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(Citation)
International Journal of Automation Technology,17(2):167-175

(Issue Date)
2023-03-05

(Resource Type)
journal article

(Version)
Version of Record

(URL)
https://hdl.handle.net/20.500.14094/0100481860

https://doi.org/10.20965/ijat.2023.p0167

Research Paper:

Automated Generation of Product Assembly Order Based on Geometric Constraints Between Parts

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[Received July 14, 2022; accepted September 8, 2022]

This study proposes a method for automating the determination of assembly order by automating the derivation of the necessary connection relationships between the parts. The proposed method minimizes the information required for the initial conditions and automatically determines the feasible assembly orders. As a general rule, based on the assumption that the assembly order for a product is the reverse of the disassembly order, once the disassembly order is derived based on the 3D CAD model and the connection relationships between the parts, the assembly order can be determined. Until now, however, the relationships between the parts are decided manually by the attendant engineers, thus, hindering the full automation of the determination of the assembly order. To achieve full automation realistically, the connection relationships between the parts should be derived automatically from the 3D CAD model, for which this study proposes an efficient method. The components were extracted from the 3D CAD model, and the bolts were identified. The connection relationships between the parts were derived from the interference conditions determined while moving each part minutely. An association chart diagram was created from the obtained connection relationships, from which multiple assembly order candidates could be derived.

Keywords: automated product assembly, disassembly, assembly order, CAD

1. Introduction

Nowadays, automation of setup work in the production process is being actively promoted. Determining the assembly order in the assembly process plays a major role in the setup work because the restrictions imposed by the assembly order on the allocation of jigs and arrangement of parts significantly affect the production efficiency. Conventionally, the assembly order is determined based on the experience of the engineers, who consider the relevant restraint conditions, work efficiency, and work safety. However, with the continuing decrease in the number of qualified engineers, problems, such as labor shortages and loss of expertise, make it a priority to determine the assembly order automatically. For products involving mechanical parts, whose assembly and disassembly are reversible, one approach is to generate the assembly order automatically by deriving the disassembly order of the products and then reversing it.

Complicating this task requires a potentially large number of possible disassembly orders. In general, there are as many combinations of decomposition orders as there are factorials of the number of parts. Thus, it is difficult to determine the most suitable order for the assembly of the target among all the candidates. The generation of a product assembly order is an NP-complete mathematical problem. The number of patterns for the assembly order increases with an increase in the number of parts. To address this issue, various methods have been proposed to reduce the number of combinations of decomposition orders based on the connection relationships between the parts, which are treated as geometrical constraints in the 3D CAD model of the product. Some previous studies have proposed a mathematical optimization method for determining the assembly order using integer linear programming [1, 2], neural networks [3], and genetic algorithm [4–6]. The other method involves expressing the constraint conditions between the parts with an evaluation function, deriving the disassembly order from the evaluation of the disassembly process, and determining the assembly order [7–10]. Another method determines the constraints between the parts based on the connection relationships, determines the disassembly order according to the constraints, and establishes the assembly order [11–17]. However, with such methods, the constraints between parts are provided as preconditions. This means that workers must manually determine the constraints in advance, making it impossible to derive the assembly order automatically from only the 3D CAD model of the product. To obtain the constraints in advance and generate a high-quality assembly order in a short time, Enomoto et al. [18–20] proposed an assembly order search algorithm with an objective function, which scores the assembly ability and efficiency of the assembly process.

In this study, we developed a system that derives the connection relationships between the parts solely from the

3D CAD model of the product. The proposed system focuses on the geometric constraints between the parts and automatically generates the assembly order from the obtained connection relationships. Furthermore, we propose a method to limit the combinations of candidate assembly orders by considering subassemblies and their gravity directions. Computing all the parts in a brute force increases the computational cost. In this study, only the bolts, which are generally used for fastening between the parts, are provided as preconditions (a flag is assigned to identify it as a bolt and axis direction), and subassemblies considering the direction of gravity during assembly are considered to limit the candidate assembly sequence.

