	2 (*X*–)	3 (*Y*+)	4 (*Y*–)	5 (*Z*+)	6 (*Z*–)
1	2	0	0	0	1	0	1
1	3	0	0	0	1	0	0
1	4	1	1	0	0	1	1
1	5	1	1	0	0	1	1
2	1	0	0	1	0	1	0
2	3	0	0	0	1	0	0
2	4	1	1	0	0	1	1
2	5	1	1	0	0	1	1
3	1	0	0	1	0	0	0
3	2	0	0	1	0	0	0
3	4	1	1	0	0	1	1
3	5	1	1	0	0	1	1
4	1	1	1	0	0	1	1
4	2	1	1	0	0	1	1
4	3	1	1	0	0	1	1
4	5	0	0	0	0	1	0
5	1	1	1	0	0	1	1
5	2	1	1	0	0	1	1
5	3	1	1	0	0	1	1
5	4	0	0	0	0	0	1

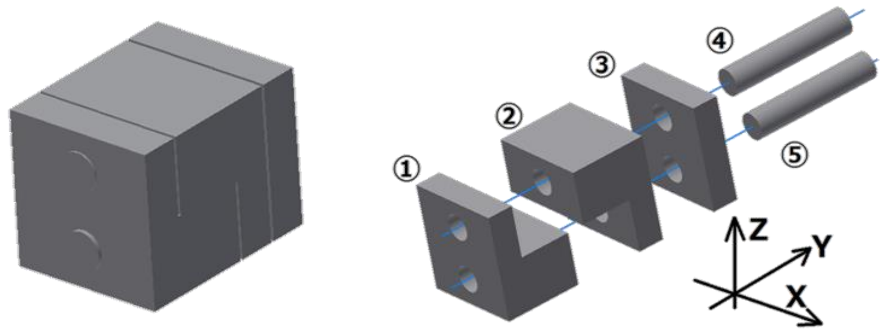

Figure 1. A sample structure that consists of five parts

2.2 Impeding Parts Set

On the basis of the positional relation matrix M_{ijk}, we can obtain the following information concerning the motion inhibition of part *j* in the *k*th direction:

$$\boldsymbol{P}(j,k) = \{\mathrm{i} \mid M_{ijk} = 1\} \tag{2}$$

referred to as the impeding parts set. Each of the elements in *P*(*j* ,*k*) corresponds to a part that impedes the motion of part *j* in the *k*th direction. For example, referring to the positional relation matrix shown in Table 1, the motion of part 1 in *Z*+ direction is impeded by parts 2, 4 and 5; that is, *P*(1, 5) = {2, 4, 5}, where the 5th direction corresponds to *Z*+. Both parts 4 and 5 can move in *Y*+ and *Y*– directions; that is, *P*(4, 3), *P*(4, 4), *P*(5, 3), and *P*(5, 4) are empty sets. It follows that *P*(*j*, *k*) = ∅ indicates part *j* is in the condition of immediately removable.

Table 2 shows the impeding parts set obtained from Table 1, that corresponds to the example product shown in Fig. 1. Each of matrix element indicates impeding parts set *P*(part, direction). Part 3 cannot move in *X*– direction since parts 4 and 5 impede the motion, thus, the element in the second column (*X*–) of the third row indicates {4, 5} for *P*(3, 2).

Table 2. Impeding parts set [$\boldsymbol{P}_{ij}$] for the sample structure

Part	Directions k					
j	1 (X+)	2 (X–)	3 (Y+)	4 (Y–)	5 (Z+)	6 (Z–)
1	4, 5	4, 5	2, 3		2, 4, 5	4, 5
2	4, 5	4, 5	3	1	4, 5	1, 4, 5
3	4, 5	4, 5		1, 2	4, 5	4, 5
4	1, 2, 3	1, 2, 3			1, 2, 3	1, 2, 3, 5
5	1, 2, 3	1, 2, 3			1, 2, 3, 4	1, 2, 3

2.3 Disassembly Process

We denote a t-step disassembly process as [(j_1, k_1), (j_2, k_2), …, (j_t, k_t)]; this means that firstly, part j_1 is removed from the product in the k_1th direction, secondly, part j_2 is removed in the k_2th direction, …, and finally, part j_t is removed in the k_tth direction. Based on the impeding parts sets previously obtained as P(j ,k) (j = 1, 2, …, n, k =1, …, m), the single step disassembly process set for the product is obtained as

$$A_1 = \{[(j_1, k_1)] \mid \mathrm{P}(j, k) = \varnothing\} \quad (1)$$

In the case of the example product shown in Fig. 1, referring to the impeding parts sets indicated in Table 2, we obtain

$$A_1 = \{[(1, 4)], [(3, 3)], [(4, 3)], [(4, 4)], [(5, 3)], [(5, 4)]\} \quad (4)$$

that is, part 1 can be immediately removed in the 4th (Y–) direction, and so on.

