A NOVEL FLEXIBLE MICRO ASSEMBLY SYSTEM: IMPLEMENTATION AND PERFORMANCE ANALYSIS

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Abstract:

Demands for micro/nano products and assembly systems have been raised significantly to meet the ever complex technical needs for modern society. In this paper, we share the experiences and results of the study on the flexible micro assembly workcell focused primarily on a novel system implementation and system performance analysis. For flexible and autonomous assembly operations, we investigated a novel model based 3D depth measurement technology for faster and cost effective means to promote autonomous micro assembly systems in various industries. Micro parts, by its nature, are known of their shapes in advance for the majority of micro applications. We take advantage of the previously known shape of micro parts and hence apply a model based approach for a faster and cost effective localization and 3D depth measure of randomly loaded micro-parts on the workcell. The proposed 3D depth measuring method is based on the pattern recognition and multi-focus technique enabling it to extract only information useful for micro parts assembly for faster recognition. For demonstration purpose, silicon based oxide gears are fabricated by bulk micromachining and are used to study performance indices and to prove the usefulness of the proposed micro 3D depth measurement technology.

Keywords: *flexible manufacturing, micro assembly, micro 3D vision.*

1. Introduction

Demands for micro/nano products and assembly systems have been raised significantly to meet the ever complex technical needs for modern society. Among many is the MEMS (MicroElectroMechanicalSystem) technology that has demonstrated, in nearly every sector, miniaturization of mechanical parts or systems [1]. However, although many studies have shown significant advances in the micro/nano manufacturing technology during the last decades, a full blown solution with flexible manufacturing capability in mind still falls short of industrial implementation in terms of mass production. For example, Fatikow *et al.* developed a flexible micro-robot for complex microsystems assembly, though the vision system became much complex for easy implementation in industry [2]. In [3], Aoyama proposed a in-situ micro robots for flexible micro assembly, but the lack of means for realtime operations may hinder immediate implementations in industry.

In this paper, we share the experiences and results of the study on the flexible micro assembly workcell especially in the implementation and performance analysis. The term "flexible" is used for multiple model assembly loaded randomly in position and orientation on the workstation. For demonstration purpose of the proposed micro-assembly system, we fabricated silicon dioxide based micro gears and assembly base *via* bulk micromachining technology. To avoid crystallographic edge formation [4], several options are tried out for anisotropic wet chemical etch of silicon parts with the photolithographic masks in Figure 1. The wafers used were 100 mm thick p-type doped Si with a Miller indices crystal orientation of <100>. The SiO_2 layer was grown using a wet oxidation process followed by Photolithography and BOE (Buffered Oxide Etch), and several parts release processes.

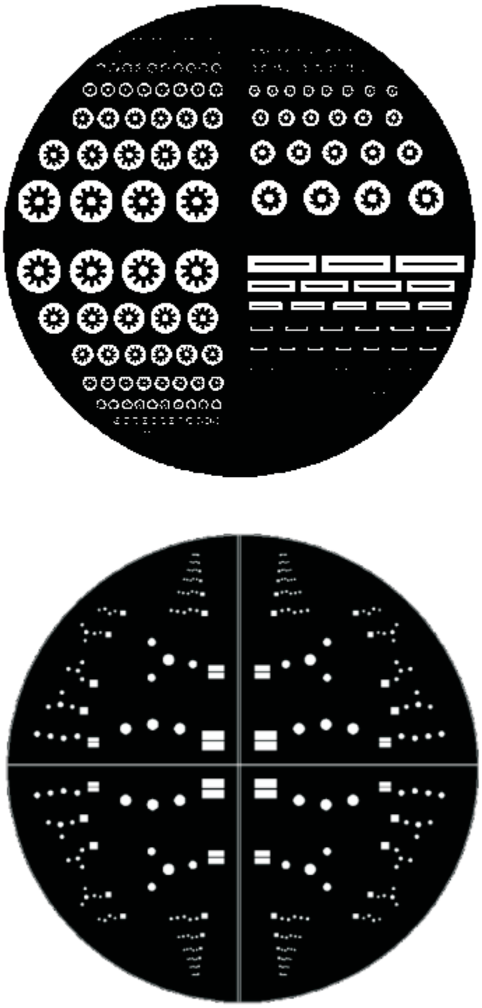


Fig. 1. Photomask for parts (top), and assembly area (bottom).

