Internet-Enhanced Automation in Micro Environment

Wen J. Li[1], Ning Xi[2], Yuechao Wang[3], and Shugen Ma[4]
[1]Dept. of Automation and Computer-Aided Engineering, The Chinese University of Hong Kong, Hong Kong SAR
[2]Dept. of Electrical and Computer Engineering, Michigan State University, USA
[3]Shenyang Institute of Automation, CAS, China
[4]Dept. of Systems Engineering, Ibaraki University, Japan

Abstract **– Recent developments in the Internet have significantly increased the human capability to reach and obtain information from remote locations. In parallel, the advent of micro sensors and actuators makes it possible for humans to sense and act in a microenvironment. Combined, the Internet and MEMS will produce a new technology for humans to sense and act in remote micro-environments, allowing the potential development of micro teleoperation and micro automation technologies. These new technologies have potential impact on several fields, including remote micro-automation and biomedical engineering. In this paper, we will present our ongoing development of polyvinylidence fluoride (PVDF) sensors that can be used force-reflective control of micro-mechanical devices over the Internet. Internet based teleoperation between Hong Kong and Michigan State was demonstrated using an event-based control scheme, which ensured stability and synchronization. Control was enhanced by multimedia feedback, which included, in addition to the traditional video, force feedback. The force fed back augmented the limited information supplied by visual feedback. 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 hence, reduce the time from design to production significantly.**

I. INTRODUCTION

The increasing popularity of the two technologies, the Internet and MEMS, has motivated their combination. By combining these two fields humans can reach further and smaller worlds and develop novel technologies to benefit existing and future engineering and scientific applications. However, to make these systems efficient and safe, multimedia information has to be supplied to the operator. In addition to the traditional video, multimedia in this paper is expanded to include haptic information. The additional haptic media introduced is force, which transfers human feeling to remote microenvironment.

An example of immediate applicability for combining MEMS and the Internet is remote-micro-automation. For instance, the well-known surface micromachining commercial foundry technology MUMPs™ (Multi-user MEMS Processes) run by Cronos Integrated Microsystem has a 2-polysilicon and 2-sacrificial-layers process that can be used to produce many micro-mechanical devices with scientific and commercial applications (MUMPs™ can now be used to produce micro optical bench micro RF switches, and micro sensors [1]). However, many surface micromachined devices need to be micro-assembled or micro-manipulated to realize a final device or during experimental tests. Case in point, a micro-reflecting mirror needs to be rotated 90° from its plane of fabrication through a fragile micro-hinge or a micro piezoresistive cantilever sensor need to be lifted up from the horizontal plane for mechanical tests and calibration. As shown in Figure 1, a micro mass platform suspended by 2 cantilevers needs to be lifted from its plane of fabrication to a vertical position for calibration. However, since the micro polysilicon beams are 2μmx30μmx200μm, forces in the order of μN are sufficient to break them. As seen in the figure, an operator hoping to lift the platform for calibration will often break the beams unintentionally due to excessively applied force through the commercial micromanipulators. Therefore, in order to avoid breaking or damaging micro objects during the manipulation process, force reflection is an essential component within the control structure of micromanipulation and micro-assembly systems.

Micromanipulation 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., [2]) or creating manipulation actuators for micro object positioning (e.g., [3],[4]). Some of the tele-operable micromanipulators may eventually have the capability to perform feedback control using piezoresistive, piezomagnetic, piezoelectric, capacitive [5], or laser [6] techniques. In this project, we propose to use polyvinylidence fluoride (PVDF) piezoelectric polymer sensors as force sensors for force-reflective control of micromanipulation or assembling systems. We have successfully demonstrated flexible PVDF polymers are laser-micromachinable and able to provide force-rate-sensing at micro scale [7]. We are currently developing PVDF sensors to be integrated with

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commercially available micromanipulation probe systems for force-reflective micro-automation applications. The fabrication of the PVDF sensing elements is described in the next section. These sensing elements (micro tips) were successfully teleoperated via the Internet using an event-based feedback control [7] scheme, which ensured stable operation under large random time delay conditions. The general structure of this scheme is shown in Figure 2, where the operator sends position commands and receives force feedback and video feedback.

