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Modelling Procedure and Development of Piezo Actuated Mechatronic Systems

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1. Introduction

The rapid growth in the last few years of high technologies such as micromanipulation, nanotechnology, scanning tunnelling and atomic force microscopy, etc. [5, 6, 8, 12, 16, 17, 18] has lead to the need of fast and appropriate modelling of components and systems for these technologies. Such systems are mostly piezo actuated and we shall further call them Piezo Actuated Mechatronic Systems (PAMS).

This paper deals with the user friendly modelling procedure development and techniques for PAMS. Because of the complexity of the problem an interactive approach for the development of modelling procedure is introduced [2, 3, 4]. It is based on expert model oriented solutions in order to help the development process. As a more detailed description the following steps are considered:

2. Theoretical background (Piezo actuator tutorials)

The advantages of the piezo actuators over the conventional ones, as the most used in micropositioning and nano-positioning actuators, should be discussed.

Advantages: *Unlimited Resolution, Large Force Generation, Fast Expansion, No Magnetic Fields, No Wear and Tear, Vacuum and Clean Room Compatible, Operation at Cryogenic Temperatures.*

Unfortunately together with the advantages some disadvantages are also present: *Small displacement, High operating Voltages, High price.*

There are two main types of piezo actuators (Fig. 1), stack and bimorph [16, 17]. The following features should be considered in order to choose the appropriate actuator:

- *Basic designs of piezo actuators.*
- *Low Voltage and High Voltage PZTs.*
- *Resolution.*
- *Open and Closed Loop Operation.*
- *Dynamic Behaviour; vi. Stiffness.*
- *Load Capacity and Force Generation.*
- *Protection from Mechanical Damage.*
- *Power Requirements.*
- *Mounting Guidelines*

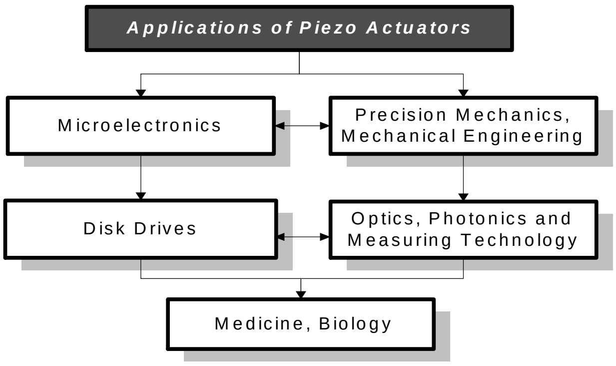

Fig.1. Applications of piezo actuators

3. Task formulation (branch oriented task modelling). Multilayer design approach

The task formulation is one of the most important stages in the development of a certain system. As a first step the pre-design of micromanipulation systems we consider the statement of the need. The reference task function, which has to be achieved by the micromanipulation systems to be designed is considered in dimensional, energetic and working spaces. The micromanipulators discussed are used for precise product orientation in the work space and successive manipulation or feeding during given operations, such as cell penetration, assembling, investigation of thin films, in atomic force microscopes and scanning tunneling microscopes [8, 12, 16, 17, 18]. To achieve the desired accuracy and functionality of the micromanipulation systems is the main goal of the design engineer.

During the last decade, it was emphasized that the design of a system implies not only an intuitive act of simple creation, but also the use of obtained results by means of analysis, optimization, and interpretation. The high strategies that are involved in the achievement of a CADS system improve the design process and ensure a higher quality of the end product and of its control especially before the product's prototype was realized. The cycles, which a mechanical system has to go through before it could be launched on the market, is shown in the upper side of Fig. 2.

