ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

Master's Thesis

OPTIMAL ASSEMBLY PART POSITIONING ON TRANSFORMABLE PIN-JIGS BY ACTIVE PIN MAXIMIZATION AND JOINING POINT ALIGNMENT

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A thesis
Submitted to the Graduate School of UNIST
in partial fulfillment of the
requirements for the degree of
Master of Science

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06. 29. 2018

Approved by

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Abstract

The production flexibility is an ability to produce several types of products in the same manufacturing system. On the other hand, the fixturing quality refers to the degree of suppression of defects from the jig and fixture system during the manufacturing process, so the quality of the product is proportional to the fixturing quality. The transformable pin-jigs, which is one of the transformable jig systems, is highly flexible, but the products assembled through this jig system are difficult to pass the quality standard because it is hard to obtain the optimal fixturing quality in the transformable jig system.

Therefore, we firstly investigated the fixturing quality factor of the transformable pin-jigs to solve this problem. When considering screwing and ultrasonic welding, which are mainly used in the assembly process, the fixturing quality factors are defined as the number of active pins and the joining point alignment. The active pin is a pin that participates in the creation of a jig shape. On the other hand, the joining point is the position where the assembly process is performed, and the alignment is the proximity between the joining point and the corresponding pin-jig point. Since these two factors are determined by the loading position of the product on the transformable pin-jigs, we have proposed the method for optimal assembly part positioning to obtain the optimal fixturing quality that minimizes the assembly defects. The proposed method is based on the iterative closest point (ICP) algorithm and is improved to consider the fixturing quality factors of the transformable pin-jigs. Three case studies have been conducted to verify the improvement of the proposed assembly part positioning compared to the classical ICP algorithm. The result shows improved number of active boundary contact pins and improved joining point alignment. Deformation analysis using the Finite Element Method was also performed to validate the proposed method increases the fixturing quality. The result shows a reduction of the stress and deformation at the optimal position.

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CHAPTER 1

INTRODUCTION

1.1. Background

Jig is a component of manufacturing system to guide a part at correct position with respect to a manufacturing tool and support it from the external forces generated during manufacturing process. The jig consists of the locators which are the unit components to sustain the machining forces (Figure1-1). If a clamp is added to the jig system, it is called a fixture. The clamp is a device that hold the part by applying external force which is called clamping force. Many studies on both jig and fixture system have been proposed, however this thesis mainly focus on jig system.

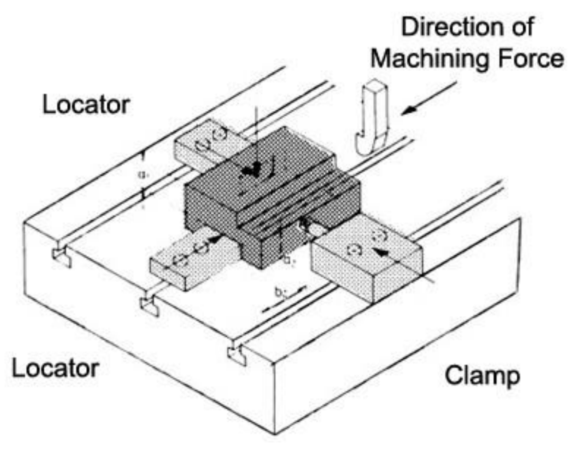


Figure 1-1. Locator and clamp (Carr Lane corp.)

The jig system can be classified into the dedicated jig, modular jig, and transformable jig according to the production flexibility. The flexibility, in the manufacturing, is an ability to produce the various product in one system. The dedicated jig is designed to produce a target product, so it has a customized shape to support the part (Figure 1-2). It is easy to fix the product on the dedicated jig since its shape fits to the target product.

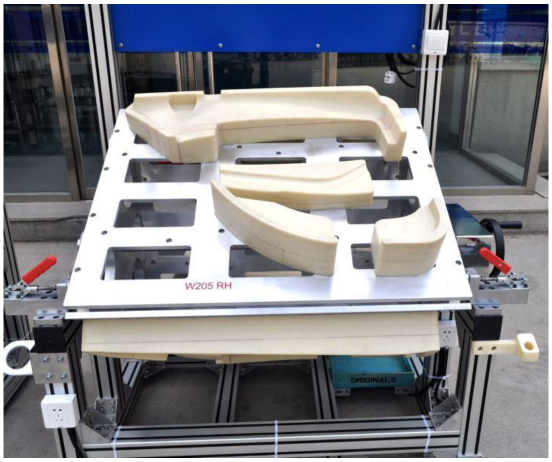


Figure 1-2. Dedicated assembly jig (KEBER corp.)

In case of the modular fixture, it has wider flexibility than the dedicated jig. It consists of modular components such as various types of plates and locators. The jig shape of modular jig is generated by the combination of those components. The locators are arranged on the base plate according to the geometrical specifications of target product (Figure 1-3).

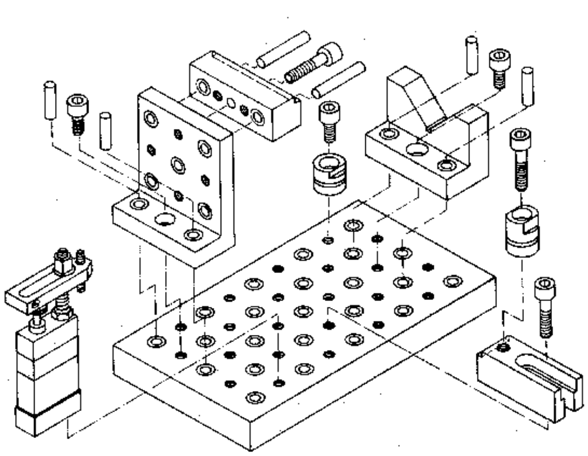


Figure 1-3. Components of modular jig (Hochbaum, 1997)

The transformable jig is an automated reconfigurable jig system. This system has a control station which automatically transforms the jig shape by rearrangement of the locators. Typically, for the system robustness, the locators are arranged at regular intervals and have one degree of freedom along the Z-axis (Figure 1-4). The system calculates the contact heights between the part and locators and then the transformable jig is reformulated according to target product.

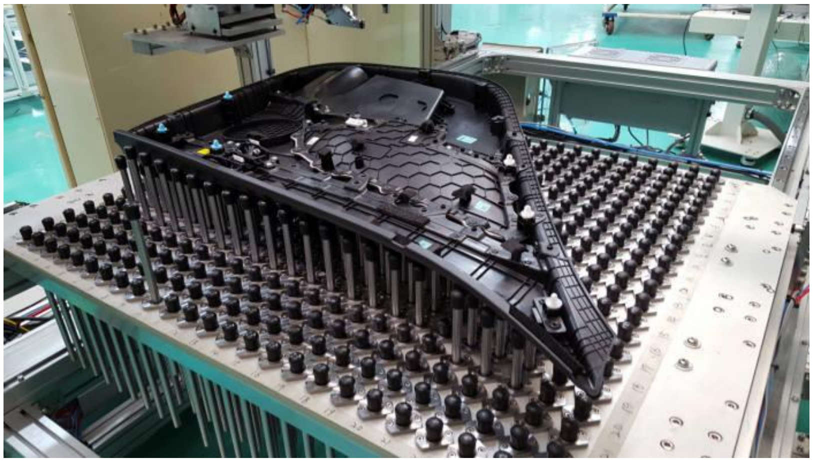


Figure 1-4. Transformable assembly jig (SEOYON E-HWA corp.)

A fixturing quality is important issue in manufacturing since the about 40% of dimensioning errors have been caused by incorrect jig and fixture design (Nixon, 1971).The fixturing quality refers to the degree of suppression of errors from the jig and fixture system during the manufacturing process. The quality of product is proportional to the quality of jig and fixture system. The fixturing quality can be evaluated by a part stability. The part stability is the extent to which the part is fixed. It can be quantitatively tested by consideration of part deformation and machining error. When the jig system has high part stability, it is considered to have a good fixturing quality. From the perspective of the fixturing quality, many manufacturers in mass production had been preferred to use the dedicated jig system since the dedicated jig is designed for the target product to have an optimal fixturing quality. They could improve a product quality, whereas they had to redesign the jig and fixture system whenever the product changes. The cost of jig and fixture account for about 10~20% of the entire manufacturing system (Bi & Zhang, 2001). In the past, the manufacturing companies produced the product for a long period (about 5~10 year), so the replacement cost of the jig and fixture system was not a big problem. However, as the global competition is emerged, the companies should rapidly respond to the customer needs to survive. As a result, the new product becomes shorter as well as the replacement cost of jig and fixture system is critically considered.

1.2. Motivation

The needs to have both the production flexibility and optimal fixturing quality in respond to the global competition. As a result, there have been a lot of efforts to improve the jig and fixture system. The typical solutions proposed over the past decades are based on the computer-aided fixture design (CAFD). The process of CAFD consists of setup, fixture analysis, unit design, and verification. In the setup planning, the analysis of setup, part, and manufacturing process is conducted to determine the component positions of jig and fixture system. The jig and fixture unit, in the next step, is designed to decide a geometrical specification of base plates, locators, and clamp. The result of those steps is verified by some kinds of feasibility analysis based on the requirement of manufacturing process.

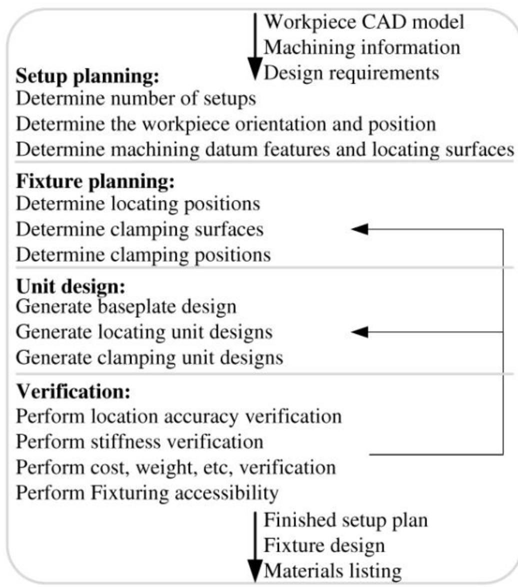


Figure 1-5. Basic elements of computer-aided fixture design (H. Wang *et al.*, 2010)

Many researches based on the CAFD have been proposed, however the fixturing quality is still major task in the manufacturing since the variation of geometrical feature of product is infinite. As a result, the transformable jig system and the optimal part positioning method are consistently developed to improve the fixturing quality to fully utilize the production flexibility.

1.3. Objective

The transformable pin-jigs is a kind of transformable jig system developed to guide the assembly parts of car doortrim panel (Park *et al.*, 2016). It has a target product family which is the variety of injection modeled plastic products.

Figure 1-6. Car doortrim panel on the transformable pin-jigs

This jig system can adjust the shape to fit the target product so the various car doortrim panels can be loaded and assembled on it. The only concern is a quality of assembly result. As shown in figure 1-7, the single parts of assembly product are completely combined under the dedicated jig system, whereas there is a gap between two single parts when they are assembled on the transformable pin-jigs. The cause of this gap defect is an unexpected deformation of the joining point on the product.

The analysis of assembly process is necessary to define the deformation factors in the transformable pin jig system. This car doortrim panel has the two assembly processes which are screwing and ultrasonic welding. Therefore, those two processes, on the transformable pin-jigs, must be analyzed to find out the causes of deformation. Furthermore, the optimal part positioning which minimizes the deformation from the assembly process, would be helpful to prevent the assembly defects.

To sum up, the objectives of this thesis are defined as i) assembly process analysis to define the deformation factors, and ii) the optimal assembly part positioning to minimize the assembly defects by minimizing product deformation on the transformable pin-jigs.

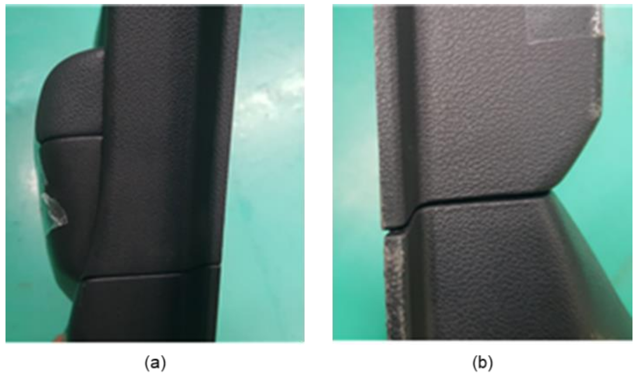


Figure 1-7. (a) part assembled on the dedicated jig and (b) part assembled on the transformable pin-jigs

CHAPTER 2

LITERATURE SUERVEY

2.1. Flexible fixture design

Flexible fixture designs proposed in the literature can be classified into two groups: modular and transformable fixtures. The modular fixture system consists of the fixture components such as base plate, locator, and clamp. There are location candidates on the base plate where the locator and clamp are assembled. Traditionally, the fixture designers had combined those fixture components based on their experience to form a fixture shape fit for a target product, but they have developed the automated reconfiguration algorithm since it is more efficient to consider the huge number of possible combinations. The transformable fixture has also the fixture components. The fixture components of the transformable fixture, unlike to the modular fixture, are arranged and fixed at regular intervals. Typically, the transformable fixture adjusts the height of fixture components to form a fit fixture shape for a target product. Many studies of product positioning optimization have been conducted to increase the fixturability.

Modular fixture design

One of the most important parts of creating a modular fixture is to design appropriate fixture modules and assemble them according to the target product. Some design criteria to design proper modular fixture module were proposed by Drake as well as the Takao has been proposed the modular fixture that meets the requirements of the flexible manufacturing system (Drake, 1984; Takao, 1988). Liu, based on those design criteria, has been classified the fixture functions into locating, guiding, clamping, supporting and linking, and proposed a systematic method to modularize the dedicated fixture according to the fixture functions (Liu, 1994).

