Development of Novel Assembly Machine based on Human Skill and Dexterity – Adaptive Motion Control utilizing Contacts among Assembly Parts

Kazuaki Iwata [*], Shinichi Hirai [*], Kouji Teramoto [*],
Soujiro Tsuchiya [†], and Kazuo Matsumoto [†]

[*] Dept. Mechanical Engineering for Computer-Controlled Machinery,
Osaka Univ., Suita, Osaka 565, Japan

[†] Nippondenso Co., Ltd.,
Showa-machi 1-1, Kariya, Aichi 448, Japan

Abstract

A new approach to the development of assembly machines based on human skill and dexterity is presented. Recently, novel assembly machines that can perform operations where parts are soft and easily deformed successfully are eagerly required. To this end, human skill and dexterity in assembly operations are firstly investigated for the insertion of a deformable tube into a plug. Secondly, a newly type assembly machine that can perform a part insertion into a deformable base is developed considering human skill and dexterity. Lastly, contact state graphs are proposed in order to analyze the process of assembly operations.

Keywords: assembly, insertion, machine, human, skill, dexterity, adaptation

1 Introduction

Automatic assembly has been achieved by securing the positional accuracy of assembly parts so far. This method yet has a drawback that it is not easy to cope with assembly operations that deal with parts including large tolerances and the operations where parts are soft and easily deformed. Most of these operations are still done by humans, and newly type assembly machines that can perform these operations successfully are eagerly required. Humans can perform the assembly operations successfully and reliably by positioning parts relatively utilizing the contact among the parts and by controlling part motion adaptively according to the contact conditions. These human abilities can be regarded as skill and dexterity in assembly operations.

Assembly of deformable parts has been studied in the past decades. For example, automatic handling of deformable parts in shoe and garment manufacturing have been studied by some researchers [1]. These studies have been, however, done for individual processes independently and few systematic approaches have been developed yet. Systematic approaches based on geometric models have been proposed in the research on rigid object manipulation. In this approach, manipulative operations are planned and are executed according to the geometric models of manipulated objects. Since solid modeling techniques allow us to treat the shape of rigid objects in a systematic and coherent manner, model-based approaches are useful for the manipulation of rigid objects. Model-based approaches have been also applied to the manipulation of deformable soft objects [2, 3, 4]. Unfortunately, it is not easy to build the models of deformable soft objects and to analyze their manipulation processes including their deformation. This implies that model-based approaches for the manipulation of deformable soft objects is now limited to simple operations. Other approaches rather than model-based approaches are thus needed to the manipulation of deformable soft objects.

Recently, transfer of human skill to mechanical machines according to human operations has been reported in some manipulative operations such as deburring [5], grasping [6] and mechanical assembly [7, 8]. The basic idea of these approaches is to measure human demonstration during manipulative operations and to extract human skill from the measurements in order to realize the extracted skill on robotic manipulators. In the human manipulation of deformable soft objects, the following specific abilities can be observed: (a) motion control of the manipulated objects utilizing their deformation, (b) adaptive motion according to sensation including visual and force sensing, and (c) recognition of process situation or its change from the sensation. Since humans acquire these abilities through actual operations, these abilities can be regarded as the components of human skill to perform manipulative operations of deformable soft objects. It is expected that transferring these abilities into robotic manipulators enables the machines to perform the manipulative operations that deal with deformable soft objects successfully and easily as humans do. In addition, once mechanical devices that imitate human operations successfully and reliably can be developed, they will enable fast and low-cost assembly operations. A special device, RCC, has been developed for the insertion of a cylindrical peg into a chamfered hole [9, 10]. With the help of an RCC device, a peg can be inserted into a hole straightforwardly despite the positional and the angular errors of the peg with respect to the hole. Note that the positioning errors of the peg cause reaction forces acting on the peg in contact and that the reaction forces are strongly depend upon the positional errors of the peg. An RCC device has a capability of absorbing the positioning errors according to the reaction forces. Extending the concept of RCC, another mechanical device called SRCC has been proposed for the insertion of a polygonal peg [11]. These devices suggest that new mechanical devices performing assembly operations of deformable parts can be developed.