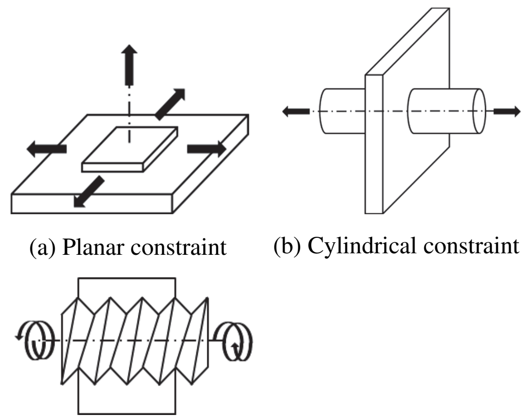
2. Connection Relationships Based on Geometric Constraints Between Parts in the Assembly Process

To identify an appropriate assembly sequence, it is important to reduce the number of assembly sequence candidates to actually feasible ones, from the large number of combinations of assembly sequences that exist (as many as the factorial of the number of components), by adding the constraints based on the relationship between the parts. This study constructs a system that automatically derives connection relationships and determines the assembly order based on the geometrical interference between the parts and the decomposition process. The system was developed using the Visual Studio 2019 (C#) program and an analysis of the CAD model using the API function in SolidWorks 2018.

2.1. Connection Relationships Based on Geometric Constraints Between Parts

The connection relationships in the assembly process indicate the geometrical constraint conditions between the parts. Constraint conditions for products whose disassembly and assembly are reversible can be classified as planar, cylindrical, and screw constraints. If disassembly and assembly works are performed ignoring these restraint conditions, interference will occur between the parts, which, in turn, will make it impossible to continue the work. Therefore, when moving a component, the presence or absence of geometrical interference between the components is determined. If interference occurs, it is determined that the component has a connection relationship.

In this study, the presence or absence of geometrical interference of components was determined when the component disassembly process was derived. The geometric relative movement between the parts is important because the moving distance and moving direction of parts during disassembly are related to the factors that cause interference between the parts. Accordingly, in this study, the moving directions, and distances of the parts during disassembly were classified as follows:



(a) Planar constraint (b) Cylindrical constraint

(c) Screw constraint

Fig. 1. Classification based on the moving directions and moving distances of the parts during disassembly.

(1) Planar constraint

When two components come into contact with each other owing to the movement of the parts when the product is disassembled or when the components are in contact with each other in the initial assembled state, interference between the parts occurs owing to planar restraint. As shown in **Fig. 1(a)**, when the parts are constrained in a plane, the decomposition direction is the outward normal direction of the contact surface, and the direction of the two orthogonal axes is parallel to the contact surface. The moving distance is a value within a range that does not cause interference with other parts.

(2) Cylindrical constraint

When the parts are cylindrically constrained, the decomposition direction is the translational direction along the central axis of the cylinder, as shown in **Fig. 1(b)**. The moving distance is a value within the range, which does not cause interference with other parts.

(3) Screw constraint

When the parts are screw-constrained, there is a proportional relationship between the rotational motion and translational motion. Originally, rotational motion and translational motion were simultaneously performed during disassembly and assembly. However, in this system, the disassembly motion owing to a screw restraint is also treated as translational motion because the rotational angle can be derived from the amount of movement of the translational motion. In this study, disassembly was performed without considering the thread interference between the bolt and fastener. The decomposition direction was outward along the central axis of the cylinder, as shown in **Fig. 1(c)**. The moving distance was the nominal length of the bolt.

2.2. Screw Constraint with Respect to the Bolt Attribute

Bolt fastening of parts is the most widely used fastening method in product assembly processes. In connection relationships involving a screw constraint, there are two priority rules for the disassembly and assembly processes:

- Rule 1: Parts to be fastened together with a bolt are disassembled after the bolt is removed.
- Rule 2: Parts fastened together by a bolt are disassembled in a coaxial direction with the bolt.

According to Rule 1, parts, which are fastened together with multiple bolts, cannot be disassembled before the bolts are removed because there are multiple rotation axes during the disassembly movement. Therefore, the first priority is the removal of bolts.

According to Rule 2, parts, which are cylindrically or screw-constrained by the bolt are assembled and disassembled in the direction along the central axis of rotation so that they move in a coaxial direction with the bolt.

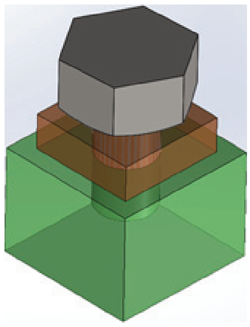
In this study, a CAD model was created wherein the bolt attribute was assigned to the bolts to perform an interference check that recognizes these priorities. Bolts and parts, which are screw-constrained, are called bolt units.

3. Determination of the Assembly Order

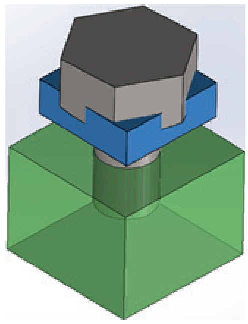
The connection relationship is derived by moving each part and determining the interference with other parts and the disassembly order. The geometrically assembled candidate assembly order was derived from the obtained connection relationship.