Typically, the base plate of modular fixture, as shown in Figure 1-3, has the holes at regular intervals as the location candidates for assembling the other fixture components. The combination of fixture components based on those holes sometimes could not hold a part properly due to the less flexibility from the discretized location candidates. To solve this limitation, Sela has proposed a reconfigurable modular fixture based on continuous location candidates (Sela *et al.*, 1997). This fixture system has the base plate and cross-block which is of a T-slot type. The cross-block is a fixture component where the locator is assembled, and it is attached to the T-slot on the base plate. Through the T-slot on the base plate and cross-block, the locators and clamps can be located at desired position for manufacturing process.

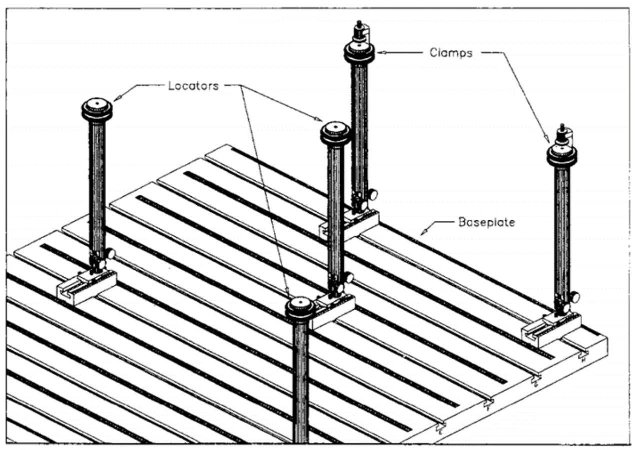


Figure 2-1 Reconfigurable modular fixture for thin-walled flexible objects (Sela *et al.*, 1997)

Wallack and Canny have been also proposed a method to increase the flexibility of location candidates for modular fixture of prismatic workpiece (Wallack & Canny, 1997). The proposed modular fixture, as shown in Figure 2-2, consists of two fixture table jaws which could translate along one direction. This fixture system gives broad variation of location candidates by adjusting the distance between two fixture table.

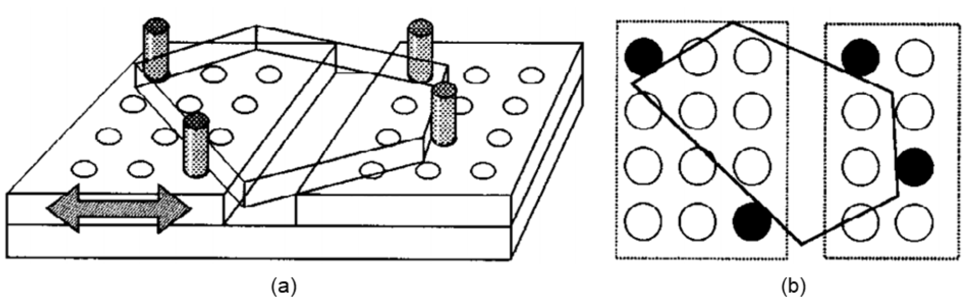


Figure 2-2. A modular fixture vise (a) general-view and (b) top-view (Wallack & Canny, 1997)

Locating scheme

A locating scheme is a kind of guideline for positioning locators on the modular fixture. The "3-2-1" locating scheme was traditionally used to hold a rigid workpiece (Figure 2-1.). Any rigid body has 6 degrees of freedom (Nee *et al.*, 2012). Since each locator prevents movement corresponding to one degree of freedom, at least 6 locators are required to accurately locate the part. As shown in the Figure 2-1, there are 6 locators A1, A2, and A3 defined in the primary reference plane A; B1 and B2 defined in the secondary reference plane B; and C1 defined in the tertiary reference plane. The A1, A2 and A3 restrain translation along the z-axis, and rotation about the x- and y- axes respectively. The B1 and B2 restrain translation along the x-axis and rotation about the z-axis. C1 restrains translation along the y-axis (B. Li *et al.*, 2001).

A typical "3-2-1" locating scheme is cost efficient to locate a part with the minimum number of locators. However, for some parts having complex geometry, the "3-2-1" locating scheme cannot meet the tolerance specification. To solve this problem, a "N-2-1" locating scheme has been proposed by Cai (W. Cai *et al.*, 1996). The larger number of locators (N ≥ 3) are used to locate the part in this scheme.

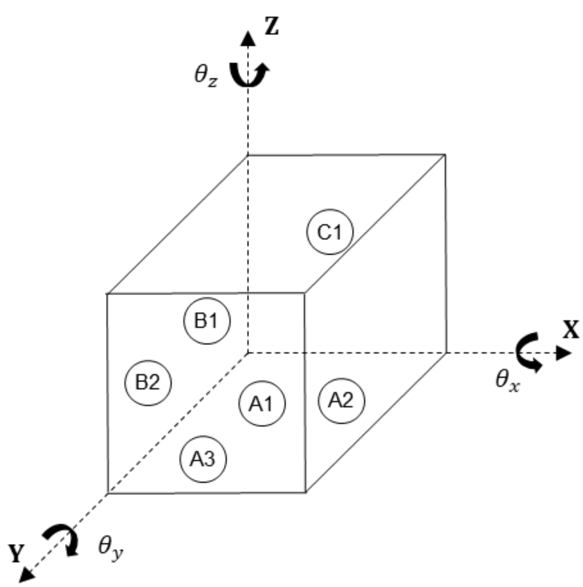


Figure 2-3. "3-2-1" locating scheme

Transformable fixture design

The pin-array type is one of most popular design of transformable fixture. The pin-array means that the pin-shape locators are arranged at regular intervals. The reconfiguration of pin-array type fixture system is easily conducted by adjustment of pin height. Hurtado and Melkote have been proposed the two types of pin-array transformable fixture, as shown in Figure 2-4, which are active pin-array and passive pin-array. The active pin-array is to hold a product by external pneumatic force, whereas the passive pin-array is to just support the weight of product (Hurtado & Melkote, 2002).

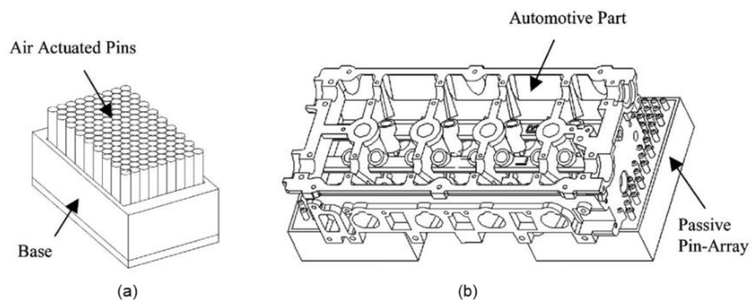


Figure 2-4. (a) active and (b) passive pin-array transformable fixtures (Hurtado & Melkote, 2002)

The typical pin-array fixtures have to use additional clamping mechanism when the stricter fixturing requirements are necessary, but it is hard to decide the location of clamp due to the dimensional variation of product. To solve this problem, the vacuum clamping cup has been attached to the top of the pin-shape locator (Arzanpour *et al.*, 2006; Do *et al.*, 2018). This vacuum clamping mechanism is very effective to hold a thin-walled product.

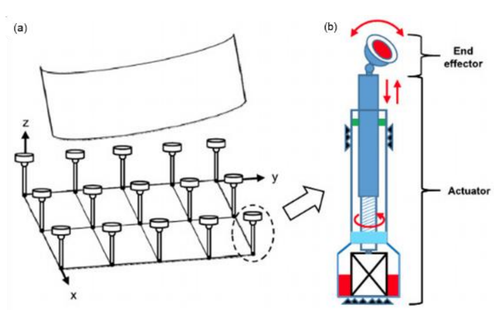


Figure 2-5. Schematics of (a) flexible fixture and (b) hybrid locator/clamp fixel (Do et al., 2018).

2.2. Part stability

The purpose of jig and fixture is to locate and hold a part on the desired position with respect to the tool during the assembly, machining, inspection, and so on. The extent to which the part is fixed is called part stability. In this section, the definitions of part stability proposed by existing studies are introduced.

Kang has proposed the evaluation criteria for the part stability through the contact stability index (CSI) defined based on the cone of friction (Kang *et al.*, 2003).Since the external forces (e.g. clamping and machining forces) and the internal forces (e.g. reactive forces) must be balanced to get a part to remain stable during the manufacturing process, the part stability has been evaluated by force balance. When α_0 and α_F are the angle cone of friction and the angle between force vector and inverse of Z-axis respectively, CSI is defined as:

$$\mathrm{CSI} = \begin{cases} 1.0 - \dfrac{\alpha_F}{\alpha_0} & \alpha_F \le \alpha_0 \\ -\dfrac{\alpha_F - \alpha_0}{\pi - \alpha_0} & \alpha_F > \alpha_0 \end{cases}$$

The part stability based on CSI is shown in table 2-1.

TABLE 2-1

PART STAILBITY BASED ON CSI

Range of CSI	Description	Part stability
$-1 \le \mathrm{CSI} < 0$	Outside the cone of friction	Unstable
$\mathrm{CSI} = 0$	On the cone of friction	Marginally stable
$0 < \mathrm{CSI} \le 1$	Inside the cone of friction	Stable

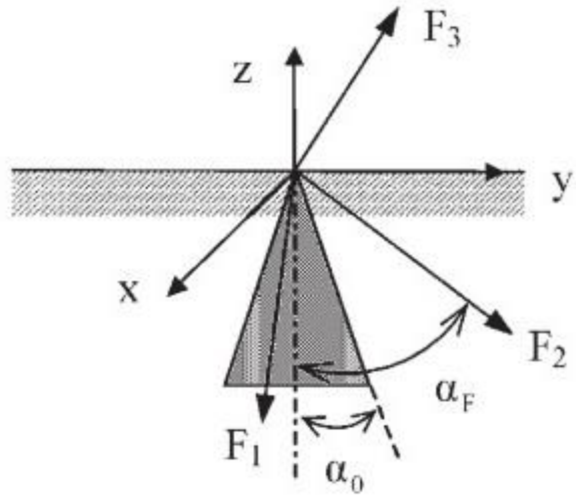


Figure 2-6. Cone of friction (Kang *et al.*, 2003)

Another part stability evaluation method based on force balance is instantaneous rotational center triangle (hereafter IRC triangle). The IRC triangle refers the triangle with three vertices as intersections between directional lines of reaction force against workpieces of three locators (Wu *et al.*, 2008). The IRC triangle has three edges and the edges are called same directed edges when they form a closed directional loop. On the other hand, if the one of the edge has different direction then it called differently directed edge. The criteria for feasible clamping force was defined according to the number of same directed edges.

Some studies based on the part displacement and deformation have been also proposed. Firstly, Qin has evaluated the part stability by error due to the part position and machining (Qin *et al.*, 2006). In this study the position error between part and fixture was evaluated by the analysis of local deformation of part at the contact points and the machining error was analyzed by only consideration of the elastic deformation of part. Asante, on the other hand, has analyzed the part stability based on the relations between the external forces and the deformation (Asante, 2010). The stable state means that the fixture restrains the sliding and revolving of the part during the manufacturing process. Since the part is affected by the contact forces and the wrench, the movement and rotation of part would be minimized when those two forces and wrench are minimized. The stiffness matrix is formulated to get the contact forces and wrench as the elements to find out an optimal stability. According to this study, the minimum eigen value of the stiffness matrix has the best stability.

Alternatively, in the cutting process, the distribution of chip thickness can be used to evaluate the part stability. The chip is a tiny piece that comes off a part. The well-distributed of the chip thickness generate no vibration, constant cutting force, and the consistent deflection of part throughout the cutting process (Chen *et al.*, 2006). The optimal spindle speed was analyzed in this study since the chip thickness has relationship with it.

2.3. Optimal fixture configuration

Optimal fixture configuration is to select the best location candidates of modular fixture to maximize the fixturability. The fixturability was evaluated by the requirements based on part stability such as force balance, deformation analysis, and so on. Therefore, the fixture configuration is optimized to fully satisfy those requirements.

Brost and Goldberg have been proposed a method to optimize the modular fixture by filtering and the user specified quality metric (Brost & Goldberg, 1996). In this work, every candidate of fixture configuration was constructed and filtered to remove the tool collision, out of translation range of clamp, and not feasible on the finite fixture plate. The filtered fixture candidates are finally scored according to the criteria specified by the user. Michael and Pelinescu have been also proposed the optimizing fixture configuration method according to the several performance criteria based for evaluating localization accuracy (Michael Yu & Pelinescu, 2001).

