Vision-based measurement of microassembly forces

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Abstract
This work describes a vision-based force sensing method for measuring microforces acting upon the jaws of passive, compliant microgrippers, used to construct 3D microstructures. The importance of jaw force measurement during microassembly is to confirm that the microgripper–micropart makes a successful grasp and to protect the microparts and microgripper from excessive forces which may lead to damage during the assembly process. Finite-element analysis of the microgripper is performed to determine the relation between the displacement and the resultant forces of its jaw. The resulting nearly linear force–displacement relationship is fitted to a first-degree equation. A mathematical model of the microgripper system validated this force–displacement relation. The proposed vision-based gripper force measurement techniques determine the deflections of the microgripper jaws during the microassembly process. The deflections in the gripper jaws are measured during the microassembly processes through computation of the relative displacements of the right and left microgripper jaws with respect to the microgripper base. Two approaches are proposed. The first approach uses pattern identification to measure these relative displacements. Two-dimensional pattern identification is performed using normalized cross-correlation to estimate the degree to which the image and pattern are correlated. The second approach uses object recognition and image processing methods, such as zero-crossing Laplacian of Gaussian edge detection and region filling. Experiments performed confirm the success of both approaches in measuring the microgripper jaw deflections and therefore the assembly forces.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Microassembly is the process of manipulating microscale components from their original location of fabrication to their final location of assembly to build a microsystem. Examples of those microcomponents include micromirrors and microcoils, which may be used to build microtransformers. Microassembly enables microdevices to protrude upward into the third dimension from the substrate, allowing the construction of complex microsystems. One of the most common microassembly techniques to fabricate 3D out-of-plane microstructures is serial microassembly, where parts are assembled, one by one, using a traditional pick-and-place concept.

Examples of serial microassembly systems include orthogonal tweezers microassembly [1], where a robotic system using two steel probes is used to dexterously manipulate and join microparts. Other robotic-based serial systems use microtweezers or microgrippers to grasp microparts and insert them into slots [2, 3]. Generally, microtweezers are considered as miniature versions of macrosized tweezers that grasp objects with two opposing tips that are flat and approximately parallel to each other, while microgrippers are generally defined as devices that ‘interface’
with microobjects using specially shaped grasping tips. Examples of microgrippers include surface-micromachined designs that are fabricated on chips, such that their tips can protrude over the edge of the chip to grasp objects [4].

Serial microassembly is commonly performed by humans with microtweezers and microscopes or with high-precision pick-and-place robots equipped with microgrippers. These systems are usually controlled with visual feedback. This feedback is achieved through human observation of the relative position and orientation of the microcomponents and the manipulator, making it possible to correct positioning errors. One such serial microassembly system was developed by Dechev et al [5]. The system makes use of a surface-micromachined microgripper that is bonded to a six-axis robotic manipulator, where the microgripper is used to grasp a micropart, remove it from the chip, reorient it and then join it using a micropart snap-lock feature to the other micropart. This six-axis robotic workstation is shown in figure 1, where the worktable moves in the x, y, z directions, and the probe is capable of rotating in the β, γ directions. Currently, significant research activity in the microassembly area is being carried out in order to commercialize the development and manufacture of hybrid 3D MEMS devices of high complexity, while maintaining high yield and low cost.

Force measurement is important during the microassembly process to protect both the microparts and microgrippers, during the grasping and joining processes, from excessive forces that may result in damage. Force sensors are used to measure the interaction forces between the micromanipulator and the microparts. Force sensing in the microscale requires the sensor capability of measuring forces in the range of $10^{-6}$ N. Microforce sensors currently in use include piezoresistive, capacitive and optical sensors. Piezoresistive force sensors integrated into microgrippers use a piezoresistive cantilever embedded into one side of the gripper, that changes resistance as the cantilever deflects, and the gripper force is determined from the deformation of the cantilever [6, 7]. A microgripper integrated with a capacitive force sensor was proposed by Lee et al [8] where a comb structure, attached to the gripper base, measures capacitance changes caused by deflections of the gripper. Compared to piezoresistive sensors, capacitive sensors do not exhibit hysteresis, have better long-term stability and a higher sensitivity [9]. A non-contact laser-based optical force sensor makes use of a laser beam reflected from a cantilever onto a quadrate photodiode. By measuring the laser beam position on the photodiode, the force applied to the cantilever is determined [10].