3.1. Parts Information from the CAD Model of the Product

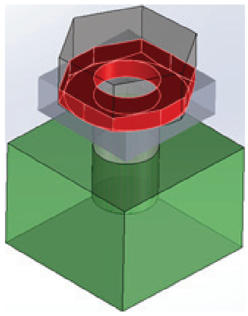
Determining the connection relationship between the parts requires the constraint conditions between the parts, disassembly order of the product, and interference conditions between the parts. To distinguish them, it is necessary to move each part and determine the presence or absence of interference. In addition, when moving a part, it is necessary to determine the distance required for disassembly, as well as the direction of disassembly, by moving the total length in the moving direction of the part. With respect to the disassembly direction, parts fixed by a screw constraint are disassembled in the positive and negative directions coaxial with the bolt, and the other parts are disassembled in the positive and negative directions of the X-, Y-, and Z-axes. Thus, the length of the components of the product and the presence or absence of interference during movement, are obtained from the CAD model of the product. To disassemble and assemble a product, it is generally necessary to determine the base parts, which will serve as the base for fixing the product with a jig. In addition, because the connection relationships between the parts interact, the starting parts are required to determine the order. Therefore, in this study, the base parts are defined.



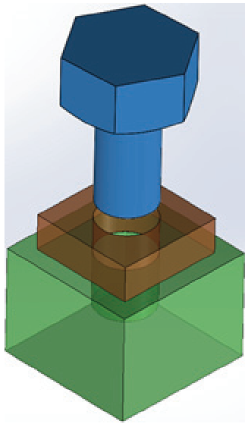
(a) Product model



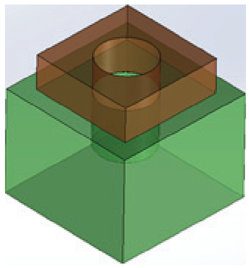
(b) Model where plate is moved to Z-axis first



(c) Interference area when plate moves



(d) Model where bolt is moved to Z-axis first



(e) Model with removed bolt

Fig. 2. Procedure for calculating geometric constraints between the parts and generating disassembly process.

3.2. Geometric Constraints Between Parts by Disassembly Process

Using the CAD model, as shown in **Fig. 2(a)**, as an example, the proposed method for generating a disassembly order can be described as follows:

(1) Each part in the assembly model is moved.

Each component in the assembly model is moved, and a check is performed to determine whether it can be disassembled as moved. If there is a priority direction for the bolt, the relevant component part is disassembled in the coaxial direction of the bolt. If there is no priority direction for the bolt, the target part is moved in the positive and negative directions of each axis in the order of the X-, Y-, and Z-axes.

(2) Interference between the moved part and other parts

is checked; if the subject part experiences no interference, it is recognized as disassembled.

When a part of the assembly model is moved, a check is performed to determine whether the interference with the part occurs from another part. If interference occurs (as shown in **Fig. 2(b)**, where the bolt head interferes with the movement of the plate), it is determined that the subject part cannot be pulled out in the direction of movement because of the interfering part (**Fig. 2(c)**). At that time, a geometric dependency relationship (moved part is defined as the "child" part and the interfering part is defined as the "parent" part) can be added to the parts that interfere with the moved part. If there is no interference, as shown in **Fig. 2(d)**, it is determined that it is possible to disassemble the part in the direction of movement.

(3) A part that can be disassembled is deleted from the assembly model, and the parts that can be disassembled are recursively determined.

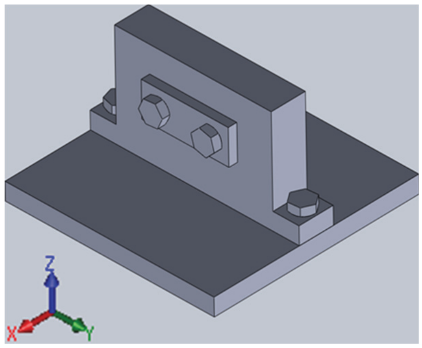
By repeating Steps (1) and (2) for all the parts and deleting a part from the assembly model each time a part, which can be disassembled is detected, more parts can be newly disassembled (**Fig. 2(e)**). Thus, the disassembly of the remaining parts can be determined.

Steps (1)–(3) are repeated until all the parts, except the base part, are removed. By repeating these steps, the parts are disassembled and removed one at a time, making it possible to derive the geometric constraints and connection relationships between the parts needed to determine the disassembly order.