In order to minimize the crystallographic edge effect of the bulk micromachining, boron is diffused on the silicon dioxide surface to slow down the sharp edge formation [5]. The boron doping process allowed the silicon to be removed while strengthening the resistance of the SiO_2 parts to the KOH etch. When used in conjunction with polyimide coating, the developed processes produced a part with good surface quality which matched the initial CAD model. Figure 2 shows high quality micro-gear parts produced by combined methods of boron doping and polyimide coating.

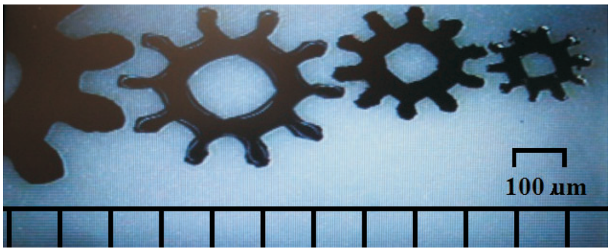


Fig. 2. SiO_2 gears in various sizes.

In order to assemble fabricated SiO_2 gears, a novel model based 3D depth measurement technology for micro parts is introduced in this paper. Unlike chemically released parts and assembled integrity by MEMS technology, flexible micro assembly is still a daunting task due to difficulties in parts visualization and assembly autonomy. Among many 3D visualization technologies, the most popular for micro scale parts is the confocal mapping [6]. The processing time of confocal mapping to obtain 10 to 100 photos for each pixel and expensive device value, though, hinders commercialization for various micro application industries. To overcome such a barrier, we investigate a novel model based 3D depth measurement technology for faster and cost effective means to promote micro assembly technology in various application fields. Micro parts, by its nature, are known of their shapes in advance for the majority of micro assembly applications. We take advantage of the previously known shapes of micro parts and hence apply a model based approach for a faster and cost effective 3D depth measure. The proposed 3D depth measuring method is based on pattern recognition and multi-focus technique enabling it to extract only information useful for micro parts assembly such as location, size, and height of a micro part. In addition, a functioning micro assembly system is developed and used to prove the usefulness of the proposed 3D depth measurement technology.

2. Assembly workcell integration

In this section, we present an integration methodology of a flexible micro gear assembly workcell with magnetic grippers, a micro precision robot, and a model based 3D depth measure system. A complete feedback loop between visual sensing and positioning/grasping of a micro part is the enabling technology of a flexible micro assembly workcell. As the name implies, micro parts can be loaded in the workcell randomly, and the vision system and the grippers will find their way to locate and grasp the micro parts. In our case, we use the micro gears and latches fabricated by bulk micro-machining for demonstration.

1. Micro precision robotic station

The assembly station used in the assembly workcell implementation is a precision micro robotic system by National Aperture with the uni-directional repeatability of 2 μm. Figure 3 is the picture of the 3 Degrees of Freedom (DOF) robotic system integrated in one assembly with a magnetic grippers.

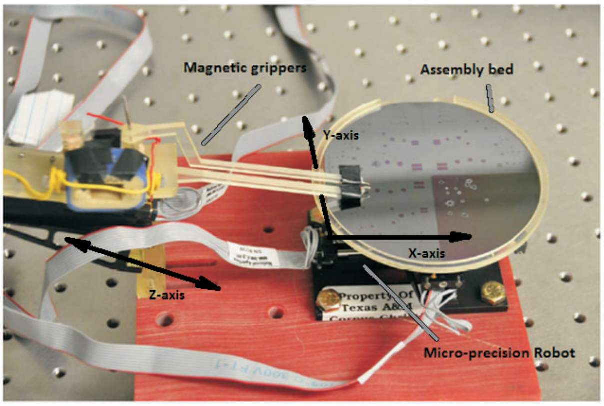


Fig. 3. 3-Axes Robotic wafer platform with a micro gripper.