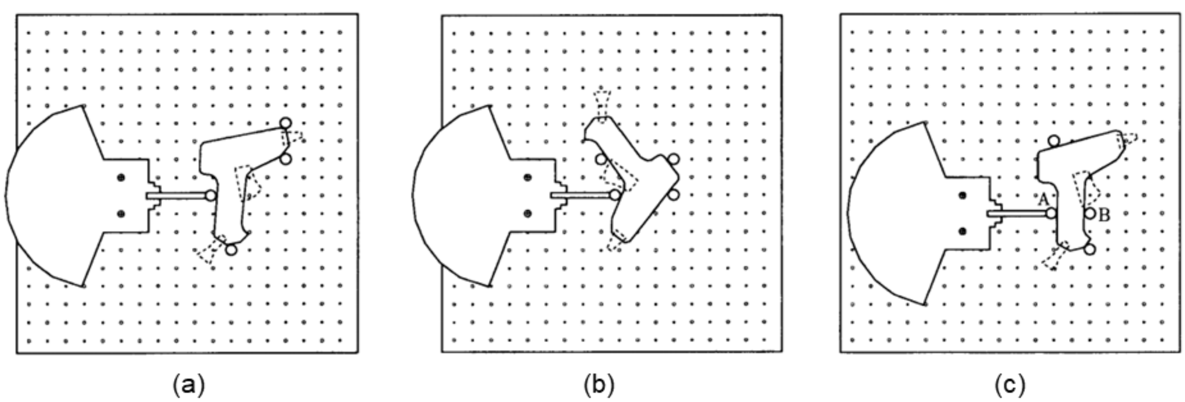


Figure 2-7. Three possible configuration candidates (Brost & Goldberg, 1996)

There are also many studies on numerical analysis-based fixture optimization. The commonly used optimization method is genetic algorithm. The optimization methods for machining fixture configuration by using the genetic algorithm have been proposed(Kaya, 2006; Krishnakumar & Melkote, 2000). They used the genetic algorithm to find out the fixture layout which minimizes the product deformation due to the machining process. Prabhaharan also used genetic algorithm to optimize the machining fixture. In this work the part deformation was modeled by finite element method and it was used on the objective function in optimization process (Prabhaharan *et al.*, 2006). In case of the Kulankara's study, the genetic algorithm was used to optimize the fixture layout, but only clamping force among the fixture components was considered (Kulankara *et al.*, 2001). Xiong has proposed the method to find an optimal fixture layout for various aerospace parts by using genetic algorithm and finite element analysis (Xiong *et al.*, 2013). B. Li and Shiu also have been used the genetic algorithm to optimize the fixture for the sheet metal assembly with laser welding (B. Li & Shiu, 2001). They proposed the prediction and correction method to determine the number of optimal number of direct locators considering the degree of metal fit-up.

The studies considering more than two objectives in optimization were also presented. Pelinescu and Wang have been proposed the multi-objective optimization method for fixture configuration based on the multiple quality criteria and trade-offs among the fixture performance requirements (Pelinescu & Wang, 2002). The Wang has been presented the multi-constraints optimization method for machining fixture configuration by considering of the repeatability, immobility and stability of fixturing (Y. Wang *et al.*, 2006).

2.4. Optimal part positioning

The optimal part positioning is to position where the fixturability is maximized. It is similar process to the optimal fixture configuration, but the fixture configuration of the transformable fixture is decided by the loading position of product, so it is preferred to be called the optimal part positioning. This positioning is based on the manufacturing process analysis and consideration of the part including the material, geometry, desired dimension tolerance and so on. Many researches on the optimal part positioning have been presented. In this section, those studies are classified according to its target product type.

Cai has proposed a method of positioning optimization for sheet panel assembly (W Cai, 2008). In order to consider the welding variation, which is a unique feature of the sheet panel assembly, the welding force was modeled as a random force with standard normal deviation. A fixture element model was constructed by applying random welding force and the finite element analysis (FEA) was performed for optimal part positioning. The author, to avoid the unnecessarily long simulations, also developed a new statistical model that transforms random optimization into deterministic optimization.

In case of the thin walled part, the flexible fixture system consists of hybrid locator and clamp fixel is presented by Do (Do et al., 2018). The fixels are arranged at regular intervals. The part for locator can adjust its height by linear actuator and it has a vacuum cup at the top to hold the part (Figure2-2). The optimal part positioning in this study consists of three steps. Firstly, the optimal roll and pitch are investigated for the maximum support capacity. The support capacity is maximized when the projected area on the x-y plane of vacuum cup is maximized. Secondly, the initial placement to locate the part at the origin of the fixture system. Lastly, the maximization of the number of fixels which hold the part is conducted by using winding number theory.

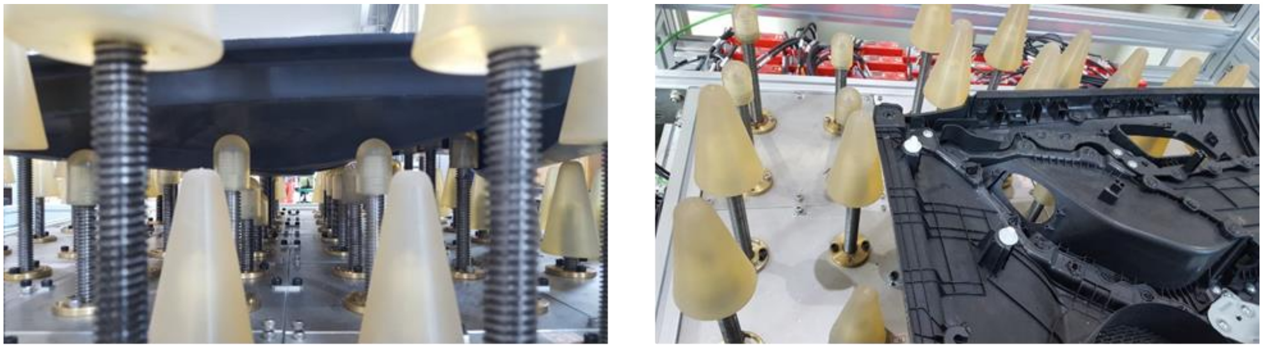
CHAPTER 3

TRANSFORMABLE PIN JIG SYSTEM

3.1. Transformable pin-jigs

The transformable pin-jigs is a kind of transformable jig designed for assembling the injection modeled product, especially a car door trim. It consists of the 80 pin-type locators at regular intervals. The locators are called a pin, and their height can be adjusted to form a jig shape. There are 2 types of pins which are designed to guide and support the assembly part. The one is underlying contact pin. It is designed to support the assembly part at the bottom. A hemispheric pin-head is accepted for the underlying contact pin to minimize the interference between the pin head and part. The other one is the boundary contact pin. The purpose of this pin is to guide the part at desired location during the manufacturing process as well as to support the part at the boundary.

Figure 3-1. Transformable pin-jigs

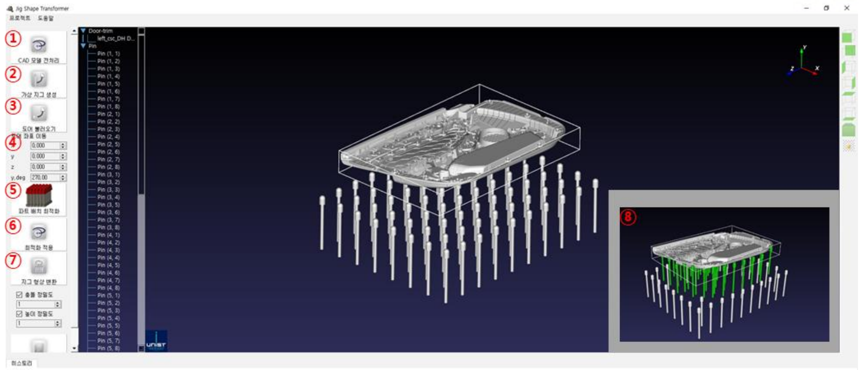


(a) (b)

Figure 3-2. (a) Underlying contact and (b) boundary contact

3.2. Jig shape transformer

The jig shape transformer is a software which calculates the jig shape according to the target product. The product CAD model is optimized to reduce the unnecessary geometric features. It is called preprocessing and it dramatically reduce the computational time. After preprocessing, this system generates the pin-jigs according to the input including the number of pins, interval, and pin-type. Then, it loads a product which is the result of preprocessing and set a loading position by adjusting the translation and rotation with respect to the origin of pin-jigs. When those setup processes are finished, this system calculates the jig shape by contact analysis between the assembly part and pin-jigs. The result of shape calculation is saved as a CSV file and it is transmitted to the transformable pin-jigs then the hardware conduct reconfiguration according to the result.



① : Preprocessing CAD (.stl → .vtp)

② : Pin-jigs generation

③ : Load a product

④ : Set a loading position

⑤ : Assembly part positioning (add-in)

⑥ : Apply a result of ⑤ to ④

⑦ : Calculate the jig shape

⑧ : Example of ⑦

Figure 3-3. Jig shape transformer (GUI)

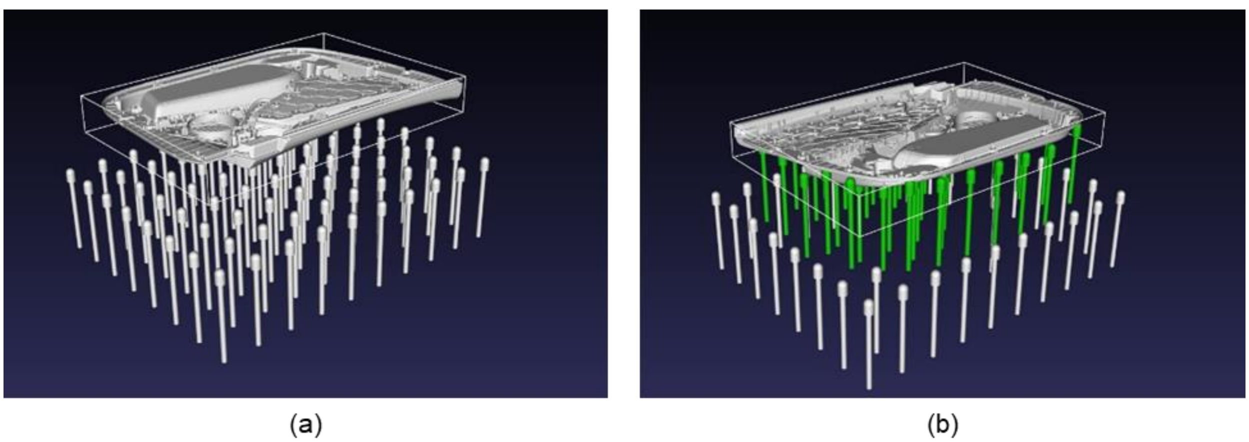


Figure 3-4. (a) Loading position (b) jig shape calculation

CHAPTER 4
ASSEMBLY PART POSITIONING ON TRANSFORMABLE PIN-JIGS

4.1. Problem statement

The injection modeled plastic assembly is a process of combining several parts to make one product. The most common methods for this assembly are screw fastening and ultrasonic welding. Both methods are generally performed along the vertical direction on the wide surface of the part to minimize the positioning error between the part and jig since the external force along other direction is more likely to push out the part.

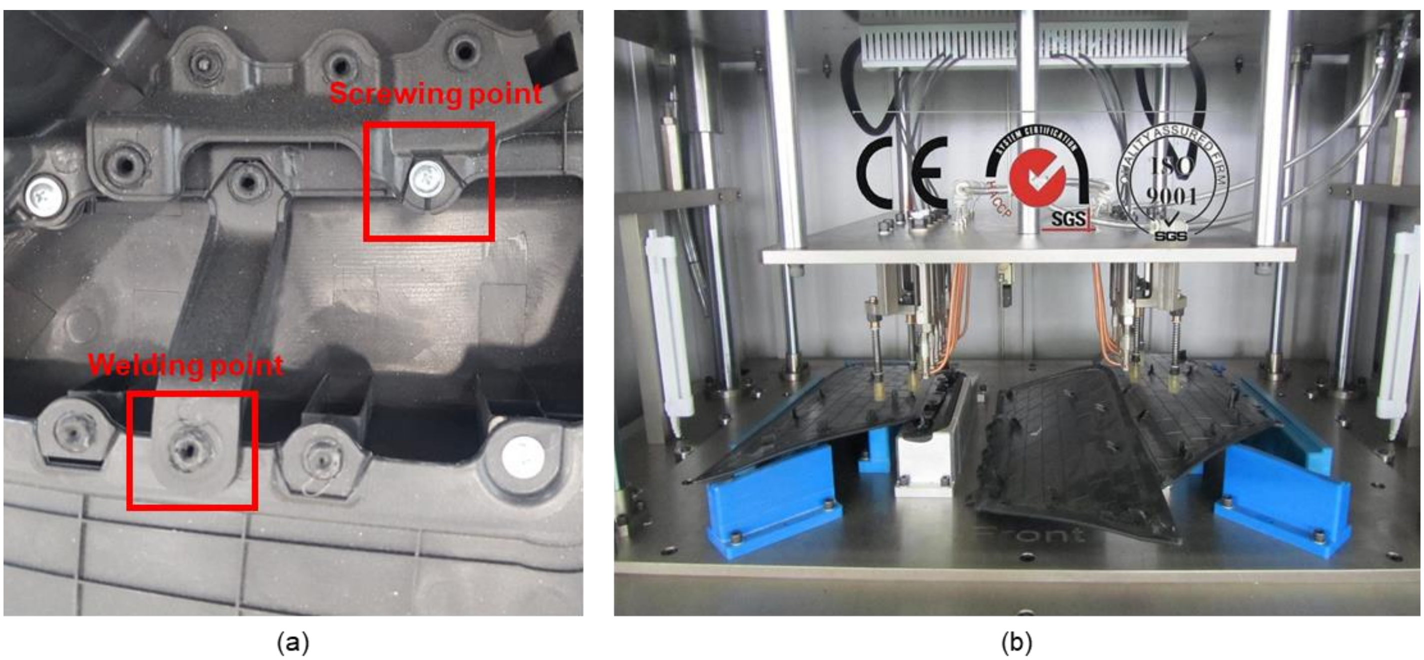


Figure 4-1. (a) Screwing and ultrasonic welding and (b) KEBER's ultrasonic welding machine

The defects caused by jig in the injection modeled plastic assembly process are mainly scratch and gap between two single parts (Figure 4-2.). The scratch occurs when the exterior of the product is damaged due to the sharp shape of the fixture. Generally, in order to prevent the scratch, the soft material (e.g. MC NYLON) is used to make a fixture as well as put a cover over a fixture. The gap occurs when the fixture has a low fixturing quality because the product is not completely fixed, or the product deforms due to the external force generated during assembly process. Since the dedicated jig supports the product through surface contact that conforms to the shape of the product, the gap defects often do not occur. However, since the point contact is made according to the shape of the product, the fixturing quality is relatively lower than the dedicated jigs in the case of the transformable pin-jigs. As a result, the gap defect occurs more frequently and therefore the fixturing quality of transformable pin-jigs must be improved.