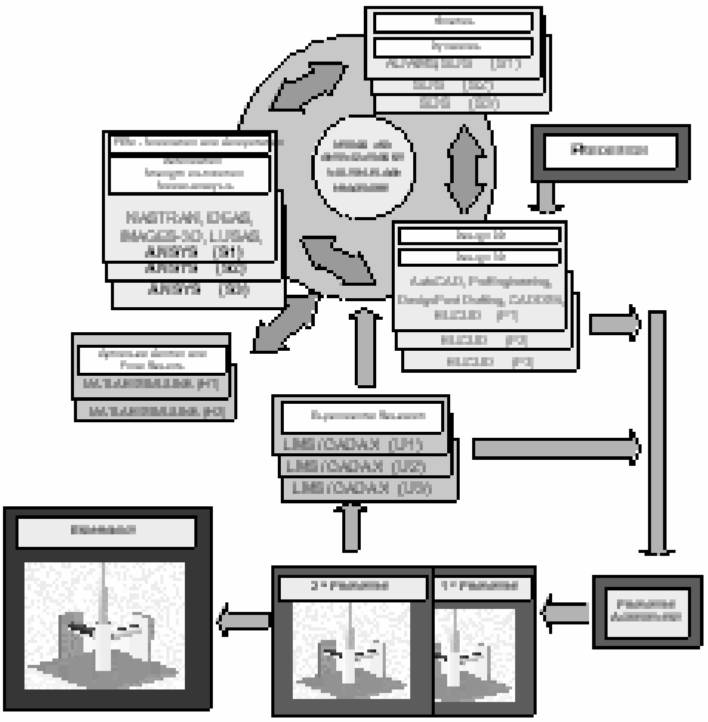

Fig. 2. Cycles of design and optimization with integrated strategies. Ways towards the optimized design and control

The first step of the cycle is represented by the Predesign. The initial project is designed with a dedicated design program such as AutoCAD, Pro-Engineer, CADDS5, EUCLID, etc. One obtains the first basis for simulation and computation with solid bodies procedures. The simulation model is obtained by means of interface data transfer. A good accuracy of model description may be directly obtained by using the own constructor & design modules of the simulation programs (such as ADAMS, SDS, etc.). The SDS-Software used in this paper, deals with 3D-modeling, computing, and animation of multi-body solid systems. At this level, the system could be optimised and controlled. The finite elements (FE) analysis is achieved on the partially improved SDS-model. Usual software tools, such as ANSYS, NASTRAN, etc. are involved. They compute deformations, eigenvalues, and distributions of strength. They also perform modal analysis of the studied system. The analysis will be normally repeated several times (S1, S2, S3) until an optimised solution is achieved. Several variants of (pre)projects (P1, P2, P3) were developed from optimisation stages on SDS and/or ANSYS. Additionally, results of simulation built a data set for the improved control.

The regulators used in order to control the system could be implemented in MATLAB/SIMULINK, or directly in SDS. The prototype, obtained as design after all these operations, will be practically achieved and experimentally tested (for example with LMS/CADAX). In case of unsatisfactory results, further optimisation activities by multiple loop procedure should be resumed.

The final product is the system with an optimised structure achieved by repeating the design and optimisation cycle. The stationary and transient information, resulted as the end of the design loops, is involved in the further control processing of the installation.

4. Criteria of comparison (A quality expert analysis)

In order to find the appropriate model for the proposed manipulation task, the following criteria for comparison of the different manipulator structures are used:

- *Number of DOF of the micromanipulator.*
- *Type of the kinematic structure.*
- *Number and type of the actuators.*
- *Optimum of coincidence of working space image with the configuration one*
- *Dimensions of the micromanipulator.*
- *Mounting and sensing possibilities.*
- *Minimum of task function deviation.*
- *Desired kinematic and dynamic accuracy*

After a certain model is chosen, different components of the robot should be analyzed. Further criteria of comparison are introduced. The criteria are introduced for 3 groups of elements: *actuators, amplifier/controllers and sensors* (Fig. 3).