In recent years, computer vision, applied through a microscopic imaging system, has been recognized to be a suitable non-contact force sensing method. Computer vision was used to measure the force applied to an elastic object in the microgripper. Greminger and Nelson [11] demonstrated a method to visually measure the force distribution applied to a linearly elastic object using contour data in an image. They used an energy minimization method to match a deformable template to the image contour data. This method may be problematic to implement for complex microgripper structures as it requires complicated and time-consuming mathematical calculations.

This paper presents a new visual force sensing method for measuring microforces acting upon the jaws of passive, compliant microgrippers, used to construct 3D microstructures. The proposed vision-based force measurement technique is reduced to a problem of determining the deflections of the microgripper jaws during the microassembly process. A nonlinear relation between the assembly forces and the displacements of the jaws is determined by performing finite-element analysis of the microgripper. This relationship is fitted to a first-degree equation, enabling the measurement of the assembly forces whenever the jaw displacements are known. A mathematical model of the microgripper system, based on the finite-element model, validated this force–displacement relation. Computer vision techniques were used to measure the deflections in the gripper jaws, during the joining and grasping processes, by estimating the relative positions of the microgripper jaws with respect to the fixed microgripper base.

The normalized cross-correlation template matching method, which estimates the degree to which an image and a pattern are correlated, is used to measure these relative positions. In a second approach, zero-crossing Laplacian of

Figure 1. A six-axis robotic system used to manipulate microcomponents.
Gaussian edge detection, region filling and object recognition are used. Experiments were performed to investigate the performance of both methods. For each approach, the jaw deflections, measured visually, were compared to the jaw theoretical deflection profiles, measured from the dimensions of both the jaws and the grasped microparts. Results confirm the success of both methods and verify that the measured jaw deflections comply with the profile variations of the microgripper. Microassembly forces are calculated using the measured jaw deflections.

This paper is organized as follows. Section 2 of this paper discusses the microgripper structure and operation. Section 3 describes the finite-element analysis (FEA) and the mathematical modeling of the microgripper system. Section 4 describes both proposed computer vision approaches. Section 5 discusses the experimental results. Finally, section 6 concludes the work.

2. Microgripper structure

2.1. Microgripper design and operation

A robotic micromanipulator is used in this research to perform serial microassembly to assemble microparts. The assembly process is performed using a passive microgripper. The passive microgripper, shown in figure 2, consists of two jaws; each is connected to the microgripper base through three compliant beams. When the microgripper gets in contact with a micropart, the jaws deflect outwards.

The microgripper is bonded to the distal link of a six-axis robotic workstation that is then manually controlled to perform microassembly tasks. The microgripper has successfully been used to grasp microparts, remove them from the substrate and join them to other microparts forming three-dimensional structures.

The microgripper assembles the micropart into a microstructure through the five steps as described in [5], which are as follows: (1) a passive microgripper grasps the micropart, (2) the micropart is removed from the chip substrate, (3) the micropart is translated and rotated through space, (4) the micropart is joined to the target joint site, and (5) the micropart is released.

The microgripper used in this research utilizes the same operating and interlocking principle as that previously introduced in [12]. In order for a microgripper to grasp a micropart, the microgripper tips are pushed against the micropart. The micropart is tethered to the substrate, and therefore a reaction force is developed on the tips, causing them to open up. To perform the grasp, the tips are aligned with the micropart, and the microgripper is commanded in the direction of the micropart. Upon contact, a contact force is developed between the tips and the micropart causing each tip to deflect outwards.

In order to join the micropart to another micropart, the distal arm is rotated about the \( \beta \)-axis. In this orientation, the microgripper is able to join the micropart by inserting the grasped micropart snap-lock feature into the other micropart, which generates a joining force that is transferred to the microgripper. After the grasped micropart is joined to the other micropart, the microgripper tips are then commanded to translate away.

2.2. Microgripper fabrication and material properties

The microgripper was fabricated using PolyMUMPs (multi-user MEMS processes) [13], a cost-effective three-layer polysilicon surface micromachining process. PolyMUMPs consists of a non-patternable nitride isolation layer, a polysilicon ground (plane) layer, two structural polysilicon layers, two oxide release layers and one metal layer for reflectivity enhancement. The designs were developed using Tanner L-Edit software to create multilayer 2D layouts, as shown in figure 3.

The microgripper is comprised mainly of polysilicon, with a Young’s modulus of approximately 169 GPa, an ultimate tensile stress of approximately 2 GPa, a density of 2330 kg m\(^{-3}\) and a Poisson’s ratio of 0.22 [14].