(a) (b)

Figure 4-2. Typical assembly defects; (a) scratch and (b) gap

The transformable pin-jigs consists of the underlying and boundary contact pins (Figure 4-3). The underlying contact pin is a pin that forms a contact at the lower surface of the product. Its pin-head is designed to be hemispherical so that it is easy to get the underlying contact with product. The boundary contact pin, on the other hand, is a pin that get a contact at the boundary of the product. The shape of its pin-head is a truncated cone which is suitable for boundary contact. The fixturing quality is improved when the number of pins used for shape generation increases since it is advantageous to support the external force as the underlying contact pins increase and to hold the product as the boundary contact pins increase.

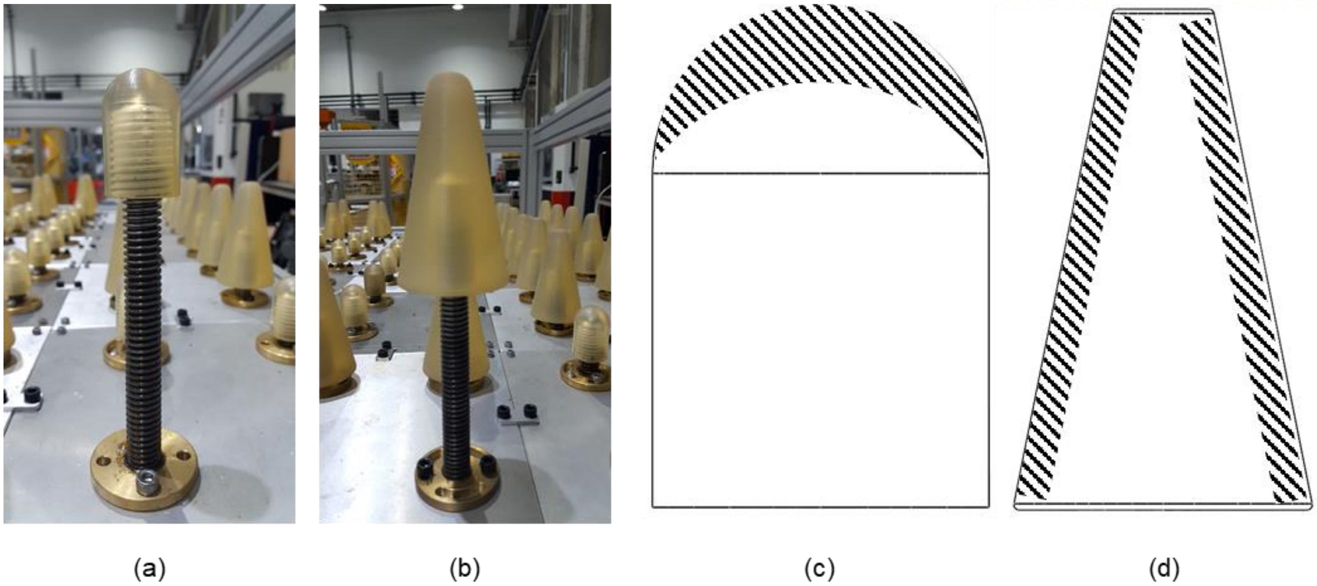
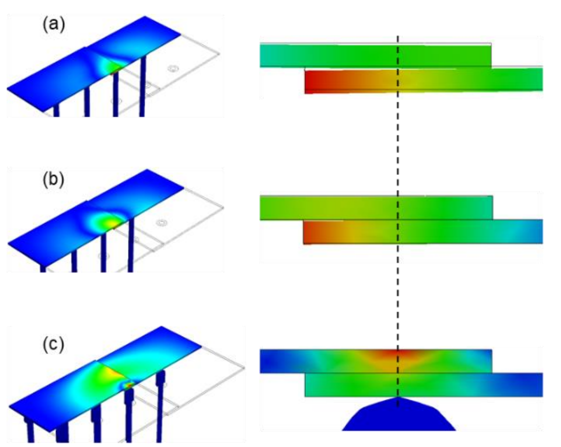


Figure 4-3. Pin types and contact areas; (a), (c) underlying contact pin and (b), (d) boundary contact pin



	Distance between pin and joining points (mm)	Max. URES (mm)
(a)	84.8	0.8992
(b)	42.4	0.3191
(c)	0	0.002670

Figure 4-4. Deformation element of assembly part validation experiment (Kim et al., 2018)

Another factor that affects fixturing quality in a transformable pin-jigs is the distance between the pin and joining point. In an experiment to analyze the product deformations in the assembly process, we verified that product deformation increases as the distance between pin points and joining points increases. (Kim *et al.*, 2018)

Considering the components of the transformable pin-jigs (the boundary contact pin and underlying contact pin) and the part deformation factor in the assembly process, to improve the fixturing quality, increase the number of pins participating in shape generation and decrease the distance between pin points and joining points. In the transformable pin-jigs, since these number of pins and distance are determined according to the position of the assembly part, an assembly part should be located at position which improves the fixturing quality. The number of pins increases when the data points and pin points are aligned because the pins are arranged at regular intervals in the transformable pin-jigs. The distance also decreases when the joining points in the data point set and pin points are aligned. Therefore, to improve fixturing quality, the objectives i) reduction of distance between the joining points and pin points and ii) increases of the number of used pins are defined as point set registration problem.

4.2. Overview

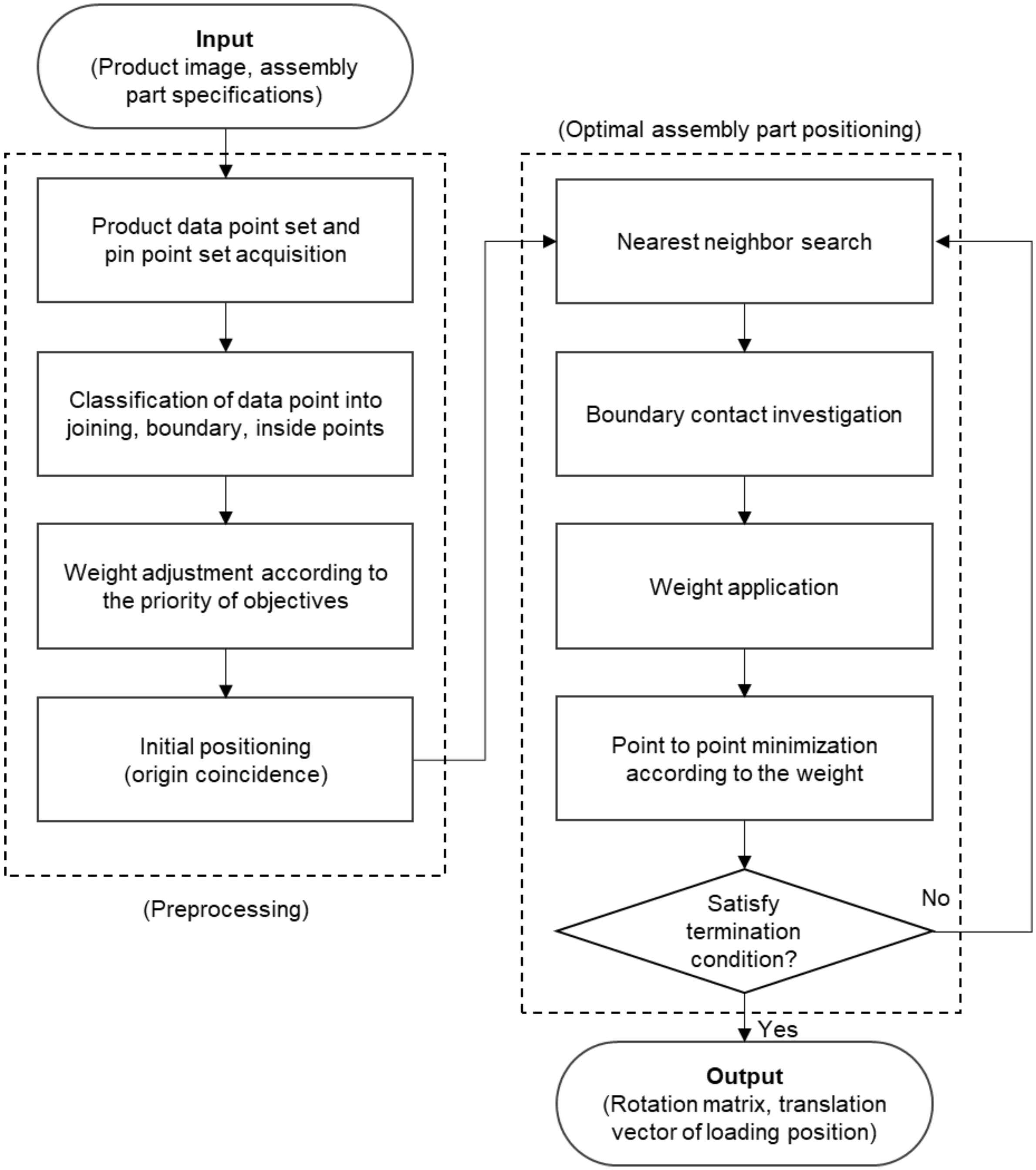


Figure 4-5. Overview of proposed algorithm for optimal assembly part positioning

4.3. Assembly part positioning on transformable pin-jigs

4.3.1. Prerequisites

Loading position

The loading position of the assembly part is expressed as [x, y, z, roll, pitch, yaw] by the coordinates of the center of the assembly part and the rotation about each axis. In case of the injection modeled plastic assembly process, only the situation where z, roll, and pitch are zero is considered because the product is generally placed horizontally on the jig. Therefore, it is defined as [x, y, yaw] where yaw is the clockwise rotational angle about z-axis.

Figure 4-6. Typical loading posture of assembly part

Point set definition

The problem of increasing the number of pins involved in shape generation and reducing the distance between pin and joining points can be defined as the problem of aligning the data pointset and the pin point set on the x-y plane. Therefore, we used the point cloud which projected the product CAD in the x-y plane at the loading position as the product data point set, and the coordinates of pins on the x-y plane are used as the pin point set.

Point set registration

The point set registration is to find the transformation that aligns the two-point sets in $\mathbb{R}^{\mathrm{n}}$ as close to each other as possible. Generally, the point sets are represented by data and model, but in this thesis, they are expressed as point set $P : \{\vec{p}_j\}, (j = 1, 2, \cdots, N_{\mathrm{p}})$ and pin point set $D : \{\vec{d}_i\}, (i = 1, 2, \cdots, N_{\mathrm{d}})$. The task of registration is presented as a least square problem.

$$\min_{\boldsymbol{F}} \sum_{i=1}^{N_d} \left\| \boldsymbol{F}(\vec{d}_i) - \vec{p}_{c(i)} \right\|^2$$

where $\boldsymbol{F}$ is the transformation for model point and $c(i)$ is the index of nearest point of $\vec{d}_i$ in *M*.

In the rigid transformation, the transformation F consists of a rotation matrix $\boldsymbol{R}$ and a translation vector $\vec{t}$

$$\boldsymbol{F}(\vec{d}_i) = \mathbf{R}(\vec{d}_i) + \vec{t}$$

By applying the $\boldsymbol{R}$ and $\vec{t}$, the least square problem is rewritten as follow

$$\min_{\boldsymbol{R},\ \vec{t},\ c(i) \in \{1,2,\cdots,N_d\}} \sum_{i=1}^{N_d} \left\| (\boldsymbol{R}\vec{d}_i + \vec{t}) - \vec{p}_{c(i)} \right\|^2$$

4.3.2. Product data point set and pin point set

Product data point set acquisition

A product data point set is acquired from top view of product which is projected to x-y plane. This image is converted to an array in MATLAB and then array components are extracted as a product data point set. Since the size of image array is not identical to the real size of product, a calibration is needed to unify the unit.

$$\text{Millimeter per pixel}: \frac{W_{real}}{W_{image}} \ or \ \frac{H_{real}}{H_{image}}$$

Where W_{real} and H_{real} are actual dimensions of product and W_{image} and H_{image}

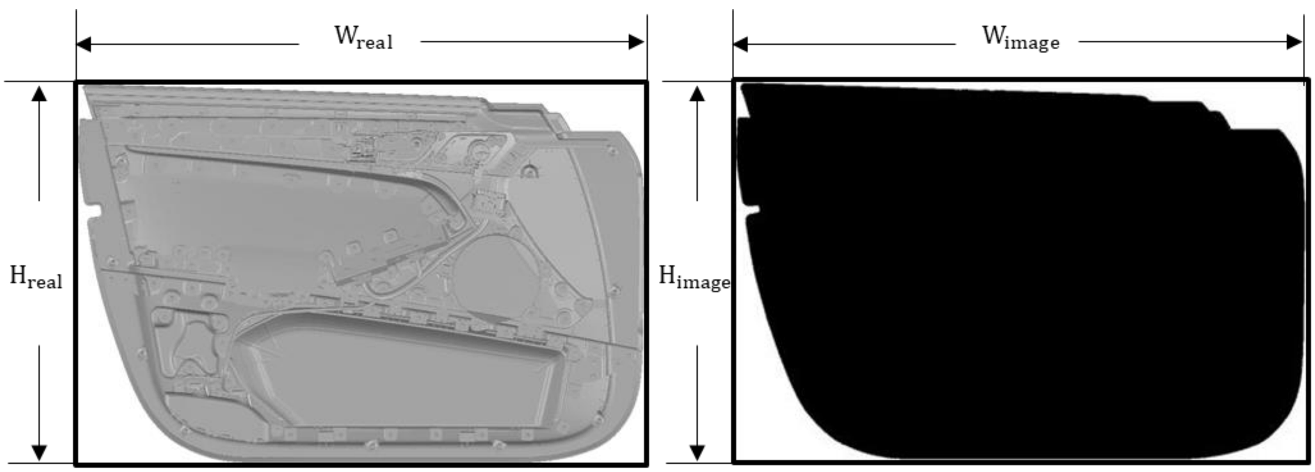


Figure 4-7. Dimensions of product and image

Classification of product data point set

Product data point set consist of three different types of points which are joining, boundary, and inside points. The joining points are the positions where the assembly process is performed. The boundary points and inside points are the points on the border and inside of product respectively. The boundary contact is possible only at the boundary points. The underlying contact, on the other hand, can be made at the all points in the product data point set. The number of point is defined as shown in the Table 4-1.