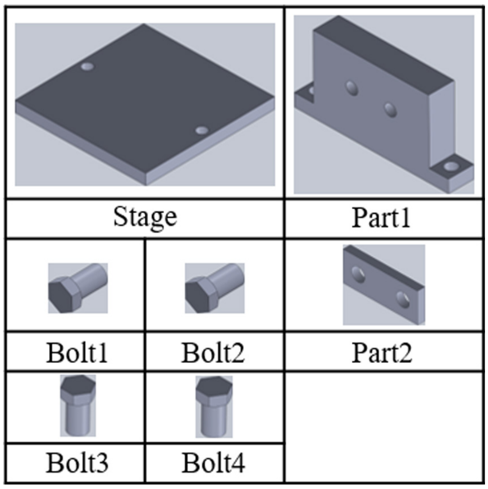
3.3. Association Chart for the Connection Relationships Between the Parts Required for Assembly Order

The method for deriving an association chart showing the priority of disassembly and assembly order of each part from the geometrical constraint conditions obtained earlier can be explained using the illustrative CAD model, as shown in **Fig. 3(a)**. **Fig. 3(b)** shows the components of the assembly model. By determining the dependency relations between the parts using the proposed method, it is possible to create an association chart for the disassembly order, as shown in **Fig. 3(c)**. The association chart shown here indicates that Part 2 can be disassembled after Bolts 1 and 2 are removed. In this association chart, the connection relationship of each part can be expressed hierarchically, and candidate assembly orders can be limited to the geometrically feasible ones from a potentially enormous list of possible disassembly orders. The details of generating an association chart for the disassembly order have been provided.

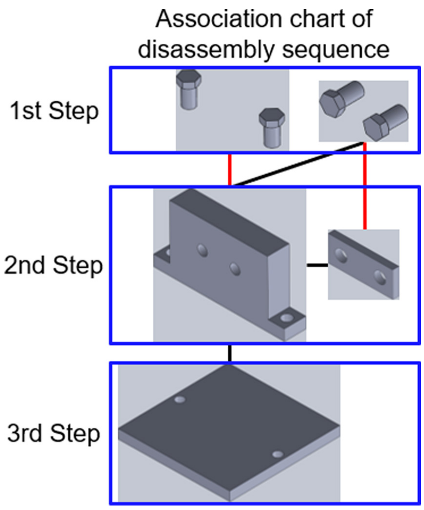
An association chart can be defined to show the parts that can be disassembled in the upper layer. As shown in **Fig. 4(a)**, Bolts 1, 2, 3, and 4 can be removed first because they encounter no interference. Consequently, they can be placed at the top of an association chart. As the other parts cannot be disassembled before some or all of the bolts are removed (because they encounter interference from one or more bolts), it is necessary to determine the part of the upper layer, which should be removed for disassembly. At this time, the child parts whose parent parts are in the upper layer are determined to have a connection relationship, and the connection relationship in the association chart is established. For example, when Part 2 moves, as shown in **Fig. 4(b)**, there is a connection re-



(a) Product model

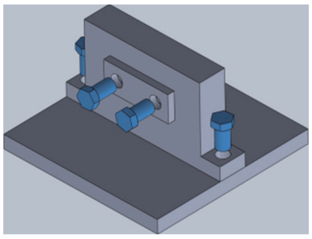


(b) Component parts

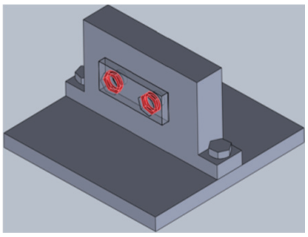


(c) Generated association chart for disassembly order

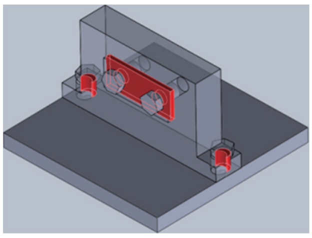
Fig. 3. Generated association chart for the disassembly order and the parts comprising the model.



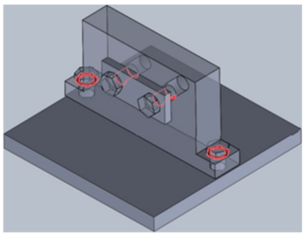
(a) Model, in which Bolts 1, 2, 3, and 4 were moved



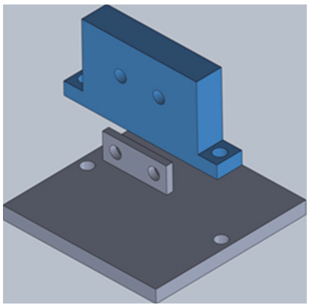
(b) Interference area when Part 2 was moved in the X-axis direction