The base station that holds the wafer has two-axis robotic module for x-y motion (Figure 3). The third axis is assembled in a tilted angle for grasping and up-down motion in one assembly. The magnetic grippers open and close the tip to grip and release a micro gear down to the size of 200 μm. Filted design of the 3rd axis in conjunction with the lengthy grippers allows not only precision pick and place operations, but maximizes the limited work space under the microscope.

2. Model based location and 3D depth measurement system

The key component to close the loop of the flexible micro assembly is the visual feedback system, with the micro 3D visualization capability. 3D measuring of micro gears is accomplished through four consecutive steps. The first stage involves the extraction of the contours so that the candidate regions of gears can be addressed. The second process entails sorting out the actual gear region among the candidate regions by comparing the extracted contours with the known information of gears. After this process, the contour that conforms the known gear shape remains, and all other contours are ignored. In the third stage, the height of each contour, which corresponds to an actual gear region, is measured with 10 different focused images. Finally, the simplified height map is developed by associating the gear regions with the obtained height information. Details of each process are discussed in the following sections.

A. Contour detection and gear recognition

Although the pixel-based recognition method is dominant in object recognition technology, we use the contour-based vector tracing approach for localization and 3D depth measuring of micro parts. With the pixel-based approach, an error of one pixel does not significantly affect the final result of the height map. On the other hand, one missed contour in the contour based approach causes a fatal error, though the result is significantly faster. Thus, the contouring method is the most important process in this step, and thus, it was consequently executed with three different binary images in an effort to obtain more reliable results.

First, the contour is extracted from a binary image. The focus of the image does not significantly affect the binary image, but the binary process is sensitive to the light condition. The micro assembly process is, therefore, performed in a well-controlled environment, and all light conditions are set as predefined adequate values. For even distribution of light intensity and to minimize the disturbance by ambient lights, infrared camera, filter, and fiber optic cables are used for the vision assembly (See Figure 4).

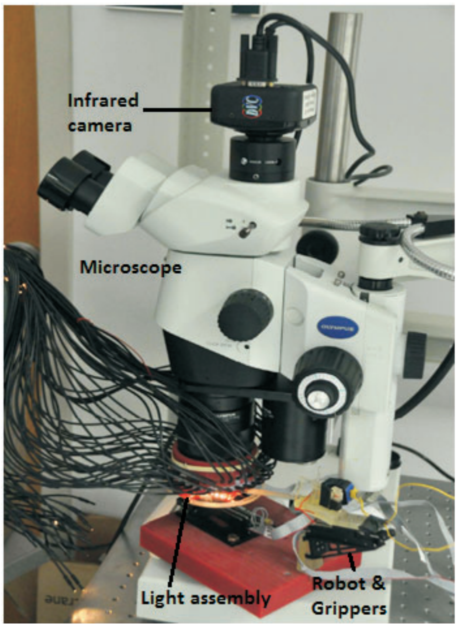


Fig. 4. Vision system and robotic platform assembly.

By analyzing the center of the recognized gear in planar coordinates, the wafer holding station moves the wafer to the exact location of the geometric center so that the gripper properly approaches the corresponding gear. The radius of the detected gear is calculated from the contour, and the gripper opens the proper amount to pick up the appropriate gear. However, the height of the gear still remains unknown. Without the height information, the gripper could be stuck by crashing into the wafer, or the gripper could miss the gear.