TABLE 4-1
CLASSIFICATIONS OF THE PRODUCT DATA POINT SET

Type	Description	Number of points
1	Joining points	N_1
2	Boundary points	N_2
3	Inside points	N_3

Where $N_d = N_1 + N_2 + N_3$

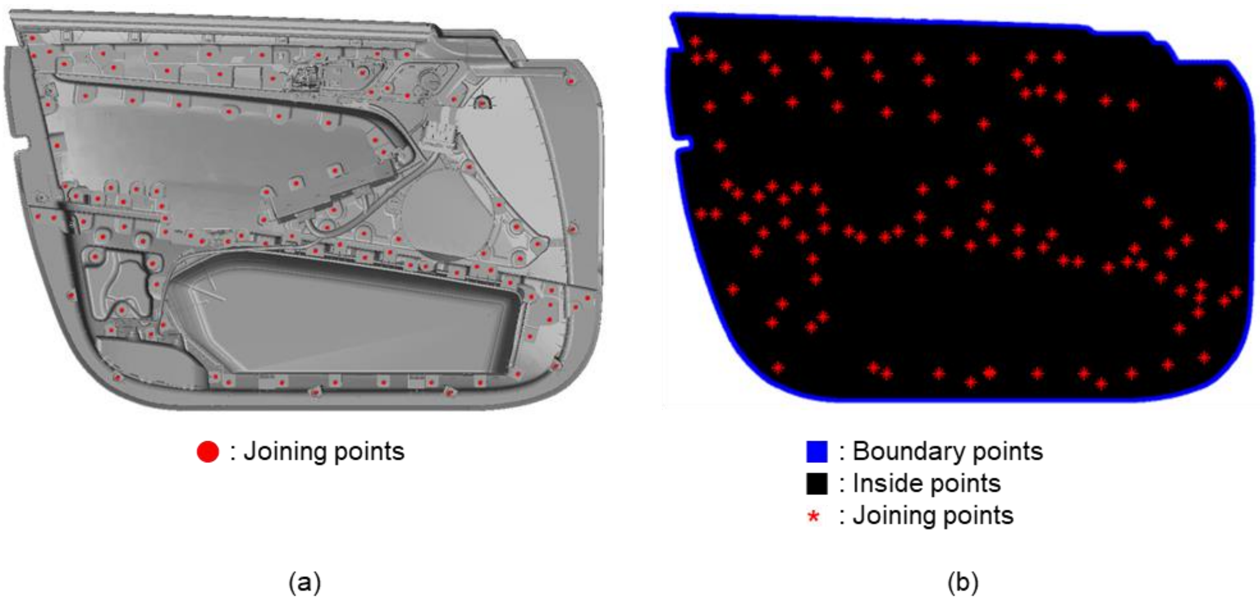


Figure 4-8. (a) product image and (b) product data point set converted from image

4.3.3. Registration of product data point set and pin point set

Iterative closest point algorithm

The iterative closest point(ICP) algorithm was used to align product data point set and pin point set. The ICP algorithm is an effective and accurate technique suitable for rigid registration and was proposed by Besl in 1991 (Besl & McKay, 1992). Various effective variants based on ICP have been developed (Rusinkiewicz & Levoy, 2001) and recently the constraint-based applications to improve registration accuracy (Shin & Ho, 2017; Zhang *et al.*, 2016), the global reference point based application (Du *et al.*, 2017), and an allowance optimal distribution based application (D. Li *et al.*, 2018) are developed.

Classic ICP

The classic ICP consists of two main steps. The first step is the nearest neighbor search, and the second step is the point to point minimization that minimizes the distance from each point to the its nearest neighbor. Steps 1~2 start from the given initial rotation matrix $\boldsymbol{R}_0$ and translation vector $\vec{t}_0$ and repeat until the termination condition is satisfied. In case of assembly part positioning on transformable pin-jigs, the initial transformation is set to coincide the centers of two sets of points.

Nearest neighbor search

The nearest neighbor search specifies the closest pin point at each product data point. It is expressed as

Nearest neighbor search: find the nearest neighbor in *P* for each point in *D* according to the known rigid transformation $\boldsymbol{R}_k$ and $\vec{t}_k$

$$\mathrm{c_{k+1}}(i) = \underset{c(i) \in \{1,2,\cdots,N_p\}}{\operatorname{argmin}} \left\| (\boldsymbol{R}_k \vec{d}_i + \vec{t}_k) - \vec{p}_{c(i)} \right\|^2$$

The algorithms widely used for nearest neighbor search are Brute-force search, Delaunay triangulation, and k-dimensional tree. Brute-force search is to calculate distances to every point in *P* and the shortest one is accepted to nearest neighbor. It is very simple and does not need any preprocessing but needs quite large computational time due to the large number of calculation. To reduce unnecessary calculations, the pin point set *P* should be divided into subsets. If a subset contains a data point, the closest neighbor should be inside this subset, and only the computation of the points of this subset is required. The Delaunay triangulation divide the pin point set *P* into triangular subsets based on the condition that the triangle should not contain any other points. On the other hand, the subsets are divided by binary search in k-dimensional tree. The k-dimensional tree needs commonly less computational time than the Delaunay triangulation since the preprocessing of k-dimensional tree is simpler (Kjer & Wilm, 2010) As a result, the k-dimensional tree was used for nearest neighbor search in proposed algorithm.

Point to point minimization

The point to point minimization is to find a transformation that minimizes the distance to nearest neighbor. It is presented as

Point to point minimization: calculate the new rotation matrix $\boldsymbol{R}_{k+1}$ and translation vector $\vec{t}_{k+1}$ by the following formulation according to the correspondence $\{i, c_{k+1}(i)\}$

$$(\boldsymbol{R}_{k+1}, \vec{t}_{k+1}) = \underset{\boldsymbol{R} \in \mathbb{R}^{n\times n},\ \vec{t} \in \mathbb{R}^{n}}{\operatorname{argmin}} \sum_{i=1}^{N_m} \left\| (\boldsymbol{R}\vec{m}_i + \vec{t}) - \vec{p}_{c_{k+1}(i)} \right\|^2$$

The new rotation matrix $\boldsymbol{R}_{k+1}$ and translation vector $\vec{t}_{k+1}$ are calculated according to following sequences.

If the centroids of product data point set and pin point set are defined as $\bar{d}$ and $\bar{p}$ with constant weight, the points deviations from the centroid are given by $\vec{d}_i'$ and $\vec{p}_j'$.

$$\bar{d} = \frac{1}{N_d}\sum_{i=1}^{N_d} d_i \quad \text{and} \quad \bar{p} = \frac{1}{N_p}\sum_{j=1}^{N_p} p_j$$

$$\vec{d}_i' = \vec{d}_i - \bar{d} \quad \text{and} \quad \vec{p}_j' = \vec{p}_j - \bar{p}$$

The summation of error is expressed as E and it can be rewritten by applying to the points deviations.

$$\mathrm{E} = \sum_{i=1}^{N_d} \left\| (\boldsymbol{R}\vec{d}_i + \vec{t}) - \vec{p}_{c(i)} \right\|^2$$

$$\mathrm{E} = \sum_{i=1}^{N_d} \left\| \boldsymbol{R}(\vec{d}_i' + \bar{d}\,) + \vec{t} - (\,\vec{p}_{c_{(i)}}' + \bar{p}) \right\|^2 = \sum_{i=1}^{N_d} \left\| \boldsymbol{R}\vec{d}_i' - \vec{p}_{c_{(i)}}' + (\,\boldsymbol{R}\bar{d} - \bar{p} \,+ \vec{t}) \right\|^2$$

In order to minimize error metric E, the translation vector $\vec{t}$ should move the rotated data centroid to the centroid of pin point.

$$\vec{t} = \bar{p} - \boldsymbol{R}\bar{d}$$

The remaining thing is to get the new rotation matrix $\boldsymbol{R}$ since the new translation vector $\vec{t}$ is decided by $\boldsymbol{R}$. By accepting the new translation vector $\vec{t}$ as $\bar{p} - \boldsymbol{R}\bar{d}$, the error metric E is simplified.

$$\mathrm{E} = \sum_{i=1}^{N_d} \left\| \boldsymbol{R}\vec{d}_i' - \vec{p}_{c_{(i)}}' \right\|^2 = \boldsymbol{R}\boldsymbol{R}^{\mathrm{T}} \sum_{i=1}^{N_d} \left\| \vec{d}_i' \right\|^2 - 2\mathrm{tr}\left(\boldsymbol{R} \sum_{i=1}^{N_d} \vec{d}_i' \vec{p}_{c_{(i)}}'^{\mathrm{T}} \right) + \sum_{i=1}^{N_d} \left\| \vec{p}_{c_{(i)}}' \right\|^2$$
$$= \sum_{i=1}^{N_d} \left\| \vec{d}_i' \right\|^2 - 2\mathrm{tr}\left(\boldsymbol{R} \sum_{i=1}^{N_d} \vec{d}_i' \vec{p}_{c_{(i)}}'^{\mathrm{T}} \right) + \sum_{i=1}^{N_d} \left\| \vec{p}_{c_{(i)}}' \right\|^2$$

Now let the $\boldsymbol{N} = \sum_{i=1}^{N_d} \vec{d}_i' \vec{p}_{c_{(i)}}'^{\mathrm{T}}$. Since the $\sum_{i=1}^{N_d} \left\| \vec{d}_i' \right\|^2$ and $\sum_{i=1}^{N_d} \left\| \vec{p}_{c_{(i)}}' \right\|^2$ is constant, the trace of ***RN*** must be maximized.

To expand the trace of ***RN***, the r_i and c_i are defined as the rows of ***R*** and the columns of ***N*** respectively.

$$\mathrm{tr}(\boldsymbol{RN}) = \sum_{i=1}^{3} r_i \cdot c_i \leq \sum_{i=1}^{3} \|r_i\| \|c_i\|$$

This formula can be reformulated according to Cauchy-Schwarz inequality and therefore the $\mathrm{tr}(\boldsymbol{RN})$ is maximized when the $\boldsymbol{RN}$ is same to $\sqrt{\boldsymbol{N}^{\mathrm{T}}\boldsymbol{N}}$.

$$\mathrm{tr}(\boldsymbol{RN}) \leq \sum_{i=1}^{3} \|c_i\|\|c_i\| = \sum_{i=1}^{3} \sqrt{c_i^{\mathrm{T}} c_i} = \mathrm{tr}\left(\sqrt{\boldsymbol{N}^{\mathrm{T}}\boldsymbol{N}}\right)$$

Since the singular value decomposition of $\boldsymbol{N}$ is $\boldsymbol{N} = \boldsymbol{U}\sum\boldsymbol{V}^{\mathbf{T}}$, the new rotation vector $\boldsymbol{R}$ is accepted as $\boldsymbol{VU}^{\mathbf{T}}$ to achieve point to point minimization.

However, the classic ICP algorithm cannot equally consider the objective i) the reduction of distance between the joining points and the pin points, ii) the improvement of boundary contact, and iii) the increasement of used pin for consisting shape of jig because the underlying points are too much. The classic ICP algorithm can mainly improve the number of used pins. To solve this inequality, weights are defined in inverse proportion to the number of points (TABLE 4-1). Typically, the joining point set has higher weight than others since the number of joining points is least. The weighted point-to-point minimization model is expressed as:

$$\min_{\boldsymbol{R},\ \vec{t},\ c(i)\in\{1,2,\cdots,N_p\}} \sum_{i=1}^{N_m} \left[\left\|\left(\boldsymbol{R}\vec{m}_i + \vec{t}\right) - \vec{p}_{c(i)}\right\|^2 \times w_i\right] \quad \text{Where } w_i = \begin{cases} w_1 \\ w_2 \\ w_3 \end{cases}$$

By applying a weight, the centroid of the product data point set is formed closer to the point where the weight is high. The weighted centroid affects the same consideration of the three objectives.

$$\overline{d}_w = \frac{1}{N_d} \sum_{i=1}^{N_d} U_i w_i d_i$$

TABLE 4-2
WEIGHT DEFINITION

Classification	Description	Weight
w_1	Weight of joining points	$\frac{N_3}{N_1}$
w_2	Weight of boundary contact points	$\frac{N_3}{N_2}$
w_3	Weight of underlying contact points	1

The joining points and inside points have always the underlying contact since they are located inside the boundary of the product. The boundary points, on the other hand, can be contacted at the boundary only when the position of the pin is outside the product boundary. If the contact pin is inside the boundary, it becomes the underlying contact. Therefore, the weight 1 and 3 are always applicable and the weight 2 is conditionally applicable. To apply the weight 2 only to the boundary contacts, the algorithm4.1 has been developed.