3. System modeling and finite-element analysis

The problem of measurement of the jaw contact forces acting upon the microgripper tips is reduced to determining the tip deflections when the tip comes into contact with the micropart.
Therefore, determining the relation between the contact forces and the deflections is necessary. Finite-element analysis (FEA) was performed to evaluate the effect of the microgripper jaw deflection on the forces acting upon each jaw and thus the microassembly forces. A mathematical model of the microgripper was developed to validate the finite-element model.

3.1. Finite-element solid modeling

Finite-element analysis was performed on the solid model of the microgripper. The designs were created using Tanner L-Edit software providing multilayer 2D layouts. MEMSPRO software was then used to generate 3D solid models, based upon the 2D layouts. The 3D solid models were then refined using SolidWorks software, by removing sacrificial layers and extraneous parts to more closely match the actual micropart fabricated by the PolyMUMPs fabrication process [13]. A commercially available FEA package (Ansys Multiphysics) was used to mesh the solid model using 3D ten-node tetrahedral solid elements. This element type was selected since it has a quadratic displacement behavior and is well suited to model irregular meshes [15].

The material properties of the microgripper material were imported into the FEA software. The structure was meshed with elements having sizes varying between 0.5 µm and 2 µm. The size of an element depends upon the structure complexity, which varies depending upon which portion of the structure is being meshed.

The deformable microgripper structure is linearly elastic. The microgripper pad is bonded to the head of a metal probe, shown in figure 4, attached to the distal link of a six-axis microassembly workstation [5]. Thus, the microgripper base motion is constrained in all six linear and rotational directions, when attached to the microassembly workstation.

When contact is made between the microgripper and a micropart, reaction forces are generated between the microgripper and the micropart. Figure 5 shows these forces at the three different stages of the microgripper and micropart contact. The force that causes the microgripper jaw to deflect, leading to bending of the compliant beams, is the vertical component of the force $F_{contact}$. The horizontal component of the force $F_{contact}$, in addition to the friction force $F_{friction}$, has no effect on the vertical deflection of the microgripper.

![Figure 5. The contact force $F_{contact}$ acting upon the microgripper as a result of contact with the micropart at its different stages.](image)

![Figure 4. Scanning electron microscope (SEM) image of a microgripper bonded to probe.](image)

![Figure 3. Multilayer two-dimensional layout of a passive, compliant microgripper.](image)
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Figure 6. The force $F_{\text{tip}}$ acting upon the microgripper as a result of contact with the micropart.

Table 1. Effect of the force $F_{\text{tip}}$ on the jaw tip deflections.

<table>
<thead>
<tr>
<th>Force ($F_{\text{tip}}$) ($\mu$N)</th>
<th>$x$-tip displacement ($\mu$m)</th>
<th>$y$-tip displacement ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.0196</td>
<td>0.55</td>
</tr>
<tr>
<td>10</td>
<td>0.0358</td>
<td>1.11</td>
</tr>
<tr>
<td>20</td>
<td>0.0587</td>
<td>2.22</td>
</tr>
<tr>
<td>30</td>
<td>0.0802</td>
<td>3.34</td>
</tr>
<tr>
<td>40</td>
<td>0.0673</td>
<td>4.49</td>
</tr>
<tr>
<td>50</td>
<td>0.0522</td>
<td>5.67</td>
</tr>
<tr>
<td>60</td>
<td>0.0199</td>
<td>6.89</td>
</tr>
<tr>
<td>70</td>
<td>$-0.0533$</td>
<td>8.23</td>
</tr>
<tr>
<td>85</td>
<td>$-0.0804$</td>
<td>10.07</td>
</tr>
</tbody>
</table>

Figure 7. Deflection of jaws in the $y$-direction, when force $F_{\text{tip}}$ is applied.

Figure 8. Deflection of jaws in the $x$-direction, when force $F_{\text{tip}}$ is applied.

During a typical microgripper grasping operation, the force $F_{\text{tip}}$ is approximately 35 $\mu$N when the jaw tip displacement is 4 $\mu$m. FEA showed that at the 4 $\mu$m jaw tip displacement, a stress of 500 MPa is generated in the compliant beams, which corresponds to 0.25 of the ultimate tensile strength of polysilicon. The magnitude of the force was varied from 5 to 85 $\mu$N, at which point the $y$-deflection exceeded 10 $\mu$m. The FEA results have shown that at this force, stresses at the intersection of the compliant beams and the microgripper base are sufficiently large to cause breakage of the compliant beams. Microgripper jaw tip deflections, presented in table 1, are plotted in figures 7 and 8.