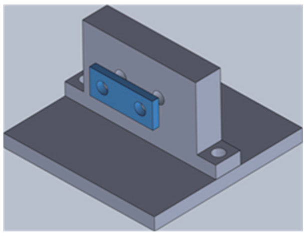
(c) Interference area when Part 1 was moved in the X-axis direction



(d) Interference area when Part 1 was moved in the Z-axis direction



(e) Model, in which Part 1 was moved in the Z-axis direction



(f) Model, in which Part 2 was moved in the X-axis direction

Fig. 4. Method for generating an association chart for the connection relationships between the parts.

lationship because the part experiences interference from Bolts 1 and 2. Similarly, when Part 1 is moved in the X-axis direction, as shown in **Fig. 4(c)**, it experiences interference from Part 2, Bolt 3, and Bolt 4; When it moves in the Z-axis direction (**Fig. 4(d)**), it experiences interference from Bolts 1 and 2. Therefore, there is a connection between the five parts. Therefore, the four bolts were removed first; and are shown in the first layer. Next, moving Part 1 in the positive X-axis direction was considered after Bolts 1 and 2 were removed (according to the screw constraint associated with the bolt attribute described in Section 2.2), and in the positive Z-axis direction after Bolts 3 and 4 were removed. Disassembly was accomplished in the latter case, where there was no interference, as shown in **Fig. 4(e)**. Similarly, Part 2 was disassembled in the positive direction of the X-axis, as shown in **Fig. 4(f)**, and the second layer was determined. Finally, the base component was defined as the third layer. An association chart showing the connection relationship between parts can be derived by investigating the connection relationships and disassembly process for all the parts.

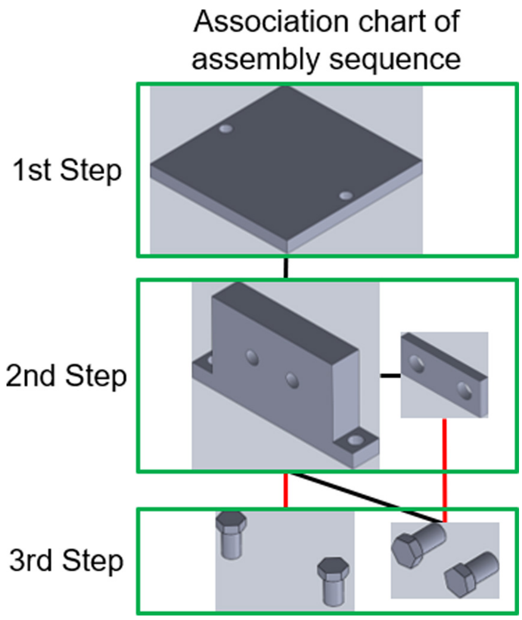


Fig. 5. Association chart showing the connection relationship related to the assembly order created by reversing the disassembly order.

An association chart of the assembly order of parts can be generated from the obtained association chart of the disassembly order. As shown in **Fig. 5**, the association chart of the disassembly order shown in **Fig. 3(c)** is reversed to form a chart for the assembly order, such that the base component is set as the top layer. The red line in **Fig. 5** shows the connection relationship of the parts, which are disassembled in the same direction; the black line shows the connection relationship of the parts, which are disassembled in another direction. In the connection relationship indicated by the red line, it is possible to disassemble the parts in the lower layer after disassembling the parts in the upper layer. Therefore, it is possible to generate an association chart for the assembly order showing the connection relationships by examining the connection relationships and decompositions for all the components.

3.4. Determination of the Assembly Order Considering the Subassemblies

When there are numerous components to be assembled, the number of combinations of assembly orders can be extensive, making it difficult to determine the assembly order uniquely, which should be used for the actual assembly. However, it is possible to limit the candidates to assembly orders that can be geometrically produced based on the connection relationships between the parts, as indicated earlier. This study proposes a method for further limiting the assembly order candidates by considering the direction of gravity during the assembly.

Assembling the next part in a sequence without fastening it (thus, having to hold the part) is inefficient, as this requires an excessive number of jigs and hands. Therefore, assembly order candidates can be further limited by applying the following rules to derive the assembly order using the association chart of the assembly order obtained in Section 3.3:

- Rule 1: Priority is given to the parts having a connection relationship with the parts in the upper layer of the association chart.
- Rule 2: Priority is given to the assembly of a bolt unit.
- Rule 3: Priority is given to the parts disassembled in the same direction as the bolt, when assembling the bolt unit.
- Rule 4: Priority is given to the assembly of parts in the upper layer of the association chart.

The rationale for these rules is summarized as follows.