In this article, we will develop a novel assembly machine according to human skill and dexterity in assembly operations. Firstly, human skill and dexterity in assembly operations are investigated for the insertion of a deformable tube into a rigid plug. Secondly, a newly type assembly machine that can perform a part insertion into a deformable base is developed considering human skill and dexterity. This machine is already in practical use for assembly lines of electric products. The main issues in the development are to follow human motion in the inserting operation and to develop a mechanism that can adjust part motion adaptively. Finally, contact state graphs are proposed in order to analyze the process of assembly operations. It is expected that assembly machines based on the proposed approach can achieve the assembly operations where the method to secure the positional accuracy of parts is not applicable.

2 Human Skill and Dexterity in Assembly Operations

In this section, human skill and dexterity in assembly operations are investigated by taking an example of the insertion of a deformable tube into a rigid plug. This operation can be found in many manufacturing processes but is not easy to be performed by conventional machines, since hoses have different initial shapes and they are often deformed during the operations. Humans can perform this operation successfully and reliably despite the deviations during the insertion process.

In the insertion of a deformable hose into a plug, the inside diameter of the hose is smaller than the diameter of the plug. Thus, guiding the hose straightly along the central axis of the plug often yields excess deformation of the hose and the insertion process may cause some failures. To avoid excess deformation of a hose, humans usually guide the hose at an adequate angle from the axis of the plug so that the edge of the plug enters into the nozzle of the hose. This motion, which has been obtained through their pre-

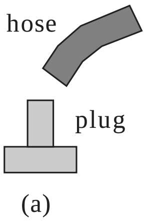


Figure 1: Insertion process of deformable tube into rigid plug

ceding experiences of the operation, helps the nozzle of a hose be inserted into a plug easily. Humans then provide an alternating motion such as a push-pull motion or a twisting motion to a hose rather than a straight motion so that the hose nozzle can be inserted into the plug completely without excess deformation of the hose. Providing alternating motion to a hose, the nozzle of a hose is completely inserted into a hose. Humans then apply an adequate force to the hose so that it can be inserted to a predetermined depth despite the friction between the hose and the plug. In addition, humans adaptively control the hose motion according to force and tactile sensation.

Studying the above insertion process with respect to the contact between a hose and a plug, it turns out that the successful human insertion process consists of three states, that is, a) approach state, b) contact state, and c) insertion state, as shown in Figure 1. The hose is apart from the plug without the contact between them at the initial state, and the hose approaches toward the plug during the approach state. The hose is in contact with the plug but the nozzle of the hose is not inserted into the plug completely during the contact state. In the contact state, the shape of a hose is deformed by the contact with the plug. Humans estimate how the nozzle of a hose is inserted into a plug and how the shape of the hose is deformed through force sensing and tactile sensation. In the insertion state, the nozzle of the hose is completely inserted into the plug. During the insertion state, humans exert inserting force to a hose and examine how deep the hose is inserted into the plug through force and tactile sensation.

From these observation, it turns out that human skillful and dextrous motion includes hose motion provided by human hands and adaptive motion with sensory feedback. In addition, humans provide adequate motion and control law according to the current process state. For example, in the insertion of a hose, humans provide straight motion during the approaching state while they provide an alternating motion to the hose during the contact and inserting states. Humans control the trajectory of the hose during the approaching state and they control vertical force applied to the hose during the inserting state. Note that these adaptive behavior requires the recognition of current process states from sensory information. This implies that human motion control consists of two feedback loops; sensory feedback and discrete-state feedback, as illustrated in Figure 2. State recognizer shown in the figure identifies the current process state from sensor signals. Once a transit of process state from one to another is detected, motion generator and control law generator provide nominal motion and control law appropriate to the new current state. Motion and control law corresponding to individual process states must be derived or must be obtained in advance and

