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ACCURACY AND CALLIBRATION OF MICROPOSITIONING ROBOTIC SYSTEMS

Abstract:
The subject of this paper is robotisation of cell-injection process and in particular development of an accuracy analysis, virtual model of micro-nano robot and calibration of the structure. To cover all requirements as high-speed, fine positioning and orientation preloaded stack piezo-actuators with closed loop are selected. Main issues of methodology for accuracy analysis and microrobot calibration are presented. Virtual model of micromanipulator is realized according to the synthesized kinematical structure with 3 DoF. The future work is related with development and calibration of real prototype of microrobot with 3 DoF according to the realized virtual model and obtained results.
Microrobot, subject of this paper could cover the working space presented by the cell size between 10μm and 30μm. It has to position and orientate the needle close to the cell membrane and finally to realize cell-injection penetrating the cell membrane with high speed thus preventing the cell from damage.

Keywords:
Robotisation, cell-injection process, structure calibration, virtual model

INTRODUCTION

Robotisation of any micro- and nano-manipulation process needs of analysis and specification of all specific parameters and requirements found in every stage of the whole process. Cell-injection, subject of this paper contains several stages that could be robotized as follows. Cell selection could be realized by fluid driven through a glass channel transferring cells to the immobilization stage. Using two digital cameras control parameters as cell size and shape will be obtained.
Microrobot, subject of this paper could cover the working space presented by the cell size between 10μm and 30μm. It has to position and orientate the needle close to the cell membrane and finally to realize cell-injection penetrating the cell membrane with high speed thus preventing the cell from damage.

ACCURACY PROBLEMS OF MICROPOSITIONING ROBOTIC SYSTEMS

a. Way accuracy:
Any moving object has six available degrees of freedom. These consist of translation, or linear movement, along any of three perpendicular axes (X, Y, and Z), as well as rotation around any of those axes. The function of a linear positioning way is to precisely constrain the movement of an object to a single transitional axis only. Any deviations from ideal straight-line motion along that axis are the result of inaccuracy in the way assembly. There are five possible types of inaccuracy, corresponding to the five remaining degrees of freedom: translation in the Y-axis; translation in the Z-axis; rotation around the X-axis (roll); rotation around the Y-axis (pitch) and rotation around the Z-axis (yaw). Since there are interrelations between

these errors, it is worthwhile to carefully examine the effects of each type of error and its method of measurement.

b .Linear positioning accuracy:

This is simply the degree to which commanded moves match intentionally defined units of length.

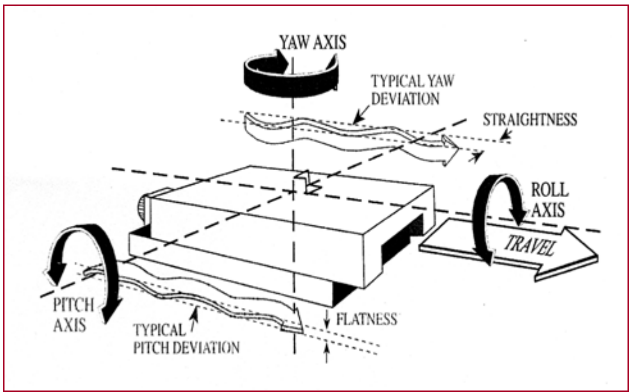

Figure 1– Possible Way Inaccuracies

Lead screw-Based Systems: Low to moderate accuracy systems typically depend on a lead screw or ball screw to provide accurate incremental motion. Such systems are often operated open loop via stepping motors; if closed loop operation is employed, it is frequently with a rotary encoder. In either case, the leads crew is a principal accuracy-determining element. Leads crews exhibit a cumulative lead error, which is usually monotonic in nature, together with a periodic component, which is cyclic and varies over each revolution of the screw. In addition, there can be backlash in the nut, which will reveal itself upon direction reversal.

