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A novel haptic platform for real time bilateral biomanipulation with a MEMS sensor for triaxial force feedback

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Abstract

A novel triaxial force sensing device developed by the authors with a MEMS sensor as core component is mounted on a subnanometric resolution nanomanipulator having three degrees of freedom (DOF). This sensorized device allows measuring forces on the nanomanipulator tip in the range of 0–3 N for normal and ±50 mN for tangential forces with a resolution of 11 bits. Together with a haptic input device, a setup was created allowing palpation and force feeling. The mathematical model used to drive the master haptic interface force feedback capabilities is based on online force and stiffness measurement. The performance of the novel setup is demonstrated with a cell palpation experiment.

Keywords: Force sensor; MEMS; Phantom; Haptic; Triaxial; Force feedback

1. Introduction

Thanks to the recent developments in micromechatronics, it is nowadays possible to access and manipulate very small objects. Fine movement resolution, force sensing for haptic feedback, high reliability and intuitive master interface are some basic requirements that have to be met by platforms for bilateral micro and nanomanipulation. These systems will spread the field of micro and nanomanipulation beyond the scientific community, and even unskilled operators will be able to interact with the micro and nanoworld. Several systems have been developed addressing this final goal, in particular using AFM as the force sensing principle and having the Phantom (Phantom 1.0, SensAble Technologies Incorporated) [1] or a purposely developed device [2] as haptic interfaces. The AFM tip enables high resolution force sensing, but its use is limited to a narrow force range and to a single degree of freedom.

A scientific field where bilateral micromanipulation platforms have increasingly been applied in the last few years is intracellular injection. Manual manipulation requires long, lengthy training and the success rate is related to the operator experience. Even for a skilled operator, the injection process results in low success rate and poor reproducibility, since he/she has to rely only on visual information coming from optical microscopy and eyestrain significantly affects the final output. Furthermore, since biological cells are irregular in configuration and easily deformable, they can be damaged during manipulation and treatment due to excessive force or hand tremor.

A typical platform for bilateral manipulation in the field of cell injection is composed of a master unit, usually an intuitive and ergonomic controller or joystick that is able to provide a force feedback, and a slave unit, a multi degrees of freedom (DOF) manipulator with micro or nanometric movement resolution. The injecting needle is placed onto the distal end of the slave unit.

Combining force feedback with vision can improve cell injection outcomes since the operator can both feel and see the cell injection process. The role played by force feedback and its advantages during such a procedure are well described in [3]. By reflecting the cellular force signal to the operator through the

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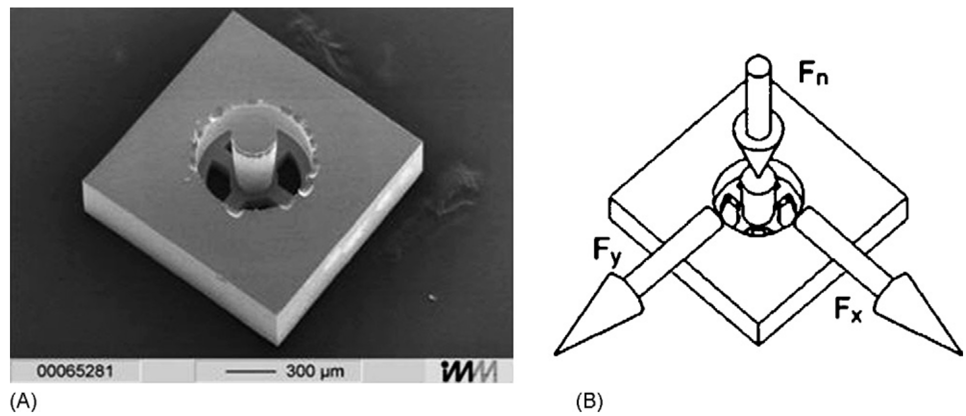

Fig. 1. (A) SEM picture of the bare silicon sensor. (B) Force components on the bare sensor.

