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Experiments in Micromanipulation and CAD-Driven Microassembly

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ABSTRACT

This paper discusses recent experiments in the manipulation and assembly of parts with 100 micron outside dimensions and submicron tolerances. The objective of this work is to develop a micromanipulation workcell which can automatically assemble LIGA (Lithography Galvanoforming Abforming) parts using an assembly plan and a CAD drawing of each of the components. The workcell consists of an AdeptOne robot, precision stages, long distance microscope, and a high aspect ratio molded polysilicon tweezers for picking up the parts. Fourier optics methods are used to generate synthetic microscope images from CAD drawings. These synthetic images are used off-line to test image processing routines under varying magnifications and depths of field. They also provide reference image features which are used to visually servo the true part to the desired position.

Keywords: Microassembly, Micromanipulation, Microtweezers, Visual Servoing, LIGA, MEMS

1. INTRODUCTION

Micro-technology is advancing rapidly. Many electromechanical operations performed by conventional fabrication technology will soon be available using MEMS (Micro-Electromechanical Systems) technology. A key to reliable and cost effective MEMS product realization is how to assemble the devices.

The objective of this project is to develop the needed technologies for a prototype robotic workcell that can assemble MEMS parts with 10-100 micron outer dimensions and submicron tolerances. Sandia National Laboratories is currently developing processes to make surface machined silicon and LIGA parts of this size and tolerance for use in weapons surety devices. LIGA parts are of special interest because they can be made of metals which makes them stronger (in tension) than surface machined silicon, and also they can contain iron which allows them to be configured as miniature electromagnetic motors. The disadvantage of LIGA parts is that they must be assembled. The required precision, operator stress and eye strain associated with assembling such minute parts under a microscope precludes manual assembly from being a viable solution. An automated assembly system is needed.

One of the key components of this project is the automated assembly of LIGA parts from their CAD drawings. These parts are originally designed using CAD packages such as AutoCAD, ProE, or Velum. The designs are then translated to GDSII which is the format that the mask shops use to develop the X-ray masks for the LIGA process. Since X-rays are used to develop the LIGA molds, both the horizontal and vertical tolerances of the parts are quite precise (submicron horizontal tolerances, and 0.1 micron over 100 microns vertical tolerance). Therefore, we have extremely accurate CAD models of the parts which can be used for assembly planning even before the parts are produced.

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Even with an accurate CAD model, there are several issues that cause micro-assembly to be a difficult assembly planning problem. As discussed by others in the field [1][2], the relative importance of the forces in microassembly is very different from that in the macro world. Gravity is almost negligible, while surface adhesion and electrostatic forces dominate. To some extent these problems can be reduced by clean parts and grounding surfaces. But the assembly plan should take these effects into account.

To date, several different approaches to teleoperated micromanipulation have been attempted. Miyazaki [3] and Kayono [4] meticulously picked up 35 polymer particles (each 2 microns in diameter) and stacked them inside of a scanning electron microscope (SEM). Mitsuishi [5] developed a teleoperated, force-reflecting, micromachining system under a SEM. On a larger scale, Zesch [6] used a vacuum gripper to pick up 100 micron size diamond crystals and deposit them to arbitrary locations. Sulzmann [7] teleoperated a microrobot using 3D computer graphics (virtual reality) as the user interface.

More recently, researchers have gone beyond teleoperation to using visual feedback to automatically guide micro-robotic systems. Sulzmann [7] illuminated gallium phosphate patches on a micro-gripper with an ion beam, and used the illuminated features to locate and position the micro-gripper. Vikramaditya [8] investigated using visual servoing and depth-from-defocus to bring parts into focus and to a specified position in the image plane. The estimation of depth from focus has also been addressed by several other researchers [9-12].

This paper takes the next step by creating synthetic images from CAD data. These images are used to test image processing algorithms off-line and to create reference image features which are used on-line for visual servoing. The next three sections describe the workcell, a unique micro-tweezers, and teleoperated experimental results. The last two sections describe an optics model used to generate synthetic images as well as ongoing CAD-Driven assembly planning work.

2. WORKCELL DESCRIPTION

Our microassembly workcell consists of a 4 DOF (Degree of Freedom) AdeptOne robot arm, a 4 DOF precision stage, micro-tweezers, and a long distance microscope (see Figure 1). The AdeptOne has a repeatability of 25 microns and is thus used as a gross motion device. The precision stage has a repeatability of approximately 1 micron and is used for fine motion. The microscope is fixed above the stage and has an electronically adjustable zoom and focus.