Linear Encoder-Based Systems: Use of a linear encoder eliminates concern over the leads crew cumulative error, as well as friction induced thermal expansion. In many systems, the leads crew can be dispensed with altogether and replaced with a non-contacting linear motor.

c. Resolution *- Resolution is defined as the smallest positional increment, which can be commanded of a motion control system. The mechanical positioning components, motor, feedback device, and electronic controller each play a role in determining overall system resolution. In stepping motor systems, the resolution is set by the lead screw pitch, motor step angle, and drive electronics. For any given pitch, two full step resolutions can be achieved through the use of either 1.8 degree or 0.9 degree stepping motors. This full step resolution can be further increased by micro stepping (electronical subdivision of each full step into 10 or 50 micro steps, producing 2000 or 10000 micro steps per revolution with 1.8-degree steppers for example).In general, it is appropriate to specify a resolution that is about five times smaller than the position error that is required by the application. The resolution of servo systems incorporating linear encoders is independent of the screw pitch, and is strictly a function of the positional feedback device.*

d .Repeatability of micropositioning systems *:*

The repeatability of a positioning system is the extent to which successive attempts to move to a specific location vary in position. A highly repeatable system (which may or may not also be accurate) exhibits very low scatter in repeated moves to a given position, regardless of the direction from which the point was approached.

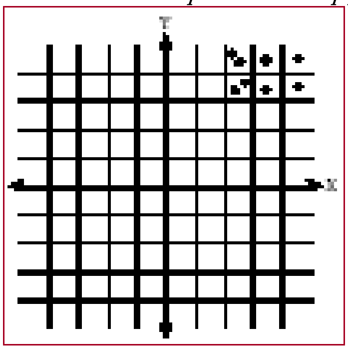

Figure 2. Low accuracy, Low repeatability

A distinction can be drawn between the variance in moves to a point made from the same direction uni-directional repeatability) and moves to a point from opposing directions (bi-directional repeatability).

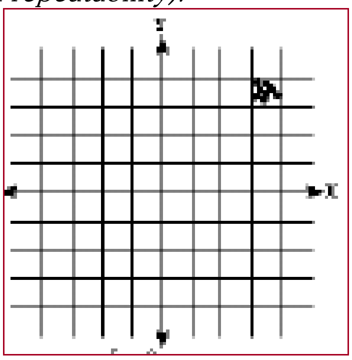

Figure 3. Low accuracy, High repeatability

In general, the positional variance for bi-directional moves is higher than that for uni-directional moves. Quoting uni-directional repeatability figures alone can mask dramatic amounts of backlash.

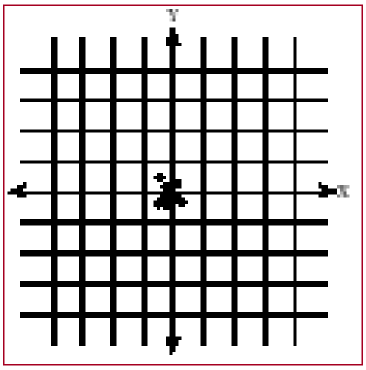

Figure 4. High accuracy, High repeatability

Measuring the stage dynamics: For measuring the dynamic response of X – Y tables and providing real-world feedback it is necessary to use a tool with both high spatial and temporal resolution: the laser interferometer. It's combination of 1.25 nm resolution, 100 kHz position update

KINEMATIC STRUCTURE AND CALLIBRATION OF MICROROBOT FOR CELL INJECTION

Mechanisms with closed kinematic chains are suitable for high-precision tasks in 3D space. The high accuracy of such mechanical systems comes from the very high structural stiffness. Generally, there are 3 types of joints between the links: kinematic, elastic and rigid. The stiffness of the mechanical construction increases in the same order. Taking account the type of the micro-manipulation process, required working space, cell size, high speed and precision a parallel kinematical structure with 3 DoF actuated by 3 stack piezo-actuators is selected (fig. 5).

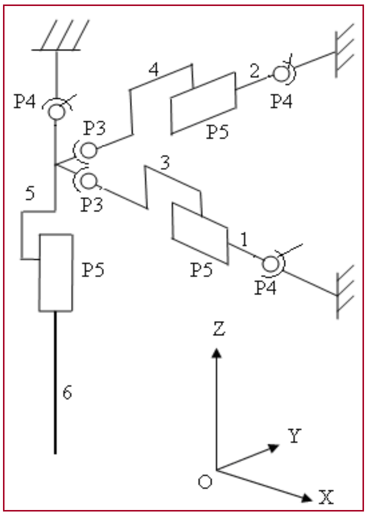

Figure 5. Kinematical chain of micro-manipulator with 3 DoF

Corresponding kinematic scheme is chosen mostly to fulfil the requirements of compact construction, high stiffness and enough working space.

