A 3 DOF Piezohydraulic Parallel Micromanipulator

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ABSTRACT

The paper presents a new parallel micromanipulator that is composed of three piezohydraulic actuation systems. The basic elements of the actuation system are a piezoelectric actuator, a bellows and hydraulic oil. The use of the flexible bellows results in a new type of parallel structure, where the joints are integrated into actuator links. The joint-free tripod-like micromanipulator is controlled using a real-time control software that is based on a multi-level architecture. Control is organised in four levels for non-linearity compensation, position feedback control, supervision and tackling of automatic operations. The presented micromanipulator provides an exceptional combination of submicrometer resolution, large work space, miniature size and advanced control.

1 INTRODUCTION

Miniaturization has been one of the most important technological trends in the last decades. Microelectronics has paved the way. The sizes of microchips have been reduced from centimetres to micrometers and very high component densities have been achieved. It is expected that microelectromechanical systems will develop in the same way. The successful fabrication and operation of microactuators and micromechanical devices provides the opportunity to produce microminiature machines and mechanical systems. Such systems are called microsystems in Europe, microelectromechanical systems (MEMS) in United States and micromachines in Japan.

Research of microsystems began to gather momentum in 1980´s and currently it is one of the most prominent research areas all over the world. Major R&D efforts exist not only in Japan, where a massive, national ten-year project on “Micromachine Technology” was started in 1991, but also in United States, many EU countries, South Korea and Taiwan. Evidence of the expectations is also seen in a number of popular articles, such as [1] and [2].

Study of microrobots and micromanipulators is an essential part of microsystems. The structures vary from etched silicon implementations to miniature mechanisms. Nevertheless, the objective of all micromanipulators is to manipulate micrometer sized objects. Small scale manipulators are needed in industrial inspection tasks and in catheter type medical inspections. The size of the micromanipulator is not important in such applications as biotechnological operations, assembly of microelectro-mechanical systems, and testing of microelectronics circuits [3].

Some prototype micromanipulators have been proposed in the literature. They have been developed for different applications and have utilised either piezoelectric, electrostatic, electromagnetic or shape memory actuation principles. Arai et al. [4], Sato et al. [5], and Morishita and Hatamura [6] have proposed micromanipulators for assembly of microelectro-mechanical systems. Hollis et al. [7], Mitsuishi et al. [8], Ikuta et al. [9] and Grace [10] have constructed micromanipulators for such microsurgical operations as minimum invasive abdominal surgery, ophthalmology and microvascular operations. Fukuda et al. [11] and Dario et al. [12] have proposed active microcatheters for intracavity interventions. Marbot and Hannaford [13] and Hunter et al. [14] have build mechanical micromanipulators for biotechnological operations. Moreover, some commercial devices exist.

The objective of this research was to develop a computer-controlled micromanipulator that facilitates automatic and semi-automatic operations. Its main applications are currently in biotechnology where needs for automating operations have emerged. For example in cell toxicology hundreds of cells are typically injected and therefore automatic micromanipulator would speed up the process remarkably. Since the size of biological objects vary from micrometers to hundreds of micrometers, the micromanipulator should be capable of both submicrometer resolution and work space of several hundreds of micrometers. Moreover, the size of the manipulator should be small to be used with a microscope.

In this paper we describe first the concept of micromanipulation. The mechanical structure and design of a piezohydraulic actuation system applied to the micromanipulator is discussed in Section 3. Section 4 provides first a short overview of parallel structures and then presents a new type of joint-free parallel structure. The software system is discussed in Section 5 and control of the micromanipulator in Section 6. Section 7 concludes the paper.

2 MICROMANIPULATION

A micromanipulator is a device that facilitates remote handling of microscopic objects under computer-assisted human control. The operator obtains visual information about the end-effector and micro objects using a microscope and a CCD camera, as shown in Fig. 1. The micromanipulator can be controlled either using a joystick or a PC keyboard. Automatic operations, such as automatic injections, can be activated using the keyboard.

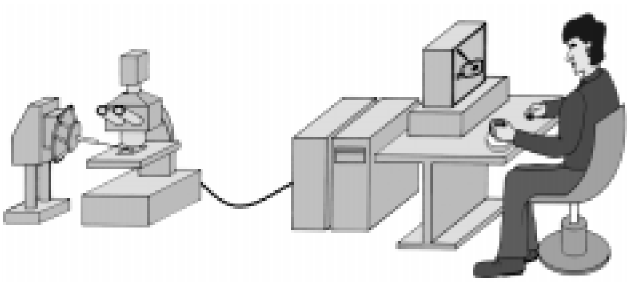


Figure 1: Concept of micromanipulation.