During assembly operations, the AdeptOne positions the micro-tweezers above the stage and within the field of view of the microscope. The precision stage is used to move the LIGA parts between the fingers of the tweezers. The tweezers are closed on the part, the stage is lowered, and the mating part on the stage is brought into the field of view. The stage is then raised into position and the part in the tweezers is release.

3. MICRO-TWEEZERS

High aspect ratio molded polysilicon (hexsil) [13] tweezers from the Berkeley Sensor & Actuator Center were mounted on the AdeptOne tool plate. These tweezers are actuated by in-situ phosphorous doped thermal expansion beams. Piezoresistive polysilicon strain gages are integrated into the tweezers for tactile feedback. The tweezers are normally closed, and require 75 mW to open 35 microns. The piezoresistive strain gages are not yet operational, but, as described later, will greatly enhance operation in the future.

Figure 2 shows the 8 mm long by 1.5 mm wide by 45 micron thick hexsil tweezers in the open (power on) position. The thermal expansion element is electrically isolated from the rest of the device. Current travels up one leg and down the other. The beam heats up and lengthens, causing the other beams in the two 4-bar linkages to rotate and open the tweezers tips. Thermal actuation has the advantages of simple fabrication and reliability with no sliding contacts which would be vulnerable to failure due to wear or contamination. The beam was made relatively long (6mm) to minimize the operating temperature for a given displacement.

High out-of-plane stiffness is desirable to ensure the tweezers tips will contact each other when the tweezers are closed. Any z-axis mismatch between the tips would apply a torque to the object being gripped, causing it to flip out of the grip.

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The hexsil fabrication process conveniently supplies the needed out-of-plane stiffness. On the other hand, in-plane stiffness should be low for efficient actuation, and sub-micro-Newtons resolution of the gripping force being applied to a fragile object. Hexsil fabrication provides flexures for linkages with low in-plane stiffness. Surface poly tweezer tips built on the hexsil foundation give the compliance for the required force resolution at the target object. Progressively larger beams make the transition from the micro to macro stiffnesses. In use, the base of the tweezer is bonded to a 2 mm wide, 25 mm long silicon bar that mounts into a fixture on the AdeptOne tool plate. In the absence of the piezoresistors, observation by optical microscope of the tweezers tip deflection indicates the gripping force. The maximum design stress in the hexsil flexures is compressive and less than 1 MPa, while the thermal expansion beam is maintained under a tensile stress of less than 0.1 MPa.

Figure 1. Micro-Assembly Workcell.

Figure 2. Hexsil Tweezers

4. TELEOPERATED ASSEMBLY

A teleoperated interface was developed to test simple pick-and-place operations. The AdeptOne, the 4 DOF precision stage, the micro-tweezers, and the focus, magnification, and lighting of the microscope are controlled through a custom developed user interface built within the Adept A-series VME controller. The image as seen by the microscope is displayed on the computer screen. The x and y position of the robot and stage are controlled by the operator by dragging a cursor on the graphical display. Sliders are used to control the z position and theta orientation of the robot and stage as well as the microscope focus, magnification, and lighting.

This interface has been used to pick up and stack two LIGA gears and up to 5 polysilicon gears (see Figure 3). The key issues discovered while performing these operations are as follows.

1. Currently, the only way to estimate when the micro-tweezers have a good grasp of the part is by watching the deflections in the tweezers. The future incorporation of the tweezers strain gages will greatly improve the ability to detect when a good grasp has been achieved.

2. When grasping a part, it is not always possible to tell if the tweezers are at the same height as the part. We often had to touch the tweezers to the part to see if it moved.
3. When stacking parts, the part on the stage was lowered and moved in x-y directions while the part in the tweezers stayed fixed. The result is that the part in the tweezers remains in focus while the part on the stage was out of focus. Even with the bottom part out-of-focus, the human operator is able to line up important image features; however, it is still very difficult to estimate height above the bottom part.
4. Since the LIGA gears were made out of permalloy (a magnetic material), we had problems with the parts being attracted to each other.

Figure 3. Micro-tweezers picking up LIGA gear.

5. OPTICS MODELING

When viewing parts on the order of 100 microns in dimension, it is important to have a precise model of the optics, including models of the field of view and depth of field. This model is even more important if the assembly is to be performed automatically from CAD information. What is needed is a way to create a synthetic image before the part is even produced. Then we can design for assembly and determine off-line the required image processing routines for assembly. In this regard, Fourier optics methods can be used to create synthetic images from CAD drawings.

