Micro Manipulation by a Compliant Piezoelectric Micro Gripper towards Robotic Micro Assembly

R. K. Jain¹, S. Majumder², Bhaskar Ghosh³ and Surajit Saha⁴

¹CSIR-CMERI, Durgapur-713209, Email:rkjain@cmeri.res.in
²CSIR-CMERI, Durgapur-713209, Email:sm@cmeri.res.in
³CSIR-CMERI, Durgapur-713209, Email:bhaskarghsh4@gmail.com
⁴CSIR-CMERI, Durgapur-713209, Email:surajitsaharaiganj@gmail.com
*Corresponding Author

Abstract
This paper presents a new design of mobile micro manipulation system for robotic micro assembly where a compliant piezoelectric actuator based micro gripper is designed for handling the miniature parts. The compensation of misalignment during robotic peg-in-hole assembly is achieved by this compliant micro gripper because the piezoelectric actuator has capability of producing the displacement in micron range and generates high force instantaneously. The throughput/speed analysis of mobile micro manipulation system is carried out for picking and placing the peg from one hole to next hole position. An analysis of piezoelectric actuator based micro gripper has also been discussed where voltage is controlled through a proportional-derivative (PD) controller. By developing a prototype, it is demonstrated that compliant piezoelectric actuator based micro gripper is capable of handling the peg-in-hole assembly task in a mobile micro manipulation system.

Keywords: Piezoelectric actuator, micro gripper, robotic micro assembly and handling etc.

1. Introduction

The rapid growth of high technologies such as micromanipulation, nanotechnology, scanning tunneling and atomic force microscopy, micro electromechanical system (MEMS) and robotics have been demanding the reliable, fast and precise actuators and sensors based systems (Bergander et al., 2003; Götz and Pagel, 2007). Use of such actuators and sensors in the development of micro assembly system provides the versatility, flexibility and robustness to achieve small and medium sized batches assembled in an economical way. In this aspect, several researchers have developed the mechanical grippers for robotic assembly using different miniature actuators like linear, pneumatic etc (Causey, 2003; Moffino et al., 2006). The major disadvantage of these grippers is that they don’t have flexible capability for compensating the misalignment of peg during robotic micro assembly. Therefore, handling and manipulation tasks need some compliant devices which can itself accommodate the misalignment of peg during robotic micro assembly. To cater this need, different types of passive compliant micro gripper have been studied by Dechev et al. (2004) and Havlik (2011) respectively. These micro grippers perform the operation along the gravity vector and they cannot be used for actively controlling errors in other directions.

For achieving the robotic micro assembly task, some active compliant based smart actuators such as Ionic Polymer Metal Composite (IPMC), Shape Memory Alloy (SMA), piezoelectric etc. are used by Deole et al. (2008) and Jain et al. (2009, 2011, 2013) respectively. The IPMC based micro grippers have compliant behavior to grasp and manipulate micro-sized flexible/rigid objects. It is actuated with small voltages and produces large displacement whereas the major disadvantage of IPMC is that the response time during micro gripping operation is not sufficient for holding the object in the long time range. Therefore, another approach is that we can use the piezoelectric actuator for developing the micro gripper. The major advantages of this actuator are that it has high micro/nano scale displacement, large force generation and no wear & tear as compared to other smart actuators. Only limitation of piezoelectric actuator is that it shows non-linear deflection characteristic (hysteresis) with voltage signal. For improving these characteristics, several researchers have also attempted on controlling of the voltage signal using different control methods along with different hysteresis models by Kim et al. (2004), Rakotondrabee and Ivan (2011), Tamadazte et al. (2012), Wang et al. (2013). The main difficulties for implementing the actuation/force response of piezo bimorph through voltage in real-time are to control the position and
sensing the force in micron range to avoid the destruction of object. In order to improve the quality of actuation through vision system and handling of the miniature parts, a new design of mobile micro manipulation system is proposed in this paper where compliant piezoelectric based micro gripper handles the object without the destruction of object. The major advantage of this mobile micro manipulation system is that the mobile micro manipulation system can handle the compliant/rigid objects by a compliant piezoelectric actuator based micro gripper and performs robotic micro assembly.