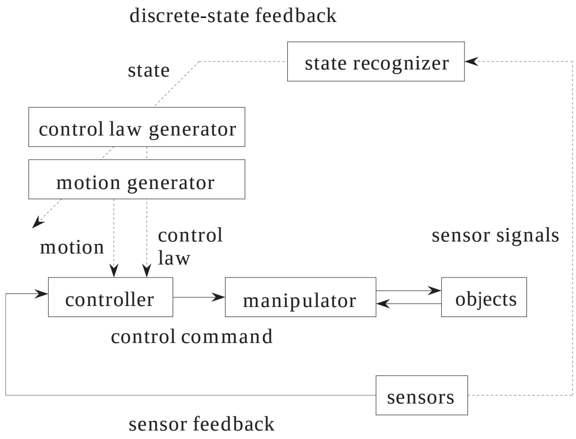


Figure 2: Sensor feedback and discrete-state feedback

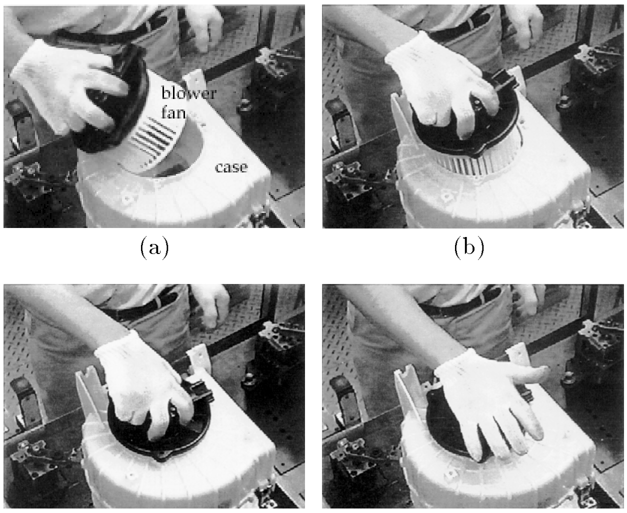
be stored in a memory so that they can be utilized according to the change of the process state. Motion and control laws corresponding to some states may be integrated into one so that the operation during these states can be performed straightforwardly by one motion and control law. Once one motion and control law corresponding to whole states can be derived, a mechanical machine that can perform the operation can be realized. In the following section, we will detail how a machine is developed for the motor insertion into a deformable base considering human skill and dexterity.

3 Development of Novel Assembly Machine based on Human Skill and Dexterity

As mentioned in the previous section, humans perform assembly operations through mechanical contacts among parts. Humans modify their predefined motion according to the sensation during the assembly operation. These human abilities can be regarded as human skill and dexterity in assembly operations. In this section, development of a newly type assembly machine based on human skill and dexterity is presented. Especially, a new machine performing the assembly of blower fans in car air conditioners is described in detail.

Nippondenso Co.,Ltd. manufactures a variety of electric products for cars and car air conditioners are one of main products. An air conditioner consists of many parts and a blower is an essential part of the conditioner. In the current production of car air conditioners, about 180,000 blowers of 15 descriptions have been manufactured per month. The lot size of the blowers is 24 and the cycle time of the blower production is 6 seconds.

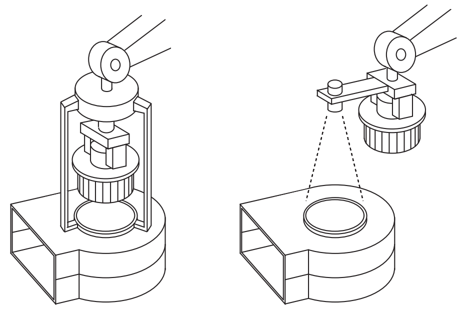
Insertion of a blower fan into a blower case is one process of the blower production. As shown in Figure 3-(a) through (d), a blower fan is inserted into a case, which are conveyed on an assembly line. Blower fan insertion has been done by humans since it is difficult to develop assembly machines for the blower fan insertion in a conventional way. In the blower fan insertion, the positioning error of a



(a) (b)

(c) (d)

Figure 3: Insertion of blower fan into case



(a) (b)