3 ACTUATION SYSTEM

3.1 Mechanical structure and design

The requirements for the micromanipulator – submicrometer resolution, workspace of hundreds of micrometers and compact size – enforce great demands for the actuators. Commercial products typically lack at least one of the required properties. Despite the very small strain, piezoelectric ceramics have beneficial properties for micromanipulation. Therefore, a piezoelectric actuator whose displacement is amplified is advantageous in micromanipulator applications. Displacement amplified piezo actuators as well as other commercial actuators were surveyed but an actuator satisfying the requirements was not found. Therefore, a new type of piezohydraulic actuator was developed, see [15] for more details.

The major objective in the structural design of the actuation system was to produce an actuator whose shape facilitates a construction of a compact tripod-like structure. As a result, the actuation system consists of a piezoelectric actuator, a small tank and a metallic bellows, as illustrated in Fig. 2. The piezo actuator is placed in the tank filled with hydraulic oil. When a voltage is applied to the piezo actuator, it deforms. When the actuator buckles, oil flows from the tank to the bellows which elongates, and vice versa: when the actuator gets straightened, oil flows from the bellows to the tank. Since the effective area of the bellows is smaller than that of the actuator, the displacement is magnified.

The piezoelectric actuator is tightened between two rubber washers using a slip ring. The coupling between a threaded channel of the tank and the bellows is sealed by a small washer. An end fitting including a venting screw is attached to the free end of the bellows. To minimize the amount of air, the system must be filled in the oil. By removing the screw during the filling, the hydraulic oil is able to flow through the system, which aims air removal.

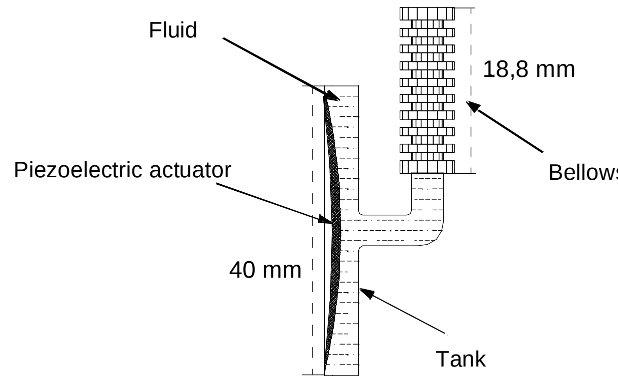


Figure 2: Overview of the actuation system.

The results of displacement experiments have shown that the movement range of the actuator is about ± 250 μm (maximum displacement 500 μm).

3.2 Piezoelectric actuator

The piezoelectric actuator (RAINBOW™) is structurally similar to unimorph type of elements. The RAINBOW™ actuator is a single element structure consisting of a PZT side and a metallic side [16]. When a voltage is applied opposite to the poling field, the wafer buckles and when the voltage is parallel to the poling field, the wafer straightens. The whole area moves but the motion is more pronounced at the centre.

3.3 Bellows

The bellows is a spring type of passive component, i.e. force required to deform the bellows is directly proportional to the displacement. The bellows is manufactured using electro-deposition where spring-quality nickel is first deposited onto a mandrel. In the end of the process the mandrel is dissolved out [17].

4 MANIPULATOR STRUCTURE AND DESIGN

4.1 Parallel manipulators

First papers on parallel manipulators were published in 1960's. Gough [18] and Stewart [19] developed independently similar parallel structures: Gough for testing of tyres 1949 (published 1962) and Stewart for a flight simulator 1965. In both structures a mobile platform was connected to a base platform using six prismatic links. These types of structures are generally known as Stewart platforms. Links are typically connected to the platforms by spherical joints. When the lengths of the links are changed, the position and orientation of the mobile platform can be controlled with respect to the base platform.

The dynamic performance of the parallel manipulators is better than that of serial manipulators, as the mass of the structure and the load are more equally distributed. Furthermore, parallel manipulators are stiff and compact. They tend to be more accurate than serial link configurations, as inaccuracies in actuators and joints do not affect the overall position of the end-effector as much as they do in the serial manipulators. Drawbacks of the parallel structures are their small workspace and reduced manoeuvrability. Although only few commercial applications currently exist, several prototypes have been constructed, see, for example, the www-page by Merlet [20].