This paper is organized as follows: a new design of mobile manipulation system for robotic micro assembly is discussed in Section 2. In section 3.1, throughput analysis of the mobile micro manipulation system is carried out. Section 3.2 covers the analysis of piezoelectric actuator based compliant micro gripper. Experimental testing setup is described in Section 4. The results of robotic micro assembly are discussed in Section 5. The conclusion is drawn in Section 6.

2. Design of mobile micromanipulation system for robotic micro assembly

In order to develop a mobile micro manipulation system for robotic micro assembly, the new design of mobile micro manipulation system is shown in Figure 1. This design consists of a mobile mechanism, one revolute joint based shaft mechanism, one linear joint based lead screw mechanism along with a piezoelectric actuators based micro gripper. The mobile mechanism is designed using two servomotors. These servo motors are housed with two soft rubber material based wheels for forward-backward motion in particular direction. The revolute joint based shaft mechanism is designed using a servomotor and bearing arrangement. A linear joint based lead screw mechanism is constructed using stepper motor and lead screw arrangement. All these three mechanisms provide three motions such as linear, rotation and step movements during handling the object. Two fingers based micro gripper is designed using two piezoelectric bimorph actuators where piezoelectric actuators are actuated at 0-60 V. This gripper is integrated at end of lead screw mechanism in a mobile micro manipulation system which provides gripping and holding operations during pick and place of the object. For visualization of robotic assembly, the camera is integrated at the top of work bench. For performing robotic micro assembly operations, a grid pattern of 49 holes (7x7) is designed where the size of grid pattern is 40 mm (length) x 40 mm (width) x 20 mm (height). The distance between one to next hole in a single row and column of grid pattern is kept 5 mm and diameter of each hole is 1.5 mm and depth is 10 mm.

3. Analysis of mobile micro manipulation system

3.1 Throughput/speed analysis of mobile micro manipulation for robotic micro assembly

For finding the throughput/speed during robotic assembly, the basic model of micro manipulator is developed in ADAMS software as shown in Figure 2. During development of model, a mobile mechanism is constructed by aluminum material where the wheels are linked with mobile mechanism through two revolute joints. For driving the mobile mechanism, two motors are individually mounted on each joints for providing the forward and backward motion. A revolute joint mechanism is mounted on the mobile mechanism which is also made by aluminum material. A revolute joint is made in revolute joint mechanism and a motor is also attached with the joint for rotating the shaft mechanism. A sliding mechanism is built using a slider which is made by perspex sheet. A linear joint is constructed between slider mechanism and revolute joint mechanism. A linear stepper motor is also mounted on the same joint for providing the motion in one direction. A two piezoelectric actuators based micro gripper is mounted on the top of the slider arm at one end so that it can perform the pick & place operation of robotic micro assembly.

In order to execute the robotic assembly, the mobile mechanism is restricted upto 40 mm with step of 5 mm as input parameter because the distance between two holes is 5 mm and depth is limited upto 10 mm. The second constraint is also given to linear slider which is limited upto 40 mm with the step of 5 mm. According to forward kinematics, the mobile micro manipulation system is analyzed. The shaft mechanism moves downward upto 10° for picking the object. The total cycle time is kept upto 10 seconds. During simulation, the behavior of revolute joint based shaft mechanism for micro manipulation system at three different rotation angles, 8°, 10° and 12° are analyzed as shown in Figure 3. At rotation angle of 8°, the piezoelectric actuator based micro gripper could not attain the desired position and robotic peg-in-hole
assembly may not be feasible whereas at rotation angle of 10°, the micro gripper can reach the desired position so that the micro parts/micro pins can be handled by this micro gripper smoothly. At last rotation angle of 12°, the gripper could reach the desired position but there is a chance to hit the grid pattern which may cause the breakage of the piezoelectric strips of the gripper. Therefore, the suitable rotation angle of shaft mechanism is 10° where the constant angular speed of shaft mechanism is set with the value of 0.261 rad/s. The total weight of micro manipulation system including peg is 245 g.

