Development of a shape-memorable adaptive pin array fixture

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\textbf{ABSTRACT}

This paper proposes an adaptive pin-array fixture. The key idea of this research is to use the shape-memorable mechanism of the pin array to fix multiple different shaped parts with a common pin configuration. The clamping area consists of a matrix of passively slid-able pins that conform themselves to the contour of the target object. The vertical motion of the pins enables the fixture to encase the profile of the object. The shape memorable mechanism is realized by the combination of the rubber bush and fixing mechanism of a pin. Several physical peg-in-hole tasks are conducted to verify the feasibility of the fixture.

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\section{1. Introduction}

As globalization has taken hold, personalized customization of a product becomes the trend of current manufacturing. However, automation of low-volume high-mix production which is the basis of personalized customization is limited by high costs and poor efficiency.

To automate the product assembly, fixtures to fix the pose of an assembly part are crucial. However, a fixture has to be carefully designed based on the experience of those who construct a robot system performing the assembly task. In addition, a fixture has been designed for each part and has been difficult to use to fix multiple parts with different shapes. Particularly in assembly tasks of low-volume high-mix production, a large number of fixtures has to be designed according to the increase of the number of parts with different shapes. Normally, the costs associated with fixtures can account for 10–20% of the total cost of a manufacturing system [1]. To cope with such a problem, we focus on an adaptive fixture which can fix multiple objects with different shapes.

To assemble a product, a robot has to fix the pose of several parts with different shapes. If we use a fixture that can fix only one part, we have to prepare a lot of fixtures to assemble a product. This is especially true for low-volume high-mix production. It is helpful if the fixture can fix the multiple sets of differently shaped parts.

We propose an adaptive fixture based on the pin array structure as shown in Figure 1. In our design, we set several pins to compose the clamping area of the fixture. The fixture can position the target part since each pin can move along vertical direction independently. The application of this fixture can increase production efficiency and reduce the cost.

The proposed pin array fixture works effectively in the assembly of low-volume high-mix production where plenty of parts are included, and they are frequently changed according to the change of product. In this case, the pose of each part needs to be fixed but the shape of a part frequently changes. In this case, reducing the number of fixtures used in the assembly is a crucial problem.

With the pin array structure, the proposed fixture can fix multiple parts with different shapes. The working process of the fixture has two steps: shape-memorize and batch-clamping. In the shape-memorizing step, the corresponding pins will be pushing up to memorize the shape of target part. In addition, the shape of target part will be kept in the fixture since we use the rubber rings to stop the vertical motion of these pins. Figure 2 shows an example of the shape-memorizing step. If we use the fixture to fix the triangular-shaped part (Figure 2(a)), the corresponding pins will be pushing up and the triangle shape will be memorized in the fixture even after we release the triangle part (Figure 2(b)). Likewise, if we continuously use the fixture to fix the rectangle part, the rectangle shape will also be memorized by the fixture (Figure 2(c)). The configuration of the pins is memorized by using the rubber ring attached to each pin. Even if the two clamping area is overlapped, the two parts
can independently be fixed if the form closure in 2D is satisfied in each clamping area.

On the other hand, in the batch-clamping step, we actually use the fixture for assembly task. The clamping area of our proposed fixture can be split into two crossing elements and can be moved in the horizontal direction. Due to the horizontal motion of the fixture, the assembly part can be grasped and is used for the assembly task.

In summary, our main contributions of this paper are as below:

1. We propose a fixture based on the pin array mechanism, which can be used for an assembly task of the high-mix manufacturing.
2. By memorizing the pin configuration, the proposed fixture can fix multiple parts with different shapes with keeping the same pin configuration.

The following is the structure of the paper: we first introduce several related works about the research on adaptive fixture design and pin array mechanism in section 2. In section 3, we show the structure of our fixture design and the detailed functions of the fixture. We construct a physical peg-in-hole task to verify the feasibility of the fixture in section 4. Section 5 explains about the limitation of the fixture. We discuss the stability of the fixture and talk about the future works in section 6. In the last section, we propose the conclusion.

2. Related works

In this section, we review the related studies by separating them into two categories, i.e. (a) the design of adaptive fixture, and (b) application of pin array mechanism.