In the calibration process, several sequential steps enable the precise kinematic parameters of the micro-nano robot to be identified, leading to improved accuracy. These steps may be described as follows:

1) A kinematic model of the robot and the calibration process is developed and is usually accomplished with standard kinematic modeling tools. The resulting model is used to define an error quantity based on a nominal (manufacturer, s) kinematic parameter set and an unknown actual parameters set which is to be identified.

2) Experimental measurements of the robot pose (partial or complete) are taken in order to obtain data relating to the actual parameter set for the robot.

3) The actual kinematic parameters are identified by systematically changing the nominal parameter set so as to reduce the error quantity defined in the modeling phase. One approach to achieving this identification is determining the analytical differential relation ship between the pose variables P and the kinematic parameters K in the form of a Jacobian,

$$\delta P = J\delta K \qquad (1)$$

and then inverting the equation to calculate the deviation of the kinematic parameters from their nominal values

$$\delta K = [J^T J]^{-1} J^T \delta P \qquad (2)$$

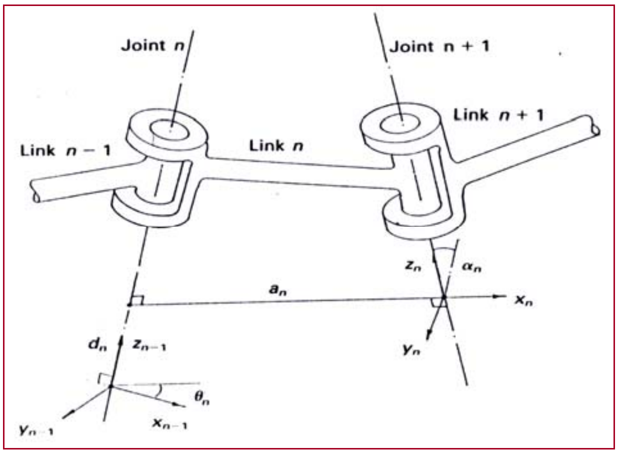

Figure 6 .Link coordinate frame allocation

Alternatively the problem can be viewed as a multidimensional optimization task, in which the kinematic parameter set is changed in order to reduce some defined error function to zero. This is a standard optimization problem and may be solved using well- known methods.

4) The final step involves the incorporation of the identified kinematic parameters in the controller of the robotic systems, the details of which are rather specific to the hardware of the system under study. In the method described here, for each position in which the robot is placed, the full pose is measured, although several intermediate measurements have to be taken in order to arrive at the pose. The device used for the pose measurements is a coordinate measuring machine CMM) with 3 axis, prismatic measuring system with a quoted accuracy of 3 microns.

ROBOTIC KINEMATICAL PARAMETERS

The fundamental modeling tool used to describe the spatial relationship between the various objects and locations in the robot workspace is the Denavit – Hartenbeg method with modifications proposed by Hayati and Mooring to account for disproportional models when 2 consecutive joint axes are normally parallel. As shown in Fig. 6 this method places a coordinate frame on each object or robotic link, and the kinematics are defined by the homogeneous transformation required to change one coordinate frame into the next.

This transformation takes the form

$$A_n = rot(z,Q_n)trans(z,d_n)trans(x,a_n) \\ rot(x,\alpha_n)rot(y,\beta_n) \qquad (3)$$

The above equation may be interpreted as a means to transform frame n-1 into frame n by means of 4 out of the 5 operations indicated. When consecutive axes are not parallel, the value of β_n is defined to be zero, while for the case when consecutive axes are parallel, d_n is the variable chosen to be zero. Using Denavit-Hartenberg method, the matrix form is usually expressed. For a serial linkage, such a robots a coordinate frame is attached to each consecutive link so that both the instantaneous position together with the invariant geometry are described by the previous matrix transformations. The transformation from the base link to the nth link will therefore be given by

$$T_n = A_1 A_2 \ldots A_n \quad . \qquad (4)$$

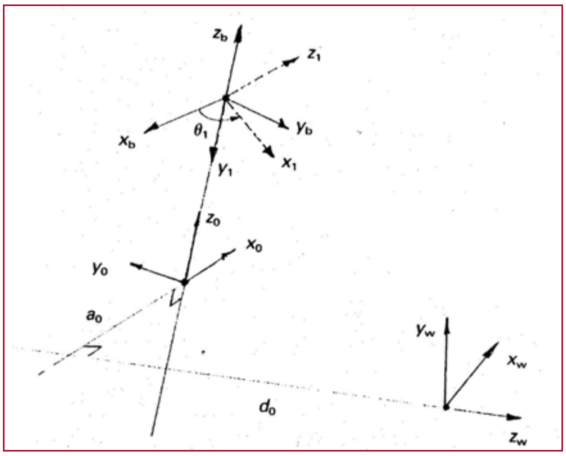

Figure 7 . Base transformations

We are interested in determining the minimum number of parameters required to move from the world frame to the frame x_1,y_1,z_1. There are 2 paths that will accomplish this goal:

