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# IMPEDANCE SCALLING APPROACH FOR TELEOPERATION ROBOT CONTROL

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***Abstract:*** *Impedance scaling approach presented in this paper is specially developed for teleoperation robot control to meet requirements to control robots and mechatronic systems with completely different dimensions and mechanic characteristics than the human operator. It is applied to the developed RoTeMiNa robot system with 6 DOF and to the mechatronic handling device with 3 DOF for micro and nano operations. The hybrid approach transferring operator motion and manipulation skills for control of the robot system for cell micro and nano manipulations is based on visual/haptic interface.*

***Key words:*** *impedance scaling, telemanipulation control, micro/nano robot.*

## 1. INTRODUCTION

Generally, the teleoperation robot control approach is applying when the human operator can't be physically there or it is pretty dangerous for him. Any micro and nano motion system is pretty difficult for the operators manipulating without the assistance of human interface. Sometimes the manipulation, *e.g.*, intracytoplasmic sperm injection, is necessary to do minute operation precisely by micrometer order [1]. In this case the manipulator is used to perform physical operation (micro and nano manipulation) to gene, nucleus, or embryo. However, this operation really depends on operator's skills and the efficiency of this task is very low. Therefore, the automation of this operation by flexible robot system with teleoperation control, improving the effectiveness of cell manipulations is strongly required.

A flexible robot system for micro and nano manipulations has much potential for bio engineering and research and industrial applications, for example cell manipulations and penetration/injections, DNS handling, exploring micro and nano physics, manipulation or assembly of mechanical micro objects, handling a micro electrode in quality control tasks, etc. In micro or nano robotics high precision movement in two or more degrees of freedom is one of the main problems and challenges [2]. Firstly, the positional precision has to be increased (< 10 nm) as the object sizes decrease. On the other hand, the workspace has to have macroscopic dimensions (> 1 $cm^3$) to give high maneuverability to the system and to allow suitable handling at the micro/nano-to macro-world interface.For the control of micro and nano robots two approaches, namely teleoperation approach or automatic manipulation are utilized. Direct teleoperation approach can realize tasks requiring high-level intelligence and flexibility. It is slow, not so precise, not exactly repeatable and engaged in many complex and challenging scaling problems. However, the task–oriented approach avoided those problems by executing only the given task in closed-loop autonomous control [3]. In the automatic control approach the robot has a closed loop control using sensor information without user intervention. The problems characterizing the automatic control in the micro and nano world are not reliable at present due to complexity of the micro and nano dynamics, difficulties in nano positioning and real time visual feedback, changing and uncertain physical parameters, and insufficient models and intelligent control strategies [4].

Two teleoperated control approaches are known – direct teleoperation and task-oriented teleoperation. In the first one the human wealth of experience in manipulation tasks is used. The operator manipulates directly in the robot control-loop using a man-machine interface. Dexterous telemanipulation enables a user to interact with the environment from a real world into the micro or sub micro world. In the case when humans use telemanipulation device only to move objects than the reaction force from the far environment has no significant effect on the performance, then measurement of the operator's position and visual feedback may be enough.

Different teleoperation techniques for micro parts handling [5], micro assembly [6], remote controlled tele nano manipulation [7–8] are developed to improve the effectiveness of the robot with control system based on the operator skills for manipulation in the micro and sub micro world. Mainly they are closely connected to reference micro and nano operation technique.

In design of any teleoperation systems, it is important to have task-based performance goals rather than trying to achieve a marginally stable, physically unachievable ideal teleoperator response [9]. This conclusion is fundamental in the development of the hybrid teleoperation control approach [9].

This paper deals with the development of impedance scaling for that approach [9] with position and visual feedback transferring operator motion and manipulation skills for control of the robot system with 6 DOF specially developed for cell manipulations. The robot key features and the hybrid teleoperation control approach for cell micro and nano manipulations using the advantages of both approaches for teleoperated robot control are also shortly presented.