Equation (1) shows that the compliant beam system has an equivalent stiffness of approximately 8 N m$^{-1}$ in the

$$F_{\text{tip}} = F_{\text{contact}} \sin \theta. \quad (1)$$

The horizontal component of the contact force $F_{\text{contact}}$ in addition to the frictional force $F_{\text{friction}}$ generates a horizontal force $F_{\text{horizontal}}$ acting upon the microgripper jaw tip. The force $F_{\text{horizontal}}$ is described by

$$F_{\text{horizontal}} = F_{\text{contact}} \cos \theta + F_{\text{friction}} \sin \theta. \quad (2)$$

Since grasping force measurement is reduced to determining the displacement of the microgripper jaw, it was important to relate the forces $F_{\text{tip}}$ acting upon the jaws to the jaw displacements occurring during contact between the microgripper and the microparts. Figure 6 shows the vertical force, $F_{\text{tip}}$, generated on the tip of the microgripper when it is in contact with the micropart.

3.2. Finite-element analysis results

Finite-element analysis was carried out with the jaw force, $F_{\text{tip}}$, applied to the microgripper jaw tip in the $y$-direction. The magnitude of the jaw tip displacement in both the $x$-direction and the $y$-direction was determined. The measured $x$-deflections and $y$-deflections are presented in table 1.

This linear force $F_{\text{tip}}$ and $y$-deflection relationship was fitted into the following equation:

$$F_{\text{tip}} = 8.0y. \quad (3)$$

Equation (3) shows that the compliant beam system has an equivalent stiffness of approximately 8 N m$^{-1}$ in the
y-direction. On the other hand, figure 8 shows that the contact force \( F_{\text{tip}} \) is a multi-valued function in the x-component, indicating the difficulty of using the x-direction displacement to determine the contact force. Moreover, the x-deformations being smaller than 0.1 \( \mu m \) can hardly be seen using a vision system.

Therefore, (3) is selected to be used in the calculation of the contact force when the y-direction jaw displacement is known.

### 3.3. Mathematical modeling of the microgripper

A mathematical model of the microgripper, that was developed in [16], is used to validate the finite-element model and to determine analytically an equation relating the microassembly forces (\( F_{\text{tip}} \)) acting on the microgripper jaw tip to the y-direction jaw displacement. As a result of the symmetries in the microgripper, calculations were carried out for one half of the microgripper structure, as shown in figure 9.

The system was simplified into three similar fixed-guided compliant beams of lengths \( L_b \), rectangular cross-section areas \( A_b \) and moments of area \( I_b \). The three compliant beams are connected to each other by means of the microgripper head, which is assumed rigid. Figure 9 shows the displacements and rotations at the beams ends. As a result of the microgripper jaw head rigidity, the x-deflection and y-deflection at the ends of each of the three compliant beams are assumed to be the same, i.e. \( X_1 = X_2 = X_3 = X \) and \( Y_1 = Y_2 = Y_3 = Y \), where \( X_i, Y_i \) are the x-deformations and y-deformations of the end of each beam \( i \), respectively. The \( \theta \) rotation at the ends of the three parallel compliant beams, with fixed-guided end conditions, is negligible and is assumed zero, i.e. \( \theta_1 = \theta_2 = \theta_3 = 0 \).

In the case where the forces \( F_{\text{tip}} \) and \( F_{\text{horizontal}} \) are applied at the microgripper jaw tip, as a result of the contact between that microgripper and the micropart, this force is divided equally between the three parallel beams, with fixed-guided end conditions, and an equivalent force of \( F_{\text{tip}}/3 \) is applied to each beam in the y-direction. A moment \( M \) is also generated as a result of the force \( F_{\text{tip}} \). Its value is divided equally between the ends of each of the three beams and has a value \( M/3 \). The moment \( M \) is expressed by

\[
M = F_{\text{tip}} \times L_h + F_{\text{horizontal}} \times L_c, \tag{4}
\]

where \( L_h \) is the horizontal distance between the microgripper jaw tip and the compliant beams ends and \( L_c \) is the average vertical distance between the jaw tip and the compliant beams.

Beam static equations [17] were used to derive the relation between forces and moments acting upon each beam end and the beam displacements and rotations. Forces and moments acting upon the beams ends can be expressed by

\[
\begin{bmatrix}
F_x \\
F_y \\
M
\end{bmatrix} =
\begin{bmatrix}
\frac{E_b}{I_b} & 0 & 0 \\
0 & \frac{12E_b}{I_b} & \frac{6E_b}{I_b} \\
0 & \frac{6E_b}{I_b} & \frac{3E_b}{I_b}
\end{bmatrix}
\times
\begin{bmatrix}
X \\
Y \\
0
\end{bmatrix}
= \begin{bmatrix}
\frac{F_{\text{tip}}}{3} \\
\frac{F_{\text{tip}}L_h}{3} + \frac{F_{\text{tip}}L_c}{3}
\end{bmatrix}, \tag{5}
\]

where \( F_x, F_y \) are the x-component and y-component of the force acting upon the end of each beam, respectively, \( M \) is the moment acting upon the end of each beam and \( E \) is the modulus of elasticity. From (5), the y-deflection of the microgripper jaw tip is therefore given by

\[
F_{\text{tip}} = \frac{36EI_h}{L_h^4} Y. \tag{6}
\]

