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A 2-D PVDF Force Sensing System for Micro-manipulation and Micro-assembly

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Abstract – **Despite the enormous research efforts in creating new applications with MEMS, the research efforts at the backend such as packaging and assembly are relatively limited. One reason for this is the level of difficulty involved. One fundamental challenge lies in the fact that at micro-scale, micro mechanical structures are fragile and easy to break – they typically will break at the micro-Newton (μN or 10^{-6}N) force range, which is a range that cannot be felt by human operators. In this paper, we will present our ongoing development of a polyvinylidence fluoride (PVDF) multi-direction micro-force sensing system that can be potentially used for force-reflective manipulation of micro-mechanical devices or micro-organisms over remote distances. Thus far, we have successfully demonstrated 1D and 2D sensing systems that are able to sense force information when a micro-manipulation probe-tip is used to lift a micro mass supported by 2μmx30μmx200μm polysilicon beams. Hence, we have shown that force detection in the 50μN range is possible with PVDF sensors integrated with commercial micro-manipulation probe-tips. We believe this project will eventually make a great impact to the globalization of MEMS foundries because it will allow global users to micro-assemble and micro-manipulate surface micromachined devices from their laboratories, and therefore, reduce the time from design to production significantly.**

I. INTRODUCTION

MEMS devices have been steadily finding their usefulness in our daily lives in the past decade. However, a major obstacle for the advancement of MEMS technology in the commercial sector is the availability of a technique for automated batch packaging and assembly. The development of such a technology will directly impact the throughput and long-term reliability of many MEMS devices. One reason for this is the level of difficulty involved. An intrinsic difficulty lies in the fact that at micro-scale, micro mechanical structures are fragile and easy to break – they typically will break at the micro-Newton (μN or 10^{-6}N) range force, which is a range that cannot be felt by a human operator hoping to assemble micro structures. This obstacle is especially problematic for devices requiring multi-degrees micro-assembly such as the 2-D micro-mirrors used to switch optical signals in all-optical networks.

And while material properties data can be used to predict fracture strength, there is no existing micro-manipulation system that can provide in-situ μN force data during assemblage of commercial MEMS devices. The consequence of this is that devices are often damaged during assembly, decreasing overall yield and driving up cost. It has been estimated that assembly cost of micro devices can run as high as 80% of the total production cost [1]. For instance, the well-known surface micromachining commercial foundry technology MUMPs™ (Multi-user MEMS Processes) run by Cronos Integrated Microsystems has a 3-polysilicon and 2-sacrificial-layer process that can now be used to produce many micro-mechanical devices with scientific and commercial applications, including micro mirrors, micro optical bench, micro RF switches, and micro sensors [2]. However, after MUMPs fabrication, many surface micromachined devices need to be micro-assembled or micro-manipulated to realize a final device or be experimentally tested. Case in point, a micro-reflecting mirror needs to be rotated 90° from its plane of fabrication through a fragile micro-hinge. Or in the case of a micro piezoresistive cantilever sensor, as shown in Figure 1, manipulation is required to lift it from the horizontal plane for mechanical tests and calibration (the sensor is a micro-mass platform suspended by 2 cantilevers 2μmx30μmx200μm in dimension). The micro cantilevers have fracture strength in the order of μN, so an operator hoping to lift the platform for calibration will often break the cantilevers unintentionally due to excessively applied force through the commercial micromanipulator probe-tips.

Micro-manipulation and control are rigorously being investigated worldwide currently. To the best of our knowledge, however, most groups are focusing on micro/nano forces at the atomic level (e.g., [3]) or creating manipulation actuators for micro object positioning (e.g., see [4] and [5]). Some of the reported tele-operable micromanipulators may eventually have the capability to perform feedback control using piezoresistive, piezomagnetic, piezoelectric, capacitive, or laser techniques [6][7]. Nonetheless, these approaches are limited by both their actuation and sensing dynamic range. Our on-going project aims to integrating PVDF sensors on commercial probe-tips used for contact micro-manipulation and assembling, which will allow a large sensing and actuation range. The sensors' force data can be calibrated to assist a human operator in exercising manipulation forces below the fracture limit of micro mechanical structures under manipulation. The resulting