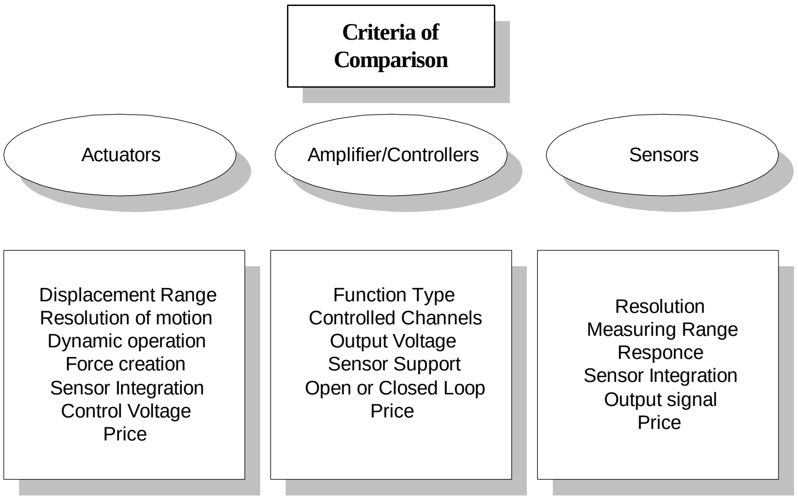

Fig. 3. Comparison criteria for PAMS components

5. Theoretical modelling of piezo actuators

In order to represent, observe and control a piezo actuated system, first a theoretical modelling is done. There are several possibilities to obtain a mathematical description of a physical system's behaviour. Mostly, the *energy* methods and the methods based on *satisfying equilibrium* conditions are used. In addition to these two approaches are also used, e.g. the experimental system identification, the bond-graph method, etc. [11].

The analytical presentation of the piezo effect is done according to the following formula:

(1) $$D = dT + \varepsilon^{T} E\,,$$

(2) $$S = s^{E} T + d_{t} E\,.$$

Definition. S = strain = constant (mechanically clamped), T = stress = constant (not clamped), E = field = constant (short circuit), D = electrical displacement = constant (open circuit), d – shows the power of piezo effect, ε^{T} – the dielectric constant at T = const, s^{E} – the elasticity constant at E = const.

The piezo element can be presented as an ideal condenser on the input, and as a spring system on the output (PT_2), Fig. 4a, [5]. Hence, a piezo actuator can be presented as a mass-spring-damper system (Fig. 5.) with the transfer function:

(3) $$\frac{K}{1 + T_1 s + T_2^2 s^2}\,.$$

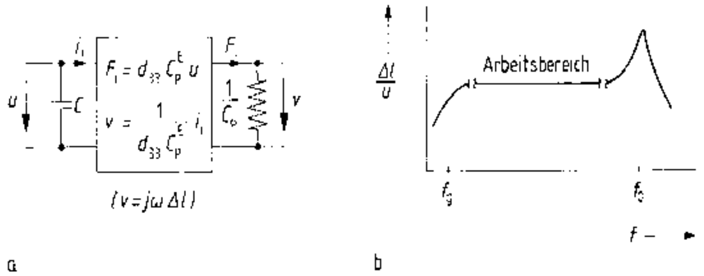

Fig. 4. Schematic presentation and working range of a piezo actuator

An example of simple stack actuator-lever system is presented in Fig. 6. The *Lagrangian formulation* of dynamics is used to obtain the equations of motion

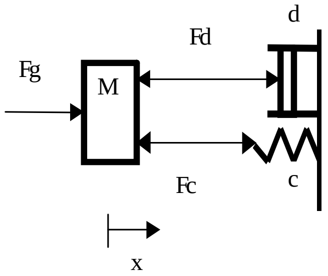

Fig. 5. Stack actuator as mass- spring-damper system

The generalised coordinates (5) according to the Lagrange equation (4) and Fig. 5 are:

(4) $$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right)-\frac{\partial L}{\partial q_i}=Q_i \qquad \text{with} \quad L=E_C-E_P\,,$$

(5) $$q_1=x,\quad \dot{q}_1=\dot{x},$$
$$q_2=\varphi,\quad \dot{q}_2=\dot{\varphi}.$$

These and other theoretical considerations are later used for the modelling and simulation of PAMS. SDS model of the system in Fig. 6 is presented in Fig. 9.