B. Simplified height map measurement method using Sum-Modified-Laplacian

Conformal mapping technique is based on measuring the focused and defocused area to create a 3D depth image. That is, due to the limited depth-of-focus of optical lenses, an object located out of the focal plane cannot be seen clearly in the image [6]. This implies measuring blurriness provides the height information of the objects [7]. The blurriness can be defined as an image gradient. When an image is described by a continuous brightness function, $I(x,y)$, its gradient at position (x,y) can be represented by a vector:

$$\nabla I(x,y) = \begin{bmatrix} G_x & G_y \end{bmatrix}^T = \begin{bmatrix} \dfrac{\partial I}{\partial x} & \dfrac{\partial I}{\partial y} \end{bmatrix}^T \tag{1}$$

The magnitude and direction of this vector are denoted as

$$mag(\nabla I) = \left[G_x^2 + G_y^2 \right]^{1/2} \tag{2}$$

$$\psi(x,y) = \arctan\left(\frac{G_y}{G_x}\right) \tag{3}$$

The partial derivatives in the above equations denote the direction and rate of change of the grayscale of each pixel. There are many ways to quantify the gradient values, such as Robel, Prewitt [8], Sobel, Laplacian, etc. The Laplacian operator is commonly used as a second order operator, represented by

$$\nabla^2 I = \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} \tag{5}$$

In order to prevent the change in x, y directions from cancelling each other, Nayar and Nakagawa [9] proposed a modified version of the Laplacian operator with a discrete approximation as

$$\begin{aligned}\nabla_{ML}^2 I(x,y) = &\left|2I(x,y) - I(x-step,y) - I(x+step,y)\right| \\ &+ \left|2I(x,y) - I(x,y-step) - I(x,y+step)\right|\end{aligned} \tag{6}$$

They proposed the sum-modified-Laplacian (SML) [10], as a focus measure at a point (x,y). It was denoted as

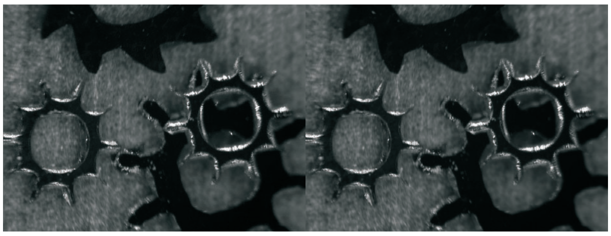
$$SML = \sum_{i=x-N}^{x+N} \sum_{j=y-N}^{y+N} \nabla_{ML}^2 I(i,j) \quad \text{for } \nabla_{ML}^2 I(i,j) \geq T \tag{7}$$

Where N is the measuring window size around the point (x,y). The parameter T is a distinct threshold value. In this research, the SML value of each pixel in a contour is calculated for height, and one representative height value for each contour region is defined by averaging SML values in that region. Although SML method works well with the micro parts, we experienced much delays on the 3D depth measure of the fabricated gears, which, in fact, becomes the bottleneck toward the near realtime assembly operation [11].

In order to overcome the latency of the SML method, we propose *a model based position and height measure technique*, namely "Simplified Height Map (SHM)" measurement method to facilitate the gear identification process using the object's geometry information. In this method, we assume that the height of each gear are known a priori and stored in the database. In addition, for demonstration purpose, we used gears with the equivalent height but without excluding overlapping possibilities. To measure the height of each region, 10 pictures with different focal planes are taken from the same view. Figures 5 (a)-(d) show four examples of different focal planes. Finally, a simplified height map is composed of the recognized gear regions with several levels of height, as shown in Figure 6.

Figure 6a) shows the extracted contours from an actual microscopic image in 3D format. The detected contours are compared with the known information of the gears. The size and shape of the gears are well-defined during the fabrication process, and the information of gears used in assembly is stored in a database before the assembly process. Contours which don't appear to be gears are ignored, and only matched contours with the database remain as regions of interest for height measurement. Figure 6b) shows the recognized gears.

(a) focus on wafer *(b) focus on lower gear*



(c) focus on upper gear *(d) focus on above gears*

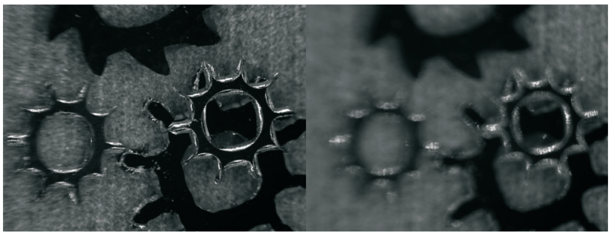


Fig. 5. Height measure using conformal mapping technique.