3.2 Analysis of piezoelectric based micro gripper

In order to attempt the dexterous handling during robotic peg-in-hole assembly, a compliant micro gripper is constructed using bimorph piezoelectric actuators as shown in Figure 4. For characterizing this actuator, we have configured it as a cantilever beam which is actuated through controlled voltage as shown in Figure 5. The flexible beam is characterized by its free length. Basically, this actuator consists of two outer active areas of PZT material and one central resistive layer for dividing the actuator into two segments of equal capacitance. When voltages are applied to the ceramic layers, a bending moment is induced in the beam. According to theory of beam for flexible cantilevered beam (Howell, 2001), the end curvature of cantilever beam \( \kappa_m \) is defined in term of radius of curvature \( R_m \) as

\[
\kappa_m = \frac{1}{R_m} = \frac{2}{\delta_m} = \frac{2\delta_m}{L_m^2} \quad (1)
\]

The end curvature of piezoelectric finger can be measured for applied voltage \( V_m \) experimentally. Therefore, the relationship between end curvature and voltage is written as

\[
\kappa_m = \frac{1}{R_m} = \frac{2K_m \delta_m}{(\delta_m + L_m^2)} = K_m \times V_m \quad (2)
\]

Where, \( K_m \) is the function of deflection which can be found experimentally. It shows the exponential behavior. Subsequently, bending moment \( (M_m) \) and voltage relationship is obtained by applying theory of cantilever beam as

\[
M_m / I_m = E_m \times (1/R_m) \quad (3)
\]

Where, \( E_m \) is Young’ Modulus of piezoelectric actuator and \( I_m \) is moment of inertia for flexible beam. After substituting the values of moment of inertia and end curvature, we can express the bending moment in term of voltage as

\[
M_m = \frac{1}{2} \times E_m \times b_m \times w_m ^3 \times V_m \quad (4)
\]

The reaction force \( F_m \) can be found by assuming uniform length of cantilevered configuration as

\[
F_m = M_m / L_m = K_m \times b_m \times w_m^3 \times V_m / 12 \times L_m \quad (5)
\]
Table 1 Numerical data for micro gripper

<table>
<thead>
<tr>
<th>Parameter for gripper</th>
<th>Notation</th>
<th>Numerical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of piezo actuator</td>
<td>$L_m$</td>
<td>45 mm</td>
</tr>
<tr>
<td>Width of piezo actuator</td>
<td>$b_m$</td>
<td>11 mm</td>
</tr>
<tr>
<td>Thickness of piezo actuator</td>
<td>$w_m$</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Voltage</td>
<td>$V_m$</td>
<td>0-60 V</td>
</tr>
<tr>
<td>Young’s Modulus of piezo</td>
<td>$E_m$</td>
<td>$4.5 \times 10^{10}$ Pa</td>
</tr>
<tr>
<td>Moment of inertia of beam</td>
<td>$I_m$</td>
<td>$1.98 \times 10^{-10}$ m$^4$</td>
</tr>
<tr>
<td>Mass of piezo actuator</td>
<td>$m_i$</td>
<td>0.0021 Kg</td>
</tr>
<tr>
<td>Lateral stiffness coefficient</td>
<td>$K_{xi}$</td>
<td>2120 N/m</td>
</tr>
<tr>
<td>Damping coefficient</td>
<td>$b_i$</td>
<td>150 N/ms$^{-1}$</td>
</tr>
<tr>
<td>Proportional gain</td>
<td>$K_p$</td>
<td>10000</td>
</tr>
<tr>
<td>Derivative gain</td>
<td>$K_d$</td>
<td>0.001</td>
</tr>
</tbody>
</table>