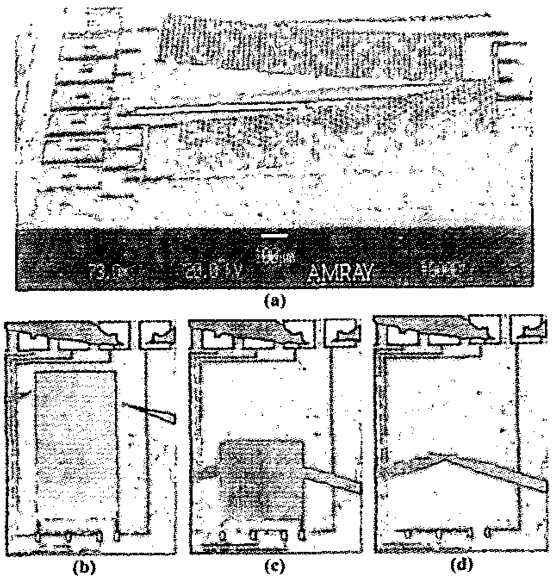

Figure 1. MUMPs microstructures are typically tested by using commercial probes without any force sensors for lifting and moving. (a) SEM picture of a surface micromachined mass-plated suspended by two polysilicon beams. (b) to (d) is a sequence of pictures showing the lifted micro device may be damaged 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.

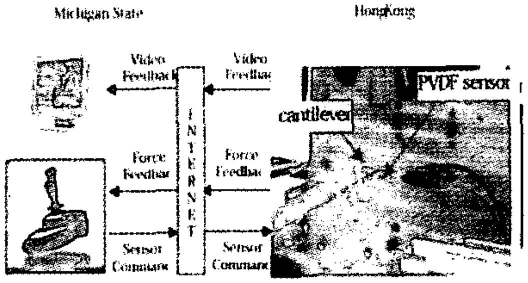

Figure 2. The video and force feedback control scheme of the teleoperation system used in the experiment.

The use of the Internet as a communication medium offers a worldwide reach at very low cost and offers an increased safety for the operators. Traditional teleoperation systems feedback included video; however, force has become an additional feasible and desirable form of feedback. Force feedback has added importance in microenvironments control architectures. Since visual feedback of micro- environments might be of low quality or might offer limited information, force feedback became essential for the efficiency and safety of operation at these small scales. However, force feedback in these systems is faced by several difficulties, one of which is scaling. At this level scaling between the micro and macro environments' forces should be carefully examined and tuned. Since the force detected is of very small magnitude, major amplification should be made which might result in an unstable system.

We believe that teleoperation using force feedback with PVDF sensors will have great impact on improving the yield of surface micro machined devices requiring post-fabrication micro assembly or manipulation. Hence, integration of the PVDF micro-tips is underway with a computer controllable micromanipulation system. The results from fabrication of the micro-tips and Internet force-feedback control are more discussed in more detail in the remaining sections.

II. PIEZOELECTRIC PVDF MICRO-TIPS

Piezoelectric materials create electrical charge when mechanically stressed. Among the natural materials with this property are quartz, human skin, and human bone. PZT is probably the most well known piezoelectric material and has been investigated widely as an actuator and sensor, even at micro scales [5]. Nonetheless, a PZT is a ceramic material and is very brittle. We have also laser-micromachined PZT micro-tips successfully in our lab but they are easily damaged even when handled with tweezers.

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 micro-tips as force-rate sensors because the charge generated by PVDF is almost linearly proportional to the force on its surfaces; therefore, the current generated by the piezoelectric approximates the derivative of the 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, including PZT.

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

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

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. 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]. We are currently using the above equation to model and optimize a micro-tip to minimize the tip size while making the detection of small and low-frequency $F(s)$ possible. Even 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.

III. LASER-MICROMACHINED PIEZOELECTRIC PVDF MICRO-TIP SENSORS

An Electrox Diode Pump Nd:YAG Laser system was utilized successfully to micro machine the PVDF polymers. The Electrox Laser system is controlled by a PC using proprietary CAD software and can be made to laser-machine any 3D shape drawn by the CAD software. Figures 3 shows a micro-tip fabricated by the Nd:YAG laser system. Also in the figure (3b) are interferometric images of the respective tips, showing the tip-radius can now be made to be less than 100μm. We are currently optimizing the laser cutting parameters to further reduce the tip radii of these micro PDVF tips.

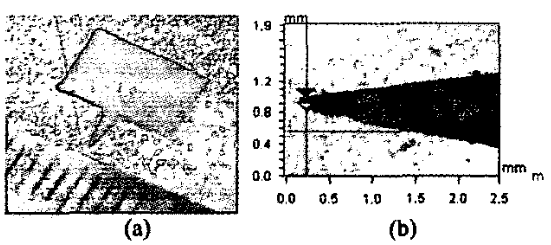

Figure 3. (a)A single laser-micromachined PVDF tip. Each tick on the scale is 1mm. (b) Interferometric image of the tip in (a).