## 2. IMPEDANCE SCALING FOR HYBRID TELEOPERATED ROBOT CONTROL APPROACH

Telemanipulation is a process where the operator has to do some tasks at the far environment where he cannot be physically. Telemanipulation is divided into two strongly coupled processes. One process is the interaction between the operator and the master device, the other one is the interaction between the slave device and the far environment contact. The master device represents the macro world at the operator site, and the slave device represents the operator at the remote site – micro or nano-world. When humans use telemanipulation device only to move objects than the movement with reaction force from the far environment which has no significant effect on the performance, then measurement of the operator's position and visual feedback may be enough. But if such tasks have to be performed when the reaction of the environment is important and significant then we need force feedback. In the case, subject of this study, only position and visual feedback are used. But, to improve efficiency of cell micro- and nano manipulations for which the operator has neither experience nor knowledge it is necessary to give perception to the operator that he is manipulating with familiar object.

But if such tasks have to be performed when the reaction of the environment is important and the slave device can make damage in the far environment like when screwing a bolt or assembling something, then we need force feedback to the operator.

In the micro-teleoperation task, the physical size of the environment and slave differs greatly from that of the human operator (master joystick), therefore it is necessary to scale up and down the informations (force and motion) exchanged between them. There are basically two approaches: linear and nonlinear scaling. In the case of linear scaling a single corresponding constant $\alpha_{s,i}$ is used between the nano/ micro robot positions $x_{R,i}$ and macro joystick angular positions $\phi_{j,i}$ :

$$x_{R,i} = \alpha_{s,i}\phi_{j,i} \,. \tag{1}$$

The two usual used scaling methods are the geometric scaling and the impedance scaling.

Scaling is one of the most important factors for successful performance of the teleoperated micro and nano manipulation since there is a large difference in the scale between the master and slave robot.

In this case the human operator has no perception about the robot end-effector dynamics and space size in which it manipulates.

Since the design of the teleoperation robot system must be based on human perceptual capabilities [10], it is necessary to quantify human perceptual capabilities, and to have means to incorporate them into the control design (design methodology, tools, and proper formulation). To improve the effectiveness of the teleoperation control is necessary the robot dynamics to be known to the operator or to be modeled to the human characteristics considered as an operator in the control system.

Hence, in the case of cell micro and nano manipulations a haptic interface has to provide the operator with the feeling that he knows the dynamics of the objects to be manipulated. This could be realized by introducing a mechanical impedance characterization, which is nonlinear scaling with corresponding constant $z_{s,i}$. It is also called impedance scaling.

The robot dynamics can be assigned to virtual coupling mechanical impedance Z, appropriate for the operator to manipulate in the micro/nano world as in familiar for him real world, as follows:

$$M\ddot{x}_{R,i} + B\dot{x}_{R,i} + Kx_{R,i} = F_i \,. \tag{2}$$

In this case the macro joystick angular positions define the force $F_i$ by which the robot axes characterizing by their impedance parameters assigned preliminary will be driven, by: $F_i = z_{s,i}\phi_{j,i}$.

Reference mechanical impedance is determined by the desired dynamic interaction, *i.e.* the dynamic accuracy [11]:

$$\begin{aligned} [\Delta E] = \sum_{1=0}^{2}\{[p^i x_r] - [p^i x_a]\} = \\ = \Delta x_d + \Delta v_d + \Delta a_d = [F][Z^{-1}] \end{aligned} \tag{3}$$

$[p^i x_r]$ and $[p^i x_a]$ – reference and actual motion parameters; $\Delta x_d$, $\Delta v_d$ and $\Delta a_d$ – position, velocity and acceleration errors, $p$ – Laplace's operator.

The dynamic error could be expressed by the coefficient of unevenness:

$$K_u = \frac{1}{A_1}\sqrt{\sum_{j=2}^{n} A_j^2} \,, \tag{4}$$

where $A_j$ are the magnitude of each $j$-the term of the Fourier series describing the output link motion.

In this way the robot will manipulate with the micro/nano object with its dynamics appropriate for the operator. This dynamics of interaction between the human operator and the robot can be modified and adjusted in any time. Hence, in this way the teleoperation control can realize a desired dynamic coupling between the macro and nano world.

## 3. ROBOT FOR CELL MICRO AND NANO MANIPULATION WITH IMPEDANCE SCALING UTILIZATION

To analyze the effects of impedance scaling method on the performance and the dynamic characteristics of the human operator, a master-slave robot system for cell micro and manipulations is utilized. High quality teleoperation and haptic interaction depends critically on advanced mechanism designs for both master and slave sides. Key issues are stiff structures and linkages, actuators with high torque/mass ratios and high linearity, compactness, high resolution position sensors.