When automating the assembly, the procedure for assembling the parts on a non-fixed object is more difficult than the procedure for assembling the parts on a fixed object. Therefore, in Rule 1, priority is given to the parts, which can be assembled on a fixed object having a connection relationship with the parts in the upper layer.

The bolt unit is the smallest unit and consists of fastened parts. Because it is difficult to assemble some parts without first fastening certain bolt units, Rule 2 prioritizes the assembly of bolt units.

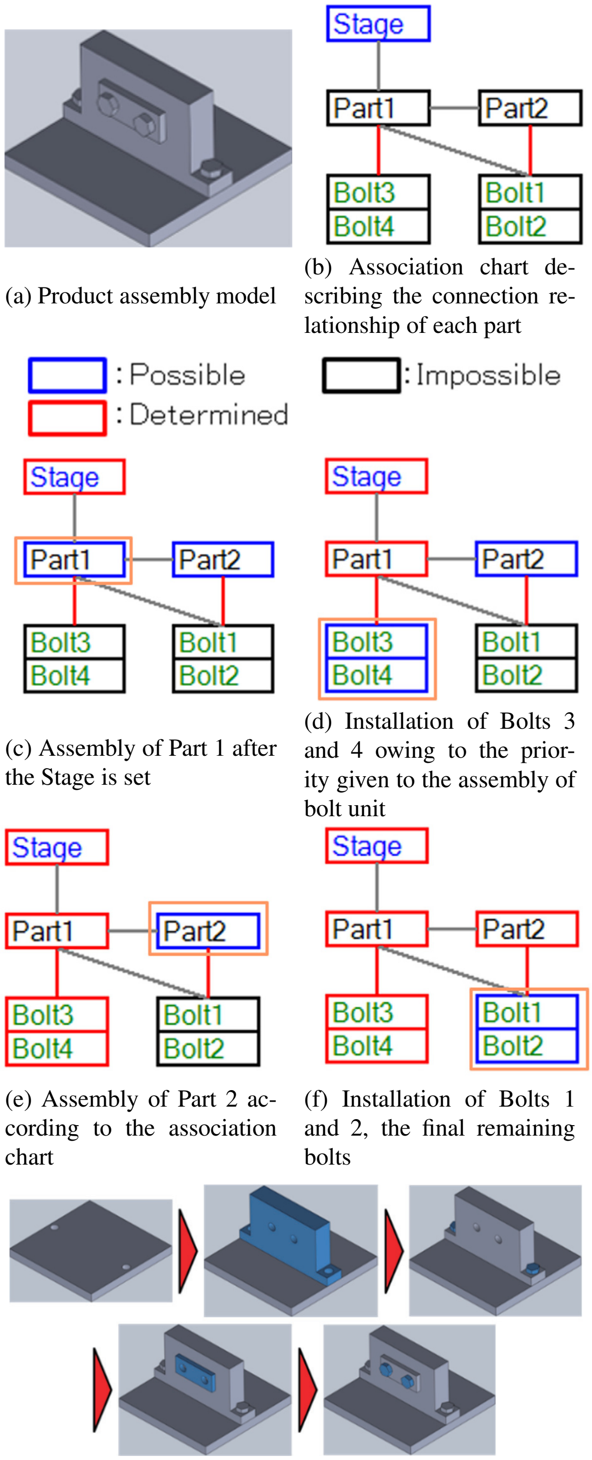
The assembly direction vector in the prescribed approach is obtained by reversing the sign of the disassembly direction vector at the time of assembly. To increase the efficiency of the procedure, Rule 3 prioritizes assembly in the same direction.

Parts in the upper layer are more likely to interfere with other parts during the assembly than those in the lower layer. Therefore, in Rule 4, parts in the upper layer are preferentially assembled to simplify their movement during assembly.

The product model shown in **Fig. 6(a)** illustrates these rules. According to the aforementioned rules, if the association chart and connection relationships of each part are determined, as shown in **Fig. 6(b)**, the assembly order should be set as follows.

First, the base component, the Stage, is set. According to the association chart, the parts that can be assembled next are Parts 1 and 2. Part 1 is assembled according to Rule 1 (**Fig. 6(c)**). After Part 1 is assembled, it is possible to assemble Part 2, or install Bolts 3 or 4, all of which have a connection relationship with Part 1. According to Rules 2 and 3, the installation of Bolts 3 and 4 is preferred (**Fig. 6(d)**). Next, Part 2 is assembled (**Fig. 6(e)**). Finally, Bolts 1 and 2 are installed (**Fig. 6(f)**). Because the bolt pairs have the same connection relationship in the same layer, for the installation of Bolts 1 and 2, or Bolts 3 and 4, any order can be chosen, as the influence on the assembly time is considered small. The assembly order determined here is:

Stage → Part 1 → Bolt 3 → Bolt 4 → Part 2 → Bolt 1 → Bolt 2.



