Tip-positioning of a 6-DOF rotational micromanipulator using SMA

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The relevant market for minute electric machine systems (MEMS) has been increasing in recent years. Micro parts made by MEMS technology must be lifted and arranged correctly. Therefore, manipulation technology and environments for assembling multiple parts in three dimensions are required. However, current commercial devices for microscopic operation are large and expensive. We proposed a rotation manipulator with 3-DOF (degrees of freedom) using a shape memory alloy (SMA) to save cost and size. This mechanism is attached to the XYZ linear stage and it enables the system to perform 6-DOF manipulation tasks. It was possible to simplify the mechanism and save weight. In addition, it performs rotations and gripping from the diagonal. Complex assembly was possible. However, because the field of view of the microscope was narrow, vibration and deflection of the mechanism were severe in the micro area. With the mechanisms that have been fabricated to date, it is difficult to have a stable tip-position to work in the desired place, because the tip-position shifts up to about 300 μm. In this study, we proposed the precise control of our micromanipulator by using image processing. The experimental results showed that the system was able to suppress the amount of movement to ± 50 μm from the target.

1. Introduction

Recently, the demand for MEMS products has increased with the spread of smart phones and medical equipment. MEMS products have an accelerometer and pressure sensor. Although they are milli-sized, the parts used for them are micro-sized. Human operators cannot assemble micro parts manually, and therefore, a micromanipulator is required. Many studies have been carried out on micromanipulators. Tanikawa et al. proposed a two-finger micro hand using parallel mechanisms[1]. This manipulator has two fingers. A multi-degree-of-freedom manipulator manipulates the objects using the fingers as chopsticks by a parallel link mechanism. The parallel link mechanism has the following advantages: high rigidity, fast operation speed, and high positioning accuracy. However, it cannot estimate the exact rotation if the object is not a sphere. Further, the operating range of the parallel link mechanism is narrow. To obtain a wide operating angle the mechanism needs to be improved. Honda et al. proposed a 6-DOF (degrees of freedom) stage using a parallel link[2]. This method does not rotate the manipulator, but operates the object by moving the worktable with 6-DOF. It can be operated with high accuracy over many DOF. However, it has disadvantages[1]. Horie et al. proposed the articulated micromanipulator[3]. This method connects operating mechanisms, resulting in an operating mechanism with a flexible structure that is movable similar to a human arm. This method can provide a large movable range of rotation. However, it must be to the manipulator tip center of rotation of each axis. The mechanism is large and high accuracy rotating shafts are required. Many studies have investigated this method, but it is large and expensive. Therefore, we have manufactured a 3-DOF rotation manipulator of low cost and small size. It can be attached to the XYZ linear stage and it can carry out 6-DOF micromanipulation. However, the tip-position was moved with an approximate 300 μm shift from the target position. We thought this was caused by the following: (i) each axis was not orthogonal, and (ii) movement of the center-of-gravity position at the time of the influence and rotation of bending. For alignment of the axes, it was necessary to change the structure of the mechanism. By changing the mechanism for alignment, higher accuracy tip alignment was possible. However, the weight of the tip was increased with the improved tip mechanism. Because the tip became heavy because of
rotational movement, there is a need to review the whole structure. The deflection problem can be solved by using a member with a high rigidity. However, the specific gravity becomes heavy. It becomes difficult to operate SMAs in this condition. For the above solution, the error will be about 100 μm. Therefore, we proposed a method that uses image processing for motion calibration of a micromanipulator.

2. Micromanipulation system

Fig. 1 shows the micromanipulation system. Size can be used to manipulate micro objects of about 100 μm. The system consisted of a microscope, a CMOS camera, a stage 2 of the 2-axis (X, Y direction) to move the camera, a work area, a liquid bridge force handling tool, a 3-axis stage (X, Y, Z direction), and a vibration isolation table. Furthermore, the controller could move the stage. Fig. 2 shows a 3-axis stage. The positioning accuracy of each stage is 0.25 μm. This mechanism together with the stage had 6-DOF. 2-axis stage of the same accuracy is used on the stage of the camera. This mechanism is a 6-DOF together with the stage.

Fig. 2 3-axis stage

This system relied on the liquid bridge force between the object and the capillary to grasp the object (Fig. 3). The advantage of this technique is that an object could be grasped without influencing either its shape or surface. Fig. 4 shows the relationship between the distance between the micro part and the tip of the capillary and the generated liquid bridging force.