Figure 4: Jig-guided insertion and vision-guided insertion

case is large since it is transported by a conveyer. In addition, shapes of the parts vary significantly since both a fan and a case are formed parts of resin and it is difficult to secure the precision of the parts in forming. Especially, it is difficult to secure the shape accuracy of a case, whose thickness is relatively small. The hole of a case, where a fan is inserted, is often distorted more than the positional accuracy of conventional assembly machines. Positioning error of a case with respect to a pallet is not also small enough. Recall that automatic assembly operations have been achieved traditionally by securing the positional accuracy of mated parts and by controlling part trajectories precisely and straightforwardly. However, it is impossible to mate parts in the insertion of a blower fan into a case hole with in the accuracy of assembly machines as far as a fan and a case are made of low-precision resin. This implies that a conventional technique that assembly operations can be performed by controlling positional accuracy of parts is inapplicable to the development of an assembly machine for the blower fan insertion.

Two methods illustrated in Figure 4 have been investigated whether these methods can be applied to the blower fan insertion or not. One method is to utilize a guiding jig in order to align a fan with respect to a case, as described in Figure 4-(a). In this approach, a guiding jig is aligned to a case hole and is fixed on it beforehand. A blower fan is then guided to the case hole along the jig fixed on the case. This approach can sufficiently achieve the tact time needed to the blower assembly but has the following drawbacks. Firstly, a number of various jigs appropriate to individual descriptions of fans should be prepared in advance. Manufacturing various guiding jigs costs expensive. Secondly, guiding jigs should be changed at the every time when the description of blowers is switched during the production of air conditioners. This switching of guiding jigs yields wasteful time. Another method is to apply a computer vision system, as shown in Figure 4-(b). In this approach, a CCD camera is equipped at the endpoint of a manipulator in order to measure the position and the orientation of a case and the trajectory of the manipulator, which operates a fan, is modified according to the measurements. This approach can cope with a variety of parts by use of computer vision system alone. Introduction of computer vision system, however, costs much and it is difficult to reduce the tact time of the inserting operation. Our goal is to develop a low-cost and reliable assembly machine that can perform the blower fan insertion as efficient as or more efficient than human operations. From this standpoint, it turns out that neither the former method using guiding jigs nor the latter method based on computer vision satisfies out goal and is applicable to the blower fan insertion. This implies that other approaches are needed to achieve our goal.

During assembly operations, humans detect how parts contact one another through force and tactile sensation on their hands, which are operating parts to be mated, and modify the hand motion according to the detection. Thanks to the above human adaptive motion, parts can be mated despite the positioning errors and the deformation of the parts. In addition, humans constrain degrees of part freedom one by one utilizing mechanical contacts among the parts instead of constraining all degrees of freedom at one time as conventional machines do. Parts with large initial deformation and parts easily deformed can be mated quickly and reliably by imitating the above human motion.

Let us record human motion during the blower fan insertion on VTR in order to analyze the human insertion process. As a result, we find that an operator performs the blower fan insertion according to the processes illustrated in Figure 5. At the initial state, an operator grasps a fan obliquely rather than horizontally and moves the fan toward the hole of a case as described in Figure 5-(a). The blower fan then comes into contact with the rim of the case hole. Since the blower fan approaches toward the case with oblique pose, contact between the blower fan and the rim of the case hole occurs without fail despite a certain range of positional errors and tolerances of the fan and the deformation of the case. In other words, approximate but robust alignment against positional errors and deformation of parts can be performed by utilizing the mechanical contact between parts and by selecting a particular pose in the part grasping. An operator detects the contact between the fan and the case from force and tactile sensation. When an operator detects the contact, he or she provides a rotational motion or a twisting motion to the blower fan with keeping the contact between the fan and the rim of the case hole, as described in Figure 5-(b). Motion of the blower fan during this state is illustrated in Figure 6. As shown in the figure, the fan is moved upwardly at the operator side with a pushing force applied to the fan so as to keep the contact while the fan is moved downwardly at the oppo-