(a) without model

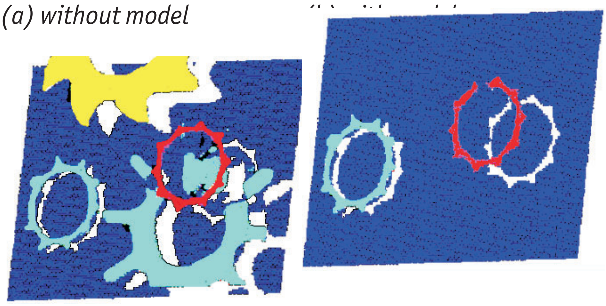


Fig. 6. SHM with a model based gear recognition.

Using the extracted gear location and height information by SHM method, our robotic grippers in conjunction with the x-y precision platform demonstrated successful pick and place operations, though current success ratio of the pick and place is fairly low to prove the usefulness of the proposed technology (See Table 1). With the tilted angle design, we achieved up to 0.5 µm z-axis accuracy of the gripping motion. The accuracy of close and open operation of the grippers, however, is not consistent overtime. In addition, although the height measure of the micro object is near realtime, processing the assembly of the micro gears on the axial shaft is yet performed with no realtime visual feedback, reducing the assembly success ratio to some extent.

3. Precision grippers

A precision pick and place grippers is designed and rapid prototyped as shown in Figure 7. The lengthy tweezer-type manipulator serves two purposes. First, it enables precision manipulation in the 1.5 cm of clearance between the assembly wafer and the microscope lens and lighting assembly. Secondly, the actuator opens and closes the grippers with the clearance on the order of 10–100 micrometer for precision operations. Therefore the arms of the lever would magnify the deflection up to 5 times to grip various sizes of micro-gears.

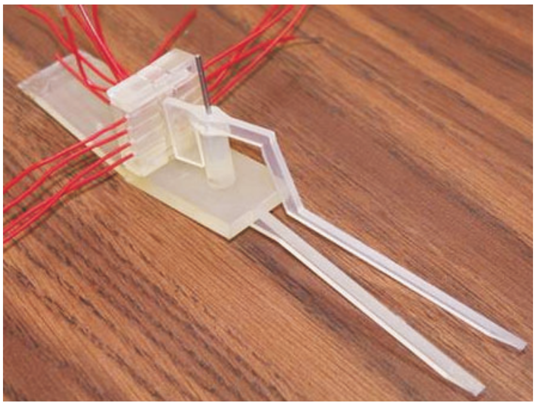
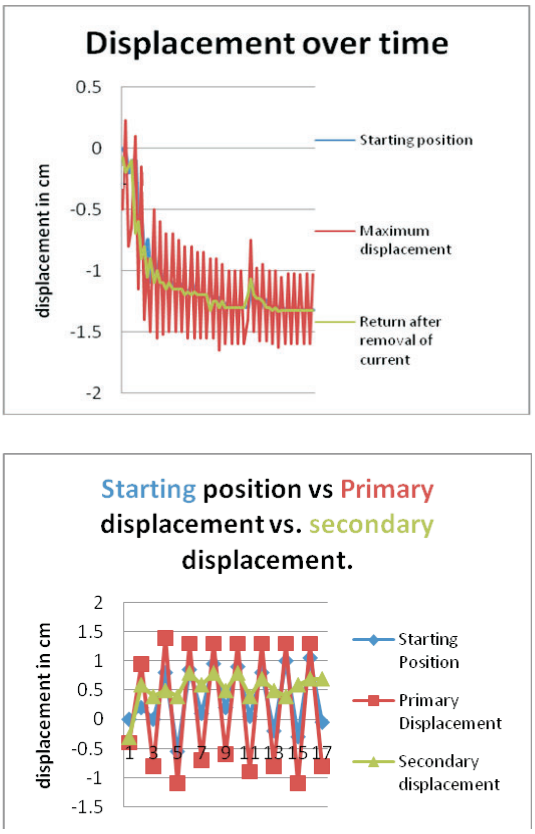


Fig. 7. Magnetic gripper assembly.