On the basis of the single step disassembly process set A_1, we obtain the two step disassembly process set as follows:

$$A_2 = \{[(j_1, k_1), (j_2, k_2)] \mid (j_1, k_1) \in A_1, P(j_2, k_2) \subseteq \{j_1\}\} \quad (5)$$

This equation expresses that all the impending parts of part j_2 in the k_2th direction, P(j_2, k_2), is listed in the disassembly process [(j_1, k_1)], that has already been obtained as a single step disassembly process in A_1; that is, removing part j_1 in the k_1 direction, part j_2 can be removed in the k_2th direction since its only impeding part in the direction is j_1. In the case of example product of Fig. 1 and Table 2, we obtain

$$A_2 = \{[(1, 4), (2, 4)], [(3, 3), (2, 3)]\} \quad (6)$$

that is, the two step processes are: remove part 1 in the 4th (Y–) direction and part 2 in the 4th (Y–) direction, and remove part 3 in the 3rd (Y+) direction, and part 2 in the 3rd (Y+) direction.

Deduction of disassembly process in this matter can be expressed in a general form for the t-step disassembly process set as:

$$A_t = \{[(j_1, k_1), ..., (j_{t-1}, k_{t-1}), (j_t, k_t)] \mid [(j_1, k_1), ..., (j_{t-1}, k_{t-1})] \in A_{t-1}, P(j_t, k_t) \subseteq \{j_1, ..., j_{t-1}\}\} \quad (7)$$

This equation means that all the impeding parts for part j_t in k_tth direction, $P(j_t, k_t)$ is listed in a (t–1)-step disassembly process [(j_1, k_1), ..., (j_{t-1}, k_{t-1})] in A_{t-1} and then j_t is to be remove in the k_tth direction.

This deduction is repeatedly performed until the target part j^* appears as j_t in the t-step disassembly process set A_t. An element of disassembly process in A_t, [(j_1, k_1), ..., (j_t, k_t)] such that $j_t = j^*$, is a disassembly process of least steps in the case of one-part-at-a-time disassembling. It should be noted that the t-step disassembly for target part j^* may not be unique; that is, there can be more than one disassembly process such that $j_t = j^*$, in A_t.

3. Integrating Plural Parts into a Group for More Efficient Disassembling Process

In general, the assembling of a mechanical product involves the process of assembling a group of several parts called intermediate products. Similarly, disassembling several parts as an integrated group of parts in the work process is possible. By integrating a number of parts into a group that can be dealt with as a single unit, the disassembly workflow can be made more efficient. The idea can be applied to the disassembly process expressed in the previous section.

Disassembly processes previously derived based on the positional relation matrix are expressed in one-part-at-a-time manner; that is, a process in t-step disassembly process set A_t consists of t steps of single part removal. However, a number of steps in such a process can be integrated into a single step, in the case that the following conditions are satisfied:

(i) The partial steps are consecutive in the disassembly process.

(ii) All the removal directions of the parts in the partial steps are identical.

(iii) All the parts in the partial steps are in physical contact.

These conditions are rewritten as follows. For a t-step disassembly process $[(j_1, k_1), ..., (j_t, k_t)]$, if there exist a consecutive steps $p, p+1, ..., q$ ($1 \leqq p \leqq q \leqq t$), where the removal directions are $k_p = k_{p+1} = ... = k_q$ and the parts j_p, $j_{p+1}, ..., j_q$ are in physical contact, then the parts $j_p, j_{p+1}, ..., j_q$ are dealt with as a single unit and to be removed in the k_pth direction in a single step as an integrated parts group.

We apply this integration to the example processes in the previous 2-step disassembly set A_2 for the product shown in Fig. 1, expressed in Eq. (6). Since parts 1 and 2 and parts 3 and 2 are both in physical contact, parts 1 and 2 can be disassembled simultaneously in a single step in the 4th (Y–) direction and parts 3 and 2 can similarly be disassembled in a single step in the 3rd (Y+) direction.

4. Disassembling Process Based on Positional Relations Matrix

The procedure of disassembling process inference developed based on the positional relation matrix in this study is summarized as follows:

(1) Prepare positional relations matrix M_{ijk}, where $i, j = 1, ..., n$ are part numbers and $k = 1, ..., m$ are the direction axes of removal.

