Simultaneous Actuation and Force Estimation Using Piezoelectric Actuators

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***Abstract* - This paper introduces a force estimation method that enables simultaneous actuation and force estimation using piezoelectric actuators. The method combines an actuator input voltage and a current together with a displacement measurement to a force estimator. The force estimator contains a non linear actuator model to approximate the present external force without the use of force sensors. The measured displacement can simultaneously be utilized in feedback control to enable precise microrobotic operations.**

The results show that the method enables estimation of both static and varying forces under simultaneous position feedback control. Experimented displacement trajectories contain both stationary and mobile phases. The achieved accuracy in force estimation according to experiments is better than 10% of the full force scale. Therefore force sensing without the use of separate force sensors is feasible, which opens new applications for force sensing in microrobotics.

***Index terms* - piezo actuator; force sensing; sensorless; simultaneous actuation; current**

I. Introduction

Micromanipulation techniques are widely used in research of several fields. Common for the majority of the cases is the required operator. For the micromanipulation techniques to be exploited in high volumes in areas such as industrial and biological applications, the role of the operator should be reduced to minimum. This can be achieved by increasing the automation level [1].

Previously the research has focused on the development of microrobots, -manipulators and tools. This has led to a situation, where the performance of the devices and tools would support fully automated systems, but the knowledge about the target is inadequate. Therefore, the research trend has recently shifted towards techniques, that gather more knowlegde about the objects to be manipulated and about the operating environment. These techniques include machine vision and various sensor developments, such as force sensors. These are not competitive techniques, but rather complimentary.

Contact sensing is one of the most important actions for example in pick and place for an operational point of view. The most generic method to sense this event is the application of force sensors. Many other methods are based on certain target properties, such as on conductivity. Also in biological applications such as in manipulation tasks related to cell cultivation and microdissection of tissues, force and contact sensing are required to enable full automation.

There are various methods to measure forces; many of the most suitable methods for micromanipulation are listed in review articles such as [2] and [3]. These methods include strain gauges, use of piezoresistive, piezoelectric and piezomagnetic effects, capacitive sensors and optical sensors [2], [3]. Perhaps the most convenient of these methods are the ones based on the piezoelectric effect, since it enables simultaneous sensing and actuation. This simplifies the mechanisms and enables further miniaturizing of the system in comparison to a setup with a separate actuator and force sensor.

Using piezoelectric materials for actuation is very common in microrobotics. This is due to their high resolution and favorable dynamic properties. However, large hysteresis, drift, temperature, self-heating and load effects decrease the open-loop positioning accuracy. Therefore, typically one of the following control methods is used to increase the positioning accuracy: feedforward voltage control, feedback voltage control, feedforward charge control and feedback charge control.

Simultaneous sensing and actuation using piezoelectric materials is not as rare as one could imagine; the mass quartz balance is perhaps the best example of this. The mass quartz balance is vibrating and a shift in the resonance amplitude is measured and this is proportional to the measured mass. Other examples can be found, where piezoceramics is actuated by ac voltage for sensing purposes, such as [4] and [5]. This sensing method gives good results when masses or other mechanical properties of objects are needed to be measured. For a more general use in microrobotics this method cannot be utilized, since it requires a certain motion to be generated for the measurement. In microrobotics, the motion trajectories can not be specified in advance and they can have some static positions as well.

Another approach is proposed in [6], where a sliding-mode based force control method is presented. It is based on a non-linear electromechanical model of the actuator and a displacement measurement using strain gauges. Force is estimated using the actuator input voltage, the output displacement and the non-linear actuator model. The difference between the model output and the real displacement is used to approximate the external force. The obtained results are quite good, but as the paper points out, any inaccuracy in the model will cause errors in the force estimation.

It has been shown that the input current and voltage knowledge contain the sufficient information to predict the displacement of a piezoelectric actuator in the absence of external forces [7].

The goal of this work is to study the feasibility of utilizing current measurement in the external force estimation.

The rest of the paper is organized as following; Section II presents the force estimation method and Section III describes the experiment setup. Results are presented in Section IV. Conclusion is at the end of the paper in Section V.