4.2 Structure and Design

Due to the advantages of the parallel structures, a Stewart platform type of configuration was selected for the micromanipulator. The manipulator consists of three identical piezohydraulic actuation systems described in Section 3. They are connected by a mobile platform forming a tripod-like parallel configuration. The tanks are rectangular in shape, which makes them easy to assemble using triangular supporting pieces, Fig. 3. This asserts a very steady and compact structure. The mobile platform is fixed to each bellows using the venting screw and a small nut. The end-effector (needle) is mounted on the platform.

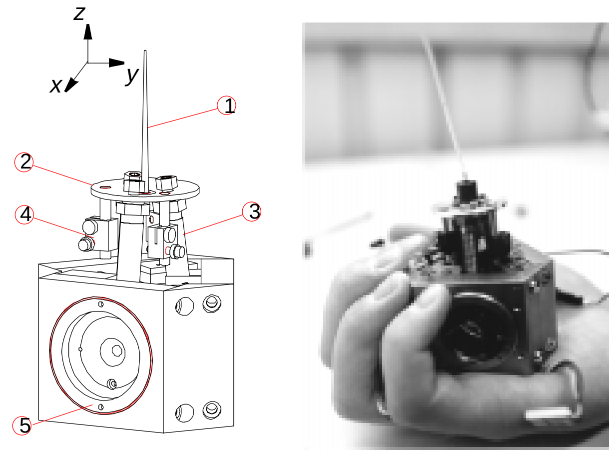
The mechanical design of the manipulator was carried out using a three dimensional CAD program package (Pro/ Engineer). With a 3-D CAD program it is possible to test the assembly of the pieces before manufacturing them. The compatibility of the pieces is important in a precision engineering device.

This manipulator differs from the conventional Stewart platform type of structures, since the bending of the bellows facilitates a joint-free structure. Using the bending character of the bellows instead of spherical joints simplifies the structure and the manufacturing process, since especially manufacture of miniaturised spherical joints is difficult. Tests and measurements have proven that it is possible to control the bellows-based parallel manipulator. By changing the lengths of the bellows the orientation of the mobile platform, and thus the position of the end-effector can be controlled.

5 SOFTWARE

5.1 Objectives

As all mechatronics systems, the microtelemanipulator requires the integration of mechanical components, electronic components and software. The nature of the microtelemanipulation requires real-time control. When force reflection from the end-effector is needed, the sampling frequency should be hundreds, even thousands of hertz. The potential commercial future also requires all components of the system to be easily available and low-cost. Consequently, Windows 95/NT was selected as the operating system instead of a real-time operating system. Due to the complex nature of code debugging and validation of real-time software, it is desirable to make the code reusable and extensible for future systems. Based on



1. End-effector 2. Mobile platform 3. Bellows
4. Magnet mechanism 5. Piezo actuator

Figure 3: Overview and photograph of the micromanipulator.

all those requirements, a real-time control software architecture is used for the microtelemanipulator system.

5.2 Structure

The software architecture conceptually consists of four levels. The first level contains the task-oriented code or objects which could be derived from a user-written code and/or class and function libraries. This provides the necessary openness and extensibility to cooperate with different applications and other systems. The second level encapsulates the first level code or objects into *blocks* which use *pins* as the only means to communicate with the outside world. Despite the interface incompatibility of the first level code, all interfaces are unified. The third level has a *strategy manager* through which a control system engineer can add blocks and connect pins. Thus, a mechanism is established, which frees a user from coding interfaces between the blocks. The fourth level appears at run-time where the pre-defined *strategy* is executed at a kernel at a high frequency. A user interface based on Win32 GUI runs at a low frequency providing down-sampled information from the kernel as well as controlling the kernel through a kernel service access point. The kernel controls the microtelemanipulator, traces the user inputs and records the history values of the measurement points and internal states.

Numerous blocks have already been implemented, such as clock to provide frequency signal for other blocks, signal generator, data source, data store, arithmetic operations, polynomial, transfer function, some linear and non-linear functions, rotation matrix, PID controller, context switching logic, service access interface, inverse kinematics model of the micromanipulator, etc. After the control strategy is defined and validated, the sequence of evaluation (SOE) is determined. The algorithm developed does not allow loops directly. However, a loop can be applied by introducing a special *unit delay* that breaks the loop at a reasonable point.

The presented approach makes the software to be a living part of the mechatronic system. Besides the generalized structure, it provides ready-made modules, for example general hardware I/O classes. It also supports multi-rate control system which makes the integration of the slow vision system simpler. The non-linear blocks and the user-definable blocks make hardware protection and all other such task easier. Different control strategies, including a closed-loop strategy and two open loop strategies, have been implemented for the microtelemanipulator system based on the software architecture.