The first choice of the grippers' actuator was EAP (Electro Active Polymer) driven by controlled currents. However, it turned out that a EAP actuator has reliability problems over time as shown in Figure 8a). The amount of displacement reduces significantly, thus frequent replacement was inevitable. In addition, unexpected secondary displacement occurred. For instance, when the tip of the EAP strip begins from rest with no potential applied at the starting position marker, the EAP displaces to the primary displacement with the potential applied (Figure 8b)).



(a)

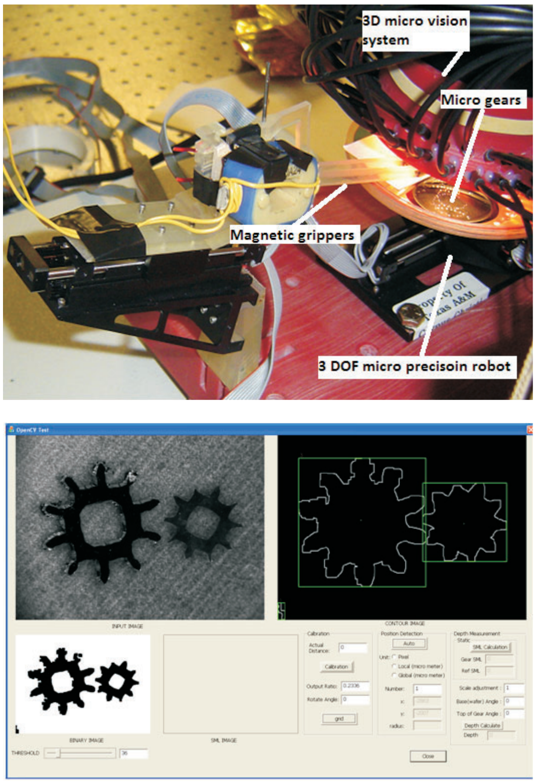
(b)

Fig. 8. EAP (Electro Active Polymer) actuator performance analysis.

While the potential remains on and constant, the EAP then begins secondary displacement in the opposite direction of the primary displacement (in the direction of the negative terminal). As a result, the actuator is changed to an electromagnetic driver for pick and place operations. Piezo-electric grippers demonstarted consistent performance with better controllability in grasp control.

3. Assembly experiments

The complete system has been implemented with a precision 3 axis robot, magnetic grippers and the 3D micro vision system (see Figure 9a)). For fully autonomous micro assembly operation, integration software has been developed to close the assembly loop between the vision sensor and the assembly grippers (see Figure 9b)).


(a)

(b)

Fig. 9. Assembly workcell (a) & integration software (b).

A complete assembly operation starts with recognizing randomly placed micro gears in the first quadrant of the assembly wafer followed by placing them at the corresponding location at the 4th quadrant. A complete assembly cycle includes gear location identification, gear height measure, robotic gripper control for pick and place operations (Figure 10). One example of the gear grasping *via* the magnetic grippers is shown in Figure 11. Figure 12 depicts the gears placed at designated locations in 4th quadrant of the wafer.

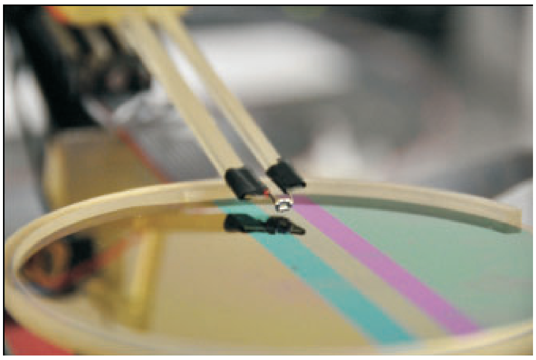


Fig. 11. Magnetic grippers holing a SiO_2 gear.