From the beam geometry, with \( E = 169 \) GPa, length \( L_h = 94 \mu m \), width \( b = 2 \mu m \), thickness \( h = 2 \mu m \) and moments of area \( I_h = \frac{bh^3}{12} = 1.33 \mu m^4 \), the force \( F_{\text{tip}} \) can be calculated:

\[
F_{\text{tip}} = 9.7Y. \tag{7}
\]

The relation between the contact force ‘\( F_{\text{tip}} \)’ and the y-direction displacements ‘\( y \)’ calculated using FEA, presented by (3), can be seen to closely match that measured analytically using a mathematical model of a simplified microgripper structure, presented by (7). This match validates the finite-element model and confirms the validity of results obtained using the FEA.

The difference between both equations is a result of neglecting the very small effect of microgripper jaw rotation, in addition to the assumption that the microgripper jaw is rigid. Both assumptions were introduced in order to simplify the mathematical modeling of the microgripper system. Equation (3) will therefore be used to measure the force when the y-direction displacement of the microgripper jaw tip is known.

### 4. Vision-based deflection measurement

Two vision-based methods are used to determine the microgripper y-direction jaw tip deflection, and therefore, the jaw forces can be calculated. Features or objects of interest in an image are found and extracted. There are three main objects of interest, the microgripper left jaw, right jaw and an object representing the fixed microgripper pad. Both the normalized cross-correlation template matching method [18] and the zero-crossing edge detection technique [16, 19] are used to determine the centers of gravity of these objects and calculate their relative positions within the image plane. Knowing their relative positions, the microgripper right and left jaw deflections can be measured.
4.1. Normalized cross-correlation method

Template matching techniques may be used to determine the microgripper y-tip deflection. Image templates representing the microgripper right jaw, left jaw and the microgripper base are used. By knowing the positions of these templates in the image plane, corresponding to the position of the three features of interest, the y-deflections of the right and left jaws may be determined.

The basic template matching algorithm consists in superimposing the template over the search area and at each position of the template, calculating a ‘correlation’ or ‘distortion’ measure estimating the degree of dissimilarity, or similarity, between the template and the image [18]. Then, the maximum correlation or minimum distortion position is taken to represent the occurrence of the template in the examined image.

The normalized cross-correlation method [18], a widely used correlation measure, is used to determine the coinciding peak coordinates between the image and the template of the object to be tracked. These peaks are calculated by the following equation:

\[
M(i, j) = \frac{\sum_{k=1}^{m} \sum_{l=1}^{n} g(k, l) f(i+k, j+l)}{\sqrt{\sum_{k=1}^{m} \sum_{l=1}^{n} f^2(i+k, j+l)}},
\]

where \(g(i, j)\) is the template of the object to be tracked specified in the form of a matrix, \(f(i, j)\) are the images used to find the object inside and are also given as a matrix, \(M(i, j)\) are the coinciding peak coordinates, \(m \times n\) pixels is the size of the template and \(k, l\) pixels are the displacements in the image with respect to the template.

An example of an image \(f(i, j)\) in which the object or templates are located is shown in figure 10. Each image \(f(i, j)\) has a size of 1280 \(\times\) 1024 pixels. Figure 11 shows the templates \(g(i, j)\) that were tracked to measure the jaw deflections. The sizes of the right jaw, left jaw and middle beam templates are 82 \(\times\) 52 pixels, 87 \(\times\) 57 pixels and 76 \(\times\) 51 pixels, respectively.

The coinciding peak coordinates between the image and the templates of each tracked object are determined, indicating where each feature is located in the image. The relative positions of the features in the image plane are calculated.

4.2. Zero-crossing Laplacian of Gaussian edge detection

Edge detection methods are used to determine the boundaries between dissimilar regions in an image. The zero-crossing Laplacian of Gaussian edge detection method is used to identify the edges surrounding the specific features of interest in the microgripper image plane. Once the borders of these features are identified, the locations of the centers of gravity of these features are determined; thus, the relative positions of features in the image can be identified.

