Ph.D. thesis

GÁBOR FELSŐ

Modelling of Micromanipulation Robot Systems and Visual-based Approach for Position Measurement

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2007

INTRODUCTION

The mechanical-technical development of the second part of the twentieth century had a considerable effect on industrial technologies, especially on the area of automated manufacturing systems. The appearance and development of the microelectronics (signal processing velocity, storage capacity, communication) contributed to a great extent to the wider appearance and spreading of robots and robot systems. This process was more accelerated as robotised production lines led to cost reduction, bigger accuracy, and the decrease of the time devoted to the working phases and consequently the more efficient operation of manufacturing systems.

Due to the development of medical biological technology and microelectronics technology from the 1990s, there was an ongrowing need for robot manufacturing systems that are capable to operate in the milli- and in the micrometer domain. What is nowadays known as microrobotics has started to unfold in the past decade in the frontier of robotics, microelectronics and medical biological technology.

The Department of Control Engineering and Information Technology at the Tecnical University of Budapest and at the Institute of Process Control, Robotics and Automatization (IPR) at the University of Karlsruhe started a large-scale research cooperation that witnessed the construction, modelling and measurement of a micromanipulation working station and the development of algorithms needed for its control. In the framework of the cooperation, a piezoelectrical microrobot has been constructed, the parts of which have been prepared in Karlsruhe. The microrobot was installed at the Department of Control Engineering and Information Technology in Budapest. In this project, the Hungarian partner primarily concentrates on the control process and the measurement technique of the robot system due to its operation in the micrometer domain.

In the first part of the thesis I review the literature and fundamental concepts of microsystem technology and microrobotics. I define the fundamental concepts based on the literature and I provide a short overview of the special procedures applied in microrobotics. I also go into detail regarding researches going on in the leading industrial countries, and through this I present the importance of this area of science.

In the next part of the thesis I outline the operation principle and system technique of piezorobots. I present in detail the construction and specification of the microrobot as a universal prototype carried out at the Department of Control Engineering and Information Technology at the Tecnical University of Budapest. I intruduce my own dynamic model of the microrobot, which describes characteristics that are inevitable for the control of the robot. In this part I discuss the control system of the robot as well.

A control system so hard to be modelled as this microrobot can only be controlled accurately by sensor-coupled procedures. In the third part of the thesis I present the navigational sensor systems, which help to control the motion of the robot. In this section I describe a place and position measurement system. I analyse the special perception problems of the microscope examining the micrometer domain and the data processor environment.

In the final part, I summarize the results achieved till now and show how this project can be later developed.

OBJECTIVES OF THE RESEARCH TASK

From the several researches going on in the field of microrobotics, in this thesis I chose to deal with the feasibility questions of the mobile robot systems which are suitable for operations with high accuracy.

To achieve this goal I set the following subtasks that needed to be solved:

1. system technical construction of a multipurpose microrobot working cell;
2. system technique and control technology modelling of a piezoelectric-driven microrobot;
3. visual global position measurement of a microrobot working cell and local position measurement of its manipulator.

Setup and construction of a micromanipulation working cell

The determination of the research aims was based on the fact that currently microrobotics has no general system technique approach, which takes into consideration its microsystem technical features that are different from the features known in traditional robotics. Therefore, it became necessary to define the major tasks of mobile systems that are able to make complex operations and change place and position in a wider domain.

A further necessary condition of the researches was to define and establish a universal environment in which the majority of mobile microrobot applications are feasible. Such microrobot working cell makes it possible to examine and validate general and microsystem technique-specific features. The additional benefit of the working cell is that it caters for several researches in the field of sensor and control technology, making it even possible to implement and compare the different results.

System technique examination of piezoelectric-driven microrobots

The mobile microrobots operating in the working cell carry out their task in a relatively wide domain in space, hence extreme accuracy is essential if we want them to make their manipulation tasks. The examination of the controllability of robots needs the analysis of their motion. In view of the fact that currently there is no universally accepted microrobot prototype or model system, I examined the mechanical features of a piezoelectric-driven microrobot. My objective was to perform mechanical dynamic examinations on a typical microrobot equipment and to establish a model in the light of sensor technique which is applicable in a micromanipulation working cell.

Sensor systems of a micromanipulation working cell

According to my objectives, I set up a method for robot sensor technique solutions in a microrobot environment. The most fundamental task of the sensors of a microrobot working cell is to provide information to the signal processing unit regarding the physical features (position, orientation, power, moment, velocity) of the microrobot and its manipulator. In my thesis I present a visual sensor system suitable for position and orientation measurement of the microrobot working cell.