In the case of cell micro and nano manipulations a teleoperation robot system (Fig. 1) with 6 DOF is developed [9]. It has 6 active joints (4 translational and 2 rotational) and a passive one, which is rotational. The robot

**Fig. 1.** General View of the robot system equipped with Microscope Carl Zeiss Axiovert 200.

RoTeMiNa is constructed by the integration of the piezo actuated nano robot [9], as a local robot structure, and micro robot positioning *xyz*-table as a regional robot structure, which position the robot end-effector into the reference-working zone. *X* and *Y*-axis of the robot regional structure have a range of 55 mm, while *Z*-axis – 100 mm.

A more compact and stiff structure than the first prototype of the nano robot with 3 DOF [12] has been specially designed. Two of them are 2 rotational joints around *x*- and *y*-axis in a range of 100 arcsec with actuator resolution of $1.6 \cdot 10^{-3}$ arcsecφ. The last joint is a translational one with a stroke of 65 μm and resolution of 1 nm. The positioning sensors here used are strain gauge sensors, integrated into the actuator body with resolution of 35 nm.

Here the most important tasks to be decided are how stable and high performance control can be obtained in spite of highly variable human operator and environment dynamics (Fig. 2.), time delays in communication channel, and other effects such as hysteresis, etc.

To meet this requirements the hybrid teleoperation approach is developed as a combination using haptic interface via PC keyboard and a master joystick and visual feedback via Carl Zeiss Microscope Axiovert 200 [13] equipped with AxioCam HRm with basic resolution of the sensor 1300 × 1030 pixels [14] and AxioVision software. The control concept realizing the hybrid teleoperated approach with impedance scaling is presented in Fig. 3.

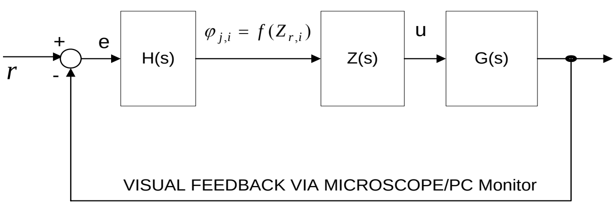


**Fig. 2.** Block diagram for teleoperated control with impedance scaling including the human operator: (*r* – reference, *e* – perceived error, *u* – control actions, *y* – control variable, *H*(*s*) – human operator transfer function, *Z*(*s*) – impedance scaling function, *G*(*s*) – controlled robot).

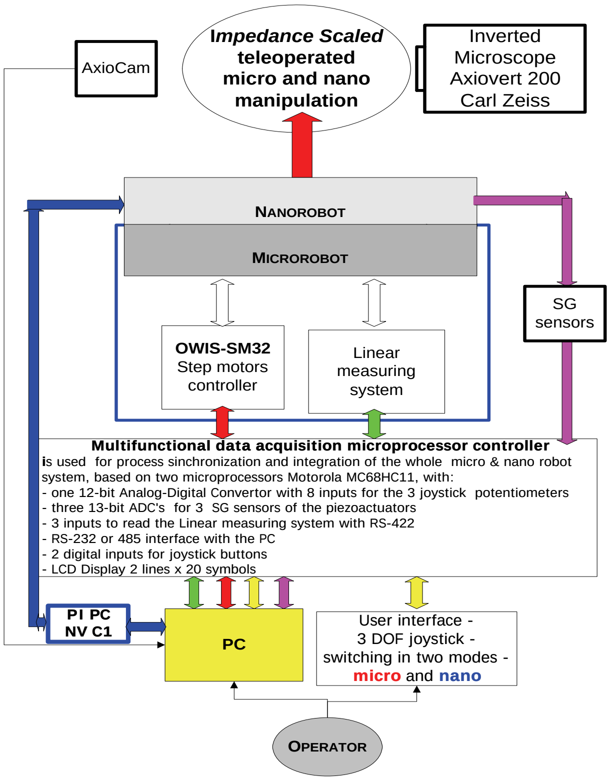


**Fig. 3.** Block diagram of the robot control concept.

As a master robot a joystick MACH-IV with 3 DOF is used. It has also start/stop button for automatic execution of cell penetration and switch mode button. The last one is used to switch either the macro positioning guidance of the regional robot structure in micro mode or to perform desired nano manipulations in nano mode.