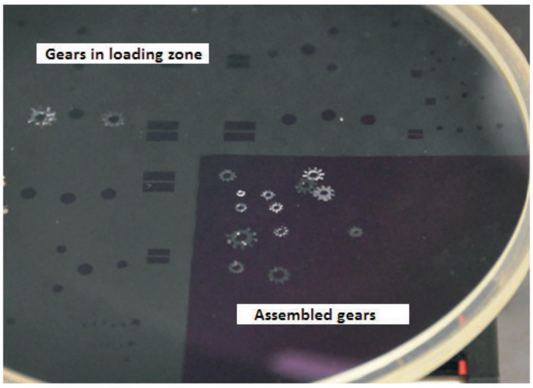


Fig. 12. Gears on the assembly workcell.

Table 1. Assembly time & root cause analysis.

	Aveg. (min)	St. Dev. (sec)	Success ratio (%)
Search for gears (x,y)	2.5	56	91
Identify gear height (z)	1.4	25	N/A
Grip gear	0.75	12	78
Move gear	0.5	15	97
Place gear	1.2	18	45

In Table 1, the results of assembly time and root cause analysis for assembly performance study are shared. The success ratio of the gear identification for x,y,z coordinates was not being analyzed due to the absence of the exact location information of each gear. The SHM method introduced in the paper improved the gear height identification speed up to 4 times faster than the conventional

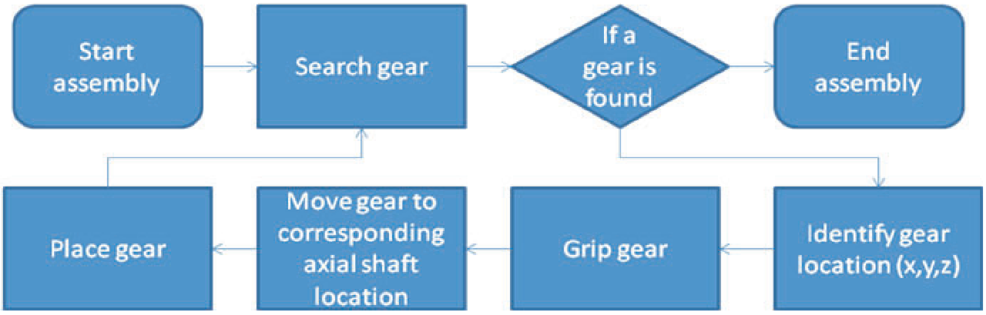


Fig. 10. Assembly sequence.

SML method. As shown in the table, gear height identification stage is no longer the bottleneck of the assembly process due to the improved process speed by the SHM method in time analysis.

In terms of success ratio, the gear placement stage is the root cause of the low overall success ratio. The overall assembly success ratio was about 77% and has yet to be improved for usefulness in industry. In order to improve the success ratio, realtime visual feedback has to be implemented for pick and place operations.

4. Conclusion

The technical challenge tackled in this research was to develop an autonomous and flexible micro parts assembly workcell. Among several components that constitute a flexible assembly workcell, the localization and 3D depth measure of micro parts were the most challenging tasks. To provide a low-cost and fast gear recognition method, we proposed the simplified height map generation for visualizing micro parts in 3D. The proposed method was designed to utilize the known models of micro parts such as size and shape, thus model based, so that it increases the reliability of the object identification and localization in near realtime fashion. Precision robotic platform and magnetic gripper have been put together with the micro 3D depth measure system.

Finally, micro gear assembly experiments were performed to prove the usefulness of the proposed system. The overall assembly success ratio was about 77% and has yet to be improved for usefulness in industry. The bottleneck process is turned out to be the gear identification stage in time analysis. However, the gear placement stage is the root cause of the low overall success ratio. In order to improve the success ratio, realtime visual feedback has to be implemented for pick and place operations.

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