(2) Generate the impeding parts sets $P(j, k)$ ($j = 1, ..., n$, $k = 1, ..., m$) based on M_{ijk}.

(3) Set $t = 1$ and make the single step disassembly process set A_1 based on $P(j, k)$. In other words, this is the list of combinations of part and direction of immediate removal.

(4) Set $t \leftarrow t+1$ and make t-step disassembly process set A_t based on A_{t-1} and $P(j, k)$.

(5) Repeat (4) until the target part j^* appears as the part j_t to be disassembled.

(6) We organize the set A_t* of disassembly processes corresponding to the target part, that are the disassembly processes in A_t such that $j_t = j$*.

(7) The integration of disassembling parts introduced in the previous section is conducted for disassembly process in A_t*.

In the case that there are more than one disassembly process in A_t*, we can select an optimal disassembly process based on an appropriate criterion.

5. Case Study

In order to examine the feasibility of the proposed disassembly process inference, we conduct a case study with a LEGO-based robot designed for the ET RoboCon competition (Hirayama, et al. 2020). A virtual LEGO block editor, LDCad (Roland Melkert, 2021), is adopted to make the assembled product model of the robot shown in Fig. 2. The robot consists of parts such as LEGO blocks, sensor units, and motors and runs on two front wheels and a single steel ball in the rear.

We deal with the disassembly process of the left arm of the robot as shown in Fig. 3. The X, Y, and Z axes and their + and – directions are indicated in Fig. 2 and 3. On the basis of the composition of parts shown in Fig. 3, the positional relation matrix of the left arm parts is organized as shown in Table 3. Accordingly, the impeding parts sets are obtained from the matrix are indicated in Table 4.

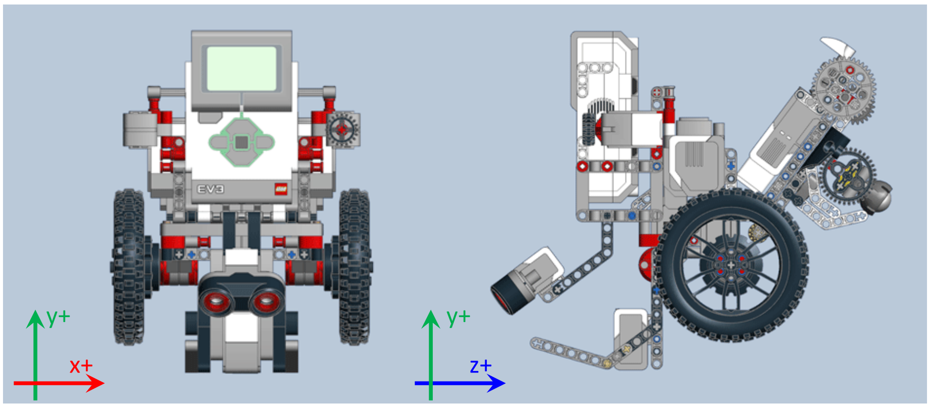

Figure 2. The model of target product

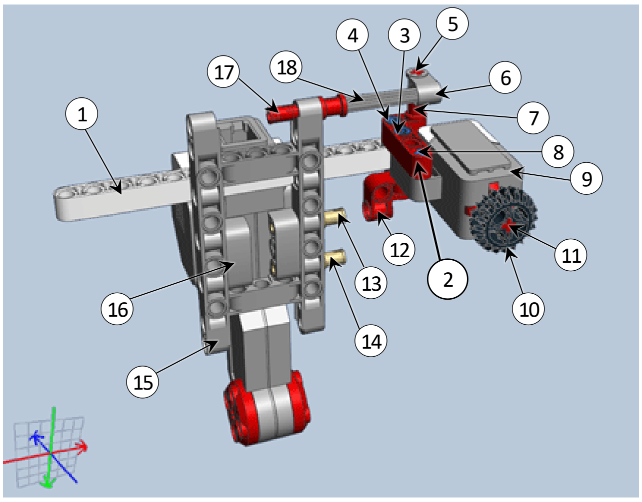

Figure 3. Target parts group

Table 3. Positional relations matrix of the left arm parts shown in Fig.3

Fixed	Moved	Directions *k*					
i	*j*	1 (*X*+)	2 (*X*–)	3 (*Y*+)	4 (*Y*–)	5 (*Z*+)	6 (*Z*–)
1	2	0	0	1	0	0	0
1	3	0	0	0	0	0	1
1	4	1	1	1	0	1	1
1	5	0	0	0	0	0	0
1	6	0	0	1	0	0	0
1	7	1	1	1	0	1	1
1	8	0	0	0	0	0	1
1	9	0	0	0	0	0	1
1	10	0	0	0	0	0	1
1	11	0	0	0	0	0	0
1	12	0	0	0	0	0	0
1	13	0	0	0	0	0	0
1	14	0	0	0	0	0	0
1	15	0	0	0	0	0	1
1	16	0	0	0	1	1	0
1	17	0	0	0	0	0	0
1	18	0	0	0	0	0	0
……	…	…	…	…	…	…	…
18	14	0	0	0	1	0	0
18	15	0	0	0	0	0	0
18	16	0	0	0	0	0	0
18	17	1	0	1	1	1	1