1) A DH transform from x_w,y_w,z_w to x_0,y_0,z_0

$$T_0^b = rot(z_0,\phi')trans(z_0,d') \qquad (5)$$

It requires only 8 independent parameters to go from the world frame to the first frame, using this path.

2) As an alternative a transform may be defined directly from the world frame to the base frame x_b,y_b,z_b, by using of 6 parameters, such as the Euler form

$$A_b = rot(z,\phi_b)rot(y,\theta_b)rot(x,\psi_b) \\ trans(p_{xb}, p_{yb} . p_{zb}) \qquad (6)$$

In this study the second path is chosen the tool transform is an Euler transform wchich requires the specification of 6 parameters.

$$A_6 = rot(z,\phi_6)rot(y,\theta_6)rot(x,\psi_6) \\ trans(p_{x6}, p_{y6}, p_{z6}) \qquad (7)$$

METHODOLOGY OF KINEMATICAL IDENTIFICATION

The kinematic parameter identification will be performed as a multidimensional minimization process, since this avoids the calculation of the system Jacobian. The process is as follows :

1. Begin with a guess set of kinematic parameters ,such as the nominal set
2. Select an arbitrary set of joint angles for the micro-nano robot
3. Calculate the pose of the robot end – effector
4. Measure the actual pose of the end-effector for the same-set of joint angles. In general

the measured and predicted pose will be different.

5. Modification of the kinematic parameters in an orderly manner in order to best fit (in a least – squares sense the measured pose to the predicted pose.

The suggested algorithm is applied not to a single set of joint angles but to a number of joint angles. The total number of joint angle sets required, which also equals the number of physical measurement made, must satisfy

$$K_p > N_x D_f \qquad (8)$$

where

K_p – is the number of kinematic parameters to be identified;

N – is the number of measurements (poses) taken;

D_f – represents the number of degrees of freedom present in each measurement;

In the system described here, the number of degrees of freedom is given by $D_f = 6$ since full pose is measured. In practice many more measurements should be taken to offset the effect of noise in the experimental measurements. Piezo-actuators realise positioning and orientation of the pipette around X and Y axes and penetration into the cell membrane by piezo-actuator along Z axis. They are modeled by prismatic joints P5 closing the mechanical construction through spherical joints (P3) and elastic hinges (P4). According to equation (1) it is possible to calculate the DoF of the end effector (link 6):

$$h = 6n - 5p_5 - 4p_4 - 3p_3 \qquad (9)$$

Where h – number of DoF; n – number of mobile links; P5, P4, P3 – kinematical joints with 1, 2, 3 DoF respectively. After replacement of known parameters into the equation (1) the DoF become equal to 3. Stack piezo-actuators with strain-gauges from PI are selected like actuation modules covering all requirements for robotization of cell-injection process. Piezo-actuators along X and Y axes (P-841.2B) are internally preloaded with maximal range of motion equal to 30μm, resolution – 0.6nm and stiffness equal to 27N/μm. Piezo-actuator realizing injection movement of the pipette along Z axis (P-841.40) is also internally preloaded with maximal range of motion equal to 60μm, resolution – 1.2nm and stiffness equal to 15N/μm. According to the kinematical structure synthesized before a virtual model of micro-manipulator with 3 DoF (fig. 8) is developed. Actuated chains along X, Y axes contain 1 piezo-actuator, pointed as A1 and A2 respectively. Third actuation chain containing piezo-actuator A3 along Z axis is fixed to the primary chain used only for injecting the pipette into the cell membrane. First and second actuation chains are used for positioning and orientation of the pipette.