2.1. The design of the adaptive fixture

The flexible fixture is a popular research direction in the robotic and mechanical design field. Bi et al. reviewed the studies of the flexible fixture design used in the production automation [1]. Wan et al. focused on the automatic fixture design methodology based on inheriting
and reusable design [2]. De et al. proposed a reconfigurable fixture to increase the flexibility of the machining task of thin sheets parts [3]. Müller et al. presented a highly reconfigurable automated handling system to transfer the benefits of mass customization to large products with lower production quantities [4]. Olaiz et al. proposed an adaptive fixture for accurate positioning of a planet carrier with very strict requirements of tolerances [5]. Vaughan et al. focus on improving the assembly process capability of aircraft wing in conjunction with an adaptive fixturing system [6]. Yu et al. presented a process for the control of machining distortion to eliminate surface errors and improve precision by using an adaptive dual-arm fixture [7]. Lu et al. designed a fixture used for the automotive industry having high modularity and flexibility [8]. Yu et al. proposed a flexible fixture design method for similar automotive body parts to decrease the repeating fixture construction cost [9]. Minh Duc et al. proposed a novel method for optimum workpiece positioning in rod-type fixtures for thin-walled components [10]. On the other hand, this paper proposes a pin array fixture design which can be used to fix multiple parts with different shapes with the same pin configuration.

2.2. Pin array fixture mechanism

Among the research on adaptive fixture design, pin array mechanism is a relatively new research field. Mo et al presented a pivoted pin array gripper in 2018 [11,12]. Fromm focuses on the gripper design-based pin array mechanism [13]. Almost all those researches had focused on how to use the pin array mechanism to design a gripper. Compared with them, the originality of this paper is to propose a unique structure to fix the target part which can fix multiple parts with keeping the same pin configuration.

3. Structure of the proposed fixture

We explain the details of the proposed fixture in this section, including the mechanism and kinematic structure. As shown in Figure 3, the fixture is composed of multiple pins to memorize the shape of the target object and the rubber bush attached to each pin. The fixture includes two crossing elements (Figure 3(a)) where the clamping motion can be generated by the relative motion between these two crossing elements.

3.1. Shape-memorizing mechanism

We assume that the target part is stably placed on the horizontally flat table and that its pose does not change even if the external force is applied from the vertically upward direction. In the shape-memorizing step, the fixture pushes the target object from the vertically upward direction. After the tip of pins contact the target object, vertical motion of the pins enables the fixture to encase the profile of the target part. A rubber ring is attached to each pin as shown in Figure 3(b). A rubber ring is used to temporarily fix the pins’ configuration and to memorize the shape of the target object by the effect of friction between a rubber ring and a pin. However, the friction force of a rubber ring is not strong enough to keep a pin’s configuration when the external force is applied to a pin. To fix the pins’ configuration under the external force applied to the part, the fixture includes the fixing mechanism of pins as shown in Figure 3(c). If we press a rubber ring from the top, the bottom part of the rubber ring is wedged. Due to the wedging force, the pin’s configuration is fixed. On the other hand, to release a pin, we press the rubber ring from the bottom. Figure 3(d) shows the fixing mechanism. Because of the friction of the rubber ring, the pin is fixed at the initial position. When the pin contacts the target object, it is pushing by the object and moves up. The pin will be fixed again after the part is released.

Figure 4 depicts the working principle of the fixture. The corresponding pins are pushed up by the target part (nut). Then, the pins’ configuration is kept because of the friction of rubber rings. The shape of target object is memorized by the configuration of pin array as shown in Figure 4(e). Likewise, we can use the different areas of the pin array to memorize the shape of other parts. After memorizing the shape of multiple parts, we fix the pins’ configuration by using the fixing mechanism. Then, it can be used for assembly tasks.

Here, we note that, if the pins are finely distributed, the fixture can be precisely memorized the shape of the target object. On the other hand, according to the distance between two neighbouring pins, the gap between the contour of target part and a pin closest to the contour occurs.

3.2. Clamping motion

After memorizing the shape of multiple parts in the shape-memorizing step, we use the fixture to actually fix one of the parts used for an assembly task. This subsection depicts how the fixture clamps the target part in the batch-clamping step.

In this step, the fixture clamps one of the parts which shape is memorized in the shape-memorizing step. After placing the fixture such that the target part is located at its corresponding clamping area of pin array, the fixture tries to clamp the target part. The relative motion between two crossing elements in the horizontal direction provides the clamping force of pins in the horizontal direction to fix
Figure 3. Rubber rings in the fixture.