Algorithm 4.1 Decision of boundary contact

Require: *match* (the index of nearest neighbor of boundary points in pin point set P, N_2 by 1 array),
dist (the distance array of between boundary point and its nearest neighbor, N_2 by 1 array),
c (the threshold of boundary contact, the default value is 0)

1: for (*i* = 1; *i* < $N_2 + 1$; *i*++) do
2: $dist_{p_{c(i)}} \leftarrow$ *dist*(*logical*(*match* == *match*(*i*)))
$dist_{p_{c(i)}}$ is a distance array between $p_{c(i)}$ to corresponding points
3: **if (**min($dist_{p_{c(i)}}$) > *c*) **do :** if min($dist_{p_{c(i)}}$) is *c*, then $p_{c(i)}$ is underlying contact pin.
4: *weight*(*i*) = w_2
5: **else**
6: *weight*(*i*) = w_3
7: **end if**
8: end for

As shown in Figure 4-9, a boundary contact is established when the nearest neighbor of the boundary point is located outside the product boundary. The fact that the pin point is located outside is that the minimum distance between all data points having this pin point as nearest neighbor is greater than the threshold *c*. Based on this, in algorithm 4.1, we determine whether a boundary contact is established by considering min($dist_{p_{c(i)}}$). When the min($dist_{p_{c(i)}}$) is greater than the threshold *c*, the pin point is able to get boundary contact with product, and *c* may vary depending on the resolution of the product image.

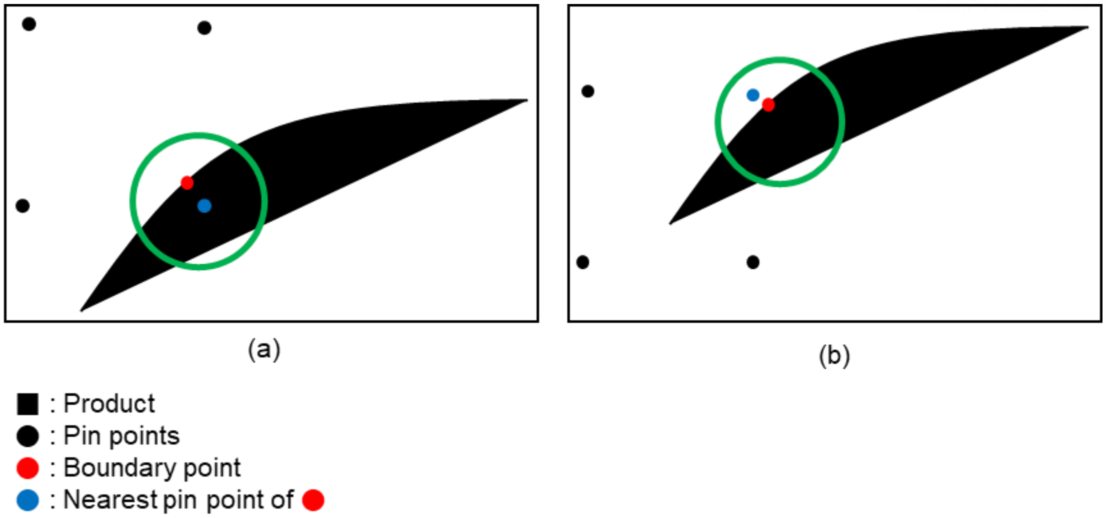


Figure 4-9. Contacts with boundary points; underlying contact (a) and boundary contact (b)

Algorithm 4.3 Proposed algorithm for assembly part positioning

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Require: *data* (product data point set D, N_d by 2 array), *pin_point* (pin point set P, N_p by 2 array), *weight* (result of *weighting* fucntion, N_d by 1 array), *type*(), nearestNeigbor(nearest neighbor search using KDtree), $\boldsymbol{i_{max}}$ (the maximum iteration number), $\boldsymbol{\varepsilon}$ (the minimum difference) $\boldsymbol{N} = \sum_{i=1}^{N_d} \vec{d}'_i \vec{p}'_{c(i)}{}^{\mathrm{T}}$, $\bar{d}_w = \frac{1}{N_d}\sum_{i=1}^{N_d} w_i d_i$, $\bar{p} = \frac{1}{N_p}\sum_{j=1}^{N_p} p_j$, $\vec{d}'_i = \vec{d}_i - \bar{d}_w$, $\vec{p}'_j = \vec{p}_j - \bar{p}$

while($\boldsymbol{i} < \boldsymbol{i_{max}}$ **or** $\boldsymbol{E_i - E_{i-1} < \varepsilon}$) **do**

    [*match dist*] ← nearestNeighbor(*data*, *pin_point*)

    weight ← weighting(*match*, *dist*, *type*)

    Calculate $\bar{p}$ and $\bar{d}$

    Calculate $\boldsymbol{N}$

    [$\boldsymbol{U}$,~,$\boldsymbol{V}$] ← SVD($\boldsymbol{N}$)

    $\boldsymbol{R} \leftarrow \boldsymbol{VU^T}$

    $\vec{t} \leftarrow \bar{p} - \boldsymbol{R}\bar{d}_w$

    $\boldsymbol{i}$++

end while

CHAPTER 5
CASE STUDY

5.1. Overview

Three case studies were conducted to verify the proposed algorithm. They are toy product data point set, toy model, and car doortrim panel (Figure 5-1, 5-4, 5-7). In each case study, the performance of initial position, result of classic ICP, and result of ICP with proposed objective function was evaluated according to the degree of alignment and the number of active pin. The product data point set for each case study is summarized on Table 5-1, 5-3, and 5-5 respectively. The positioning result is also arranged in the Table 5-2, 5-4, and 5-6 respectively. The two types of figures representing the positioning results are given, which are the overlapped and respective plot.

Furthermore, one case study was conducted to validate the objective of this optimization. The ultrasonic welding process was simulated by using the commercial CAD program, SOLIDWORKS 2017. By using this tool, the deformation of toy model was analyzed by a Finite Element Method. The result of initial position and optimal position were compared.

5.2. Assembly part positioning

5.2.1. Toy product data pointset

The toy product data pointset was intentionally designed to have optimal position on the transformable pin jigs. The width of this pointset was slightly smaller than the interval of pin-jigs so that it could be tightly fixed by pin-jigs as shown in the Figure 5-1. Furthermore, the joining points of this pointset were located near to the vertices which is proper to align the joining point and pin point. The number of points were presented at the Table 5-1. The transformable pin-jigs, introduced in the Chapter 3, has 120mm of interval, but in this case study, the interval was set to 30mm for the smaller toy product data pointset.

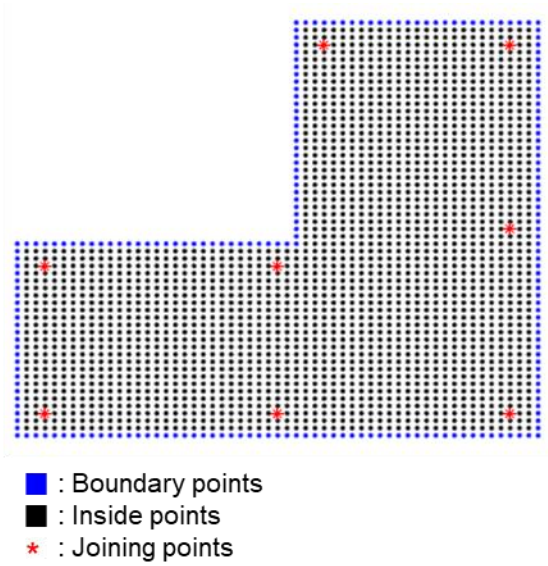

Figure 5-1. Toy product data point set

TABLE 5-1
TOY PRODUCT DATA POINT SET

Specifications		Pin setting	
Height (mm)	56	Number of pins (X-axis)	4
Width (mm)	56	Number of pins (Y-axis)	4
Number of joining points	8	X-axis Interval (mm)	30
Number of boundary points	224	Y-axis Interval (mm)	30
Number of inside points	2,117	Boundary contact offset (mm)	7.5

Optimal part positioning Result

The joining point should be located close to the pin point to minimize the product deformation as well as prevent the assembly defects due to the deformation. The result of the proposed assembly part positioning method, as shown in the Figure 5-2, most appropriate to this requirement of joining point alignment than the initial position (coincidence of centroids of product pointset and pin pointset) and the classic ICP. Furthermore, the number of active pins increased at the optimal position from the proposed method. The transformations including rotation and translation were presented at the Table 5-2.

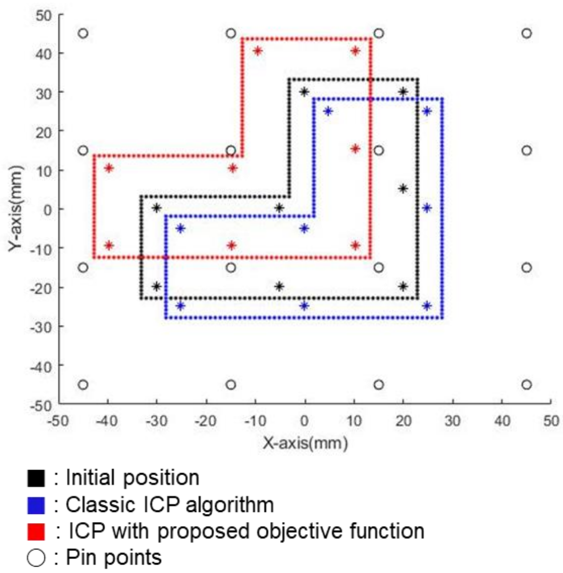

Figure 5-2. Positioning result of toy product data point set

Table 5-2
ASSEMBLY PART POSITIONING RESULT
(TOY PRODUCT DATA POINT SET)

		Initial Position	Classic ICP	**ICP with Proposed objective function**
Transformation	Clockwise rotational angle about Z-axis (degree)	0	0.00	**0.10**
	Translation along X-axis (mm)	0	5.00	**-9.55**
	Translation along Y-axis (mm)	0	-5.00	**10.40**
Joining points alignment error (mm)	Mean	14.96	15.56	**6.25**
	Standard deviation	5.06	1.90	**1.20**
Number of used pins	Boundary	0	0	**7**
	Underlying	3	3	**1**

The joining point alignment was improved through the proposed assembly part positioning method. The mean of distance between the joining points and pin points was reduced to 6.25mm from initially 14.96. The number of active boundary contact pins was increased to 7 from 0, but the number of underlying contact pins was decreased to 1 from 3. There was a trade-off between the number of boundary and underlying contact pins since the product area is limited. Nevertheless, it could be evaluated to be improved since the total number of active pins was increased.

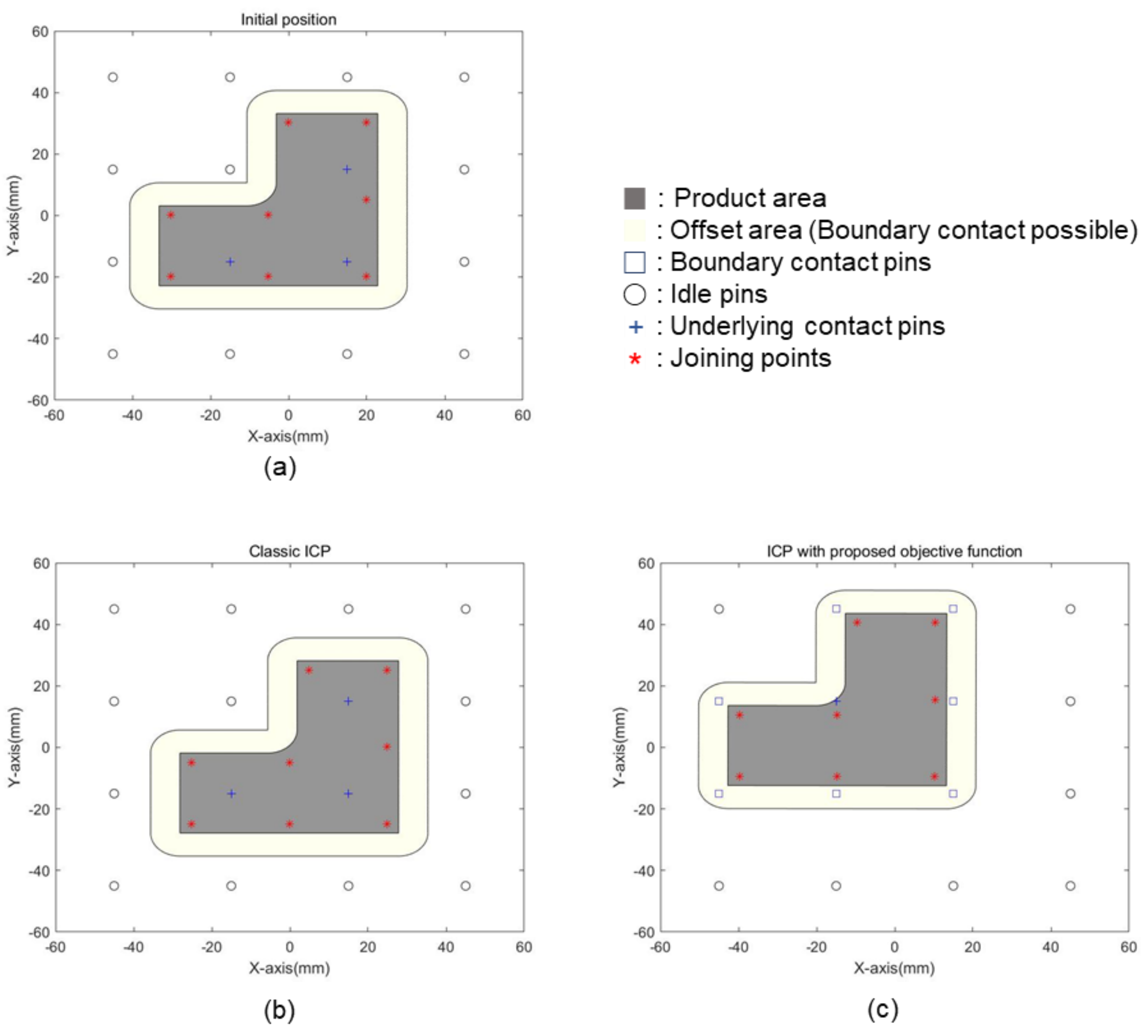

Figure 5-3. (a) Initial position, (b) classic ICP, and (c) ICP with proposed objective function (toy product data point set)

5.2.2. Toy model

The second case was toy model. Toy model was kind of typical single part of injection modeled plastic product. It was designed for loading at our transformable pin-jigs, so the interval of pin-jigs was set to 120mm. The only 5 x 5 pin-jigs were needed to hold this toy model, the number of pins was set to 5 for each X-axis and Y-axis. The number of points were presented at the Table 5-3.