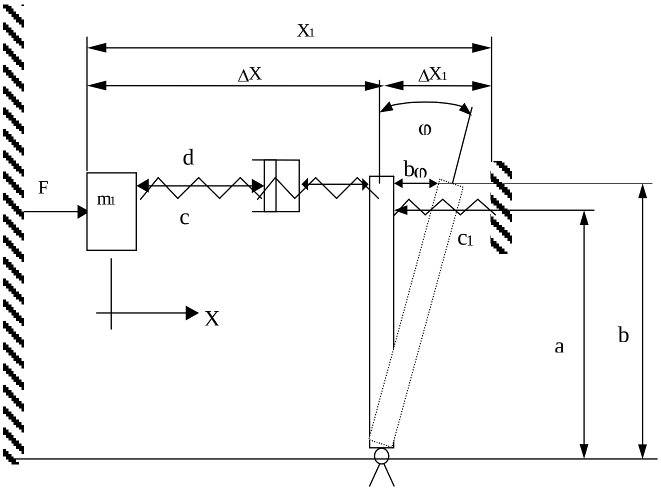

Fig. 6. Stack actuator-lever system

6. FEM and solid bodies modelling and simulation

The simulation of the robot, like for any machine or plant, represents an important step towards its successful development [10, 11, 13, 14, 15, 19]. Some examples of simulation with the SDS Program are shown in Fig. 8 to Fig.11. The program gives the opportunity to process dynamic mechanisms in 3D in the following way:

- *Dynamic calculation of a mechanism composed of rigid bodies.*
- *Kinematic computing (law of forced motion on the articulations of the mechanisms).*
- *Complex calculation (laws of forced motion on the articulations of the mechanisms, free motion on other joints and possible closing of remaining joints).*
- *The calculation of flexible bodies using modelisation of multi-jointed parts.*

The block-algorithm in Fig. 7 [19], shows the steps and procedures in solving theoretical and practical tasks.