Fig. 3 Liquid bridging force

Fig. 4 Relationship between the distance and the liquid bridging force

Fig. 1 Micromanipulation system, with (a) overall view and (b) work space enlarged view
3. 6-DOF rotational manipulator

Fig. 5 shows an overview of the mechanism. An SM A actuator was used for the X- and Y-axes. Fig. 6 shows the structure of the X- and Y-axes. The SMA was light weight and it was difficult for vibration to occur compared with a motor. In addition, simplification of the mechanism could depend on tension. Z-axis using a servomotor (Smart Servo RC-1: Toki Corporation) operating at SMA. Fig. 7 shows the structure of the Z-axis. We used an Arduino Due microcomputer. This controlled the bio-metal. This mechanism had a structure that rotated around the tip of the capillary. The manipulator could perform such alignment and grip from the diagonal. Time it takes to 30° rotation is about 10 seconds.

![Fig. 5 Overall mechanism](image)

However, continuous work was difficult because the capillary tip moved during rotation (Fig. 8). The amount of transfers of the capillary tip portion was measured (Table 1). The result show that the tip movement was up to about 300 μm. The reasons for this movement are that each axis was not orthogonal and the movement of the center-of-gravity position at the time of influence and rotation of bending. With the above solution, an error of about 100 μm would occur. Therefore, we proposed a method using image processing. For a solution from the viewpoint of the mechanism, it is necessary to examine the entire structure.

![Fig. 6 Structure of the (a) X- and (b) Y-axes](image)

![Fig. 7 Structure of the Z-axis](image)

**Table 1 The amount of tip movement**

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4. Improvement of the mechanism by image processing

The tip of the mechanism moved, as shown in section 3. Therefore, to recognize the tip-position before rotation, when the tip was moved, the XYZ stage returned to its original position. This system could solve the movement problem of the tip at the time of rotation.

4.1 Recognition of the capillary tip

First, it was necessary to recognize the capillary tip to make a correction. A template matching method was used for this.

• Template matching method

The template matching method is a method to investigate the position of an object and to track moving objects. First, an image needs to be prepared of the object to be tracked. Then, the template image needs to be moved in the input image to be explored, to examine the similarity with the input image. To calculate the degree of similarity y the sum of absolute difference (SAD), sum of squared difference (SSD), and normalized cross-correlation (NCC) were used. The equations are shown below, with (1) SAD, (2) SSD, and (3) NCC. \[ R_{\text{SAD}}(a, b) = \sum_{i=0}^{W-1} \sum_{j=0}^{H-1} \left| I(a+i, b+j) - T(i, j) \right| \] \[ R_{\text{SSD}}(a, b) = \sum_{i=0}^{W-1} \sum_{j=0}^{H-1} \left( I(a+i, b+j) - T(i, j) \right)^2 \] \[ R_{\text{NCC}}(a, b) = \frac{\sum_{i=0}^{W-1} \sum_{j=0}^{H-1} I(a+i, b+j)T(i, j)}{\sqrt{\sum_{i=0}^{W-1} \sum_{j=0}^{H-1} I(a+i, b+j)^2} \times \sqrt{\sum_{i=0}^{W-1} \sum_{j=0}^{H-1} T(i, j)^2}} \]

where \( a \) and \( b \) are the scanning positions, \( T(i, j) \) the brightness value of the template, and \( I(i, j) \) the brightness value of the image.

SAD and SSD have high similarity for small values. Similarity of NCC is high for large values. These methods were used selectively, depending on the application. It should be noted that the template matching method that was used in this study sought similarity using NCC. In general, the detection of a rotated object is difficult with the template matching method.

Color and brightness values varied greatly in the image from normal. However, because the micro domain had little light volume, the luminosity value and color seldom changed. Therefore, it was possible to recognize change in angle by lowering the setting of the degree of similarity. The capillary tip could be tracked at all times.

4.2 Correction of the mechanism by the XYZ stage

4.2.1 Correction in \( X, \) and \( Z \)-axis direction

In our method, the origin was placed at the central coordinates of the input image. When the tip moved away from this point, the stage adapted to return to the home position automatically (Fig. 9). Movement of the XYZ stage by the controller was adapted so that the camera stage also moved. This system did not affect the work.