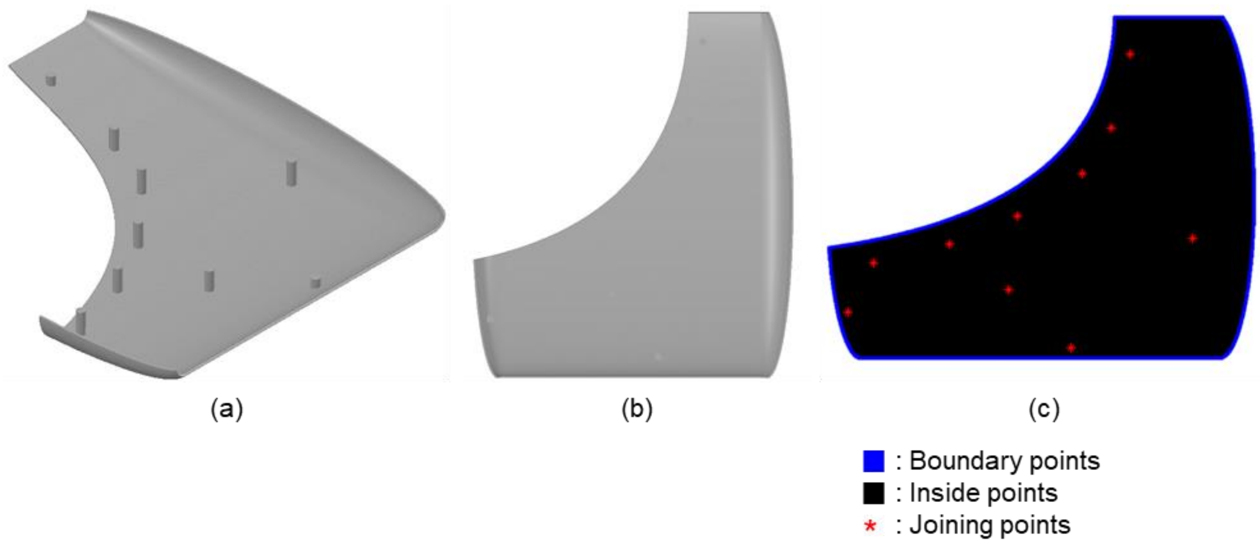

Figure 5-4. (a) general view, (b) top view, and (c) product data point set (toy model)

TABLE 5-3
TOY MODEL

Specifications		Pin-jigs setup	
Height (mm)	400	Number of pins (X-axis)	5
Width (mm)	300	Number of pins (Y-axis)	5
Number of joining points	10	X-axis Interval (mm)	120
Number of boundary points	2,310	Y-axis Interval (mm)	120
Number of underlying points	265,762	Boundary contact offset (mm)	30

Optimal part positioning Result

The transformation including the rotation and translation was presented at the Table 5-4. The result of proposed method had higher rotational angle to align the joining points. As a result, the mean error of joining points alignment was reduced to 39mm from initially 45.35mm. The total number of both active pins (boundary and underlying contact pins) was same to 10, but the number of boundary contact pins was increased to 3 from 2. It could be more effective to hold the product during assembly process since the boundary contact pins are more appropriate to hold a product than the underlying contact pins.

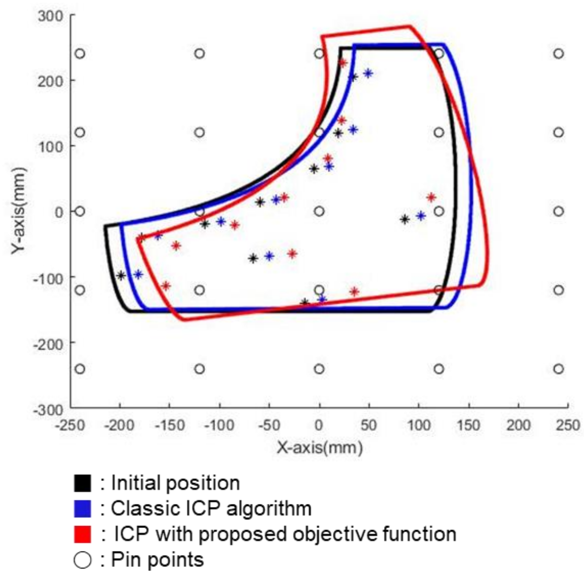

Figure 5-5. Positioning result of toy model

TABLE 5-4
ASSEMBLY PART POSITIONING RESULT
(TOY MODEL)

		Initial Position	Classic ICP	**ICP with Proposed objective function**
Transformation	Clockwise rotational angle about Z-axis (degree)	0	-0.52	**-10.04**
	Translation along X-axis (mm)	0	27.60	**43.55**
	Translation along Y-axis (mm)	0	8.09	**30.78**
Joining points alignment error (mm)	Mean	45.35	44.10	**39.00**
	Standard deviation	20.04	19.36	**12.63**
Number of used pins	Boundary	2	1	**3**
	Underlying	8	8	**7**

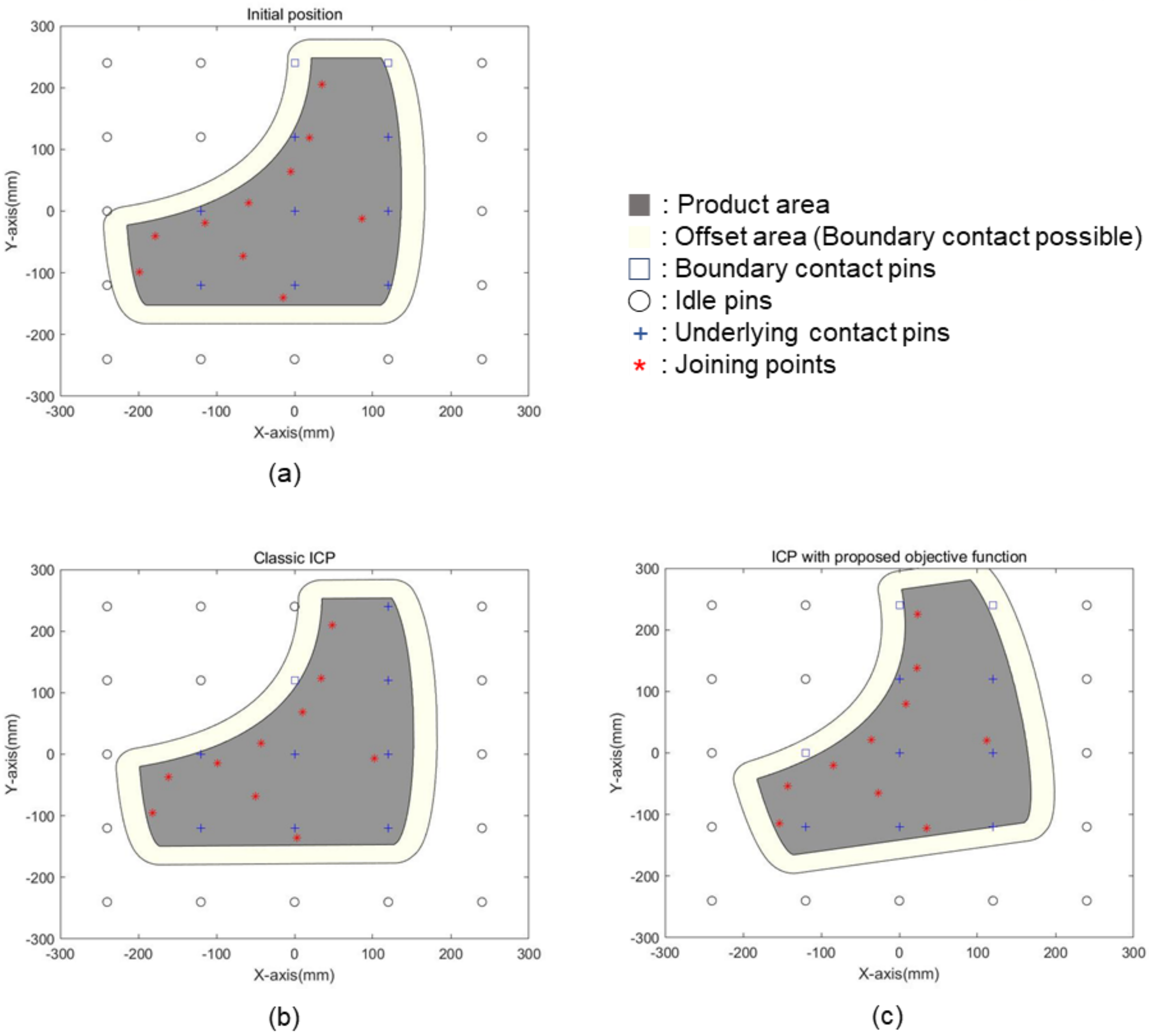

Figure 5-6. (a) Initial position, (b) ICP result, and (c) proposed algorithm result (toy model)

5.2.3. Car Dootrim panel

The third case was car doortrim panel. It was one of product in the target product family for the transformable pin-jigs. The specifications and the number of points were presented at the Table 5-5, and every pin in the transformable pin-jigs were used considering its size.

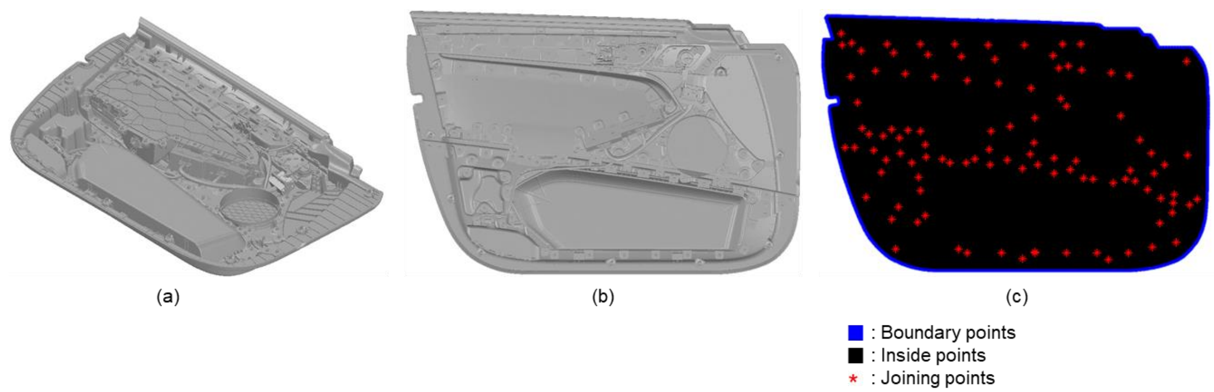

Figure 5-7. (a) general view, (b) top view and (c) product data point set (car doortrim panel)

TABLE 5-5
CAR DOORTRIM PANEL

Assembly part specifications		Pin setting	
Height (mm)	710	Number of pins (X-axis)	10
Width (mm)	930	Number of pins (Y-axis)	8
Number of joining points	106	X-axis Interval (mm)	120
Number of boundary points	3,159	Y-axis Interval (mm)	120
Number of inside points	532,856	Boundary contact offset (mm)	30

Optimal part positioning Result

The transformation of proposed assembly part positioning method was presented at the Table 5-6. The result shows the improvement of mean error of joining points alignment from 46.68mm to 44.11mm. The total number of both active pins was same to 45, but the number of boundary contact pins was increased since the proposed method considered the boundary contact pin was more effective to hold the product.