4.2.1. Laplacian of Gaussian. The zero-crossing edge detector determines locations in the Laplacian of an image where the value of the Laplacian passes through zero [19]. The Laplacian of an image is a 2D isotropic measure of the second spatial derivative of an image which highlights regions of rapid intensity change and is therefore often used for edge detection. Before edge detection of the microgripper image, the image is first smoothed with a Gaussian smoothing filter in order to reduce its sensitivity to noise. The 2D Laplacian of Gaussian function with Gaussian standard deviation \(\sigma\) therefore takes the form

\[
\Delta G_\sigma(x, y) = \frac{\partial^2}{\partial x^2} G_\sigma(x, y) + \frac{\partial^2}{\partial y^2} G_\sigma(x, y).
\]

The 2D Laplacian of Gaussian \(\Delta G_\sigma(x, y)\) is the image processing mask (filter) that is used to detect edges in the image. This mask is a small 2D array whose coefficients determine the nature of the image processing process. Discrete convolution is performed, which is defined as a shift and multiply operation where the mask is shifted over the image, and its values are multiplied with the corresponding pixel values of the image [20]. The linear filtering of the image \(I\) of size \(M \times N\) pixels with a filter mask \(\Delta G_\sigma(x, y)\) of size \(K \times L\) pixels is obtained by the expression

\[
c(i, j) = \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} \Delta G_\sigma(k, l) I(i-k, j-l).
\]
the Laplacian changes sign. Zero-crossings always lie on closed contours; hence, the output from the zero-crossing detector is a binary image with single pixel thickness lines showing the positions of the zero-crossing points. Figure 12 shows the microgripper image before and after the zero-crossing Laplacian of Gaussian edge detection technique was applied.

4.2.2. Image dilation and erosion. Cavities and complex structures in the resulting image, shown in figure 12(b), cannot be detected accurately and therefore a region filling technique is implemented [16, 20, 21]. Region filling, or flood filling, is accomplished iteratively using dilations, complementation and intersections, as shown in figure 13(a). Morphological erosion is also used for eliminating irrelevant details from a binary image. Erosion is used to eliminate all objects in the image except the largest ones, as shown in figure 13(b). These image processing processes were performed using built-in modules in commercially available image processing software packages [22].

4.2.3. Object recognition. From the final binary image, objects of interest are extracted through calculation of the area of each object through addition of their pixel values. These objects are the right jaw, the left jaw and the middle beam corresponding to the microgripper pad, shown in figure 13(b). The locations of the centers of gravity of these objects within the image plane are determined, enabling the calculation of their relative positions. Since the middle beam represents the fixed pad of the microgripper, therefore the deflections of the right and left jaws can be calculated by subtracting the initial jaw relative positions, with respect to the fixed pad before deflection, from their current relative positions.

5. Experimental results

5.1. Experimental setup

Here, we briefly describe the equipment that was used to perform experiments. This includes a six-axis robotic system that was used to manipulate microcomponents and a video microscope system that was used to acquire experimental images.

5.1.1. Robotic workstation system. A six-axis robotic workstation forms the basis of the microassembly system [5, 16], shown in figure 1. The first three axes of the robotic manipulator are orthogonally mounted linear stages providing Cartesian positioning of the chips beneath the microgripper end effector. A rotational stage (α) mounted on the distal end of these first three Cartesian axes allows the MEMS chip to be rotated. Two more degrees of
freedom (β and γ) are serially mounted to the base frame, allowing for two degrees of rotation of the end effector. Five-phase stepper motors are used to drive the three translation stages providing a linear resolution of 0.5 µm. Stepper motors are also used to drive the rotational stages providing a rotational resolution of 0.072°.

5.1.2. Video microscope system. The video microscope system consists of an Infinitube in-line assembly and a Nikon CF60 L Plan Epi 20× objective. A co-axial illuminator is connected in-line with the optics to provide illumination of the MEMS chip. Using green light, the optical resolution of this system is approximately 0.9 µm. The video camera used is a digital, monochrome unit from Pixelink (model # A741) with a 2/3” CCD and a resolution of 1280 × 1024 pixels. Combined with the microscope system, the resulting field of view is 427 µm × 320 µm, with a depth of focus of 1.5 µm. The microscope system is mounted on a three-axis translation stage, which is mounted onto the six-axis robotic workstation.

5.2. Microgripper operation

The microgripper is bonded to a probe tip connected to the robot β and γ axes. The microchip is placed on the x, y, z, α base stage. The base stage is translated along the x, y and z axes to align the gripper tips with the micropart interface feature [12], preparing to grasp it. In this paper, a fixed micropart was specially designed and fabricated for on-chip testing of the proposed visual force sensing technique. A SEM image of the microgripper, aligned with the fixed micropart, is shown in figure 14.

