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Assembly process monitoring algorithm using force data and deformation data

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ABSTRACT

In robotic assembly with smaller repeatability than the assembly tolerance, failure should not occur. However, in the industrial field, assemblies may fail because of positional errors in the assembled parts and other factors. Owing to the characteristics of position control, the robot tries to move to the desired position irrespective of the failure of assembly. This situation causes excessive contact force, which can lead to the damage of parts and robots. To prevent this, an assembly process monitoring algorithm is proposed in this study. The role of this algorithm is to monitor, from the sensor information measured in the assembly process, whether the assembly state is formed; thus, the robot may recognize whether the assembly is normally performed or not. In this study, the monitoring performance was verified by applying the algorithm to the process of assembling the parts of a tablet PC.

1. Introduction

Recently, robotic assembly has been expanded to the assembly of tablet PCs and smart phones with high difficulty because the assembly parts and tolerances are relatively small [1–3]. In the industrial field, robotic assembly is mostly conducted through position control of a robot manipulator. In theory, such assembly must always be successful because the robot's repeatability is smaller than the assembly tolerance of the components. However, assembly failure frequently occurs because of position errors in the part supply process, inflow of foreign matter, and other factors. Owing to the nature of position control, the robot tries to reach the commanded position irrespective of the success or failure of the assembly. In case of failure, excessive insertion force is often applied to the parts, which may damage the parts and/or the robot [4]. An algorithm for monitoring the assembly process is needed to prevent this.

An interaction between workers and the environment of the assembly line is becoming increasingly important [5,6]. For collaborative human-robot manufacturing cell, a control framework for the assembly of automobile parts was proposed in [7]. In addition, a system for flexible assembly process with the worker using a dual arm robot is proposed, which allows fenceless human robot cooperation [8]. But the scope of the research in [7,8] is different from our scope. The goal of this study is to make the assembly process completely automated without the aid of a worker.

Numerous studies on robotic assembly have proposed various methods to search for the assembly position through force control schemes [9,10]. A force control-based hole detection algorithm that is easily applicable to the square peg-in-hole assembly was proposed in [9]. A force-controlled hybrid system that allows the controller to recognize changes in the state of the assembly step was proposed in [10]. Although it is possible to perform precision assembly using force control with a high success rate, this process takes too much time and thus cannot replace human workers. Hardware such as the remote center of compliance (RCC) is used to compensate passively for the position error generated during the assembly process [11]. However, there is a limit in the position error that can be compensated by the RCC and its performance deteriorates sharply as the position error increases.

Many studies adopted vision sensors to improve the assembly performance. A micro vision system was used for precision assembly but its performance was adversely affected by illumination changes in [12]. A stereo camera was used for welding car doors in [13] and visual servoing was implemented to obtain the pose information of a product in the 3D space in [14], but both methods failed to obtain sufficient accuracy for assembly. The assembly of a back shell with a smartphone was conducted using a closed-loop approach that uses eye-in-hand visual servoing with two monocular cameras in [15], but this method has a disadvantage that the field of view (FOV) of the vision system must be

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changed according to the size of the part to be assembled.

Many attempts have been made to develop the algorithms that detects failure in the assembly process [16–20]. A recovery method using a F/T sensor data that diagnosed the position errors occurring in the assembly process of electronic connectors was proposed in [16]. Also, the peg-in-hole assembly was conducted using a method to guide the searching of the hole by mathematically modeling each contact using the sensor data [17]. However, these methods in [16,17] have a disadvantage of requiring additional mathematical models which are difficult to be applied to various assembly parts. The support vector machine (SVM), which is a powerful binary classifier, was adopted, but did not show satisfactory results due to its fundamental limitation in [18]. The relative change-based hierarchical taxonomy (RCBHT) was used to abstract force/torque data, but this increased the computational load significantly, thus degrading real-time performance. In [19], a fault detection and isolation (FDI) strategy was used to detect the assembly failure and compensate for the errors by approximating the assembly process of an electric connector with a linear model. However, it was difficult to linearize most parts to be assembled because of the complexity of the contact force generated in the assembly process. A machine learning based system to detect a slip of grasped parts from a gripper using a F/T sensor was proposed in [20]. This machine learning based approach requires datasets for each state, which makes it difficult to cope with various parts in an assembly line.

In this study, we propose an assembly process monitoring algorithm that is easy to apply in industrial sites. The main contribution of this study is that the proposed algorithm enables the robots to recognize the success or failure of the assembly in real time while performing a high-speed assembly process based on position control. In addition, the proposed simple models, based on force or deformation, make this algorithm convenient for field applications where various parts should be assembled. Another contribution is that this algorithm is versatile, and thus it can be used in combination with either 6-axis force/torque sensors or deformation sensors attached at the robot's wrist.

This paper is organized as follows. Section 2 introduces the object to be assembled and the assembly process, and presents the concept of assembly state defined in this study. Section 3 discusses the modeling of the assembly process. Section 4 presents the procedure to monitor the assembly process based on the proposed models. In Section 5, the effectiveness of the proposed algorithm is verified through various experiments. Finally, in Section 6, conclusions are presented.