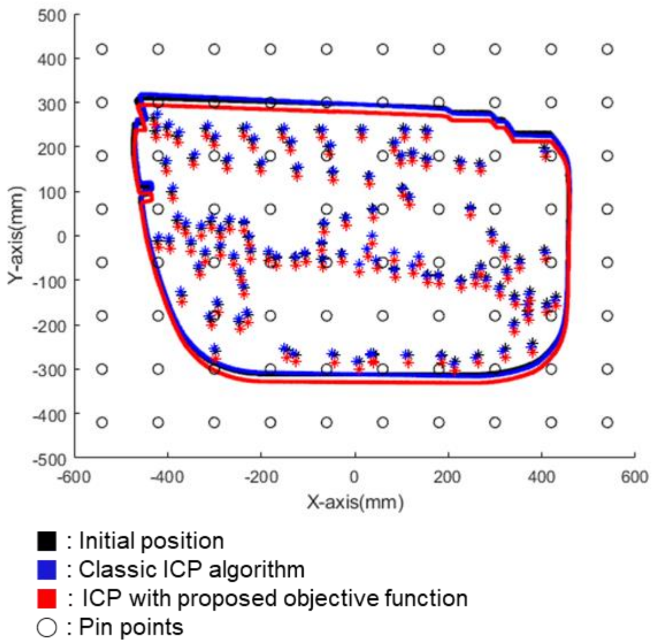

Figure 5-8. Positioning result of car doortrim panel

TABLE 5-6
ASSEMBLY PART POSITIONING RESULT
(CAR DOORTRIM PANEL)

		Initial Position	Classic ICP	**ICP with Proposed objective function**
Transformation	Clockwise rotational angle about Z-axis (degree)	0	1.15	**0.37**
	Translation along X-axis (mm)	0	1.44	**1.95**
	Translation along Y-axis (mm)	0	0.20	**-17.73**
Joining points alignment error (mm)	Mean	46.68	46.42	**44.11**
	Standard deviation	15.70	15.87	**16.51**
Number of used pins	Boundary	6	6	**8**
	Underlying	39	39	**37**

The proposed assembly part positioning method moves the product downward, as a result more boundary contacts were possible at the upper edge of product. The initial position and result of the classic ICP and proposed method were not much different. The reason of this phenomenon was considered that the shape of car doortrim panel is very similar to the rectangular. Since the transformable pin-jigs has regular intervals, so there could be not big difference when the product with symmetric geometry was loaded on this system.

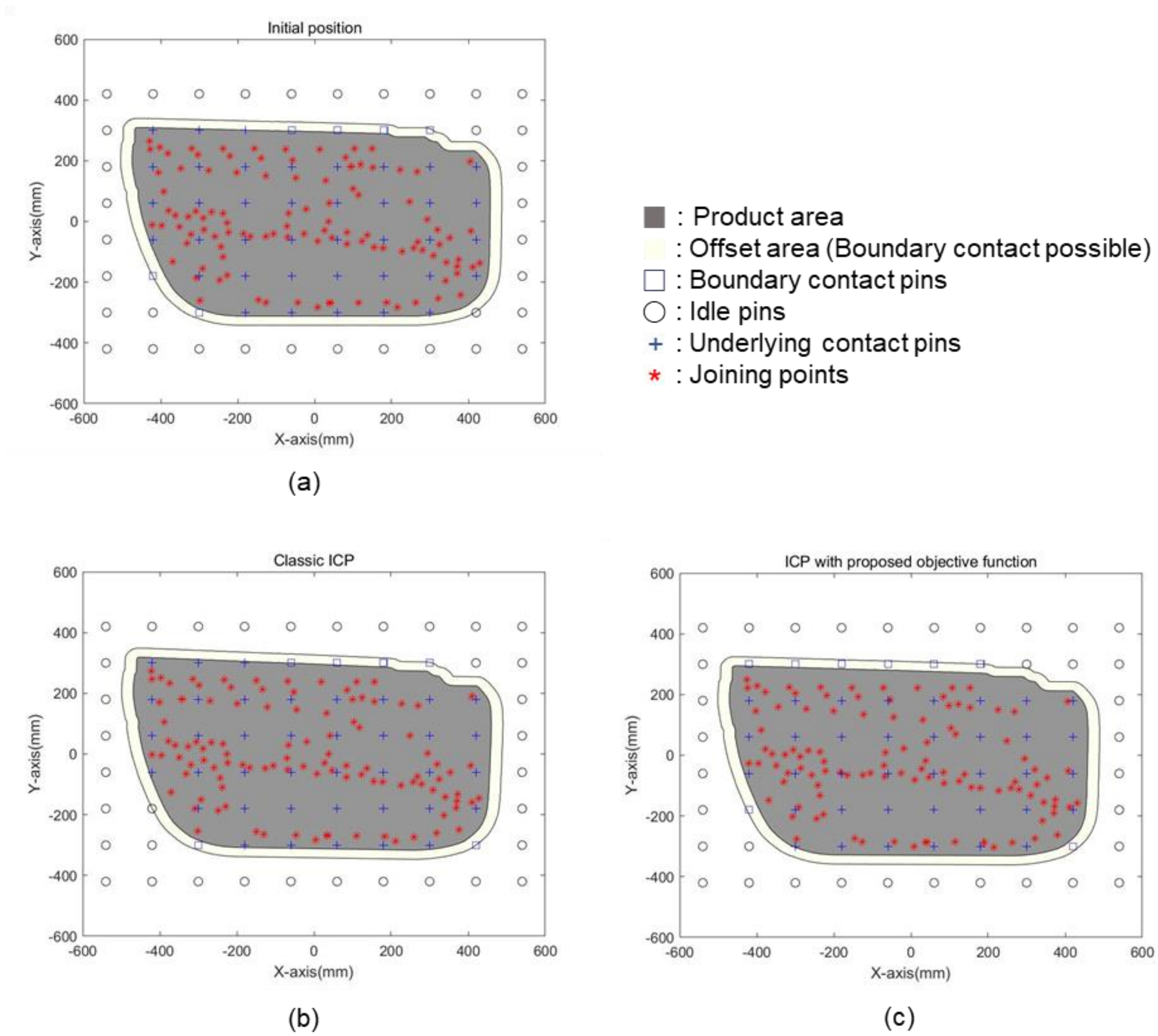

Figure 5-9. (a) Initial position, (b) ICP result, and (c) proposed algorithm result (car doortrim panel)

5.3. Deformation analysis

5.3.1. Setup

The toy model as presented in the second case study of verification experiment was used to validate the optimization objective. There are 10 joining points and each point was pressed by 10N. The deformation analysis was conducted 10 times per initial position and optimal position to simulate the assembly process using ultrasonic welding. The material of toy model was set to ABS and the material of pin-jigs was selected to the AISI 1020 carbon steel.

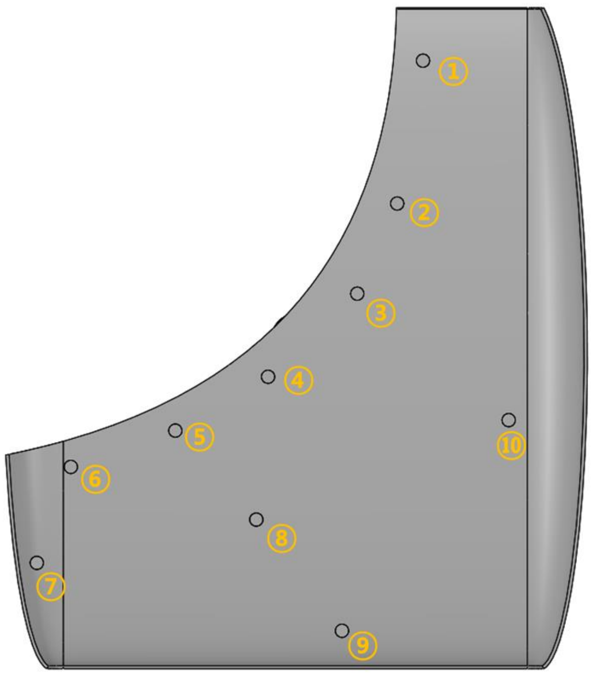

Figure 5-10. Joining points on toy model

The joining points was labelled as shown in Figure 5-10. Only the deformation generated at the joining point (cylinder on the toy model) was analyzed since the assembly quality was determined of this deformation.

This experiment was designed to validate the effect of joining point alignment to the part deformation. Therefore, the loading position was optimized by considering only the joining point alignment. As a result, the optimal position was determined to [-5.87mm, 11.35mm, 2.65°] which are translation along x-axis and y-axis, and rotation about z-axis respectively.

5.3.2. Result

The result, as shown in the Table 5-7~8, the stress and deformation were reduced at the first joining point, whereas there was not big difference on the other joining points. As a result, the average stress and deformation were decreased. According to this result, the proposed assembly part positioning method could improve the fixturing quality by reducing the stress and deformation on the assembly part. However, the proposed method could not guarantee to improve the all joining points. The reason of this phenomenon was that the proposed method focused on the minimization of total alignment error. Therefore, if the objective function is redesigned for every joining point has the equal alignment error, then the deformation and stress at the joining point will be close to equally distributed. This redesigned method will not guarantee to minimize the total alignment error, but it will guarantee to get the close to uniform assembly quality among the joining points.

TABLE 5-7
DEFORMATION ANALYSIS OF JOINING POINTS (TOY MODEL)

Joining point	Deformation			
	Mean (mm)		Standard deviation (mm)	
	At initial position	At optimal position	At initial position	At optimal position
1	0.1005	0.0843	0.0080	0.0070
2	0.2691	0.2693	0.0161	0.0162
3	0.3805	0.3803	0.0191	0.0190
4	0.3133	0.3128	0.0172	0.0170
5	0.2398	0.2400	0.0134	0.0133
6	0.0804	0.0816	0.0048	0.0049
7	0.0117	0.0114	0.0017	0.0017
8	0.5091	0.5112	0.0093	0.0088
9	0.0868	0.0869	0.0063	0.0063
10	0.2677	0.2678	0.0138	0.0138
Average	0.2259	0.2246	0.0110	0.0108

TABLE 5-8
STRESS ANALYSIS OF JOINING POINTS (TOY MODEL)

Joining point	Stress			
	Mean (10^5 N/m^2)		Standard deviation (10^4 N/m^2)	
	At initial position	At optimal position	At initial position	At optimal position
1	2.0725	1.8462	3.3555	3.1207
2	1.9975	1.9992	0.0442	0.0282
3	1.9908	1.9904	0.0282	0.0204
4	1.9900	1.9900	0.0000	0.0000
5	1.9917	1.9904	0.0381	0.0204
6	1.9908	1.9904	0.0282	0.0204
7	1.9821	1.9788	0.3526	0.3314
8	1.9571	1.9708	0.3557	0.2041
9	1.9038	1.9900	2.1023	2.1121
10	1.9908	1.9900	0.0282	0.0000
Average	1.9867	1.9736	0.6333	0.5858

CHAPTER 6

CONCLUSION AND FURTHER WORKS

6.1. Conclusion

The optimal part positioning offers the opportunities to get an acceptable fixturing quality for manufacturing process on the transformable jig system. The production flexibility of this system, through the optimal part positioning, can be fully utilized even in the mass production which has a strict standard.

In respond to those opportunities, the optimal assembly part positioning method is proposed based on the iterative closest point algorithm (ICP) with an improved objective function designed to maximize the number of active pins and to minimize the alignment error between the joining points and pin points. The reason of considering those objectives is that the part deformation decreases when the joining points and the corresponding pin point are aligned as well as the support capacity is proportional to the number of active pins.

The three case studies are conducted to verify the improved objective function in ICP. The toy product data point set, toy model, and car doortrim panel are used to generate product data point set. The pin-jig setting considers the size of test model. The positioning result of proposed objective function is compared with the initial position and positioning result of classic ICP. The results of three cases commonly show the improvement of joining point alignment and increase of the number of active boundary contact pins. The number of underlying contact pins does not change or decreases. The reason of this phenomena is due to the trade-off between the boundary contact pins and underlying contact pins. The maximum number of both active pins is limited since the product area is limited. In this thesis, the weight of boundary contact is higher than the underlying contact since the role of former is to guide and support the part, whereas the latter can only support the part. The redesigned objective function shows the corresponding result to those consideration.

The validation experiment was also conducted to examine the objective function. The result shows the optimization decreases the one of joining points while maintaining the deformation of remaining joining points.

To sum up, the deformation factors in the transformable pin-jigs were defined as the number of active pins and the alignment of joining point and pin point. The assembly part positioning based on those two deformation factors was presented as point set registration problem. The Iterative Closest Point algorithm was used to solve this problem, and the improved objective function for the transformable pin-jigs was proposed. The product deformation evaluated by Finite Element Analysis was minimized at the optimal loading position calculated by the proposed assembly part positioning method. Therefore, we concluded that the proposed assembly part positioning method for the transformable pin-jigs could minimize the product deformation and prevent the assembly defects.

6.2. Further works

The optimal part positioning method proposed in this thesis consider only the projected area on x-y plane at the loading position. As a result, it could not consider the geometric feature of product shape. There could be an area where the pin is not able to contact due to the tool interference. To consider those vulnerable area to contact, the weight of those area could be adjusted. This idea needs a preprocessing step which evaluate the area by the degree of the contact possibility. The result of this preprocessing could be applied to the objective function as the weight adjustment.

The objective function proposed in this work consider the priority of the positioning goals which is the joining point alignment and active pin maximization. The degree of importance was decided based on the inequality not optimized. If the priority is optimized, then the result will be more suitable for the positioning objectives.

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Acknowledgement

First of all, I would like to express my deep gratitude to my advisor Prof. Duck-Young Kim who is the best mentor I've ever met. He consistently allowed this thesis to be my own work, but steered me in the right direction whenever I needed his advice. I would also like to thank to my other committee members, Daeil Kwon and Sang-Hoon Kang, for their precious time, helpful advice, and feedback for my thesis.

Next, I would like to share this joy with Smart Factory laboratory members, Dr. Jin-woo Park, Dr. Sujeong Baek, Mr. Woonsang Baek, Mr. Jongil Park, Mr. Keebeom Park, and Mr. Kichang Namgung. It was a very valuable experience for two years and thank you for leaving me with memories that I will never forget.

Lastly, I would like to take this opportunity to express my deep appreciation to my family, mother, father, and brother. Thanks to their endless love and belief, I was able to complete my research successfully. Again, thanks for the opportunity to take M.S. degree.