II. Force estimation method

This section presents the proposed force estimation model. The model should estimate the external force without any force measurement.

From [8] we can derive that the displacement of a piezoelectic actuator can be described as a function of current and voltage:

$$d(t) = f(i(t), V(t)), \tag{1}$$

where $d(t)$ is displacement of the actuator, $i(t)$ current and $V(t)$ voltage. This applies when external force is constant.

Linear dynamic system can be modeled by a two-port model [9], as presented in Fig. 1.

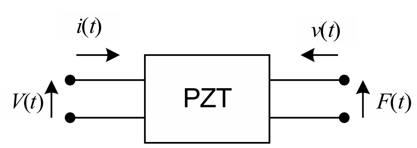

Fig. 1: Two-port model of piezoelectric actuator. F(t) presents the force and v(t) the actuator velocity. Redrawn from [9].

The two-port model together with the general knowledge about the load effect on piezoactuators suggests to include the force to (1):

$$d(t) = f(i(t), V(t), F(t)) \tag{2}$$

This can be presented with respect to the force:

$$F(t) = g(i(t), V(t), d(t)) \tag{3}$$

This would suggest that by measuring the actuator input current and voltage, and the resulting displacement, the force could be estimated. This could be done simultaneously with a tradition position control of the actuator. Fig. 2 presents the block diagram of the proposed force estimation method.

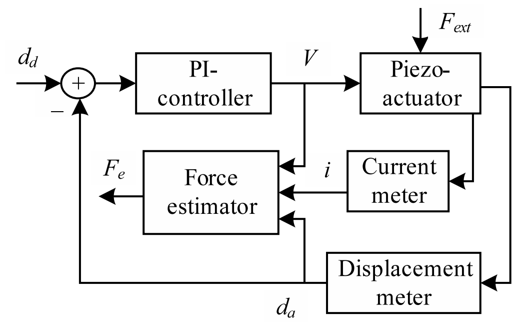

Fig. 2: Block diagram of the proposed force estimation method.

In the figure, d_d and d_a present the desired and actual displacements. V presents the voltage and i the current. F_{ext} presents the external force and F_e the estimated force.

A. Force estimator

This section discusses the force estimation model. The model has three inputs: voltage V, current i and actuator displacement d, and one output, external force F.

In order to minimize the manual labor in the force estimator creation, a modeling method which is supported by software tools should be selected. One of this type of well established methods are neural networks [10]; tools for creating and training neural networks exist in commercial softwares.

Training data is obtained by driving the trajectory presented in Fig. 3 with several different static loads: 0 N, 34 mN, 61 mN and 90 mN.

A 10*1 feedforward backpropagation network is chosen for the force estimation model. Fig. 4 combines the trajectories driven with different loads to the same figure. The figure presents actual loads and training results, continuous line presents the actual load and the dashed line the force estimation of the model.

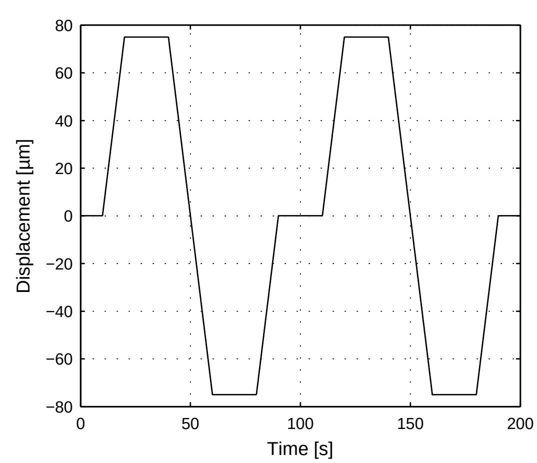

Fig. 3: Displacement trajectory for obtaining the training data.