(a) Product assembly model

(b) Association chart describing the connection relationship of each part

(c) Assembly of Part 1 after the Stage is set

(d) Installation of Bolts 3 and 4 owing to the priority given to the assembly of bolt unit

(e) Assembly of Part 2 according to the association chart

(f) Installation of Bolts 1 and 2, the final remaining bolts

(g) Determined assembly order according to the association chart and bolt unit

Fig. 6. Determination of assembly order (an example).

4. Case Study for Determination of Assembly Order

A case study was conducted to confirm the effectiveness of the proposed automated assembly order generation system. The case study used the part of the belt drive unit model used in the product assembly challenge at the

World Robot Summit 2020. **Fig. 7** shows the products and components used in this study.

The association chart of the assembly order obtained from the disassembly order and connection relationship in Sections 3.2 and 3.3 is shown in **Fig. 8**. As indicated in **Fig. 8**, Part 1 is in the second layer and it is a part, which interferes with the Stage. The constraint relationships between the parts can be correctly derived as a connection relationship for other components. Thus, the proposed method can automatically generate an association chart of the connection relationships relevant to the assembly order.

Figure 9 shows the results of determining the assembly order from the obtained association chart according to the rules described in Section 3.4. After the Stage is set, Parts 1 and 9 can be assembled; however, Part 1 is assembled first using Bolts 1 and 2, according to Rules 1 and 2. Next, Part 9 is assembled according to Rule 4. As Part 9 is a bolt unit using Bolt 8, it is assembled in the order of Part 10, Part 11, Bolt 8, Part 8, and Part 7, according to Rules 2 and 3. Next, Part 4 is assembled according to the connection relationship with the already assembled parts, and Bolts 4, 5, 6, and 7 are installed according to Rule 2. Next, the bolt unit consisting of Parts 3 and 2 is assembled using Bolt 3, according to Rule 2. Finally, Parts 5 and 6 are assembled according to their connection relationships.

The results confirmed that the connection relationship can be automatically established, and the assembly order can be automatically derived using the proposed method.

5. Conclusions

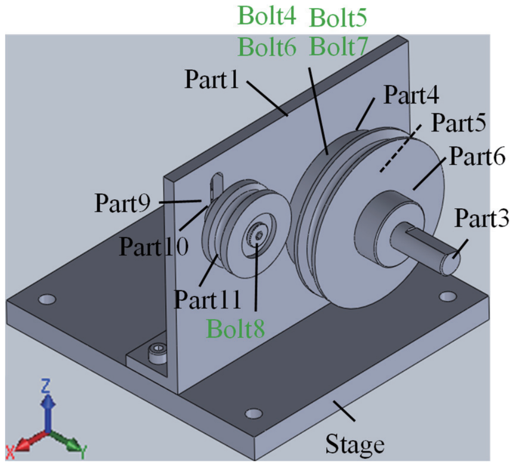
This study developed a method for automatically deriving connection relationships from a product assembly model to automate the determination of assembly order in an assembly process. The proposed automated assembly-order generation system determines the assembly order from an association chart expressing the connection relationships in the disassembly order and interference information regarding the product and its bolt units. A case study to verify the effectiveness of the proposed method resulted in the following observations.

(1) The connection relationship can be automatically determined by setting the bolt and base components and examining the interference and disassembly of parts from the 3D CAD product assembly model.

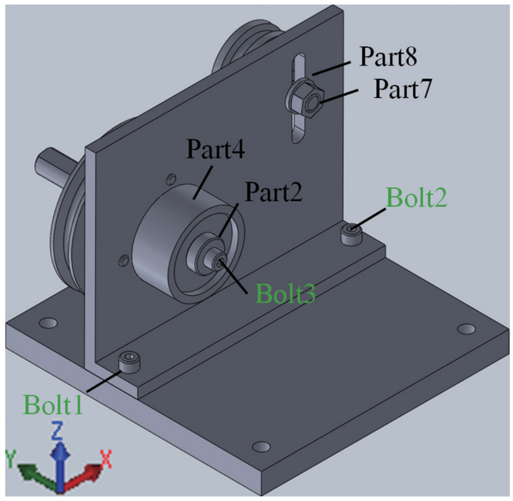
(2) Because the connection relationships of parts can be expressed in an association chart, which shows the parts that can be assembled in a hierarchical structure, it is possible to reduce the number of assembly order candidates to a more workable set of feasible candidates for the actual assembly.