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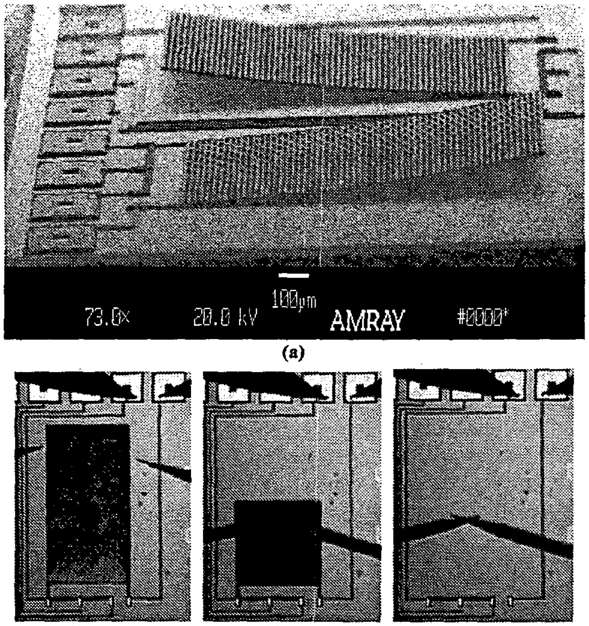
technology will allow close monitoring of the magnitudes and directions of micro-Newton scale forces in multi-dimensions. The data can also be used to establish a micro-manipulation model via an on-line learning scheme. As a result, contact/impact forces can be regulated to maintain safety margins and improve yield and reliability during micro-assembly – factors that will eventually make automated batch micro-assembly feasible. Force feedback is important in microenvironment control architectures, since visual feedback of microenvironments might be of low quality or might offer limited information -- force feedback becomes essential for the efficiency and safety of operation at these small scales.

We have demonstrated both 1D and 2D sensing systems recently that are capable of detecting impact force when a manipulation probe hits a silicon substrate or when it lifts up a microstructure. Our current results are presented in the following sections.



(a)

(b) (c) (d)

Figure 1. MUMPs microstructures are typically tested by using commercial probes without any force sensors for lifting and moving. (a) SEM picture of a surface micromachined mass-plate suspended by two polysilicon beams. (b) to (d) is a sequence of pictures showing the lifted micro device may be damaged suddenly due to excessive force applied by a human operator. In (d) the mass-platform disappeared from microscope view due to breakage of the beams, which "sprung" the structure to a different physical location.

II. PIEZOELECTRIC PVDF SENSORS

Piezoelectric materials create electrical charge when mechanically stressed. Lead Zirconate Titanate (PZT) is probably the most well known piezoelectric material and has been investigated widely as an actuator and sensor, even at micro scales [6]. However, PZT is a ceramic material and is very brittle. PVDF, on the other hand, is a polymeric piezoelectric material and is very flexible. In addition, it is easy to handle and shape, exhibits good stability over time, and does not depolarize when subjected to very high alternating fields. Yet, the trade-off is that PVDF cannot be used optimally as an actuation material as in the case of PZT.

In this project, we have investigated the possibility of using PVDF as force sensors because the charge generated by PVDF is almost linearly proportional to the force on its surfaces -- the current generated by the PVDF can be related to an applied force. Moreover, PVDF is an ideal piezoelectric rate-of-force sensor because of its low-Q response, ease of use, and compliance -- properties that are lacking in most non-polymeric piezoelectrics.

The voltage output *V(s)* of a PVDF sensor due to an applied force *F(s)* in Laplace domain can be written as [8]:

$$\frac{V(s)}{F(s)} = \frac{d_{33}}{A\varepsilon_{33}^{T}/h}\,\frac{\tau s}{1+\tau s} \qquad (1)$$

where A is the area of the crystal plate, h the thickness of the plate, ε_{33}^{T} is the mechanical strain in the 3 direction due to tensile stress T in the 3 direction (which represents the thickness direction), τ is the time constant of the PVDF sensor and is calculated as $\rho hC_p/A$, where $\rho h/A$ is R_p, the resistance of the PVDF sensor and ρ is the resistivity of PVDF, and C_p is the capacitance of the PVDF. The above transfer function is a high-pass filter type, so an undesired characteristic of the PVDF sensor is that its lower limit of frequency response is $> 1/\tau$, indicating that measurement of constant force is not possible (no DC response). However, with proper electrical circuit design, a few mHz input can still be detected [8]. Our current effort in optimizing a sensor design for maximum sensitivity at low frequency force input is based on Eq. 1 above. As rate-of-force sensors, PVDF have already proven to be effective in controlling force damping in *macro* robotic manipulators [9]; we are currently investigating its applications in the micro-world.