Figure 4. The pins are pushed up by target object and keep their position because of the friction of rubber rings.
the target part. The actuator used to generate the horizontal motion of the two crossing elements is shown in Figure 5.

We analyse the mechanism where the target part can be fixed by the clamping motion of the crossing elements. We assume that, after the target object is clamped, the friction force in the vertical direction between the target part and a pin is large enough. We check if the form closure in the 2D horizontal plane is satisfied by the clamping motion of the crossing elements.

In the shape-memorizing step, by the motion of the fixture compressing an object in the vertical direction, the pins contacting the object are displaced in the vertical direction. However, the pins without displaced do not exert any forces to the target part in the horizontal direction at this time (Figure 6(a)). In the batch-clamping step, by the clamping motion of the crossing elements in the horizontal direction, two pins near the clamping area enter in contact with the target part as shown in Figure 6(b). In this state, the form closure is not satisfied since four contacts are necessary to satisfy the form closure in the 2D plane. From this state, the crossing elements is further displaced. The pins which have already contacted the target part cause elastic displacement and keep contacting with the target part. Finally, the form closure is satisfied after more than four contacts are established.

If we memorize the shape of multiple parts in the shape-memorizing step, an overlapping area between two parts is encountered as shown in Figure 7(a). With the clamping motion of the crossing elements, the pins included in the overlapping area will not contact the target object. However, even in such cases, the fixture can fix the target part if the 2D form closure can be satisfied by using the remaining contacts with the pins as shown in Figure 7(c).

Here, we note that, if the pins are finely distributed, the amount of relative motion between two crossing elements can be very small. In this case, the pose of the target object
can be precisely defined and the amount of the pins’ elastic displacement can be small. On the other hand, if the distance between two neighbouring pins becomes larger, the pose of clamped target part becomes different from the pose of target object in the shape-memorizing step. In this case, the pose of target object is determined by minimizing the pins’ elastic energy.

Let \( n_i = (x_i, y_i)^T \) be the unit inner normal vector at the \( i \)-th \((i = 1, \cdots, c)\) contact point of the object projected onto the horizontal plane. Let \( V = (v_{obj}^T, w_{obj})^T \in \mathbb{R}^3 \).

**Figure 8.** Experimental setup.

**Figure 9.** The fixture memorized the ‘L’, ‘T’, ‘X’ shape after fix the first group of part.

**Figure 10.** The batch parts with the same shape can be fixed after the fixture memorized the shape. (Contacting pins are marked in red).
Figure 11. Result of the peg in hole experiment.
be the linear and angular velocity of the target part. The condition for the form closure can be satisfied when the solution of the following equation

\[ N^T G^T V \geq 0 \]  

(1)
is \( V = 0 \), where

\[ N = \text{diag}(n_1, \ldots, n_c) \]  

(2)

and \( p_i \) denotes the position vector of the \( i \)-th contact point. This condition can be examined by solving the linear programming problem. But, one of the necessary conditions is that the matrix \( GN \) is full row rank [14,15].

4. Experiment

We construct the proposed fixture and connect it to the wrist of UR-3 robot as shown in Figure 8. Peg-in-hole tasks of parts with several different shapes are conducted to verify the feasibility of the proposed fixture. We choose the peg-in-hole of alphabet parts as the target.

Figure 9 shows the pin array of the fixture after memorized ‘L’, ‘T’, ‘X’ in order where the red dashed line shows the clamped area. In the batch-clamping phase, the form closure can be satisfied and we can fix these three parts by using the common pin configuration as shown in Figure 10 where the contacting pins are marked in red. The snapshot of peg-in-hole experiment of these parts is shown in Figure 11.

Figure 12. The fixture cannot align the target part in some cases.

Figure 13. Pin array by which we can fix both ‘F’ and ‘T’ parts where contacting pins are marked in red.
Figure 14. Pin array by which we can fix neither ‘F’ nor ‘T’ parts.

Figure 15. Pin array by which we can fix two cylinders with different radius.

Figure 16. Pin array by which we cannot fix a cylinder with smaller radius.
The experiment in Figure 11 contains the same two sets of tasks. The first set ((a.1)–(c.4)) shows the shape-memorable function of the proposed fixture. The shape of ‘L’, ‘T’ and ‘X’ will be memorized in turn in the fixture. Afterward, this specifically shaped fixture is used to verify the shape-memorable function. We know that the fixture can still fix the ‘L’ and ‘T’ part again after it memorized the shape of all the three parts.