IV. EVENT-BASED INTERNET CONTROL

Delay in communication links has several effects on the stability and synchronization of teleoperation systems. Even more so when force feedback is included. These effects exist due to the use of time as the reference variable; therefore, if a non-time based reference is used the system would become immune to delay. This suitable action or motion non-time reference variable is called *event*. The event-based controller design was first introduced in [10]. The planning and control of the traditional time-based and the event-based schemes are shown in Figure 4.

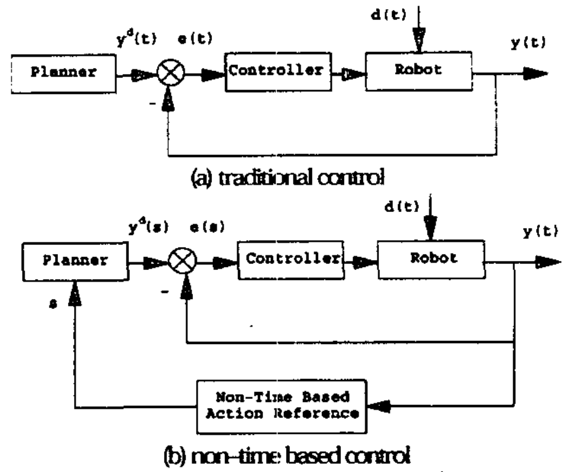

Figure 4. Comparison between traditional time-based and event-based planning and control.

Event-based control results in not only stability but also event synchronization. Because of delay, visual feedback does not reflect the current state of the system. Meaning that the operator is most of the time viewing an old state of the system. However, by using event-based control, the force is event synchronized. This implies that the force always reflects the most up to date state of the system making the control more efficient and safe.

V. EXPERIMENTAL RESULTS

The experimental set-up and results of the force-feedback teleopration of the PVDF micro-tips are described in this section.

A. Experimental Setup

The PVDF micro-tip cut in the shape given in Figure 3 was used as a piezoelectric sensor for our Internet force-reflection experiment. This tip is about 2.5mm long with about 0.8mm at the triangular base. The output from this sensor is amplified using an inverted amplifier with feedback gain of 50. Its signal is then feed to an 8255 analog-to-digital conversion (ADC) card connected to a PC for signal transmission to the Internet. The sensor experimental setup, which is housed in the Advanced Microsystems Laboratory (AML) of The Chinese University of Hong Kong, is shown in Figure 5. The sensor tip is currently attached to an x-y computer-controlled positioning table, which can be controlled via the Internet by a force reflection joystick in the Robotics and Automation Laboratory (RAL) at Michigan State University. The x-y positioning table will eventually be replaced with a computer-controlled micromanipulator. A cantilever is attached to a vibration drum and has a tip vibration of ~50μm to 2mm from in the frequency range of 1 to 120 Hz. The AML sensor tip position can be manipulated by the RAL joystick to contact the vibrating cantilever. The RAL operator observes the AML tip position using a video-conferencing software. The force of the vibrating cantilever sensed by the tip is send to RAL via the Internet. Once the force is received the force feedback joystick plays it. After that the operator generates a new movement command to be sent to the sensor via the Internet.

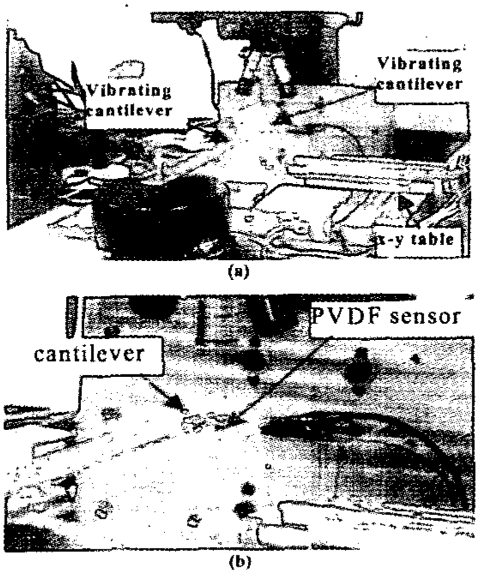

Figure 5. (a) Experimental setup. (b) Close-up of the PVDF tip.

B. *Internet Based Control Results*

The experimental results presented here relate to the testing done between Hong Kong and Michigan State. During this experiment the operator (RAL) sends position increment commands and receives force feedback from the sensor (AML). The position increments are sent for both x and y axes while the force is sensed only in the y axis.

