49

Simulation-based evaluation of assemblability for machine parts

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Abstract

A framework of evaluating assemblability using assembly simulation is proposed. Current assemblability evaluation methods perform evaluation by looking up the evaluation table. The table usually contains typical assembly features, to which assemblability scores are specified. Although the method is quick and is tuned for the shop floor based on the factory engineer's experience, it may not be applicable to new situations or other sites. This paper describes a simulation-based method for a rational foundation of the evaluation that can be easily applied to different situations. Evaluation is performed in two ways; One is based on the simulated motion of each part in assembly procedure. Possibility of deviation of the motion from nominal assembly motion is evaluated through the simulation. Another is based on the simulation of robot motion for the assembly procedure. Scores for assemblability are generated by evaluating those robot motions.

Keywords

Assemblability, assembly simulation, contact state, configuration space, assembly robot, operability

1 INTRODUCTION

Manufacturers are facing harsh situation these days. Lot size of production becomes smaller to comply with various consumers' needs more correctly. Changes or innovations of product design become frequent to catch their hearts quickly. Shorter term to the distribution of products is a requisite to overcome the competitors. These pressures in time make it difficult to do 'learning by practice.' This is why companies consider it important to evaluate the assemblability of product that greatly affects productivity of the shop floor, preferably in computerized way.

Current approach of evaluation of assemblability is based on experience and expertise of

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production engineers in the shop floor (Boothroid, 1983). Though the experience should not be neglected, we are in doubt of its effectivity as the products and environments are changing very rapidly these days.

To make the evaluation robust for changing situations, we consider rational and objective evaluation method is necessary. Measures generated using computer simulation based on physical and mathematical basis would be helpful for the purpose. Of course there exist measures or methods for assemblability that are acquired only by expertise and are indispensable, but we should clearly distinguish these two types of measures.

In this paper, we propose a scheme to evaluate assemblability of product using simulation of its assembly process. We describe two approaches; one is based on the behavior of parts in assembly process and the other is based on analysis of the motion of assembly robots.

2 SIMULATION-BASED EVALUATION OF ASSEMBLABILITY

Common way to evaluate the assemblability is to use looking-up tables as shown in figure 1. Features of product that may affect assemblability such as symmetricity of parts, and number and size of holes in it, are enumerated. Values of estimation are shown in the table corresponding to each of those features. Engineers can easily estimate the assemblability as a sum of those values. This looking-up table is arranged by production engineers of the shop floor. They decide and maintain the values in the table based on their experiences. As the method is mainly based on the experience or expertise of those production engineers, it is only applicable to their shop floor.

This 'know-how' based evaluation is quick and accurate for the restricted type of product and the particular shop floor, as it is best tuned for the manufacturing environment and the product family. However, the method has no explicit rational or logical basis. This makes it difficult to show the designer of the product what is wrong with the design. It may also be difficult to apply the method to different sites or changing situations as the manufacturing process or environment is not considered explicitly in the method.

As stated above, development of new products or new manufacturing process is becoming rapid these days. It is ambiguous that the experience can cover new situations. Range of applicability of the method should be clear and the result of evaluation should provide designers with sufficient information for the change of the design. A new method is considered necessary to suffice these needs.

We propose a scheme shown in figure 2 that evaluate the assemblability based on the computerized simulation of assembly process. Possible behaviors of parts and tools in assembly process will be predicted through the simulation. Factors on the assemblability are estimated by evaluating the obtained behaviors. As the method is based on rational basis with manufacturing process and environment explicitly considered, it will be applicable to any different situations if data about the product, process and environment is provided.

We notice that this method may be slow as it needs a lot of calculations for the simulation. It requires the precise information or the model of the product, tools and environment to get the accurate results. We also understand the utilization of experience or expertise of engineers is requisite to summarize the evaluation results and get the final assemblability value. Still we consider the new method provides the general evaluation that is clear for the designers of the product as well as the engineers of other process or sites.