We further conducted the peg-in-hole experiment by using three groups of target parts: F/T, G/C, big and small circle parts as shown in Figure 12. These are the examples where we need to carefully choose the clamping area.

Figure 13 shows a successful case of fixing ‘F’ and ‘T’ parts. The fixture can memorize the shape of both ‘F’ (a.2) and ‘T’ (b.2) parts at the same time. In this case, cylinder with smaller radius. Experiment was failed since clamped area of the cylinder with smaller radius is included in the clamped area of the cylinder with larger radius.

the experiment was successful in placing both ‘F’ and ‘T’ parts since the vertical lines between ‘F’ and ‘T’ does not share the same clamping area as depicted in this figure.

On the other hand, Figure 14 shows the failure case. The pick-and-place experiment failed since the vertical lines between ‘F’ and ‘T’ shares the same clamping area as depicted in this figure and the form closure can be satisfied for clamping neither ‘F’ nor ‘T’. We also choose many other groups of the target objects in which the shape of one of the objects is close to another except ‘F’ and ‘T’ part such as ‘G’ and ‘C’ part. The result of the experiment is the same as Figures 13 and 14 shown.

Figure 15 shows the successful case of fixing two cylinders with different radius. The experiment was successful since the shape of two cylinders are memorized in the different area of pin array. On the other hand, Figure 16 shows the failure case of fixing a

5. Discussion

In this section, we discuss how the fixture well fixes multiple parts with different shapes by using the common pin configuration. As a necessary condition for the form closure, we checked the rank of the matrix $GN$ in Equation (1) as a function of the distance between two memorized areas. We use two target parts, i.e. an equilateral triangular prism and a square pillar.

The pin is simplified as a point, and the distance between two pins is 5 mm as shown in Figure 17(a). In the first case, an equilateral triangular prism is used as the target part where the dimension of the bottom surface is width $w = 45$ [mm] and the height $h = 45$ [mm]. As shown in Figure 17 (b), the triangular prism was fixed with 17 contact points. The matrix $GN$ is full row rank in this case. In the second case, a square pillar is used as the target part where the edge length of the square is $w = 45$ [mm]. It should be noticed that if there is no overlap between two memorized areas, the form closure is satisfied [16].

To fix a square pillar, the number of the contact points becomes 24 and the matrix $GN$ becomes full row rank (Figure 18). Then, we consider a situation where there is overlap between two memorized areas.

![Figure 17](image17.png) Fixing an equilateral triangular prism by using the proposed fixture.

![Figure 18](image18.png) Fixing a square pillar by using the proposed fixture.

![Figure 19](image19.png) The distance between two memorized areas.

![Figure 20](image20.png) The form closure condition when memorizing two objects with different shapes.
Let \( d \) and \( c \) be the distance between the two memorized areas (Figure 19) and the number of the contact points on the triangular prism. Figure 20 shows the relationship between \( c \) and \( d \). It can be seen that the number of the contact points increases as \( d \) increases. When \( d \) is larger than 25.0 [mm], the necessary condition for form-closure is satisfied.

We focus on the update of the current design since the fixture still has the following problem. First, the current fixing mechanism is not very stable. It is unstable since the pins are fixed just by the friction of the rubber rings. We add three more layers and two more cylinders on the two crossing parts and the new crossing parts can fix the pins tightly. Figure 21 shows the details of the fixing mechanism of the future design. We use the rubber layer which is stuck into two metal layers. The hole of the rubber layer is smaller than the hole of the metal layer. The relative motion of the upper three layers is actuated by two independent air cylinders. We can use the upper three layers to brake and release the vertical motion of the pins (Figure 22).

The second problem is that we have to move the pins back to the initial positions manually in the current design. We are trying to construct a new mechanism to solve this problem in the next version of the fixture.

6. Conclusion

This paper proposes a pin array fixture for high-mix production. It can be used to fix multiple parts with different shapes. We also can fix the batch parts with the same shape after the fixture memorized the shape. The results of peg-in-hole assembly experiments verify the feasibility of the fixture. However, there are still several deficiencies that need to improve on the proposed design. We will optimize the design to avoid the limitation in the future.

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No potential conflict of interest was reported by the author(s).

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