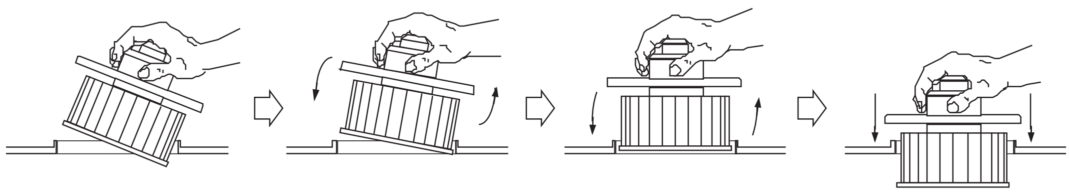


Figure 5: Process of human insertion of blower fan

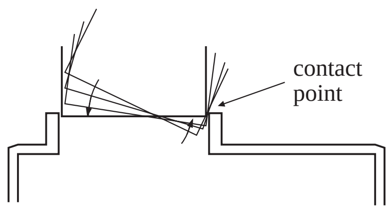


Figure 6: Motion of blower fan in human insertion

site side. Namely, an operator provides 3D spatial motion including rotational motion to blower fans. At the same time, an operator controls the magnitude and the direction of the pushing force according to the reaction force at the contacting point. By providing a rotational motion with keeping the contact, the blower fan can be aligned to the case hole certainly and more accurately in this state than in the state corresponding to Figure 5-(a). An operator detects that the fan is aligned to the case accurately as shown in Figure 5-(c) and then pushes the blower fan downwardly as described in Figure 5-(d). According to the above processes, the insertion of a blower fan into a case hole can be achieved rapidly and reliably despite positional errors and deformation of the fan and the case.

A novel assembly machine shown in Figure 7 is developed in order to achieve the automatic assembly of the blower fan insertion by imitating the human operation and motion illustrated in Figures 5 and 6. This assembly machine consists of a multi-axis mechanical manipulator and a newly developed floating device, as sketched in Figure 8. The multi-axis mechanical manipulator provides nominal motion to the blower fan to be mated while the floating device corresponds to fine motion, that is, adjusting motion according to reaction forces. Nominal motion is obtained by analyzing human motion during the insertion. As a result, nominal motion consists of two motions; approaching motion toward the case with the fan oblique as shown in Figure 5-(a) and twisting and rotational motion described in Figure 5-(b). The approaching motion is determined so that a blower fan come to contact with a case around the hole rim at the manipulator side despite any positional errors of the parts. Note that since the developed assembly machine involves no external sensors, it is impossible to detect the contact itself between the fan and the case. However, reaction forces due to mechanical contact between the fan and the case results in the displacements in the floating device. Thanks to the displacements in the floating device, the blower fan can be guided along the case with keeping pushing force adequately. Next, nominal motion corresponding to twisting and rotational motion is provided to the blower fan by the manipulator. During this nominal motion, the contact between the fan and the rim of the case hole is maintained due to pushing forces provided by the floating device. Namely, relative positioning of a blower fan with respect to the rim is performed by utilizing reaction forces resulting from mechanical contacts between parts. Providing twisting and rotational motion to a blower fan with applying a pushing force, the developed assembly machine can insert a blower fan into the case hole despite positioning errors and deformation of the parts.

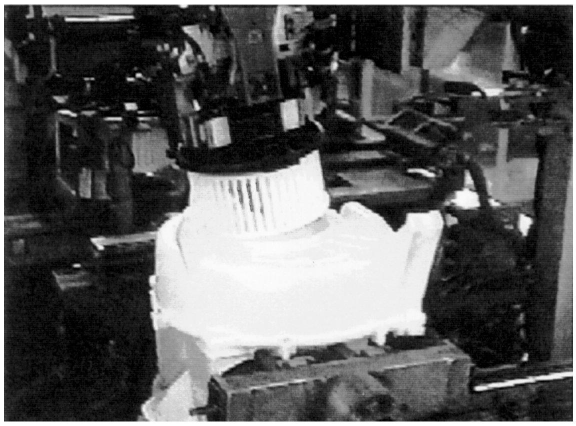


Figure 7: Assembly machine capable of performing blower fan insertion

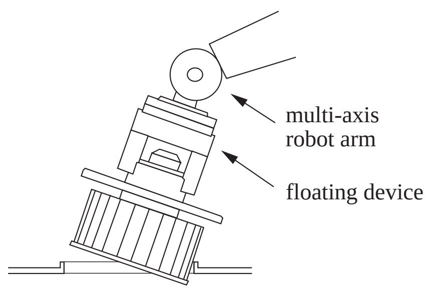


Figure 8: Structure of developed assembly machine

The developed assembly machines have been in practical use for assembly lines of blowers. Performance of the machine is equal to or better than that of humans.