(3) The number of assembly orders can be further reduced by considering the bolt unit screw constraint.

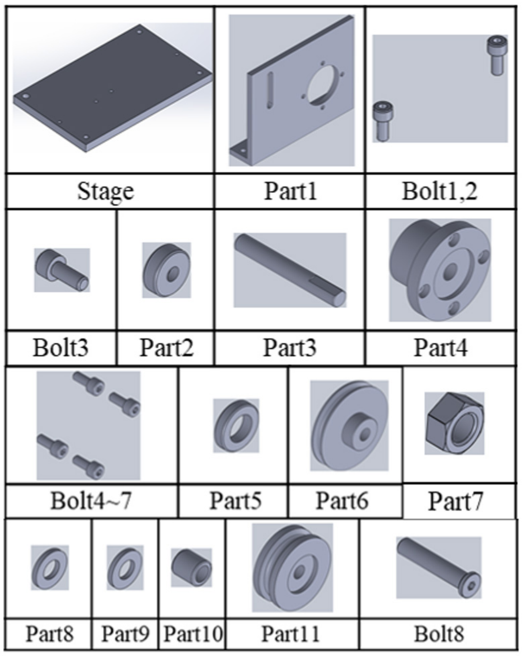
In the future, this study will realize the automation of path generation for each part and offline teaching of an



(a) Product assembly model (front view)



(b) Product assembly model (back view)



(c) Component parts comprising the assembly model

Fig. 7. 3D CAD model for the case study.

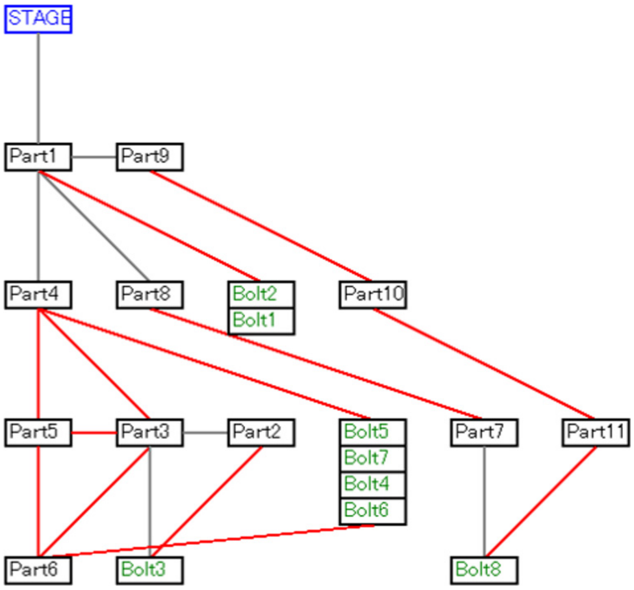


Fig. 8. Association chart of the assembly order obtained from the disassembly order and connection relationship between the parts.

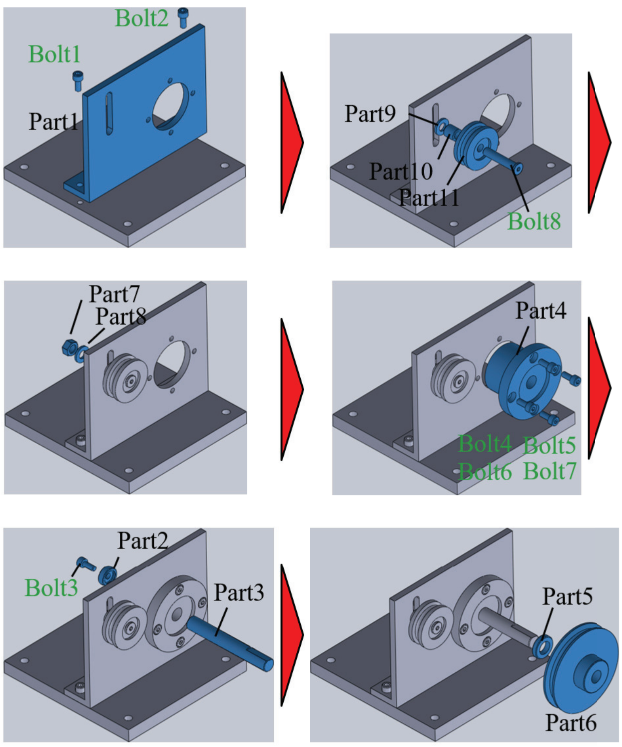


Fig. 9. Determination of assembly order from the obtained association chart.

industrial robot during assembly. Furthermore, we plan to continue considering a method to determine the assembly order by examining evaluation functions, such as the efficiency of industrial robots or work safety of operators.

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