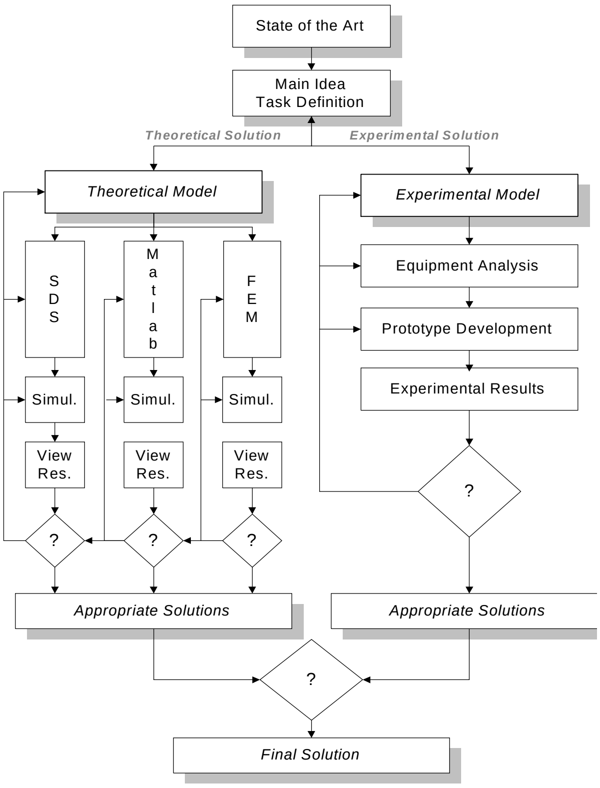

Fig. 7. Design process algorithm of PAMS development

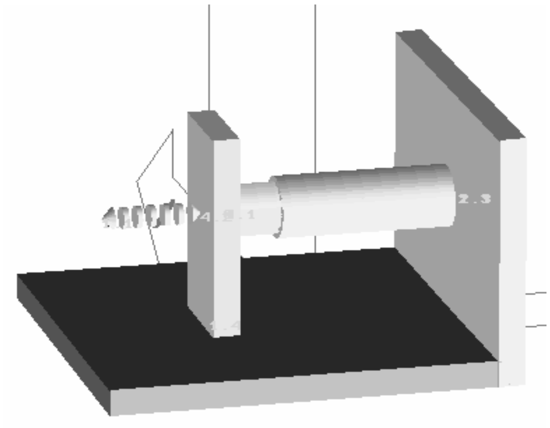

Fig. 8. One DOF actuator-spring system

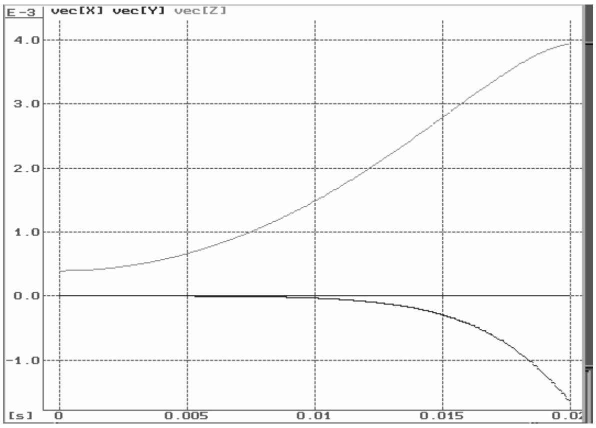

Fig. 9. Components of the force vector

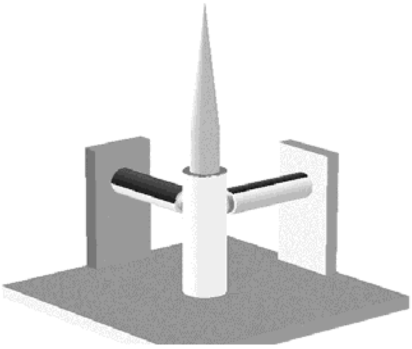

Fig.10. 3-DOF (stack) piezo actuated manipulator

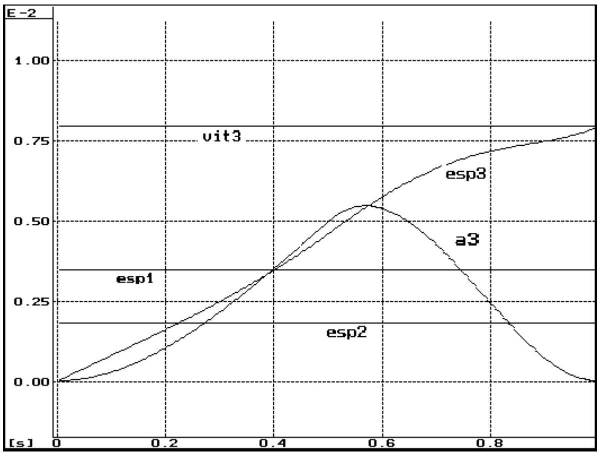

Fig. 11. Motion parameters of the end-effector

7. Steps towards achievement of an experimental prototype

The criteria are obtained on the basis of analysis of the available actuators and appropriate sensors, amplifiers, controllers and devices. The alternative rules are introduced to simplify the interactive process of designing and investigation.

- *Intelligent Control Requirements*

In order to achieve the high accuracy of the micro positioning systems a position servo control is needed. The advantages of the position servo control are:

- ➢ *very good linearity, stability, repeatability & accuracy;*
- ➢ *automatic compensation for varying loads or forces;*
- ➢ *virtual infinite stiffness (within load limits);*
- ➢ *elimination of hysteresis and creep effects.*

The scheme in Fig. 12 shows a typical closed loop servo control of piezo actuated micromanipulation system.

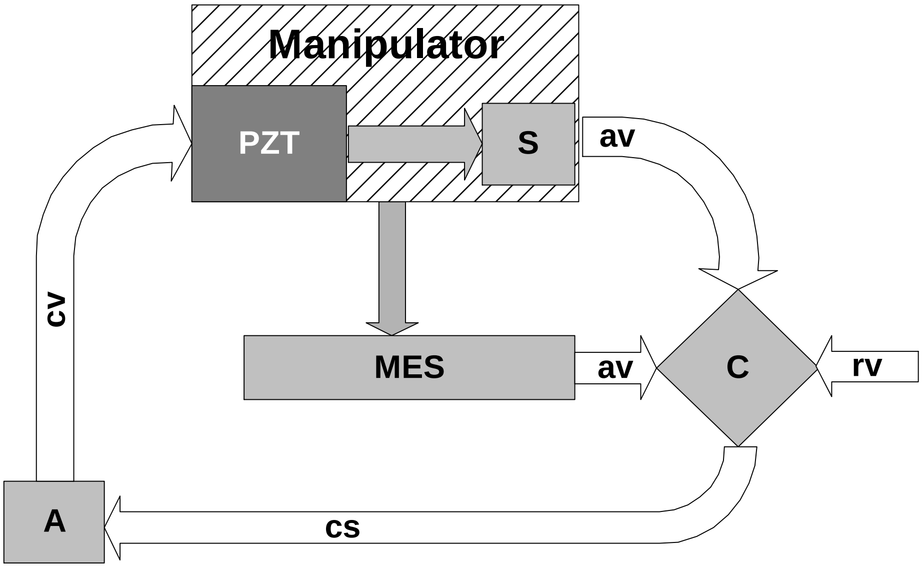

Fig. 12. Closed-loop servo control block-scheme
(PZT – piezo actuator; S – sensor (actuator); MES – sensors (manipulation system);
C – controller; A – amplifier; av – actual value; rv – reference value; cs – control signal;
cv – control voltage)