haptic interface during bilateral biomanipulation, it is possible to detect clearly the membrane penetration event. Furthermore, the force feedback information to the operator enables minimally invasive injection, reducing any physical damage to the cellular structure, thus increasing the success rate of cell embryonic development. In [4], the force applied by the injecting needle is estimated by contour measurement from the visual system. This may be a critical disadvantage in some injection tasks where real force feedback is required. Placing a real force sensor as close as possible to the injecting tool is of course the most suitable solution. In [5,6], the force sensor is made by piezoelectric polymer, PolyVinyliDene Fluoride (PVDF). This material can be modeled as a capacitor that is able to generate charges on its plates under the effect of pressure, sound or heat. Then, if a charge amplifier is used, a linear relationship exists between the applied force and the corresponding integral of the voltage output from the charge amplifier. Because of this working principle PVDF are more suitable for dynamic loading measurements, than for static ones. The same principle has been also used in [7] to investigate the mechanical properties of single living cells at different stages of cellular development. However, even if PVDF demonstrates to be a suitable sensor for cell biomanipulation, its performance is affected by several unsolved problems such as the pyroelectric effect and the high sensitivity to acoustic waves and ground vibrations that can disturb the sensor readings. Moreover, all these solutions are limited to monoaxial force sensing. Measurement of these forces in three directions is crucial to operators interacting with the haptic display since it provides them with the membrane interaction forces, as they would feel in palpation [8]. However, conventional force sensors have large dimensions and are too heavy to be placed on the tip of a micro or nanomanipulation system. For triaxial high-speed bilateral biomanipulation, it is highly desirable to install a miniaturized multiaxial force sensor directly onto the tool tip. If the size of the sensor is miniaturized, the mass of the sensor reduces dramatically and the resonant frequency of the elastic body, composed of the manipulator and the sensorized tip, increases. This would enable real time bilateral manipulation, where the operator's hand movements are mapped in real time onto the tip of the slave manipulator. A triaxial force sensor fabricated by silicon micromachining for this purpose is reported in [9]. The proposed sensor, having dimensions of 4.5 mm × 5.0 mm × 525 μm without considering cabling and the eventual packaging, is however still bulky for a fine bilateral micro and nanomanipulation platform.

In this paper, a novel haptic platform for real time bilateral micro and nanobiomanipulation with triaxial force feedback is introduced. The core component that enables the multi degrees of freedom force sensing is a MEMS-based silicon triaxial force sensor, properly customized to act as probing end of the slave unit. The sensor, represented in Fig. 1A and described in details in [10,11], allows the measurement of normal and tangential components of an applied force, as in Fig. 1B, with a fully integrated silicon structure. The sensing element consists of a cylindrical mesa and four tethers. A piezoresistor (1 kΩ), dimensioned and positioned to obtain maximum sensitivity, is ion-implanted in each tether and used as an independent strain gauge. The bare sensor force sensitivities are 2 mN for normal and 0.4 mN for tangential loadings.

A nanomanipulator with three degrees of freedom of movement and a nanometric resolution is the slave unit, where the force sensor is mounted on. This system is controlled by a commercial haptic interface, which also applies the triaxial force feedback to the operator. A double vision system focused on the target location completes the setup. In order to evaluate the performances of the proposed platform, it is applied to a cell palpation and injection tasks. However, with just minimal modifications of the probing unit, it can be easily applied to other bilateral manipulation tasks where triaxial force feedback, small dimensions and high movement resolution are key requirements. Examples range from eye surgery [12] to nanomanipulation [13].

2. Design and fabrication of the force sensing device

Two main problems have to be solved in order to apply the bare silicon triaxial force sensor to a real working scenario. First, the four piezoresistors must be electrically connected to the acquisition electronics, then the sensitive part of the MEMS device must be mechanically interfaced with the target in such a way that would not compromise the information about the force orientation and intensity. To achieve this first goal, the MEMS sensor is directly mounted onto a flexible circuit made from