When the microgripper is displaced towards the micropart, grasping takes place in four different stages beginning from the instant a properly aligned microgripper and micropart touch. Figures 15 and 16 show the microgripper and micropart mating surfaces and the different stages of the microgripper–micropart mesh.

In stage I, the microgripper inclined surface (2) slides along the micropart corner edge (6) until point (3) coincides with point (6). In stage II, the microgripper edge point (3) slides along the horizontal micropart surface (7). In stage III, the microgripper edge (3) slides back along the inclined micropart surface (9) until it reaches its end in the beginning of stage IV. In the final stage IV, the microgripper edge (3) moves along the microgripper surface (10), and the microgripper surface (5) meets with micropart surface (7). Stage IV is only achieved correctly when the microgripper and micropart are aligned properly. An example showing poor alignment is shown subsequently.

As the microgripper moves towards the micropart in the x-direction, the microgripper jaw tip is displaced in the y-direction in the manner previously discussed. To determine the microgripper deflection profile when the microgripper moves towards the micropart, the micropart and microgripper dimensions must be measured accurately. It is not possible to rely on the microstructure design drawings in order to obtain these dimensions. Due to fabrication errors, the fabricated microcomponent dimensions are slightly different from their designed dimensions; hence, dimensions can only be obtained from the microscope images of the parts.

The microgripper jaw edge profile, represented by the solid line in figure 15, is determined directly from the image. As a result of the limited optical resolution of the microscope
system, the edges of the microgripper do not appear sharp in the image (i.e., edge is of one pixel thickness). Edges appear blurry since they are three pixels thick, as shown in figure 17. An assumption was made that the true edge lies in the middle of the blurry image, as shown in figure 18. Using the assumed microgripper jaw edges, the measurement of the microgripper edge profile, presented by the solid line in figure 15, was possible.

However, it is not possible to measure the edge profile for the micropart, represented by the dotted line in figure 15, since that actual micropart edge, where contact with the microgripper is achieved, is hidden under the microgripper jaw. The micropart edge profile was obtained using a microscope image of a specially designed and fabricated removable micropart structure. The removable micropart, shown in figure 19(b), has the same dimensions as the micropart shown in figure 14 and 19(a), since they are both fabricated on the same chip parallel to each other. The similarity between the fixed and the removable microparts can be noted in figure 19.

5.3. Force measurement using normalized cross-correlation method

The performance of the proposed force sensor approach using the normalized cross-correlation method [18, 23] is investigated in this section. The microgripper is aligned with respect to the micropart to be grasped, where, as previously
mentioned, the micropart is fixed to the substrate only for the purpose of on-chip testing. The microgripper is translated in the \( x \)-direction towards the micropart in steps of magnitude 1 \( \mu \text{m} \). Images are captured at each step. A computer algorithm, written using Matlab [22], uses the ‘normxcorr2’ program to perform the calculations. The microgripper jaw deflections are measured at each step, in the manner described in section 4.1. Using (3), forces on the right and left jaws are calculated. Figures 21 and 22 show the experimental left and right jaw deflections, using the cross-correlation method, when compared to their deflection profiles. Results show that the jaw deflections, measured experimentally, followed their deflection profiles, shown in figure 20, after contact between the microgripper and the micropart takes place. The only exceptions were the left jaws during stages III and IV. This will be discussed subsequently in section 5.5.

The magnitudes of the \( y \)-direction contact forces \( F_{\text{tip}} \) acting upon the right and left microgripper jaws are calculated by substituting the deflection values into (3). The variation of the forces with respect to the microgripper step displacement in the \( x \)-direction is shown in figure 23. Results show that the values of the forces acting upon the microgripper \( F_{\text{tip}} \) did not exceed 30 \( \mu \text{N} \), which is a force high enough to grasp the micropart without generating a stress that may cause the microgripper to break.

5.4. Force measurement using zero-crossing Laplacian of Gaussian edge detection

The performance of the proposed force sensor approach using zero-crossing Laplacian of Gaussian edge detection is investigated in this section. Similar to the experimental procedures of when applying the normalized cross-correlation method, the microgripper and the micropart are aligned, and the microgripper is translated in the \( x \)-direction towards the micropart with steps of magnitude 1 \( \mu \text{m} \). Images are captured at each step, in the manner described in section 4.2. A computer algorithm, written using the Matlab Image Processing Toolbox [22], performs edge detection, dilation and erosion processes.