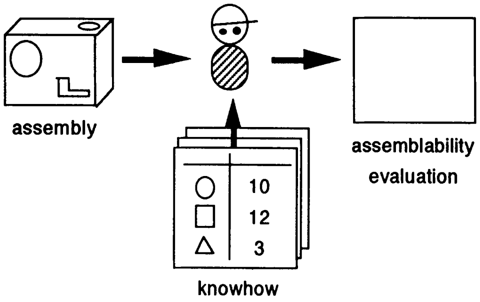

Figure 1 Current method of the evaluation of assemblability.

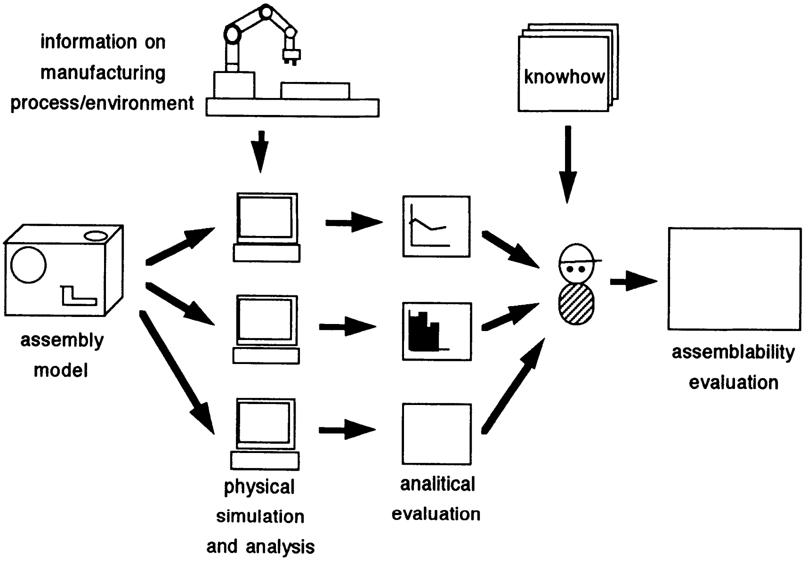

Figure 2 Proposed simulation-based evaluation of assemblability.

In this paper we discuss two approaches for this method. One is to evaluate the predicted behavior of parts and the other is to evaluate the simulated behavior of the assembly robot. The former is described in 3 and the latter in 4.

3 EVALUATION BASED ON SIMULATED BEHAVIOR OF ASSEMBLED PARTS

3.1 Basic concepts and assumptions

We simulate the possible behavior of parts in assembly process to get a factor of assemblability. Possibility to deviate from nominal states of the assembly procedure is estimated. If the possibility is high, it means that the product is difficult to assemble. Details for the evaluation are described in the following sections.

We gave the following two assumptions for this evaluation;

- Assembly procedure is given beforehand. Here we do not argue how to generate appropriate assembly procedures for the product. In other words, we evaluate an assembly product and its assembly procedure as a pair.
- Assembly procedure is carried out such that pairs of faces are in contact. The restriction gives reliable assembly procedures as well as making the problem simpler. For this type of assembly procedure, operations are performed stably by pushing the part to the contact face and sliding it along the face.

Besides these assumptions, our current system handles only polyhedral shapes. Analysis is made on kinematics and statics aspects. Examples shown here is two dimensional though we think its extension to three dimensional case is not difficult. See 3.6. We also limit the analysis to include one-point contact only.

3.2 Representation of state in assembly procedure

The state of two parts in contact can be described with pairs of geometric elements of both parts. We call this state "contact state" and use it as basic representation of state of parts in assembly procedure. Figure 3 shows possible contact pairs of geometric elements. Note that some special or rare cases are omitted such as a pair of vertexes in contact. Assembly procedure is represented by the sequence of face-to-face contact states.