One of the key problems of microsystem technique is that because of technological reasons several parameters of any individually realized system differs from a model with ideal parameters, and the measurement of the parameters is rather difficult. Besides this come the insecurities of the macroenvironment, the final result being a multi-parametric non-linear system which is influenced by the environment significantly. Consequently, for controlling the position and the orientation of the robot system I propose a fuzzy- and neural network based control instead of a traditional control method based on accurate mathematical model. Actual implementational opportunities are hence not dealt with in detail.

RESEARCH METHOD, EXPERIMENTS, EXAMINATIONS

In the course of the research I reviewed and studied the most important microsystem researches that are currently running according to the literature. In the framework of this investigation I have dealt with the international microrobot and industrial research and development directions and applications.

The Department of Control Engineering and Information Technology at the Tecnical University of Budapest hosted the large-scale research work in the framework of which the construction of a micromanipulation working cell took place. The planning and construction of the sensor systems, the accomplishment of the the image processing algorithms and the experiments were carried out here. I made the examination of the micromanipulation working cell and the testing of the control algorithms at the Process Control, Robotics and Automatization Institute at Karlsruhe.

In the focus of the experiments at both institutes we placed a piezoelectric-driven microrobot, that was originally developed by the German partner. The piezoelectric-drive had the advantage that with a relatively little expenditure a mechanical system with high accuracy and small steps could be achieved. The piezoelec-drive made it further possible, that the system was not fixed-rail, but rather a mobile one.

The operational principle of the microrobot is the following: The robot stands on three identical, cylinder shaped, piezoelectric ceramics legs, which are supplied with five electrodes. Four electrodes are placed on the exterior surface of the leg, parallel with its longitudinal axis, and one electrode can be found on the interior surface. Voltage can be applied onto the electrodes (typically 100 V till 300 V), with which the extension, shortening and bending of the legs can be done. With the appropriate control of the electrodes of the three legs, the robot body can be moved on the workbench (glass plate) few µm away. Applying a sawtooth voltage function (with $U_{pp} = \pm$ 150 V), the microrobot can move with a maximal speed of 5 mm/s, continuously. An experimental manipulator is connected to the microrobot, as well; the connector ends as a shaped metal sphere. The metal sphere can be rotated with three piezoelectric legs, that are identical to the legs used for moving the microrobot body, which yields to the rotation of the manipulator itself. Therefore, the robot becomes a mobile system with five degrees of freedom: two translational and three rotational.

The microrobot is controlled with a microcontroller based multi-processor architecture connected through the serial and the parallel interfaces to the host computer. Separate microcontrollers are responsible for the movement of the robot legs and the manipulator, and for the communication with the host. The operational amplifiers are connected after the D/A converters that applies the voltage to the electrodes of the piezo legs.

It is important to emphasize that the research work started on a microrobot built at the University of Karlsruhe based on an experimental way. The creation of the mechanical model made it possible to plan the robot operations and a new prototype could be built using the results of the mechanical model. An advanced control electronics was built as well.

The examinations make the establishment of the contact between the microrobot and the external world necessary. Now, we understand that the definition of the „environment" of the microrobot is essential, that is universal and can be found in almost every industrial application. The micromanipulation working cell is defined on the Department of Control Engineering and Information Technology and all of the examinations and research works detailed below have been done in this working cell.

The basic steps (go ahead, go back, etc.) were established with instructions forwarded to the control electronics of the microrobot, and the manipulator is controlled on the same way. The examination of the robot motion and the positioning of the robot body and its manipulator require highly accurate position informations. Many of the microrobot applications do not make it possible to place sensors directly onto the robot body, or onto the manipulator. It is necessary to mention that in order to keep the absolute error of the measurement on a low level, the sensors are also adviced to place in a system that is fixed to the working cell and not to the mobile unit. The highly accurate manipulations do not make it possible in most cases to make any interaction except the manipulations, therefore, the measurement should be done on a visual manner without any physical contact to the system. Therefore, the position detection of the defined micromanipulation working cell is based on visual sensors.

One of the most important tasks of the micromanipulation working cell is the manipulation with high accuracy. The visual observation of the micrometric domain therefore requires the application of a microscope. The micromanipulation domain was illuminated by a parallel light source beside the diffuse background lighting, that enlightens the microrobot manipulator as well and projects a shadow onto the object surface. The camera fixed onto the microscope creates images on the manipulator and the image is sent to the host computer. The position of special points of the manipulator can be determined using image processing algorithms. Another measurement method was also investigated, that is based on the out-of-focus principle, primary in order to measure the orientation of the manipulator.