4 Analysis of Assembly Process using Contact State Graphs

As mentioned in the previous section, humans perform assembly operations successfully and reliably by positioning parts relatively utilizing the contact among the parts and by controlling part motion adaptively according to the contact conditions. In this section, we will develop a process model of assembly based on a symbolic description of geometric constraints among parts so that the assembly process can be analyzed systematically.

Assembly is a process of locating and fixing parts together in a desired configuration. In this assembly process, humans mate parts by moving one part along the appropriate surface of the other, as described in the previous section. During the operation, the parts contact each other at different surfaces. As the operation proceeds, the contacting pair of surfaces may change as shown in Figure 9. At the beginning, the moving part is not in contact with the fixed part and is therefore free to move. By contacting different surfaces, the moving part is guided to the desired destination despite uncertainties such as tolerancing errors and sensing errors. During this process, the part motion is constrained by the contact, and the geometric constraints vary in accordance with the change of contacting surfaces. As the constraints change, a manipulator often needs to change its control law accordingly. If hybrid position/force control is used, for example, the selection matrix along with the constraints frame must be changed. In impedance control, stiffness and damping matrices as well as motion trajectories must be changed so as to be consistent with the geometric constraints. Therefore, the geometric constraints due to the contacts are a fundamental characteristic to investigate when control laws and task strategies are being planned.

As shown in Figure 9, individual faces, edges, and vertices of the parts are labeled as face k, edge l, and vertex m, respectively. Assuming that all objects are polyhedra, which consist of vertices, edges, and faces, all contact pairs between parts can be represented by a combination of fundamental pairs, that is, (1) vertex – face contact, (2) edge – edge contact, and (3) face – vertex contacts. Vertex – face contact represents a contact between a vertex of the moving part and a face of the fixed part. The geometric constraints imposed on the parts are determined by listing all the contacting pairs between the two. For example, contacts shown in Figure 9-(d) are described as follows:

(edge 1 – edge 5 , vertex 3 – face 8)

The state of the assembly process described in the list of all the contacting pairs is referred to as *Contact State*. Each contact state has different constraints depending on the geometry of each contacting pair involved.

The contact state is determined by the position and orientation of one part relative to the other. Without loss of generality, we assume that one part is carried around by the robot and the other is fixed in space. Let us denote the position and orientation of the moving part by the six-dimensional vector $q \in V^6$ with respect to a coordinate system fixed to the other part. Some configurations of the moving part are prohibited because of the geometric interference between the two parts. The set of possible configurations is called *Admissible Configuration Space* and denoted by R. The admissible configuration space R is divided into subsets that possess a different contact state N_i,