For controlling the voltage of piezoelectric actuator system, a proportional-derivative (PD) control law is applied. According to this law (Craig, 2005), the force through voltage signal by adjusting the PD gains in the controller is controlled which is written in term of proportional gain ($k_p$) and derivative gain ($k_d$) as

$$F_m = -k_p \delta_m - k_d \delta_n \quad (6)$$

In order to find the value of $k_p$ and $k_d$, a piezo actuator is considered as spring mass damper system with mass ($m_i$), lateral stiffness coefficient ($K_{xi}$) and damping coefficient ($b_i$) as shown in Figure 6. The equation of a spring-mass damping system can be written as

$$m_i \ddot{\delta}_i + b_i \dot{\delta}_i + K_{xi} \delta_i = F_i \quad (7)$$

By equating (6) and (7), we can get

$$m_i \ddot{\delta}_i + b_i \dot{\delta}_i + K_{xi} \delta_i = -k_p \delta_i - k_d \delta_i$$

$$m_i \ddot{\delta}_i + (b_i + k_d) \dot{\delta}_i + (K_{xi} + k_p) \delta_i = 0$$

$$m_i \ddot{\delta}_i + b_i \dot{\delta}_i + k_p \delta_i = 0 \quad (8)$$

The deflection is controlled through voltage by adjusting the value of $k_p$ and $k_d$. For finding these values, bimorph piezoelectric actuator based finger is considered as spring-mass-damper system and a PD control law is applied. A hit and trial method is used which satisfies the critical condition of mass damping system. Using these data in MATLAB-2008 software, the gripping characteristic of piezo actuator fingers are obtained as shown in Figure 7.

4. Experimental testing setup

A mobile micro manipulator with piezo actuator based micro gripper is developed where micro manipulator moves in X, Y and Z-coordinate system. The functional requirements of a 3-DOF micro manipulator are performed by one mobile mechanism, one revolute joint mechanism and one lead screw sliding mechanism. During development of mobile mechanism, the two wheels are mounted in the side of the chassis. These wheels are driven by two digital servo motors (Model: Hitech, HS-85MG) and allows the forward and backward motion simultaneously. These servo motors are operated at 4.8 V through servo controller kit (Make: Parallax, USA). For controlling the lead screw and stepper motor, stepper controller kit is used to control the linear motion with micro steps. The servo and stepper controllers are assembled together with high speed real-time Basic Stamp micro controller (Model: BS2e, Make: Parallax, USA). The basic schematic layout for controlling the process is shown in Figure 8. The operating voltage requirement is ranging from 4-16 VDC. For controlling the piezo actuator based micro gripper, the customize control (high voltage amplifier and micro controller) is developed where the voltage can be adjusted through frequency. This is also integrated with high speed micro controller.
For controlling of all kits, an input data through Basic Stamp software (V1.3 Version) is sent to micro controller accordingly where a PD control algorithm is implemented for correcting the error. For providing the feedback to the system, a camera (Model: CVAJM-309AS-PAL, Make: JMK) based vision system is used. The camera head is mounted on the top of micro gripper because real-time data can be collected during pick & place and peg-in-hole assembly. A marker is placed on top of peg for tacking the position of peg during assembly in real-time.

5. Results and discussions

In order to perform the experiments with the piezo actuator, it is separately clamped in a cantilever configuration with a holder. A laser displacement sensor is placed at 42 mm from piezo actuator clamp position so that displacement can be easily measured when we supply the voltage to a piezo actuator. By applying a voltage (0-60V) through micro controller and high voltage amplifier, it shows maximum deflection up to 1.5 mm as shown in Figure 9. The reverse effects are also achieved by changing the voltage polarity to the piezo actuator. When we reduce the voltage from high to low the piezo bimorph bender does not follow the same path to return to its original position. It is observed that piezo actuator has a deflection error (hysteresis) of 0.2 mm. For improving the quality of actuation, the voltage is amplified through a customized controller where the frequency is adjusted in the voltage amplifier for achieving the desired characteristics. The improved characteristic in term of deflection of piezo actuator by applying a PD control system is also shown (Figure 9). It shows the deflection error is now reduced from 0.2 mm to 0.02 mm. Subsequently, this voltage can be sent to micro gripper for handling the miniature parts.