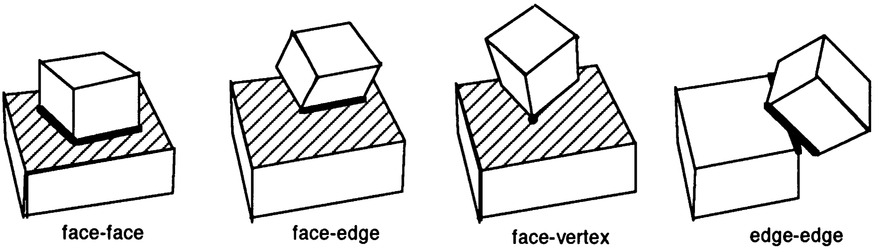

Figure 3 Contact state.

For two dimensional case as shown in figure 4, assembly procedure is assumed to contain at least one edge-to-edge contact state and slide the part keeping the contact. Possible degree of freedom (DOF) of the part to be mated is a translational motion along the contact edge. Tumbling motion that breaks the contact state has a rotational DOF around each of the two contact vertexes.

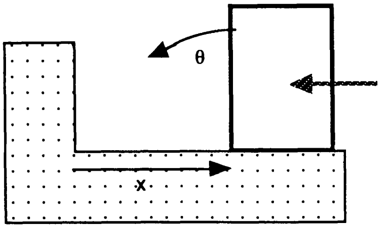

Figure 4 Possible motion of the part in contact in two dimensional case.

3.3 Prediction of the behavior of parts in assembly procedure

At each state of assembly procedure, some DOFs exist as described above. For assessing the assemblability by estimating behavior of a part in an assembly procedure, we enumerate changes of the state possible in the nominal states in the assembly procedure.

We introduce the concept of contact configuration space or cc-space for this purpose. It is an extension of configuration space (Lozano-Perez, 1986). A combination of position and orientation of the part in contact is represented as a point in the space that has every possible DOF as its axis. If a part is free, it has three DOFs in two dimensional case, but as the part is in contact with other part the number of DOFs i.e. the number of axis of the cc-space is reduced. For example, the part in figure 4 has two DOFs; one is translational motion along the contact edge and the other is rotational motion around the contact point. Cc-space corresponding to this state has translation distance x and rotation angle θ for each axis, as shown in figure 5.

Simulation is made based on this cc-space to get the possible changes of state. Cc-space is divided into mesh and every point at the crossing is checked if the part has any other interference with parts. Thus the space is segmented into two types of area, those with interferences and those without interferences. The border between two areas shows the contact state. We can get the possible change of contact state using this map in cc-space. In figure 5 nominal assembly procedure is represented by x-axis that is translational motion along the contact edge. The part may leave this nominal assembly procedure by tumbling around the contact vertex. In cc-space it is represented by leaving from x-axis into upper area. When some element of the part collides with other part, the point in cc-space reaches the border of the interference area.

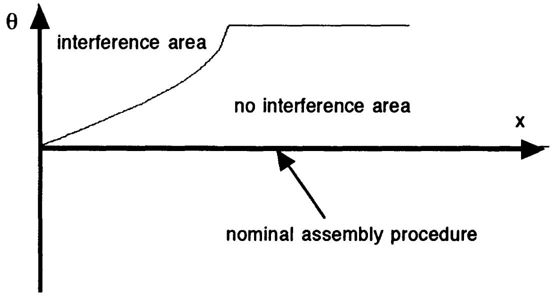

Figure 5 Contact configuration space for the part in figure 4.

3.4 State transfer graph

We get cc-space for each contact state of assembly procedure. Simulation on cc-space gives possible change of contact states from the nominal state. This is summarized in state transfer graph as shown figure 6. It represents possible changes of state around a nominal state of the assembly procedure. In the figure, solid arrows show the nominal assembly procedure.