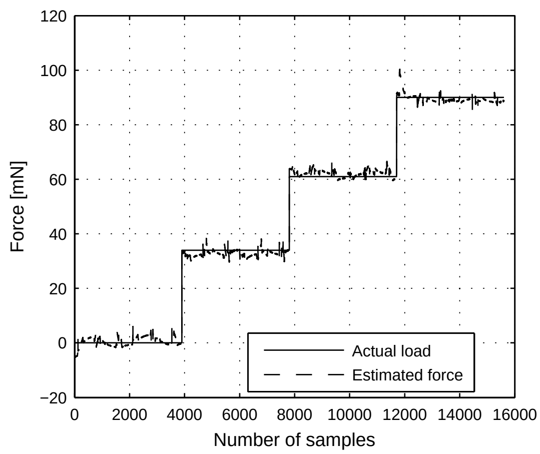

Fig. 4: Training results, continuous line presents the actual load and the dashed line the force estimation.

III. Description of the experiment

This section describes the control implementation and the experiment setup. The implementation of the force estimation requires a control software, a data-acquisition board with analog inputs and outputs, a voltage amplifier (Piezo Systems EPA 102), a current meter (Keithley 160B), a displacement meter and a piezo actuator. Data-acquisition is performed with a National Instruments AD-board (PCI-6052E). The position of the piezoelectric actuator is measured with a laser displacement meter (Mel Mikroelektronik M5L/0,5). The piezo actuator used in the experiments is a bimorph bender NB38*4*0.6 from Tokin.

The control software is implemented using Matlab, with a real-time xPC Target toolbox. The displacement of the piezo actuator was controlled using a PI controller, gain was 0.1 and the integrator 3, used control frequency is 2 kHz.

The external force is produced in two ways: (i) by attaching lead weights on to the actuator and (ii) using a plastic cantilever that acts as an spring type of load. Lead weights produce constant force on to the actuator, while the force generated by the cantilever is displacement dependent, as is described by the spring force equation:

$$F_{spring} = -k \cdot x , \tag{4}$$

where F_{spring} is the force generated by the spring, k the spring constant and x the distance by which the spring is elongated.

Fig. 5 presents the measurement setup. In the figure, a plastic cantilever pushes the piezoelectric bender downwards. The cross sectional dimensions of the plastic cantilever are 7.5 mm x 1.0 mm and the bending length is 23 mm.

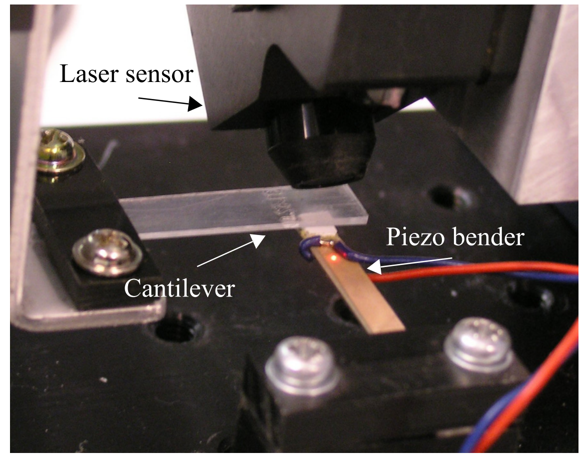

Fig. 5: Measurement setup.

IV. Results

This section presents the experimental results of the force estimator. All experiments are carried out for five times and the results in this section present typical results.

The trajectory presented in Fig. 3 is driven with the following static loads: 0 N, 22 mN, 47 mN and 77 mN. These are combined to a same figure as was done in Section 2 by presenting only actual loads and the corresponding estimated forces, Fig. 6.

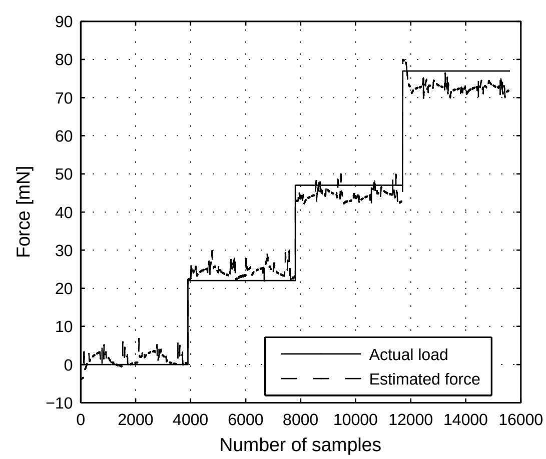

Fig. 6: Results of static force measurements.