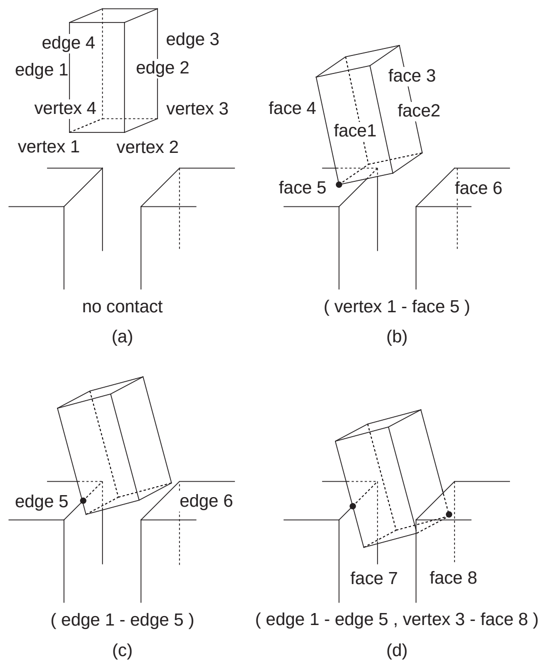


Figure 9: Contact states

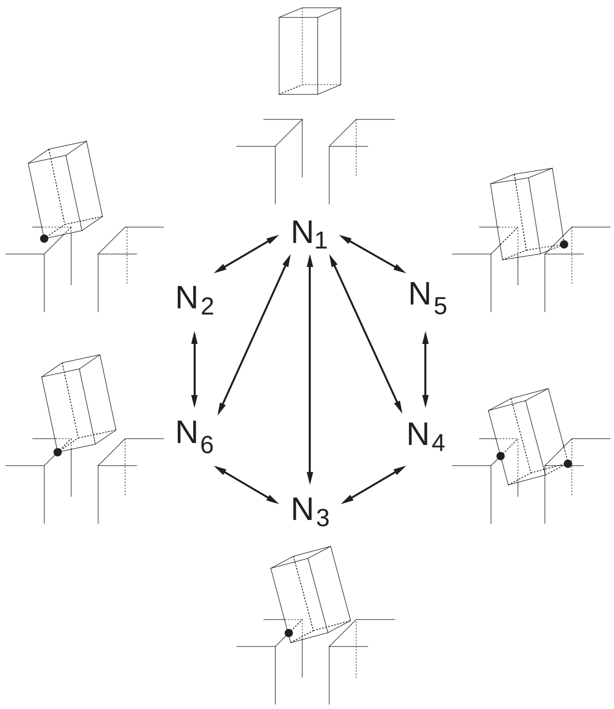


Figure 10: Graph representation of contact state transitions

and the set of part configuration involved in the state N_i is denoted by subset $R_i \subset R$.

During assembly operations, the contact state may change from one to another. Let us model the change of contact state by a transition in a graph. As shown in Figure 10, we represent each contact state by a node of the graph and the possible transition between two contact states is denoted by the arc connecting the corresponding nodes. An arc connecting node N_i and N_j shows that the contact state can transit from N_i to N_j directly without visiting other states except N_i and N_j. No arc from node N_2 to N_3 can be found in Figure 10 since direct transition from N_2 to N_3 is impossible. This graph is referred to as *Contact State Graph*. Investigating all admissible contact states and all possible transitions among the contact states, we can generate a contact state graph that provides a symbolic representation of assembly.

Recall that an arbitrary mating process can be regarded as a series of transitions among contact states. This implies that mating process can be described by a path in the contact state graph from a node corresponding to the initial contact state to a node corresponding to the goal state. Namely, the contact state graphs have a capability of describing all mating processes. Thus, assembly operations can be analyzed by use of the graphs and the planning of assembly operations including motion planning and control law planning can be carried out on contact state graphs [12].

5 Concluding Remarks

Development of a novel assembly machine based on human skill and dexterity in assembly operations has been presented. It is difficult to develop assembly machines performing assembly operations that deal with parts including large tolerances and the operations where parts are easily deformed. This results from the conventional approach to automatic assembly that the operations can be achieved by securing the positional accuracy of assembly parts. In this article, we have proposed a new concept to automatic assembly that assembly operations can be performed by utilizing human skill and dexterity in the operations. In human operations, parts are often guided along other parts to carry out the relative alignment among parts despite positional errors and deformations of the parts. Human skill and dexterity in the insertion of blower fans into deformable cases with positional errors have been studied and have been realized on a newly developed assembly machine consisting of a multi-axis manipulator and a novel floating device. It has been demonstrated that the developed machine is capable of performing the blower fan insertion quickly and reliably as humans do. This machine is already in practical use for actual assembly lines of air conditioners. In the latter part of this article, a contact state graph has been proposed as a mathematical tool to analyze the processes of assembly operations.

There exist many assembly operations still performed by humans. Especially, assembly operations dealing with flexible and deformable parts such as cords and tubes in electric products are difficult to be automated. Development of automatic assembly machines for these operations is eagerly required. Applying the approach described in this article, it is expected that new assembly machines capable of performing these operations can be developed in future.

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