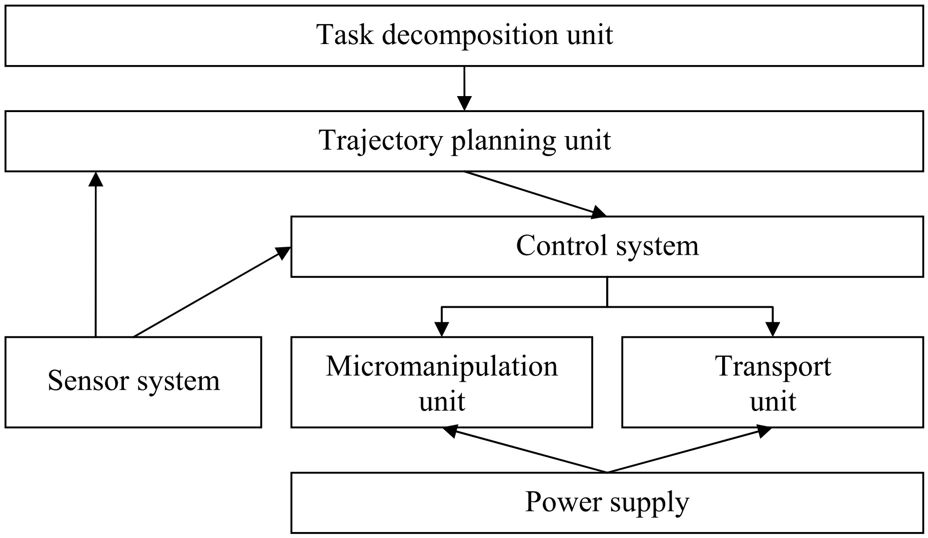
In order to measure the position of the microrobot, we placed active illumination (LEDs) to the robot body. The position and the orientation of the robot body can be defined on the camera image taken from suitable position using image processing algorithms. The procedures were implemented and applied on experimental objects and they provided acceptable measurement results.

The most considerable problem is the non-deterministic motion of the microrobot. Although, the robot approaches according to the pre-calculated trajectory, the manipulator does not get into the desired position in case of an open-loop control. This has more reasons. First, the control system uses the input data gained from the global sensor system, the accuracy of which is 0.1 till 1 mm only. The other problem is the local friction between the robot legs and the workbench, which is not known exactly. Finally, there are numerous insecurities due to the inaccurate shaping and assembly of the robot system and its components. The smallest error in the position of the legs may lead to a more considerable difference between the theoretical and the actual behaviour of the microrobot. Therefore, the sensor system has to fit into a closed loop control.

NEW SCIENTIFIC RESULTS

Thesis 1

I determined the system hierarchy of a micromanipulation working cell. The system technique of a micromanipulation working cell that is applicable for micromanipulations and transport tasks and set up from a microrobot mechanism, a sensor system and a control system, is drawn on the following block chart.



The task decomposition unit breaks down the global task given to the microrobot working cell into elementary steps and transfers them to the trajectory planning unit. The trajectory becomes the path input to the control system. The task of the unified control system unit is to operate the transport and micromanipulation unit in a variable and partially known environment, in order to carry out transport and manipulation tasks according to the trajectory. The small size of the systems makes it necessary, that both the micromanipulation and the transport unit shall take part in the manipulations, therefore the two units cannot be separated on the level of planning and control but on the level of operation. The transport unit moves the microrobot body, the micromanipulation unit rotates the manipulator. The power supply provides the neccessary level of signal and power. The sensor system measures the data of position and orientation of the robot body and of the manipulator and provides them to the control unit. Considerable changes in the working area and due to the inexact operation of the tranport and manipulation units, the microrobot system potentially can go out of the control domain. Therefore, the controlability of the system requires that the trajectory planner should re-plan the path based on sensor information.

Own publications [P1], [P4], [P5] and [P6] are linked to the results formulated in the thesis above.