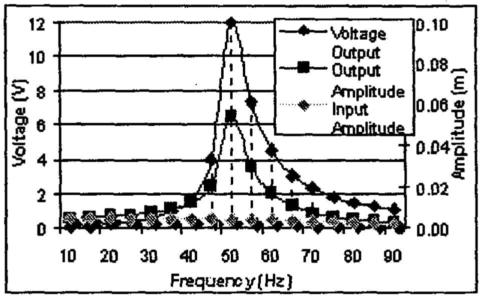


Figure 2. Responsivity of a PVDF strip from Measurement Specialties, Inc. (MSI) Company.

A commercial PVDF strips from Measurement Specialties, Inc. (MSI, Shenzen, China) was used in our sensing system. The responsivity of the strips were tested and the results are given in Figure 2. These strips have a resonant frequency of ~55Hz, and as indicated by Figure 2, the output voltage is higher for PVDF sensors at higher input frequencies, even if the input force amplitude remains constant.

III. 1-D SENSING SYSTEM

In [10] we have demonstrated an 1-D system (see Fig. 3 and Fig. 4) capable of sensing μN force, i.e., force signals from manipulating a micro structure could be detected. In that work, the micro-manipulator was manually controlled for positioning the probe-tips during micro-manipulation. We have since then integrated the manipulator with a computer controllable controller and have investigated in more detail the performance of the 1-D system. The results are presented in this section.

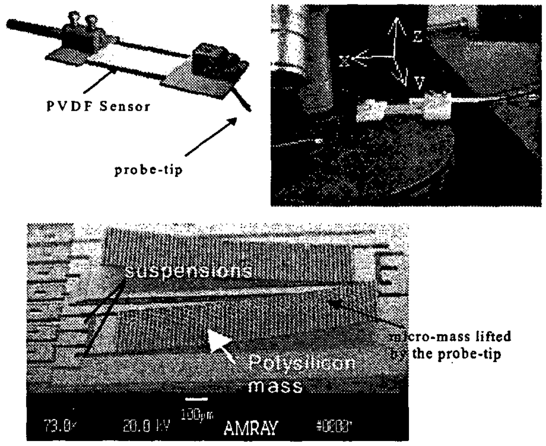


Figure 3. 1-D PVDF force sensor probe. This orientation of the PVDF plate allows sensing of force in the z-direction.

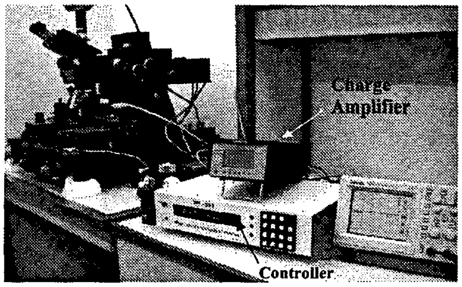
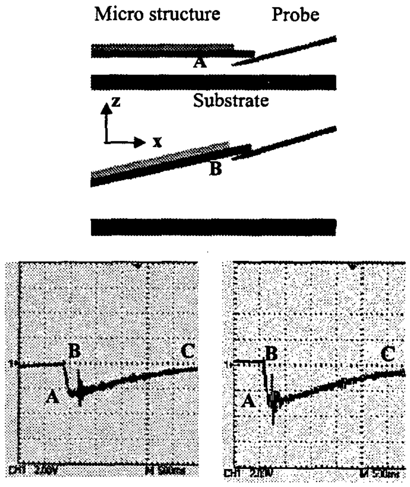


Figure 4. The computer controllable micro-manipulation station.