2. Analysis of assembly process

2.1. Experiment environments

The assembly of the base frame and side frame of a tablet PC shown in Fig. 1, was selected for the verification of the proposed assembly process monitoring algorithm in this study. From the perspective of assembly, the two parts are characterized as follows. First, they are too flat to be grasped with a finger-type gripper. Second, they are vulnerable to an external force because the base frame is mounted on the side frame although they are made of plastic, and thus have elasticity. Third, the assembly process is more complicated than a simple peg-in-hole process because an earphone terminal is protruded. Fourth, there is an assembly tolerance of 0.5 mm in the left and right directions, and 1.0 mm in the forward and backward directions.

Fig. 1(c) shows the system configuration for assembly experiments. In this study, a DENSO's VM-6083G industrial robot, which was connected to its controller and the PC, was used to implement position control with a repeatability of 0.1 mm. An external timer (RTX) was used to ensure the real-time performance that was not guaranteed by the Windows operating system. The control period for position control and assembly state monitoring algorithms was set to 10 ms. The computation time for the proposed algorithm is 1.5 ms which is much less than the control period. The tool coordinate system of the robot was set at the earphone terminal of the base frame so that the pose information of this frame can be known from the pose information of the tool coordinate system relative to the base coordinate system {W} of the robot. Note that pose means position and orientation. In addition, SCHMALZ's suction pads (FM-SW 76 × 22) and a vacuum pump (EVE-TR 10) were used to grasp the flat base frame.

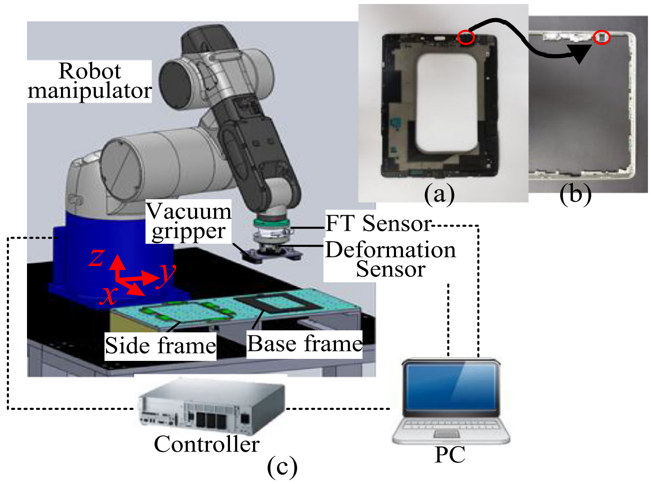

Fig. 1. Assembly parts and experimental setup: (a) base frame, (b) side frame, and (c) system configuration.

Two sensors were used to monitor the assembly process. One is ATI's Gamma, a commercial 6-axis force/torque sensor, which is mounted at the wrist of the robot to measure forces and torques in the x, y, and z directions. The other is a Magic Gripper, developed by the Korea Institute of Machinery and Materials [21], which has a passive stiffness function, like the RCC, to prevent the buildup of excessive contact force owing to the abnormal contact that may occur during the assembly process. It also has a function to quantitatively measure the degree of its deformation in response to external forces. As shown in Fig. 2, the Magic Gripper is in the form of a Stewart platform and can measure the displacement between the upper and lower plates. The displacement measuring part consists of three compliance bars and six linear variable differential transformer (LVDT) modules. The linear displacements measured by the LVDTs are converted into three linear deformations and three rotational deformations in the x, y, and z axes of the lower plate coordinate system with respect to the upper plate coordinate system. In this study, the force/torque sensor is attached to the upper plate of the Magic Gripper, and the suction gripper module is attached

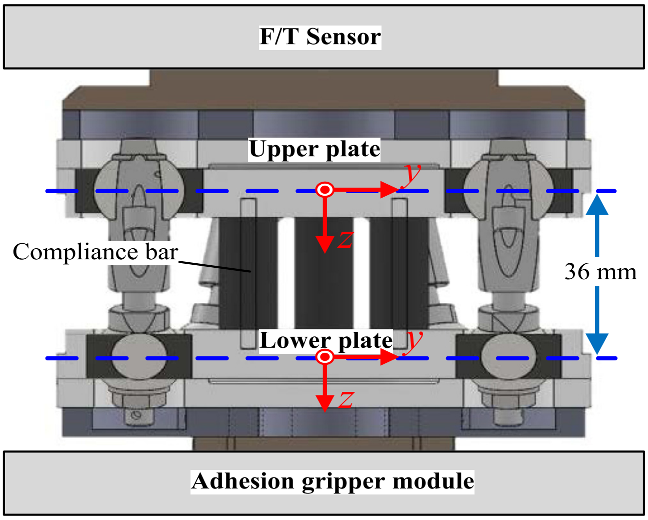

Fig. 2. Magic gripper.