Specially developed multi-functional data acquisition microprocessor controller MSD is used for process synchronization and integration of the whole micro & nano robot system with the joystick as a teleoperation interface [9]. Since those two tasks are rather different a specialized controller unit has been synthesized based on two micro processors Motorola MC68HC11 as an autonomous unit.

User Interface and Peripheral device setting menus in Windows user program have been developed as a control panel (Fig. 4). The operation performance can be observed also in the control panel monitor, as well as in sensor SG Feedback and Step Motors Feedback. Micro positioning of the robot can be performed both manually – scaled teleoperated or automatically. When the robot reaches the working zone the cell manipulations could be performed using operator-manipulating skills by visual feedback via digital camera AxioCam HRm. The cell injection realized by the translation in z-axis also can be performed both manually-scaled teleoperated by the joystick or by start/stop button automatically. The stroke and as well the injection speed can be defined by the operator. The orientation around *x* and *y*-axis is performed by the operator using the visual feedback and the joystick in nano mode.

The joystick calibration using personally adjusted impedance scaling parameters is foreseen to be performed personally for every operator and before starting

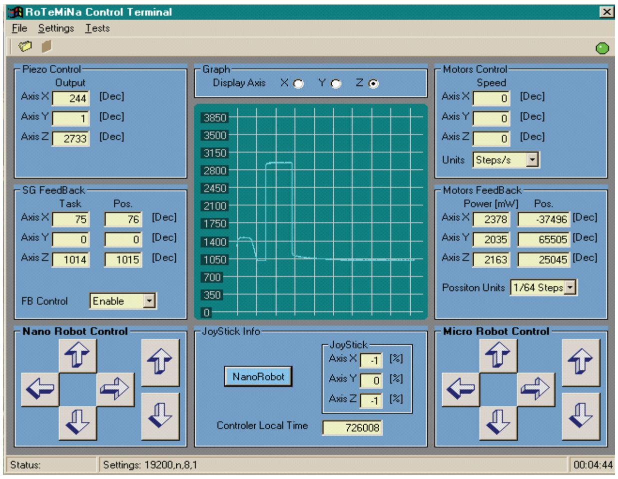


**Fig. 4.** RoTeMiNa robot control panel.

the robot manipulations by self-calibration impedance scaling procedure. Two types of scaling can be applied – linear and impedance.

In the linear scaling case the following equation is used:

$$\dot{x}_{R,i} = \alpha_{s,i}\phi_{j,i}. \tag{5}$$

Hence, here the macro joystick angular positions $\phi_{j,i}$ define the robot joint velocities via corresponding constants $\alpha_{s,i}$ defined by the human operator.

The impedance scaling here is adjusted personally using the joystick self calibration procedure and the result is reducing the manipulation time.

## 4. CONCLUSIONS

An approach of impedance scaling has been proposed here in order to give a preliminary known and handy for the operator dynamics of the robot system manipulating in micro and nano range. Giving that perception to the human operator allows increasing the effectiveness of the teleoperation control for the robot applied for micro and nano cell manipulations.

Teleoperation hybrid approach transferring operator motion and manipulation skills for controlling the robot system for cell micro and nano manipulations is further developed based on the linear (velocity) or impedance scaling approach. The time for the operation to be performed is reducing using familiar for the operator dynamics which is the main request especially for the cell manipulations.

The robot system with 6 DOF utilizing the teleoperated control approach with impedance scaling is shortly presented. It consists of regional structure with 3 translational joints with a range of 55 (100) mm, repeatability of less than 2 µm, linear sensor resolution of 0.1 µm. The local robot structure with 3 DOF has been developed in a way to guarantee the precise reference three-dimensional nano motion and control for sample manipulation or injection in sub-micrometer or nanometer range.

Two of the joints are rotational around *x* and *y*-axis in a range of 30 mrad with actuator resolution of $1.6 \cdot 10^{-3}$ arc·s. The last joint is a translational one having a stroke of 65 µm with resolution of 1 nm. The sensors used for the local robot structure are strain gauge sensors integrated in the piezo actuator bodies with resolution of 35 nm.

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