First, we provide a simple review of microscope optics [14]. Referring to Figure 4, the total linear magnification of a compound microscope is

$$x'' = m_e m_o x \quad \text{where} \quad m_e = -\frac{f_e}{z_e'} \quad \text{and} \quad m_o = -\frac{f_o}{z_o'} \quad (1)$$

where z_o' is the distance between the adjacent principal foci of the objective and the eyepiece, z_e' is the distance from the posterior principle focus of the eyepiece to the image plane of the CCD camera, f_o is the focal length of the objective, and f_e is the focal length of the eyepiece. This equation is important since it tells us that we can model the microscope as a single lens with magnification $m = m_e m_o$.

Figure 4. Microscope's Optics

Figure 5. Geometric depth of field.

The depth of field can be determined by analyzing Figure 5. The in-focus object plane is denoted as B, and the corresponding in-focus image plane is denoted as B'. When the object is moved out of focus to planes A or C, a point on A or C is projected into a disk of diameter b_g on object plane B. The resulting disk in the image plane has diameter b_g' . By using similar triangles, the geometric depth of field is given by

$$\Delta_g = \Delta_1 + \Delta_2 \approx \frac{nb_g'}{mA} \quad (2)$$

where n is the refractive index of the optics, b_g' is the defocused blur in the image, and A is the numerical aperture of the optics [14]. This expression is valid if object blur b_g on plane B is much less than the lens aperture a . Solving this equation for the defocused blur in the image,

$$b_g' = \frac{2mA|\Delta|}{n} \quad (3)$$

where $\Delta = \Delta_1 \approx \Delta_2$.

In addition to the geometric depth of field, Fraunhofer diffraction is also important as the objects being viewed approach the wavelength of light. Rayleigh's Criteria [15] says that the diameter of the Airy disk is

$$b_r' = \frac{1.22\lambda m}{A} \quad (4)$$

where λ is the wavelength of incident light. This is the diameter of the first zero crossing in an intensity image of a point source when viewed through an ideal circular lens with numerical aperture A and magnification m .

Assuming linear optics, the geometric blur diameter and the Airy disk diameter are additive. Adding Equations (3) and (4) and solving for Δ , the total depth of focus is given by:

$$\Delta_T = 2\Delta = \frac{nb'}{mA} - \frac{1.22\lambda n}{A^2} \quad (5)$$

where $b' = b_g' + b_r'$ is the acceptable blur in the image. The first term is due to geometric optics, while the second term is due to diffraction from Rayleigh's criteria. Since Equation (5) must always be positive, the acceptable geometric blur must be larger than the Airy disk. Note that even when the object is in perfect focus ($\Delta_T = 0$), there is still a small amount of blurring due to diffraction. For example, the parameters for the microscope used in the experiments are $n=1.5$, $\lambda=0.6$ microns, $A=0.42$, $m=6.9$, and $\Delta_T = 0$. The resulting image blur due to diffraction (Airy disk diameter) is 12.026 microns. If the acceptable image blur is 12.45 microns (approximately 1 pixel on a 1/3 inch format CCD), then $\Delta_T = 0.22$ microns. Therefore, two points separated by b'/m or 1.8 microns will become indistinguishable if the points are moved as little as 0.22 microns out of the focal plane. That is not much distance to work with!

The next problem is how to generate synthetic images which account for the geometric field of view and the Fraunhofer diffraction. Using Fourier optics [15], a stationary linear optical system using incoherent light is described in terms of a 2D convolution integral:

$$I_{im}(x', y') = \iint I_{obj}(x, y) S(x - x', y - y') dx dy \quad (6)$$

where $I_{im}(x', y')$ is the image intensity, $I_{obj}(x, y)$ is the object intensity, and $S(x, y)$ is the impulse response or point spread function. This convolution is more efficiently computed using Fourier Transforms:

$$\tilde{I}_{im}(u, v) = \tilde{I}_{obj}(u, v) \tilde{S}(u, v) \quad (7)$$

where the tilde represents the 2D Fourier Transform of the function.

Considering only the geometric depth of field, the impulse response is

$$S(r', \theta') = \begin{cases} 1/b_g' & r' \leq b_g'/2 \\ 0 & r' > b_g'/2 \end{cases} \quad (8)$$

where r' is the radial distance for the impulse location in the image plane. The impulse response is radial symmetric about the impulse location and independent of θ' . Therefore, a geometrically defocused image is the focused image convolved with a filled circle of diameter b_g' . This is shown on the left side of Figure 6 before "FFT of Geometric Out-of-Focus Image."