Some basic experiments were performed to calibrate the sensor signal in lifting a micro structure. After the probe-tip is positioned under a micro mass suspended by 2 cantilevers (as shown in the illusions of Figure 5), the probe-tip was commanded to move upward to lift the micro structure to a certain displacement (in positive z-direction), then the probe was made to stop at that position. As shown in the signal output of Figure 5, a signal can be immediately detected (A) from lifting up the structure, then the probe-tip undergoes a vibration (B) which indicates either the micro structure is broken, or the structure is giving a reactive force to the probe-tip, or the system is vibrating due to sudden stop. After the vibration of the sensor due to the reaction of the structure, we have observed that the signal returned to original value (C) after a certain time (2sec), this phenomenon is due to the piezoelectric nature of the PVDF sensor – the change cannot be stored in the sensor under static deflection. We have observed experimentally, as predicted by Eq. 1, the amplitude of the measured signal depends on the speed of movement of the probe-tip, which is coupled to the PVDF sensing elements. From varying the velocity of manipulation, the plot of peak voltage from impact is generated (see Figure 6), which indicate that the sensor output voltage increases with manipulation velocity.



(a) (b)

Figure 5. Signal from lifting plate at (a) V = 2000μm/sec, (b) V=3000μm/sec.

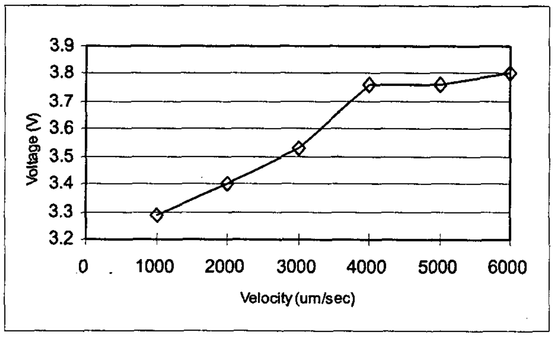


Figure 6. Peak amplitude of output voltage versus impact velocity from lifting up a micro structure.

The force of the probe-tip impacting the substrate holding the micro structure can also be detected by the PVDF sensing system. In this experiment, a controller was used to move the probe-tip to approach the substrate (in negative z-direction) at different velocities. Once the probe-tip touched the substrate, an impact signal can be detected (Figure 7). The peak amplitude of the output voltage from impact with different impact velocities on the substrate was also investigated (see Figure 8). Again, the peak voltage from impact increases with increasing impact velocity.

Based on the consistent results of the 1-D system, we have extended our system into a 2-D sensing system by redesigning the 1-D system. The design and experimental results of the 2-D system are given in the next section.

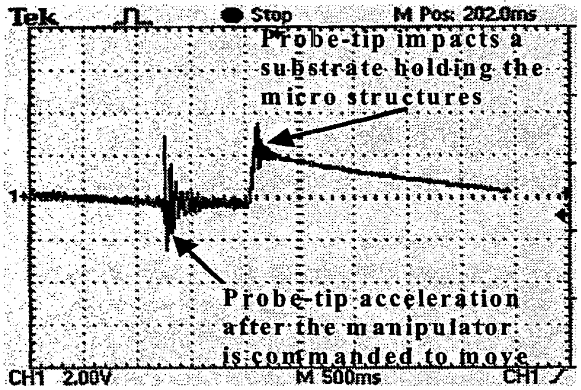


Figure 7. Typical output of the sensor signal during manipulation movement and impact.

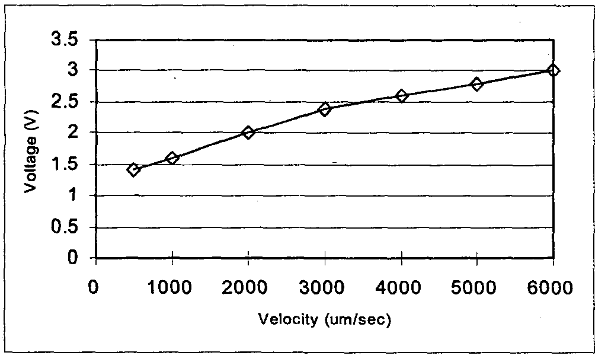


Figure 8. Peak amplitude of output voltage versus impact velocity on the substrate.

IV. 2-D SENSING SYSTEM

A. Design of the 2-D Sensing System

A conceptual illustration of the 2-D system is given in Figure 9 below.

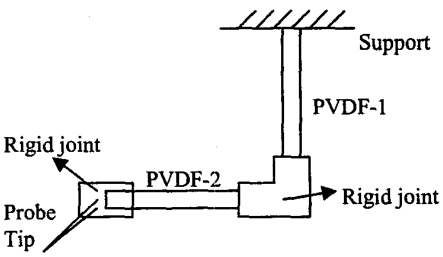


Figure 9. Conceptual illustration of the 2-D Sensing System.