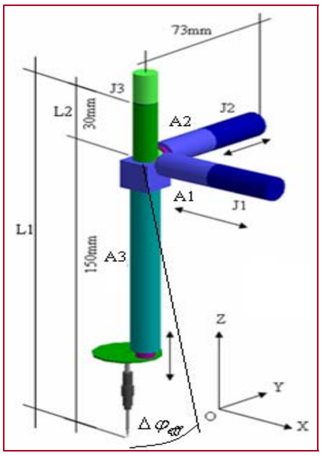

Figure 8. Virtual model of microrobot

The angular deflection of the end-effector could be obtained according to the equation (10):

$$\Delta\varphi_{eff} = \frac{\Delta l_{A1}}{L1} = \frac{\Delta l_{eff}}{L2} \qquad (10)$$

Where $\Delta\varphi_{eff}$ - angular deflection of the end-effector; Δl_{A1} - linear deflection of actuator A1 or A2; Δl_{eff} - linear deflection of the end effector;

Gear ratio is obtained by equation (11):

$$n = \frac{\Delta l_{eff}}{\Delta l_{A1}} = \frac{L2}{L1} = \frac{180}{30} = 6 \qquad (11)$$

According to the range of used stack piezo-actuators $\Delta l_{A1} = \Delta l_{A2} = 30\mu m$, the range of end effector motion on X and Y direction is $\Delta x = \Delta y = \Delta l_{eff} = 180\mu m$. The range of end effector motion on Z direction is determined of used actuator P-841-67 as $\Delta z = 60\mu m$.

The working space of the micro-manipulator represents part of a sphere with maximal range of motion along X and Y axes equal to 0.18mm and along Z axis respectively 0.060mm.

For improving the dynamic parameters and removing backlashes in the manipulator the structure must be tensed. By this reason the elastic joint of the primary chain is tensed by means of X and Y arrangement of the two actuators. The angular stiffness of this joint (P-176.60) is $k\varphi = 40$ Nm/rad. When the joint is deformed up to the admissible rotation angle

$\Delta\varphi_j = 0.5^0 = 0.008726$ [rad], the strain forces of the actuators are:

$$F = k_\varphi \Delta\varphi_j / L_1 = 11.63[N]. \qquad (12)$$

The actuators must be displaced on X and Y direction as $\Delta l_X = \Delta l_Y = L_1 \Delta\varphi_j = 0.2618[mm]$.

The effective displacement of the end effector will be $\Delta X = \Delta Y = L_2 \Delta\varphi_j = 1.5708[mm]$.

As a regional structure moving micro-manipulator into the working space is used macro-manipulator with 4 DoF. The whole system is modeled into the interactive environment of SDS 2004+ for investigation of its kinematics (fig. 9).

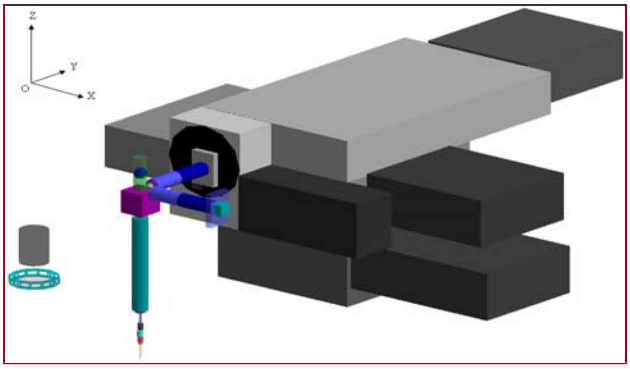

Figure 9. Virtual model of microrobot mounted to the regional structure with 4 DoF

The linear resolution of the macro-robot is around 0.1mm, maximal range of motion on X and Y axes are equal to 50mm and along Z axis is 30mm. Rough positioning and orientation is realized by macro-manipulator and fine displacement and cell-injection are performed by micro-manipulator respectively. We have to use the device for pose measurements, such like a coordinate measuring machine CMM) with 3 axis, prismatic measuring system with a quoted accuracy of 3 microns. In order to maximize the joint motion for the experimental poses the common working volume of the microrobot and CMM was regarded as a parallelepiped with 12 points, where pose measurements have to be taken. The calibration on the base of suggested methodology required to take the data and type in the results for parameters - $\Delta\varphi_{eff}$, Δl_{eff}, L1 and L2 as more important for the high precision robotic movements .

Conclusion

Virtual model of micromanipulator is realized according to the synthesized kinematical structure with 3 DoF. As actuation, modules are selected preload stack piezo-actuators with closed loop suitable for applications with high-dynamics. By elastic hinges closing the mechanical construction are reduced backlashes and the precision of the robot is increased as a result. The future work is related with development and calibration of real prototype of microrobot with 3 DoF according to the realized virtual model and obtained results.

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