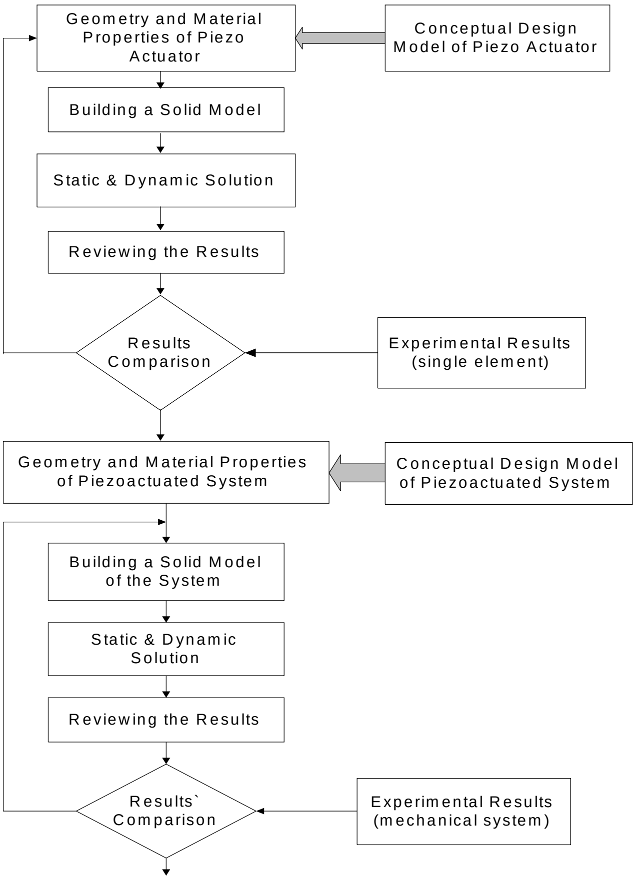

Fig. 13. Algorithm for piezo actuated system FEM analysis

The block-algorithm in Fig. 7 [19], shows the steps and procedures in solving both theoretical and practical tasks. As a sub-step during the theoretical development of a PAMS model (in this case by the FEM based program ANSYS), the following algorithm is considered (Fig. 13) [3].

For the successful development of a prototype micromanipulator the following steps should be also taken into account:

- *Power Supplies Requirements.* Electronics play a key role for maximum performance of piezo translating stages and piezo driven NanoPositioning systems such as Flexure NanoPositioners or Tip/Tilt Platforms. Since a piezo actuator transforms even sub-millivolt changes of the control voltage into a movement, it is important to use low noise, high stability servo controllers and amplifiers. For dynamic applications, piezo actuators require high charge and discharge currents. Those requirements are best met by power amplifiers that can output and sink high peak currents while the average current is of secondary importance.
- *Sensors Requirements.* The micropositioning systems are with a very high accuracy, hence, sensors with very high resolution are necessary for the position,

speed and force control of piezo actuated systems. Closed loop bandwidth of a PZT/sensor/servo controller system is limited by the mechanical and electrical properties of the system. The following features of different high resolution sensor types used for closed loop control of PZT actuators.

- *Strain Gage Sensors* – high bandwidth, extremely small, long term position accuracy,cost effective
- *Linear Variable Differential Transformers (LVDT)* – good temperature stability, controls the position of the moving part rather than the position of the piezo actuator, cost effective, extra space for mounting required
- *Capacitive Sensors* – highest resolution of all commercially available sensors, excellent long term stability, excellent frequency response, extra space for mounting required.

Based on the theoretical and simulation results an experimental set-up (Fig.14) including microrobot prototype has been developed. The general view of the experimental set-up is shown on Fig.15. Strain gauge sensors are applied as a full Wheatstone bridge. They operate by preamplifier AE101 HBM®. For the data sensor acquisition the data acquisition board from National Instruments is used, i.e. NI-DAQ LAB PC$^+$ board with the corresponding NI-DAQ 4.9 application software. A laser line emitter with differential diode is used for measurement and calibration purposes. As a controlled power supply for the piezo actuators with capacitive loads a PC card power supply NV C1 [13] is used. It can drive with nanometer resolution up to three axes via virtual control instruments designed in LabView.