Table 4. Impeding parts sets [$\boldsymbol{P}_{ij}$] of the target parts group

Part *j*	Directions *k*					
	1 (*X*+)	2 (*X*–)	3 (*Y*+)	4 (*Y*–)	5 (*Z*+)	6 (*Z*–)
1	4, 7	4, 7	16	2, 4, 6, 7	3, 4, 7, 8, 9, 10, 15	4, 7, 16
2	3, 4, 7, 8, 9	3, 4, 7, 8, 15	1, 3, 4, 8, 9, 12	6, 7, 18	3, 4, 7, 8, 9, 10	3, 4, 7, 8
3	2, 9, 12	2, 9, 12, 15	9, 12	2, 18	2, 8, 9, 12	1, 2, 4, 9, 12
4	1, 2, 7	1, 2	1	2	1, 2, 3, 8, 9, 12	1, 2
5	6, 7	6, 7	7		6, 7, 18	6, 7
6	5	5, 15, 17	1, 2, 7, 9, 18	18	5, 18	5, 18
……	…	…	…	…	…	…

Let part 2, shown in the upper right of Fig 3, be the target part to be disassembled. The disassembly process inference is conducted based on the procedure described in the previous section, The single step disassembly process set is obtained based on the impeding parts set, which is partially shown in Table 4, and expressed as

$$A_1 = \{[(5, 4)], [(10, 5)], [(11, 5)], [(12, 3)], [(14, 1)], [(18, 1)]\} \tag{8}$$

The two-step disassembly process set obtained based on A_1 and the impeding parts sets is expressed as

$$A_2 = \{[(5, 4), (6, 1)], [(10, 5)], [(11, 5)], [(12, 3), (13, 1)], [(14, 1)], [(18, 1), (6, 4)]\} \tag{9}$$

The following multi-step disassembly process sets, A_3, A_4, ..., are accordingly obtained and the target part 2 appears in the 5-step disassembly process set,

$$A_5 = \{[(5, 4), (6, 1), (7, 4), (18, 1), (2, 4)], [(10, 5)], [(11, 5)], [(12, 3), (13, 1)], [(14, 1)], [(18, 1), (6, 4), (5, 4), (7, 4), (2, 4)]\} \tag{10}$$

Referring to A_5 in Eq.(10), the two 5-step disassembly processes for the target part 2 are obtained as [(5, 4), (6, 1), (7, 4), (18, 1), (2, 4)] and [(18, 1), (6, 4), (5, 4), (7, 4), (2, 4)]. The second one can be integrated since the intermediate disassembling steps (6, 4), (5, 4), (7, 4) satisfy the conditions of integration introduced in section 3. That is, the parts 5, 6, and 7 can be simultaneously disassembled in the 4th (*Y*–) direction. Taking into account this integration, the inferred disassembly process for part 2 is determined as shown in Table 5.

Table 5. Disassembling process

Step	Parts	Direction
1	18	1 (*X*+)
2	5, 6, 7	4 (*Y*-)
3	2	4 (*Y*-)

7. Conclusion

The disassembling process for a specific part of a product is required in some situations but often not prepared. In the current study, we proposed a method to infer a disassembly process of a specific part based on the positional relation matrix. The method deduces the disassembly process of the target part with the shortest steps, in the condition of one-part-at-a-time manner. We also introduced an integration of disassembling parts based on the obtained process. A case study was conducted and the result confirmed the feasibility of the proposed method; the effectiveness of the integration approach was also demonstrated. In this paper, we confined the disassembling directions to six, that is, the two directions in the three axes of *X*, *Y*, and *Z*, for the sake of simplicity and understandability; however, the proposed method is capable of dealing with more number of directions.

The disassembly process inference proposed in this study has several limitations including that a part has to be removed in a single movement and that the working space for disassembling tools such as screw driver is not taken into account. Expansion and generalization of the method to take into account these limitations are left as the future works.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

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The journal’s policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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