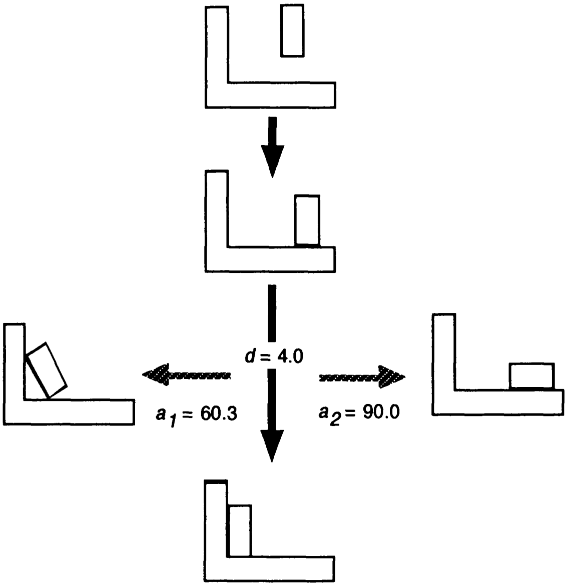

Figure 6 State transfer graph.

3.5 Evaluation of state transfer

We use the ease of the state transfer in assembly procedures as a measure of assemblability. If states easily transfer to the nominal state, we consider assemblability of the part is high. If states are apt to transfer to states other than the nominal assembly procedure, assemblability of the part is considered to be low.

As a way to estimate the ease of state transfer we propose to evaluate the average angle *a* from nominal state to other contact state in cc-space. If the average angle is large, it is considered that the collision states are remote and the part has high assemblability. Another measure we propose is the length of nominal state *d*. If it is short, the part is considered to have higher assemblability and vice versa.

These values are also shown in figure 6. Note that the tumbling direction is classified and the corresponding average angles before the collision are calculated. As another example, we evaluate the case of an L-shaped part. In this case the assembly procedure has two steps as shown in figure 7.

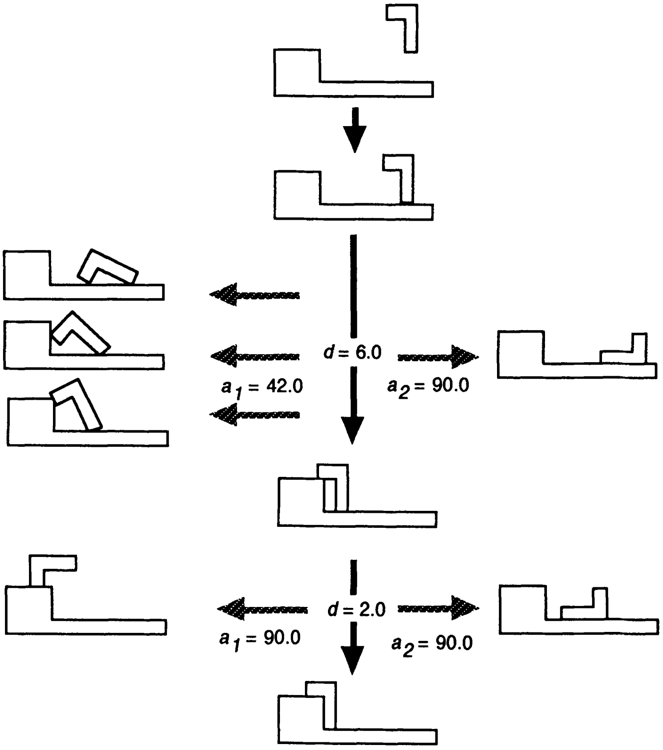

Figure 7 State transfer graph for an L-shaped part.

3.6 Possible extensions

We are now extending the method to have a three dimensional capability. The degrees of freedom of the part in motion for three dimensional case are analyzed as follows;

- A pair of faces in contact: When only one pair of faces is in contact as shown in the left side of figure 8, the part to be mated has two translational DOFs plus one rotational DOF along the contact face. If we think the motion that removes this contact pair is made only by tumbling i.e., rotating the part along the contact edge, there exists one additional rotational DOF for each contact edge.
- Two pairs of faces in contact: When two pairs of faces are in contact as shown in the right side of figure 8, motion of the part is restricted to one translational DOF along the common edge of two contact faces. Tumbling motion to break the contact may have one rotational DOF along the contact edge on each contact face provided that such motion is possible.