After that, a prototype of micro manipulator with piezoelectric actuator based micro gripper is developed as shown in Figure 10. The piezo actuator based finger is activated through electrical actuation instead of conventional motor. Each finger attempts dexterous handling of micro parts. During handling the object by piezo actuator based fingers in peg-in-hole assembly, the $F_{i1}$ and $F_{i2}$ are reaction forces applied with static frictional coefficient ($\mu$) by the piezo based fingers through voltage in a micro gripper. During holding the peg -(size: diameter 1 mm and 30 mm length, material steel), frictional force components of these reactions are dominated along with the weight of peg (W) as shown in Figure 11. The peg touches the hole at the chamfer position. The
The sum of frictional force components along with weight of the peg must be equal or greater than vertical reaction force \((N)\) component balances at chamfer angle \((\theta)\) through force balance equation which is given below:

\[
\mu F_1 + \mu F_2 + W \geq N \cos \theta \quad (9)
\]

Where, \(\mu = 0.3\) (for steel); \(\theta = 45^\circ\); \(W = 0.6\) mN.

In order to attempt the robotic micro assembly operations such as pick & place and peg-in-hole assembly in single row-hole positions, the cycle time is represented in Figure 12. It shows that experimental data for total cycle time during pick & place operation is almost same as compared to other conventional methods. For comparing the rigid peg (steel) assembly with compliant peg (plastic) assembly, the experiments are conducted with similar size of plastic peg and experimental data are also plotted (Figure 13). It shows that the performance of compliant peg is much better than that of the rigid peg during micro assembly.

In order to perform the peg-in-hole assembly with different hole sizes in rigid and compliant peg assembly, experiments are conducted with different hole grid pattern such as hole diameters 1 mm, 1.5 mm and 2.0 mm respectively. It is found that perfect peg-in-hole assembly is possible in Case-II (Table 2).

### Table 2 Analysis of robotic micro assembly

<table>
<thead>
<tr>
<th>S. No</th>
<th>Cases</th>
<th>Rigid peg assembly</th>
<th>Compliant peg assembly</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Hole dia 1 mm</td>
<td>Assembly possible but peg jammed in hole</td>
<td>Assembly possible without jamming peg</td>
<td>Assembly failed</td>
</tr>
<tr>
<td>II</td>
<td>Hole dia 1.5 mm</td>
<td>Assembly possible with misalignment compensated</td>
<td>Assembly possible with misalignment compensated</td>
<td>Successful assembly</td>
</tr>
<tr>
<td>III</td>
<td>Hole dia 2.0 mm</td>
<td>Assembly possible and misalignment compensated</td>
<td>Assembly possible and misalignment compensated</td>
<td>Successful assembly</td>
</tr>
</tbody>
</table>

By a piezoelectric actuator based micro gripper, the misalignment is compensated through controlled voltage during peg-in-hole assembly. After these experimental performances, it is clearly indicative that piezoelectric actuators can be used in order to develop the micro gripper for micro manipulation system because it has easy control system. Using this micro gripper, dexterous handling is possible for both the rigid or compliant peg for assembly and allows precise positioning. This kind of micro gripper can easily perform the pick & place and peg-in-hole assembly with 10 mg load carrying capability. The major advantage is that piezo actuator can automatically adjust misalignment during operation. This device has exhibited acceptable handiness and potential of handling numerous millimeter-scale components through a controlled voltage. The device can also perform complex micro fabrication and assembly which allows precise positioning and compensation ability for the misalignment during peg-in-hole assembly as compared to other conventional methods.

### 6. Conclusion

In this paper, a novel design of mobile micro manipulation system where design of piezo actuator based compliant micro gripper is discussed. In robotic micro assembly, compliant piezo actuator based micro gripper helps for accommodating the misalignment of peg during peg-in-hole assembly. During development of piezo actuator based micro gripper, bimorph piezo actuator is used as an active actuator. It
is verified that use of bimorph piezoelectric strips help in manipulation task for holding and lifting the rigid/flexible miniature components without utilizing any conventional motor. It is also demonstrated that the novel design of three DOF based mobile micro manipulation is capable of handling the peg during robotic micro assembly. These potentials save energy, space and resources in an industry during robotic micro assembly.

Acknowledgement

The authors are grateful to the Director, CSIR-CMERI, for publishing the paper which is the part of entitled project “Development of piezo actuator based micro manipulation system” under SINP on “Intelligent Devices and Smart Actuator” (Proj. No. ESC-203/10), financially supported by CSIR, India.

Reference