6 CONTROL

6.1 Overview of the control system

The micromanipulator can be controlled using either open or closed-loop control. In teleoperation open-loop control is typically sufficient, since the operator closes the loop. In applications that are not critical to imperfections of the manipulator, open-loop control can therefore be used to reduce the hardware costs. However, an increasing number of micromanipulation applications, especially those that involve automatic operations, require for example high absolute accuracy, high speed and elimination of drift. To fulfil the requirements closed-loop control must be applied.

The control of the micromanipulator is organised in multiple levels, as illustrated in Fig. 4. The first level consists of three local feedback-loops that compensate non-linearities, such as hysteresis, and drift of the piezoelectric actuators. The displacements of the actuators are measured using strain gages.

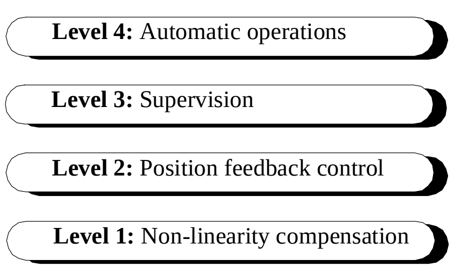


Figure 4: Control levels of the micromanipulator.

The position of the end-effector is controlled at level 2 using Hall sensors. The objective of this global feedback loop is to improve the absolute accuracy and the dynamic performance of the manipulator.

Level 3 supervises the micromanipulator. It monitors the control signals of the actuators and warns the operator when the micromanipulator approaches the limit of the workspace. If the manipulator is driven, in spite of the warning, to the edge of the workspace the software prevents movements to unfavourable directions.

The fourth level will be used to tackle automatic manipulation. It generates the trajectory of the end-effector for example in automatic cell injections. Pattern recognition properties of the vision system can be used to further automate the operation.

6.2 Sensors

The movement of the end-effector is detected using a vision system built at VTT Automation (Technical Research Centre of Finland). The vision system uses a DSP system together with the chamfer matching algorithm to detect the position of the end-effector [21]. However, the vision system cannot be used in on-line control as the speed of the vision hardware is currently too slow. The ultimate goal is to use the vision system in on-line control in the future but it requires more powerful hardware.

The orientation of the mobile platform and thus the position of the end-effector is currently measured using Hall sensors. As the Hall sensors do not directly measure the position of the end-effector, the vision system must be used off-line to calibrate the Hall sensor measurement. The vision system measures the movement of the end-effector only at the *xy*-plane and therefore two Hall sensors are used. The Hall sensors are mounted atop the actuator tanks, and permanent magnets are attached on the mobile platform using movable rods, as presented in Fig. 3.

When the end-effector moves along the *x*-axis, for example, both magnets move with respect to the Hall sensors. Both sensors respond and therefore a mapping must be found between the output voltages of the Hall sensors and the coordinates of the end-effector. The relationship between the Hall sensor signals and the coordinate estimates is presented in Equation (1):

$$\begin{aligned} \hat{x} &= f_1(u_1, u_2) \\ \hat{y} &= f_2(u_1, u_2) \end{aligned} \qquad (1)$$

where $\hat{x}$ and $\hat{y}$ are the estimates for the end-effector coordinates, u_1 and u_2 are Hall sensor voltages and f_1 and f_2 are functions describing the mapping between the Hall sensor signals and the end-effector coordinates.

The mapping has been determined using regression analysis and it has the following form:

$$\begin{bmatrix} \hat{x} \\ \hat{y} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{21} & a_{31} & a_{41} & a_{51} \\ a_{12} & a_{22} & a_{32} & a_{42} & a_{52} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_1 u_2 \\ u_1^2 \\ u_2^2 \end{bmatrix} \qquad (2)$$

6.3 Closed-loop control

The structure of the closed-loop controller is presented in Fig. 5. This section concentrates on the position feedback control of the manipulator, i.e. on level 2. Saturation control was briefly discussed in Section 6.1. Local feedback loops and algorithms for automatic operations are under implementation.

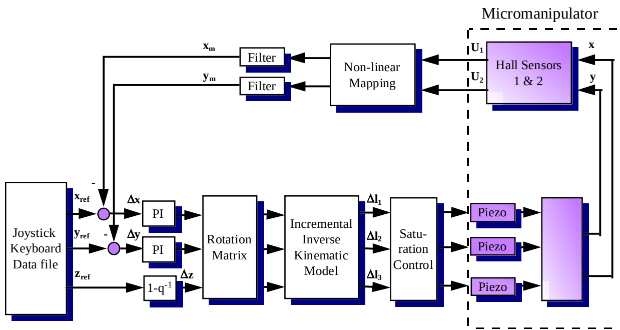


Figure 5: Overview of the controller structure.