Based on this design, the dimensions of the PVDF elements can be engineered to sense micro-Newton forces in two directions theoretically. This sensing system can be used to sense and decouple forces from two directions and also used to detect a total reactive force from a micro structure during manipulation and assembling as give by the analyses below.

In Figure 10, the geometric parameters of the sensing system are given. To solve the force components which are acting on the ends of the two PVDF sensors (Point A and B), F_A and F_B must be decoupled from the total force F applied on the end of the probe-tip (Point C). We have assumed that the lengths of PVDF-1, PVDF-2 and the probe-tip are known, which are denoted as l_{OA}, l_{AB} and l_{BC}, respectively. Also, the angle θ the probe-tip makes with the substrate plane can be set during the fabrication of the sensing system. Furthermore, the PVDF was assumed to be rigid and the force applied to the PVDF elements only act on the probe-tip (in reality, the PVDF elements may bend due to the weight of the rigid joint).

The force component F_1 is the component of F which is perpendicular to the line OC, and can be written as:

$$F_1 = F\cos\alpha \tag{2}$$

where α is the angle between F_1 and F.

The distances L_1 and L_2 can be written as:

$$\begin{aligned} L_1 &= l_{OA} + l_{BC}\sin\theta \\ L_2 &= l_{AB} + l_{BC}\cos\theta \end{aligned} \tag{3}$$

where θ is the angle between the probe-tip and x direction.

Therefore, the length from Point O to Point C is:

$$\mathrm{OC} = \sqrt{(l_{OA} + l_{BC}\sin\theta)^2 + (l_{AB} + l_{BC}\cos\theta)^2} \tag{4}$$

The moment applied at the Point O from F_1 can be written as:

$$M_O = F_1 \cdot OC \tag{5}$$

The moment applied at the Point O from F_B can be written as:

$$M_B = F_{By} \cdot OB = F_B \cos\theta_B \cdot OB \tag{6}$$

where θ_B is the angle between the force F_B and line OB, that can be found :

$$\theta_B = \tan^{-1}\left(\frac{l_{OA}}{l_{AB}}\right) \tag{7}$$

F_{By} is the component of F_B that is perpendicular to the line OB, where OB can be written as:

$$\mathrm{OB} = \sqrt{l_{AB}^{\,2} + l_{OA}^{\,2}} \tag{8}$$

On the other hand, the moment applied at the point O from the force F_A can be written as:

$$M_A = F_A \cdot l_{OA} \tag{9}$$

where F_A is the force component acting on point A, and is perpendicular to the line OA.

The total moment can be written as:

$$M_O = M_B + M_A \tag{10}$$

So, Eq. 10 can be written as:

$$\begin{gathered} F_1 \cdot OC = F_B \cos\theta_B \cdot OB + F_A \cdot l_{OA} \\ F_1 = \frac{F_B \cdot \cos\theta_B \cdot OB + F_A \cdot l_{OA}}{OC} \end{gathered} \tag{11}$$

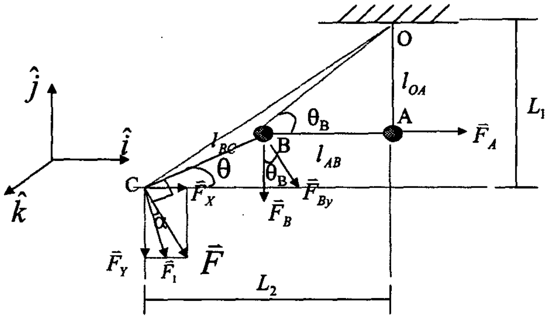


Figure 10. Diagram of the 2-D Sensing System with its geometric parameters.

Hence, F can be solved as:

$$F = \frac{F_B \cdot \cos\theta_B \cdot OB + F_A \cdot l_{OA}}{OC \cdot \cos\alpha} \tag{12}$$

The above equation relates the forces measured by PVDF-1 and PVDF-2 to a reaction force F acting on the probe-tip. The components of force F in x and y directions can now be written as:

$$\begin{gathered} F_X = F\cos\theta_C \\ F_Y = F\sin\theta_C \end{gathered} \tag{13}$$

where θ_C is the angle between the reaction force F and x direction.

Hence, the 2-D system sensor output can be predicted by knowing the geometric parameters of the PVDF sensors, the angle of the probe-tip, and the applied reaction force vector from a micro structure.