The microgripper jaw deflections are measured at each step in pixels, which are then converted to \( \mu \text{m} \). Using (3), forces on the right and left jaws are calculated. Figures 24 and 25 show the experimental left and right jaw deflections, using the zero-crossing edge detection method, when compared to their deflection profiles. Results show that the jaw deflections, measured experimentally, closely followed their deflection profiles, shown in figure 20, after contact between the microgripper and the micropart takes place. The only exceptions were the left jaws during stages III and IV, which will be discussed subsequently.
5.5. Validation of vision-based deflection measurement approaches

Deflections of the left and right jaws, calculated using both computer vision techniques, were compared to their theoretical values, shown in figure 20. The theoretical deflection profiles represent the exact measurements of the microgripper jaw deflections when a correct alignment between the microgripper and the micropart is achieved. In the performed experiments, there was a slight microgripper–micropart misalignment. The misalignment forced the left microgripper jaw tip to always touch the micropart surface, causing the experimental left jaw deflections to follow exactly the left jaw deflection profile, shown in figure 20. Figures 21 and 24 show the proximity between the left jaw deflections, measured using the proposed vision-based measurement techniques, and the left jaw deflection profile, which validates both proposed methods. Small deviations of the measured values from the deflection profiles exist and are discussed in the subsequent section.

5.6. Accuracy of proposed methods

When both proposed vision-based measurement methods were used, the measured microgripper jaw deflections did not precisely follow their theoretical deflection profile. Deviations between measured and theoretical values existed for both left and right jaws, after contact between the microgripper and the micropart takes place. These deviations are shown in figures 27 and 28. As previously mentioned, as a result of a small misalignment between the microgripper and the micropart, the microgripper left jaw tip is forced to touch the micropart surface at all times. Figures 27 and 28 show that the deviations for the left jaw measurements were within the range of ±0.5 µm, for both proposed methods. These deviations are results of the limited resolution of the used video microscope system (0.9 µm).

The deviation between the measured right jaw deflections, when both vision-based methods were used, and the right jaw deflection profile reached 1.0 µm, in stages III and IV, as shown in figures 27 and 28. This is a result of the microgripper–micropart misalignment. The misalignment prevented point (3), in the right gripper jaw, from sliding on surfaces (9) and (10), shown in figure 15. Instead, point (1) slides on both surfaces (4) and (5).
5.7. Discussion of results

Both proposed vision-based force measurement approaches provide the same magnitude of error (±0.5 µm). When the error exceeds this range of error, this is a sign of a misalignment or a wrong contact between the microgripper and the micropart, as seen for the case of the right microgripper jaw. Deviations and errors, larger than the allowable range (±0.5 µm), require that corrective actions be taken to remove the source of misalignment or wrong contact.

Although both vision-based methods have the same level of measurement precision, nevertheless, computer calculations required to perform measurements using the Laplacian of Gaussian edge detection are more complicated than those required by the template matching approach. Therefore, the normalized cross-correlation template matching method is recommended to be used in real-time operation for its faster speed of calculations and for its robustness.

It is worth pointing out that in order to achieve higher accuracy and smaller measurement errors, a vision system with a higher optical resolution may be recommended. However, microgripper deflection errors do not lead to large force measurements errors; therefore, there is no need to use a system with a very high optical resolution unless high force measurement accuracy is required.

6. Conclusions

New vision-based force sensing methods for measuring microforces acting upon passive microgrippers jaws have been developed. The vision-based force measurement technique is reduced to determining the deflections of the microgripper jaws during the microassembly process. A FEA was performed to determine the relation between the assembly forces and the microgripper jaw tip deflections. Jaw deflections are measured, during the joining and grasping processes, by computing the relative displacements of the right and left microgripper jaws with respect to the fixed microgripper pad. The microforces acting upon the microgripper jaws were therefore measured accordingly. The normalized cross-correlation template matching method was used to determine the positions of templates in the image. Using templates, corresponding to features of interest such as the right jaw, the left jaw and the pad fixed to the robotic manipulator, jaw deflections were measured. In another approach, zero-crossing Laplacian of Gaussian edge detection and object recognition were used to determine the locations of the features of interest in the image, enabling the measurement of the jaw deflections. Experiments confirmed the validity and success of both approaches, showing that the measured microgripper deflections complied with their profile variations, when the microgripper is well aligned with the micropart. Small deviations in the measured deflections result, in the range of ±0.5 µm, which are results of the limited resolution of the vision system (0.9 µm). Experiments showed that misalignments between the microgripper and the micropart cause higher deviations, and therefore higher forces are generated.

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References