Thesis 2

I set up a model to describe the dynamic behaviour of a piezoelectric-driven microrobot and I validated the model with measurements. The movement of a piezoelectric-driven microrobot making discrete steps is described by an approximate linear system model.

a) Based on electrostatic and solid-state models, the deviation ξ of a pipe-shaped piezoelectric actuator's end-point, when applying a mechanical force F and an electric voltage U is $\xi = k_F F + k_U U$, where constants k_F and k_U are functions of the geometry and the material constants of the piezoelectric actuator:

$$k_F = \frac{4}{3\pi} S_{11}^E \frac{l^3}{R_2^4 - R_1^4}$$

$$k_U = -\frac{8}{3\pi} d_{31} l^2 \frac{R_1^2 + R_1 R_2 + R_2^2}{R_2^4 - R_1^4} \cdot \sin\frac{\Phi}{2}$$

b) The movement of the microrobot can be described with a unit of second order, that is linear in stages. The movement equation of the microrobot in undamped case is as follows:

$$\ddot{x}(t) + \omega_0^2 x(t) = \omega_0^2 \left[p(t) - k_U U(t) \right],$$

where $x(t)$ is the position of the microrobot, $p(t)$ is the position of the piezoelectric actuator's end-point, $U(t)$ is the applied voltage on the electrodes, m is the mass of the microbobot, k_U and k_F are constants as above, and $\omega_0^2 = \frac{1}{mk_F}$.

c) Applying a sawtooth voltage to the piezoelectric actuator, the resulting movement of the microrobot is the superposition of a straight-line uniform motion and an oscillating motion in a steady-state. The position $x(t)$ and the velocity $v(t)$ time-functions of one period of the microrobot motion in steady-state are as follows:

$$x_T(t) = \left[\frac{2U_0 k_U}{T} t - \frac{\mu g}{\omega_0^2 \sin\frac{\omega_0 T}{2}} \sin \omega_0 t \right] \cdot \varepsilon(t), \qquad \text{if } 0 \le t < T/2;$$

$$x_T(t) = \left[\frac{2U_0 k_U}{T} t - \frac{\mu g}{\omega_0^2} \left(\frac{\sin \omega_0 (t - T)}{\sin\frac{\omega_0 T}{2}} + 2 \right) \right] \cdot \varepsilon\left(t - \frac{T}{2} \right), \qquad \text{if } T/2 < t \le T;$$

$$v_T(t) = \left[\frac{2U_0 k_U}{T} - \frac{\mu g}{\omega_0 \sin\frac{\omega_0 T}{2}} \cos \omega_0 t \right] \cdot \varepsilon(t), \qquad \text{if } 0 \le t < T/2;$$

$$v_T(t) = \left[\frac{2U_0 k_U}{T} - \frac{\mu g}{\omega_0} \frac{\cos \omega_0 (t - T)}{\sin\frac{\omega_0 T}{2}} \right] \cdot \varepsilon\left(t - \frac{T}{2} \right), \qquad \text{if } T/2 < t \le T,$$

where U_0 is the amplitude of the sawtooth voltage, T is the period-time, μ is the friction constant between the piezo legs and the working surface defined macroscopically, g is the gravity constant.

d) The average velocity of the microrobot in a steady-state is $\bar{v} = \frac{2}{T}\left(U_0 k_U - \frac{\mu g}{\omega_0^2}\right)$, the length of one step is $L = 2\left(U_0 k_U - \frac{\mu g}{\omega_0^2}\right)$.

e) Based on the evaluation of the singularities of the model, the working domain of the piezoelectric-driven microrobot is determined as follows:

$$\mu \le \mu_{\max} = \frac{U_0}{mg}\frac{k_U}{k_F}.$$

Own publications [P2] and [P7] are linked to the results formulated in the thesis above.

Thesis 3

I created a mathematical model to describe the change of the position and the orientation of the microrobot and I worked out a parameter estimation procedure to determine the position and the orientation of the microrobot from measured marker positions. The position and the orientation of a mobile microrobot system having 3 degree-of-freedom and making discrete movements are defined by the chain of operators describing the elementary steps. The position and the orientation of the robot can be determined by a parameter estimation procedure based on an orthogonal projection from contactless measures of markers placed on the robot body.

a) The matrix $\mathbf{M}_i$ of the position and the orientation of a discrete-step microrobot after the step i can be chained from the elementary steps defined by the *STEP* operators ($\mathbf{O}_{j,j+1}$):

$$\mathbf{M}_i = \mathbf{O}_{0,1} \cdot \mathbf{O}_{1,2} \cdot \ldots \cdot \mathbf{O}_{i-1,i}$$

where the *STEP* operator $\mathbf{O}_{j,j+1}$ contains the shift and rotational transformation defined in the co-ordinate system ${}^{j}K$ in the step j of the microrobot, $\mathbf{M}_i$ is the matrix formed from the position $x_{RKP,\,i}$ and $y_{RKP,\,i}$ and from the orientation φ_i of the microrobot center:

$$\mathbf{M}_i = \begin{bmatrix} \cos\varphi_i & -\sin\varphi_i & x_{RKP,i} \\ \sin\varphi_i & \cos\varphi_i & y_{RKP,i} \\ 0 & 0 & 1 \end{bmatrix}.$$

b) The least-square estimate of the position and the orientation of the robot $\hat{\mathbf{m}}$ can be determined from n markers' positions $\mathbf{p}$ placed on the mobile microrobot body and measured by visual sensors:

$$\hat{\mathbf{m}} = \left(\mathbf{X}^T\mathbf{X}\right)^{-1}\mathbf{X}^T\mathbf{p}\text{, where}$$

$$\hat{\mathbf{m}} = \begin{bmatrix} \hat{r}_1 \\ \hat{r}_2 \\ \hat{t}_x \\ \hat{t}_y \end{bmatrix} \quad \mathbf{p} = \begin{bmatrix} x'_1 \\ y'_1 \\ x'_2 \\ y'_2 \\ \vdots \\ x'_n \\ y'_n \end{bmatrix} \quad \mathbf{X} = \begin{bmatrix} x_1 & -y_1 & 1 & 0 \\ y_1 & x_1 & 0 & 1 \\ x_2 & -y_2 & 1 & 0 \\ y_2 & x_2 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots \\ x_n & -y_n & 1 & 0 \\ y_n & x_n & 0 & 1 \end{bmatrix},$$

i.e. the parameter matrix $\mathbf{X}$ contains the known position of the markers in the local co-ordinate system of the robot, vector $\mathbf{p}$ contains the position of the markers from the visual measurement in the world co-ordinate system, vector **m** contains the position t_x and t_y of the center of the robot and the orientation φ (r_1 = cos φ és r_2 = sin φ) of the robot body.

Own publications [P3] and [P8] are linked to the results formulated in the thesis above.

APPLICATION OF THE RESULTS

In Hungary, a research project in the field of microrobotics was first started on the Department of Control Engineering and Information Technology at the Technical University of Budapest. In this research, the author undertook a significant role. Considerable theoretical and experimental research works have been accomplished in this topic during the last ten years. The Microrobot Laboratory was established in the frame of the research project and it also provided the infrastructure for several scientific student reasearches (TDK), graduate theses and doctoral researches.

Microrobotics is a relatively new research area, which combines the latest results of robotics, signal processing, microsystem technology and sensor techniques. Several realized application examples can be found in the literature that use microrobot systems to the accomplishment of special tasks. The considerable part of the experimental realisations gives solution to special task exclusively. In the future, the elaborated versions of these systems are expected to be applied in mass production of microsystems. But systems with general aim are not known that could be applied in a mobile environment. The importance of such systems is significant in case of production of microsystems, testing and production control. The piezoelectric-driven microrobot investigated in my research is such a general aim system. Its system analysis provided a mathematical model to plan, produce and operate microrobots with a similar operation principle.

Microrobotics becomes part of the educational activity of the Department. Several lectures, among others „*Intelligent Systems*", „*Machine Vision*", „*3D Vision Systems*" and „*Robots and Sensors*" deal with sensor technique, control technology and signal processing problems of microrobotics and provides them as examples of robot applications. The realized microrobot devices are applied in measurements of practice lectures of „*Intelligent Robots*" and „*Autonomous Systems*".

Several research activities also started in the field of microrobotics: optimal trajectory planning of mobile robot systems, cooperation procedures in multi-agent systems, that aim to solve robot control tasks in special microrobot environment.

The microrobot research activity created additional scientific cooperation area with the Institute of Process Control, Robotics and Automatization (IPR) at University of Karlsruhe and other partner institutes of European universities in the field of sensor technique and control technology. In this framework, Hungarian students made research and graduate theses at the foreign partner institutes, and guest lecturers were also invited. The common results were also published in scientific journals and international conferences. Cooperation was also established with the Institute of Measurement and Automation at the Budapest College of Technology (BMF) in the field of fuzzy-based control of microrobots.

The establishment of the Microrobot Laboratory was financially supported by the Volkswagen Foundation. In the past years, some domestic and EU projects were successful and made it possible to extend the tool set of the laboratory.

Microtechnology and nanotechnology are key target areas of the EU FP7 frame program. The Department of Control Engineering and Information Technology is about to apply with a partner university on the reasearch area of microrobotics (health industry application) and therefore, we plan to continue the research project in microrobotics.

PUBLICATIONS

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