We think the extension is rather straightforward but we need a faster algorithm for collision check to lessen the computational burden that will increase.

Evaluation methods are not restricted to those measures described above. Another aspect to be applicable for evaluation is statics of the part at the nominal contact state (Mason, 1985). On the assumption that the force and moment acting on the center of gravity of the part during the assembly operation, we can analyze simple statics to get the range of force and moment that will not tumble but slide the part. If there exist large area of this zone, we evaluate the part with high assemblability.

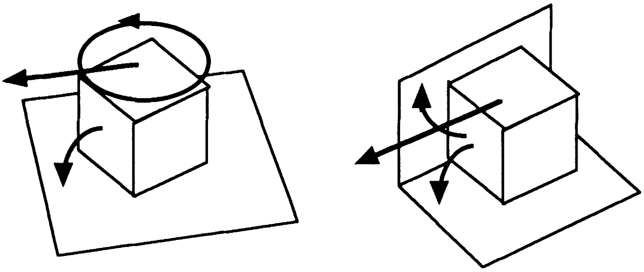

Figure 9 Possible motion of the part with a pair of faces in contact (left) and two pairs of faces in contact (right).

4 EVALUATION BASED ON SIMULATED MOTION OF ASSEMBLY ROBOT

4.1 Basic concepts

Ease of assembly is affected by the tools that assemble the parts. It also differs for the different procedures. We propose to estimate assemblability by evaluating the procedures performed by the assembly robot that assembles the part (Hiraoka, 1993). If the procedure can be easily performed by the robot, we consider the part having high assemblability. The idea is that we can evaluate the assemblability of a product by evaluating the performance of the robot assembling it.

We simulate the motion of the robot for the evaluation. Simple manipulator with 3 degrees of freedom is used. Currently the end-effector and its grasping motion are not considered.

4.2 Simulation of motion of assembly robot

We consider the motion of the robot is given by production engineers or is generated by motion planning system. As we do not have such facilities, we generate simple robot motions as follows.

First we generate the motion of parts that has two portions; one is the motion where the part is mated with other part and the other is the motion where the part is transferred by the robot to other places. We derive mating motion from the assembly procedure mentioned above. For transfer motion we connect the part's feeder and the end of mating motion by a straight line segment. Another point would be added in the middle if it is necessary to avoid some collisions. We give the motion constant velocity along the path for ease of comparison.

Next we generate motion of the robot from the acquired motion of the part. Based on kinematic model and shape model of robot, we convert motion of the part into motion of the robot by using inverse kinematics. Motion is altered if collision is detected. Figure 10 shows a display of the simulation.

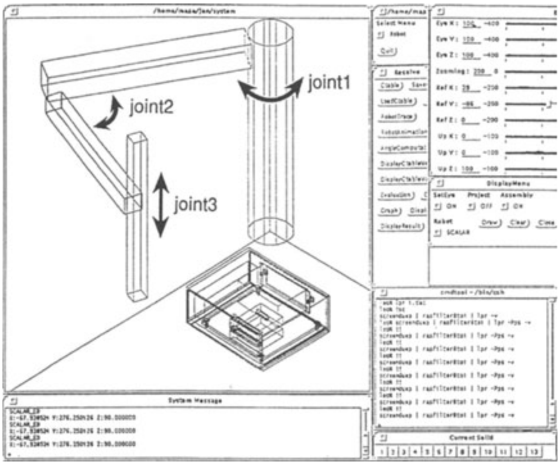

Figure 10 Display of simulated robot motion

4.3 Evaluation of motion as a measure of assemblability

As measures of assemblability we evaluate motion of the robot. If the motion is easy to perform by the robot, assemblability of the part should be high. We use the following measures of performance for evaluation.