Figure 6. Block Diagram of synthetic image generation.

Considering only Fraunhofer diffraction, the impulse response is

$$S(r', \theta') = \pi^2 a^4 \left| \frac{2J_1\left(\frac{2\pi a r'}{\lambda f}\right)}{\frac{2\pi a r'}{\lambda f}} \right|^2 \quad (9)$$

where $J_1(\bullet)$ is the first order Bessel function, a is the aperture radius, λ is the wavelength of light, and f is the focal length of the lens. This function is also radial symmetric about the impulse location and independent of θ' . In addition, it is the expression used to generate the Airy disk. It would be computationally expensive to convolve this expression with the original image without the use of Fourier Transforms. Fortunately, there exists a simple expression in the Fourier domain. With incoherent light, the Fourier Transform of the impulse response is given by the autocorrelation of the aperture (pupil) function with its complex conjugate:

$$\tilde{S}(u, v) = \iint P^*(x, y) P(x + \lambda z' u, y + \lambda z' v) dx dy \quad (10)$$

For a circular aperture of radius a , the pupil function is

$$P(r, \theta) = \begin{cases} 1 & r \leq a \\ 0 & r > a \end{cases} \quad (11)$$

and the resulting transfer function is given by

$$\tilde{S}(r_{uv}) = 2a \left[a \sin^{-1} \left(\sqrt{1 - \left(\frac{r_{uv}}{2a} \right)^2} \right) - \frac{r_{uv}}{2} \sqrt{1 - \left(\frac{r_{uv}}{2a} \right)^2} \right] \quad (12)$$

where r_{uv} is the radius in image frequency. Therefore, the complete transfer function is the product of the Fourier Transform of the geometric blur and the transfer function in Equation (12). Both act as low pass filters on the image. Figure 7 shows the geometric image of a 100 micron gear, while Figure 8 shows the geometrically out-of-focus and defracted image.

Figure 7. Geometric Image with $m=20$ and 12.45 microns/pixels.

Figure 8. Image 25 microns out of depth of field.

In the next section, we show how this synthetic image can be used to test image processing routines and to generate reference image features for control.

6. OFF-LINE ASSEMBLY PLANNING

Since we are currently limited to visual sensing, much of our work has concentrated on developing a optics simulator and off-line image processing extractor which will be used to generate an augmented assembly plan. In Figure 9, the bold boxes represent computer programs which process the data files in the remaining boxes. The off-line system reads in the task plan from one file and the boundary representation of the CAD part from the ".dxf" file. A synthetic image is generated using the Fourier Optics from which a variety of image processing routines are tested and image features are automatically selected for control.

Figure 9. Block Diagram of CAD to Assembly Process.

To date, we have successfully tested using the synthetic image to visually servo a LIGA gear to a desired x,y position. Figures 10-12 show a sequence of images as the gear on the stage is visually servoed to the reference image position. Figure 10 shows the synthetic image which was generated from the CAD information. The part was recognized and located by finding the center of the part and then searching for 18 gear teeth on the outer diameter and a notch on the inner diameter. Its location in the image serves as the reference position. Figure 11 shows a real part as seen by the microscope and the application of the same image processing routines to locate the gear. Next, the part is visually servoed to the reference position at 30 Hz using the x,y centroid of the gear. Figure 12 shows the final position of the gear after visual servoing. Currently, the repeatability of the visual servoing is 1 micron in the x and y directions.

7. CONCLUSION

This paper described a prototype micromanipulation workcell for assembly of LIGA parts. A unique high aspect ratio molded polysilicon (hexsil) tweezers was used to pick up and stack the LIGA parts via a teleoperated interface. We have also demonstrated the ability to visually servo the LIGA parts to a desired x,y position between the tweezers. Fourier optics methods were used to generate a synthetic image from a CAD model. This synthetic image was used to select image processing routines and generate reference features for visual servoing. In the near future, we plan to generate a sequence of synthetic images which represent assembly steps, e.g. tweezer grasps gear, locate shaft, and put gear on shaft. Again, these images will be used to select image processing routines and generate reference features for visual servoing. Also, adding strain gage feedback from the tweezers will help with in-contact motion during the assembly.

Figure 10. Synthetic reference image.

Figure 11. Initial location of real gear.

Figure 12. Final position after visual servoing.

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