To emphasize the delay problem over the Internet Figure 6 plots a sample of round trip delay between the operator and the sensor. It is clear that the delay is random with no specific pattern or model. If not dealt with, this delay might cause instabilities and desynchronizations. However, as will be seen in the experimental results, the approach used gave a stable and synchronized system.

Figure 7 shows a plot of the desired position increments in both directions and a plot of the played force with respect to the event. It is clear that the commands are random, which is typical of a teleoperation scenario. This makes approaches based on prediction of forces or virtual forces non-realistic. Therefore, actual force had to be sensed and fed back. We have also analyzed force felt by the operator, the force sampled for the sensor and the error between them. We have observed that the force felt is closely following the one sampled from the sensor. Although they do not occur at the same time instant, the system is still stable and event synchronized. Despite the random time delay experienced between Hong Kong and Michigan Sate, the system performance is stable and the error has a small value at all times and converges to zero. This implies that, for the given sampling frequency, the system is transparent. Meaning that in case the operator was controlling the sensor from a local machine a similar force profile would have been experienced.

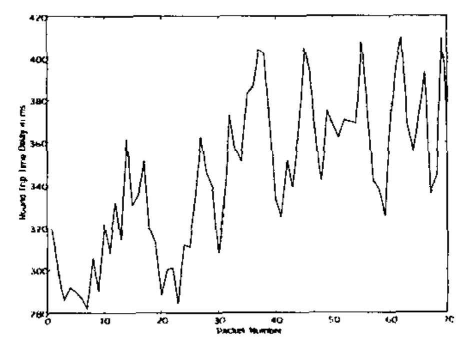

Figure 6. A sample of round trip delay between Hong Kong and Michigan State.

C. *PVDF Sensors for Micromanipulation Systems*

Our current focus is on producing a customized PVDF-based sensing system for commercially available micro manipulation systems. We intend to demonstrate a 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. Figure 8 shows a picture of our micro sensing system under development. The preliminary output response of the probe-manipulation system is given in Figure 9.

VI. CONCLUSION

We have demonstrated that micromachining of PVDF polymeric tips is possible using a Nd:YAG laser system, which will allow the force signal-feedback via the Internet to a remote joystick. In addition, an event-based control scheme was used to control the position of the tips via the Internet. This approach resulted in a stable and synchronized system with force reflection. We now work to integrate PVDF sensor tips onto Internet-controlled micromanipulators to demonstrate 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 sensing system integrable with commercial micro manipulation equipment. However, the use of force feedback for microenvironments has difficulties, such as proper force scaling, and will be addressed in our future work.

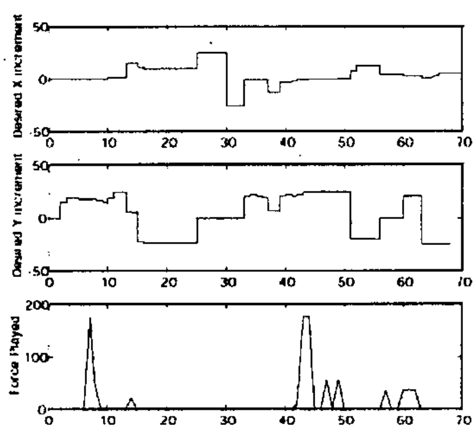

Figure 7. Plots of the desired position increments and the force felt by the operator.

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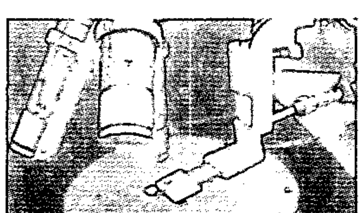

Figure 8. A custom-made PVDF sensing systems for commercial micro manipulation tips.

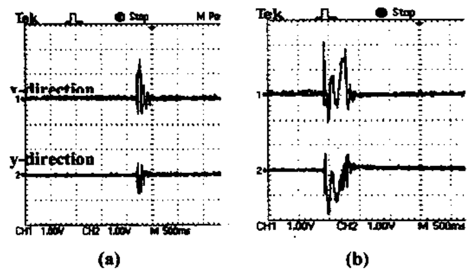

Figure 9. Experimental voltage output of the 2-D PVDF sensing system for a commercial probe manipulator. Shown are the 2-D sensor signals of the probe-tip impacting a substrate at (a) v =3000μm/sec, and (b) v =6000μm/sec.

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