The position feedback controller consists of two parts: two PI controllers and a feedforward controller. Moving the end-effector into a certain direction generally requires the contribution of all three actuators. Therefore, an inverse kinematics model that determines the lengths of the actuators for a given pose of the mobile platform is needed in the position controller. In closed-loop control a difference between the reference position and the measured position is utilised and therefore, an incremental form of the inverse kinematics model is needed. The incremental model provides changes in the actuator lengths that lead to the desired change in the pose of the mobile platform. In addition to the incremental inverse kinematics model, the feedforward part must include a rotation matrix which maps the operation frame of the micromanipulator to the platform frame.

Since it is difficult to measure the *z*-translation of the end-effector using the vision system, Hall sensor measurements cannot be calibrated in 3-D. Therefore, only *x*- and *y*-coordinates can currently be controlled in closed-loop, whereas the *z*-coordinate is open-loop controlled.

6.4 Experimental results

The results that demonstrate the elimination of drift are presented in Fig. 6. In the experiment, the end-effector was first commanded to move slowly along the *x*-axis, was then hold for five seconds and finally moved back. Although the reference signal was held at a constant value in open loop control, the end-effector moved slightly, because of the drift of the piezoelectric actuators. When closed-loop control is introduced, the drift can be totally eliminated.

The micromanipulator has been demonstrated in the separation of micro particles. The tests show that the micromanipulator can easily be used for handling glass spheres whose diameter varies from 10 to 100 micrometers. Fig. 7 illustrates the separation of two micro spheres whose diameters are 40 µm and 20 µm. Based on the experiments, the planar workspace of the manipulator covers 1.5 mm and 0.6 mm in *x*- and *y*-axis directions, and its maximum vertical displacement along the *z*-axis is about 0.25 millimetres. The displacement resolution of the manipulator is better than one micrometer.

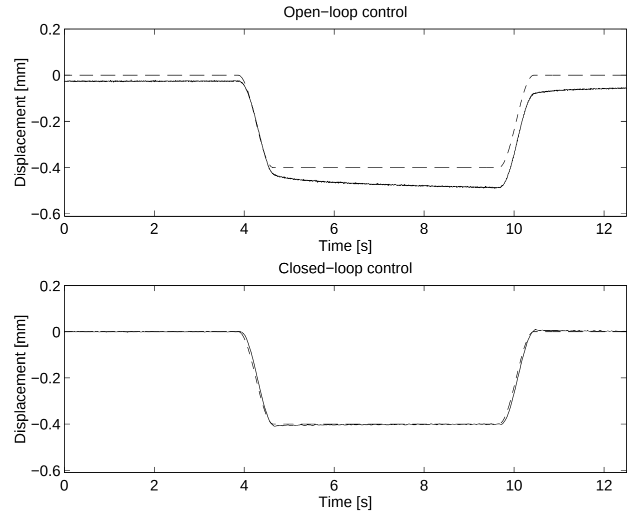


Figure 6: Results of the open and closed loop control experiments. Reference signal is presented using a dashed line.

Figure 7: Separation of micro particles.

7 CONCLUSIONS

A three-degrees-of-freedom parallel micromanipulator has been developed. The micromanipulator is actuated using a new type of piezohydraulic actuator composed of a piezoelectric wafer, a bellows and hydraulic oil. Three actuation systems are connected in a tripod-like parallel configuration. The use of the bellows in the actuation systems results in a new type of joint-free parallel structure where the joints are integrated into the actuation links. The micromanipulator is controlled using a real-time control software built on Windows 95/NT. The control of the micromanipulator is organised in four levels. The first level compensates non-linearities of the piezoelectric actuators and the second level controls the position of the end-effector. Level three is a supervisory level which ensures that the end-effector moves inside the workspace. Level four tackles automatic operations. Even though the presented micromanipulator is small, it still provides both submicrometer resolution and work space of several hundreds of micrometers. Furthermore, advanced control and machine vision algorithms make automatic operations possible.

ACKNOWLEDGMENT

The authors wish to thank the Technology Development Centre of Finland (TEKES) and the Academy of Finland for funding the project. Moreover, we acknowledge the fruitful collaboration with Juha Korpinen and Jouko Viitanen at VTT Automation (Technical Research Centre of Finland) and Hannu Kojola and Markku Ojala at Wallac Oy. We like to thank the Electrical Workshop at TUT as well for constructing the mechanical parts.

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