B. Experimental Results

Our current focus is on producing a customized PVDF-based 2-D sensing system for commercially available micro-manipulation systems. We intend to demonstrate force-reflective commercial micro manipulation tips using our PVDF sensors. We are also improving the low frequency response of our sensing system by using a charge amplifier to convert the high impedance output to a usable low-impedance voltage signal. The actually 2-D system constructed is shown in Figure 11.

The 2-D sensing system was tested to investigate the performance of the probe-tip touching the substrate similar to the 1-D system. The controller was again used to command the manipulator to move the probe-tip downward to the substrate at different velocities. As shown in Figure 12, signals from both sensors can be detected, hence, impact force information in 2-D can be obtained.

The probe-tip was also used to lift up micro structures similar to the experiments performed for the 1-D system. Two-dimensional sensor signals were detectable as shown in Figure 13. Currently, we are able to detect distinctive signals when excessive force applied by the probe-tip breaks a micro structures. (see Figure 13). Our ongoing effort is to calibrate the PVDF sensing elements and to decipher the frequency contents of various signal errors such as environmental vibration and vibration due to sudden stoppage of the sensing system. Eventually, we could extract only the interaction force between the probe-tip and the micro structures if these signal errors can be filtered.

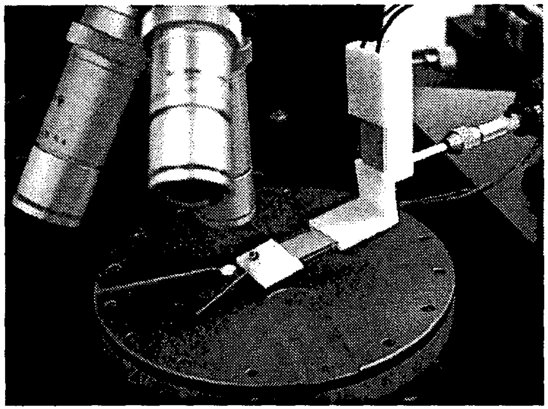
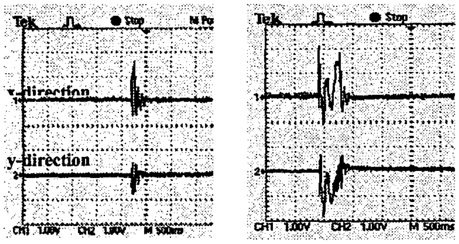


Figure 11. Photograph of the actual 2-D sensing system integrated onto a micro-manipulator.



(a) (b)

Figure 12. 2-D sensor signals of the probe-tip impacting a substrate at (a) v =3000μm/sec, and (b) v =6000μm/sec.

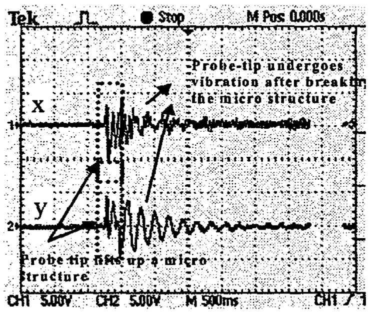


Figure 13. 2-D sensor signal from the probe-tip lifting a micro plate at v =3000μm/sec.

V. CONCLUSION

We have demonstrated that PVDF polymeric sensors can be used to sense micro-Newton forces when integrated with a commercial micro-manipulator with a probe-tip. Furthermore, we have demonstrated that a 2-D sensing system can be designed to perform force and impact detection – lifting of a micro structure has been demonstrated. We now work to improve the PVDF sensing system into a force-feedback micromanipulator to demonstrate automated micro-assembly of MUMPs structures with force-feedback control. We are also working on improving the low frequency response of our sensing elements and developing a 3-D sensing system integrable with commercial micro manipulation equipment. The goal for this project is to demonstrate a force-sensing micro-assembly system, including hardware and software, integrable to existing commercial micromanipulators, and capable of operating in automated assembling mode or tele-operated mode. Ultimately, this technology can be used to achieve micro-automation in batch assembling of MEMS devices such as micro-mirrors, micro-optical-lenses, and general micro sensing and actuation devices. In addition, this technology can potentially be used in bio-manipulation, including embryo injection and cell separation, and to understand the force interactions of micro-biological systems.

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