![Fig. 9 Correction in X- and Z-axis direction, with (a) non corrected and (b) corrected](image)

4.2.2 Correction in \( Y \)-axis direction

Edge detection mechanisms were used to correct in the \( Y \)-axis direction. At first, for pre-processing of the image, a Canny optimum filter was used. Canny considered a one-dimensional model of the edge. It had the following three desirable criteria:

(i) A low possibility of edge detection failure and a low probability of wrong edge detection;
(ii) A line and point where edge detection was performed near the center of the true edge; and
(iii) The edge detection result is only given with respect to one edge.

Criterion (i) is defined by the SN ratio, (ii) by the accuracy of the edge position, and (iii) by multiple peaks. Canny was approximated by the first derivative of the Gaussian function:

\[
f(x) = -\frac{x}{\sigma^2} \exp \left( -\frac{x^2}{2\sigma^2} \right)
\]

The edge was detected when the target object was in focus. The edge could not be detected when the object was out of focus. When the mechanism was rotated, the capillary tip or the upper part was not focused (Fig. 10).

![Fig. 10 Edge detection of the tip-end of a micro capillary, with (a) the input image and (b) edge detection](image)
This occurred because the depth of field of the microscope was narrow. This study took advantage of this feature. If the tip was out of focus and the upper part was in focus, the Y-axis stage moved forward. If the tip and the upper part were both out of focus, the Y-axis stage moved back. Fig. 11 shows the correction method of the Y-axis, seen from the side the system. When the tip was in focus, the Y-axis stage stopped. This system was in a state such that the tip would always be in focus.

![Diagram of microscope setup](image)

Fig. 11 Correction in the Y-axis direction (a) forward and (b) backward

5. Experiment

5.1 Experimental overview

Fig. 12 shows the experimental setup. The amount of movement of the capillary tip was measured when the user moved the mechanism. The measuring device "AD413T-I2 Dino-Lite Pro 2" was used. The measurement method is described here. At first, it obtained the images before an d after the rotation. The pixel values of the capillary tip were obtained in both images and the difference was calculated (Fig. 13). The values were converted from pixel to μm. The experiment verified the improvement in the mechanism by image processing.

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Table 2 The amount of tip movement after correction

5.2 Experimental results

Table 2 shows the experimental results. The numbers in parentheses are those pre-correction.

A correct tip-position could be observed for all rotations. The error in the tip-position could be suppressed to ±50 μm distance from the origin. The portion which was not moving is moving. However, it was considered a measurement error. In addition, it was possible to operate with an error around ±50 μm (Fig. 14). It was possible to control large tip movements.

![Image of measurement method](image)

Fig. 13 Measurement method

![Experimental setup images](image)

Fig. 12 Experimental setup

![Images of tolerance ranges](image)

Fig. 14 Tolerance range
5.4 Experimental of micro parts assembling

This experiment compares the operational time of assembling micro parts. Assembling task performs alignment of chip capacitors (width 400, height 200, depth 200 [µm]) of two. Fig. 16 shows a chip capacitor. Handling was using the liquid bridging force. It is necessary not only movement of the XYZ-axis direction, the rotating frame about the axis of each the task. Figure 16 shows the experimental landscape. Fig. 15 (d) shows the state of alignment. Table 3 shows the experimental results.

If no correction, there has been the object would fly by the movement of the tip. Work was continued has been difficult. It was not if there is a correction. I thought operability was improved. From the experimental result, we note that the working hours have been shortened by approximately 21% by introducing this correction system. Work efficiency is improved by controlling the amount of movement of the tip. The reasons for the improvement in the working efficiency of this task are the introduction of the correction system that improve a motion, the decrease in the movement that interfere with the work, and the handling position accuracy in the rotational motion of each axis. With the amount of movement of the mechanism is suppressed to ± 50µm, operation is easier. Therefore, I have found that the support that has been proposed by the present study is valid. However, subtle vibrations would still occur. This vibration could occur because of the angular control of the bio-metal.

6. Conclusion

The system developed in this study made it possible to correct the movement of a capillary tip. Although the position accuracy of handling was about 300 micrometers, it was able to suppress to ±50 micrometers. The effectiveness of the correction mechanism by the image processing is confirmed. Also, the work efficiency of about 21% is improved by experiments. The system verified the validity of microscopic work. It was also required to be able to use the other end effector.

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REFERENCES