- Duration of the procedure: The measure is important as the time duration necessary for the assembly procedure directly affects productivity. In our simulation much difference does not arise for the robot as constant velocity is applied for the motion of parts.
- Joint angular motion: Total change of joint angles and maximum joint angular velocity are used as measures to perform the assembly procedure.
- Operability: Operability (Kotosaka, 1991) is defined as derivative of the joint motion necessary to realize the particular motion of the end-point. Compared to the manipulatability that shows the kinematic performance of robots (Yoshikawa, 1984), operability evaluates kinematic performance of a particular motion for the robot. For the specified motion of end effector *r* and Jacobian matrix *J*, we can calculate

$$Oj = \frac{1}{m}\left(\dot{\mathbf{r}}_j^T (\mathbf{J}\mathbf{J}^T)^{-1} \dot{\mathbf{r}}_j\right) \qquad (1)$$

where m is the number of joints. This represents the difficulty of motion of the robot when the end-effector has the motion of r_j in direction j.

4.4 An example and its results

As an example we use two types of framework for small computers. Both are shown in figure 11, one with hard disk drive that is removable sideways and one with hard disk drive removable from above. Simulation was made with the robot shown in figure 10 and the measures described above are compared for these two types. Results are shown in tables 1-4. In tables 1, 2 and 3 results for the motions to mate a part and for the motions to transfer a part are seperately shown.

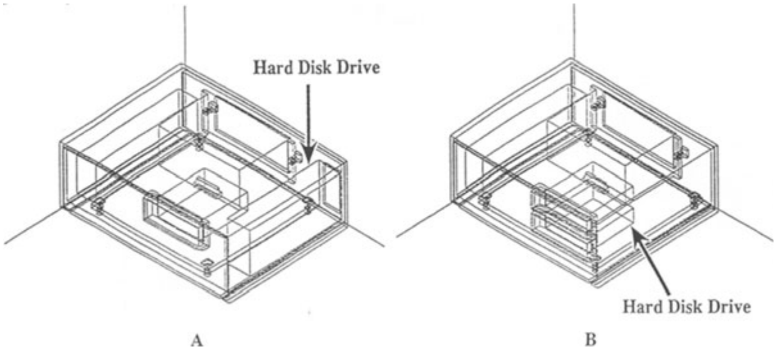

Figure 11 Two types of framework of small computer used for example.

Table 1 Duration of assembly procedure (simulation steps)

	mating	*transfer*
A	40	200
B	46	196

Table 2 Total changes of joint angles

	joint1		*joint2*		*joint3*	
	mating	*transfer*	*mating*	*transfer*	*mating*	*transfer*
A	0.00	1.52	0.00	1.48	40.00	24.98
B	0.01	1.26	0.24	1.16	0.00	38.93

Table 3 Maximum joint angular velocity (per simulation step)

	joint1		*joint2*		*joint3*	
	mating	*transfer*	*mating*	*transfer*	*mating*	*transfer*
A	0.00	0.02	0.00	0.04	2.00	1.24
B	0.00	0.02	0.01	0.03	0.00	5.00

Table 4 Operability for disassembling operation of hard disk drive

	start	*end*
A	1.00E+00	1.00E+00
B	3.40E-05	2.30E-05

Major differences in the motion are seen in vertical joint 3. For operability shown in table 4 the start point and the end point of disassembling the hard disk drive are compared. The vertical motion that is necessary for mating the drive into the product A can be performed only by vertical joint 3. This makes worst evaluation from kinematic viewpoint. To be fair, we think we should evaluate the motion from other viewpoint such as compliance.

5 CONCLUSIONS

In this paper we propose a new framework for evaluating assemblability of products using simulation of assembly procedures. As the method is based on rational and objective basis, it will be robust for different or changing situations. Two approaches are described. One is based on the evaluation of simulated mating motion of parts. Analysis on the contact configuration space is applied. The other is taking the tools and environments for assembly into consideration. We evaluate the assemblability by way of the performance analysis of simulated motion of the assembly robot.

Further research is necessary to integrate these measures into a single value assemblability. It is definitely necessary to incorporate the expertise and experience of production engineers. More accurate simulation including various aspects of assembly operations and investigations to relate the measures based on simulations with actual productivity are required.

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