The force estimation gives relatively good approximation of the actual force. Some variation, however, occurs during different phases of the trajectory. Some offset is also present in the estimated forces. With the three lightest loads, the offset is 2 - 3 mN, but with the heaviest load the offset is slightly over 4 mN. The average absolute value of the error between the actual load and the estimated force is 2.8 mN and also the median error is very close to this (2.83 mN). The maximum error during the experiments is slightly below 8 mN. The applicable force range of the estimator is in minimum 0 - 90 mN, which is the range of the loads used for the training. This, in combination with the maximum error of 8 mN, results in a total estimation accuracy better than 9% of the full scale.

The same trajectory is driven against the plastic cantilever to test how the force estimator follows a varying force. Results of this experiment are presented in Fig. 7, continuous line presenting the displacement of the actuator and the dashed line the estimated force. Unfortunately, the actual force is unknown in this experiment and therefore, only qualitative validation is possible. The results show that the shape of the estimated force is as it should be for a spring type of force. This indicates that the force estimator can follow varying loads.

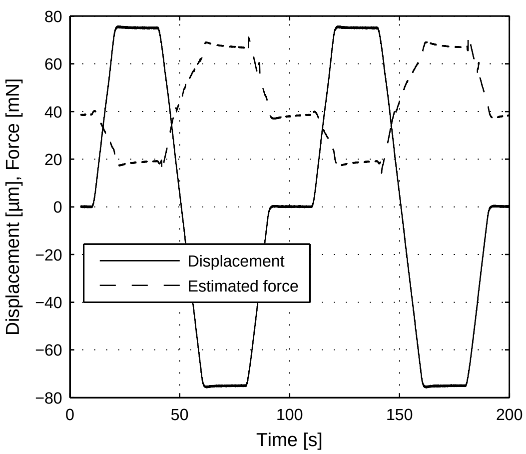

Fig. 7: The piezoactuator driven against a plastic cantilever.

To obtain a rough estimate on the shape of the actual force in this experiment, a fitted curve is created. This curve is based on (4), to which an offset is added. The spring constant and the offset are approximated by finding a best fit so that the measured actuator displacement would be the spring elongation distance and the estimated force would be the spring force. Since the values of the fitted curve are as close to the force values of the estimator as possible, quantitative conclusion cannot be made. However, the shape of the curve should be accurate to some extent, with an assumption that the deformation of the plastic cantilever is fully reversible and thus the force follows the spring force equation. The fitted values for the spring constant k and for the offset are 0.33 mN/µm and 42 mN.

The comparison between the fitted curve and the estimated force indicates the existence of both hysteresis and drift in the force estimator, Fig. 8.

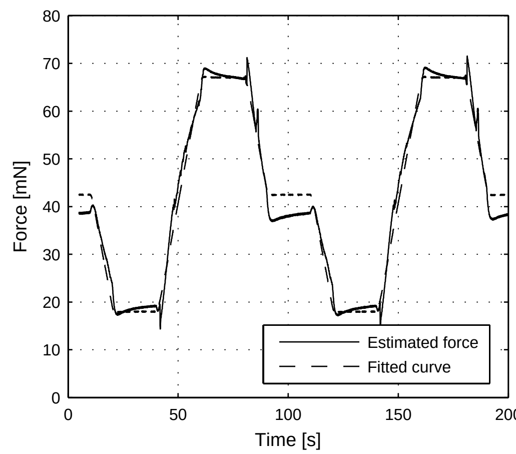

Fig. 8: Estimated force and a fitted spring force curve.

V. Conclusion

The proposed force estimation method is able to estimate both static and varying external forces with relatively good accuracy. The obtained accuracy is better than 10% of the full scale. This is not as good as the performance of separate force sensors, but adequate in many microrobotic tasks. The main benefits of the sensorless force estimation method proposed here are: (i) the simplification and (ii) enabling further miniaturization of the mechanics compared to systems with separate force sensors, and (iii) enabling force sensing in applications where it has been unreachable.

Future work includes improving the force estimation model to reduce the existing hysteresis and drift in the system.

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