Preliminary experimental results for orientation and the translation obtained are in the range of 0–1.10 mrad and 0–65 μm and resolution of 10 nm.

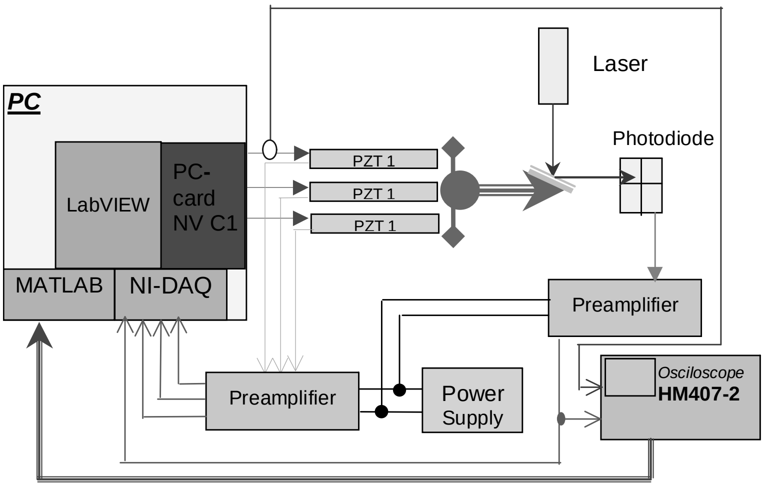

Fig. 14. Block scheme of the experimental set-up

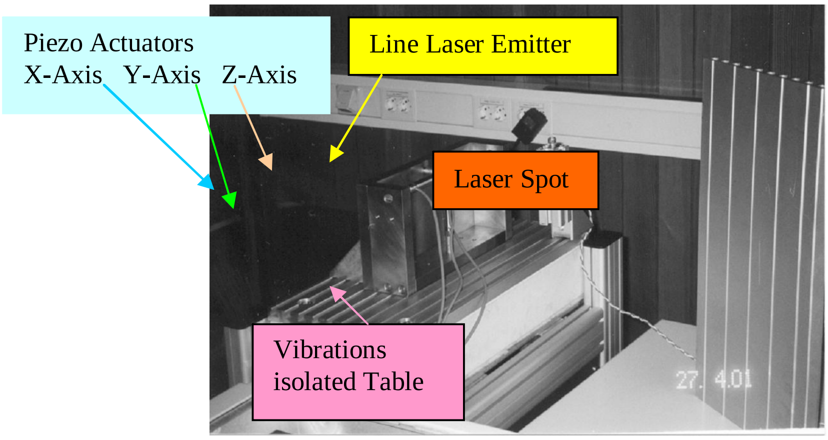

Fig. 15. Photo of the microrobot experimental set-up and laser unit for displacement measurement

8. Conclusions and future work

The paper shows how a researcher can faster develop a PAMS, particularly a microrobot for cell manipulations, based on the developed procedure and the self-accumulated research experience.

Here the microrobot experimental set-up is also presented. Experimental results for orientation in X and Y direction in a range of 240 arc sec and for translation in Z direction in a range of 65 μm are obtained with resolution of 10 nm.

The paper shows some of the experience of the researchers gathered during the project “Modelling and Simulation of Piezoactuated Microrobot for micro and nanomanipulators” sponsored by DAAD & DFG.

The control of the microrobot using LabView is under development.

The modelling procedure considered here is mostly oriented as an educational tool for a virtual learning process. It is a module of a Virtual Mechatronics Lab under development.

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Процедура моделирования и развитие пиезо-активируемых мехатронных систем

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(Резюме)

Обсуждается развитие пиезо-активируемых мехатронных систем для микро- и наноманипуляций. Синтезирана кинематическая структура микроробота, основанная на пиезоелементы. Симуляция осуществляется при помощи SDS програмы. Показаны экспериментальные результаты для ориентации в X и Y направлении и для трансляции в Z направлении в диапазоне микро- и нанометрах.