

# PARALLEL MECHANICAL SYSTEM FOR 3-D MEASURE OF SMOOTH SURFACES

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*Abstract: A new parallel manipulator POLMAN-3 for the use of the measurement applications is presented in the paper. It is parallel mechanical arrangement with three degrees of freedom equipped with typical slide gauges and computer for acquisition of the data. Manipulator is consist of three properly situated serial-parallel chains connected in parallel way to mobile platform, which has the form of half-spatial cross. It is equipped with spherical joints and is attached to actuated mechanisms with using six identical rods similarly to the DELTA robot [1]. Because of good isotropy [2] of the mechanical part, and homogenous space structure, mechanism has very good kinematic manipulability, and so the generated errors are similar in each direction in 3-D space and similar to errors of slide gauges. All gauges are mounted in the base of the system. Manipulator can be use for the measure of smooth surfaces after technological operations. Because of special geometry some properties of its are similar to the cartesian manipulator. Adopted kinematic systems allows for easy solution of both inverse and direct kinematic tasks [3]. Mechanical construction of the system are modular and very light, each elements are low cost in fabrication.*

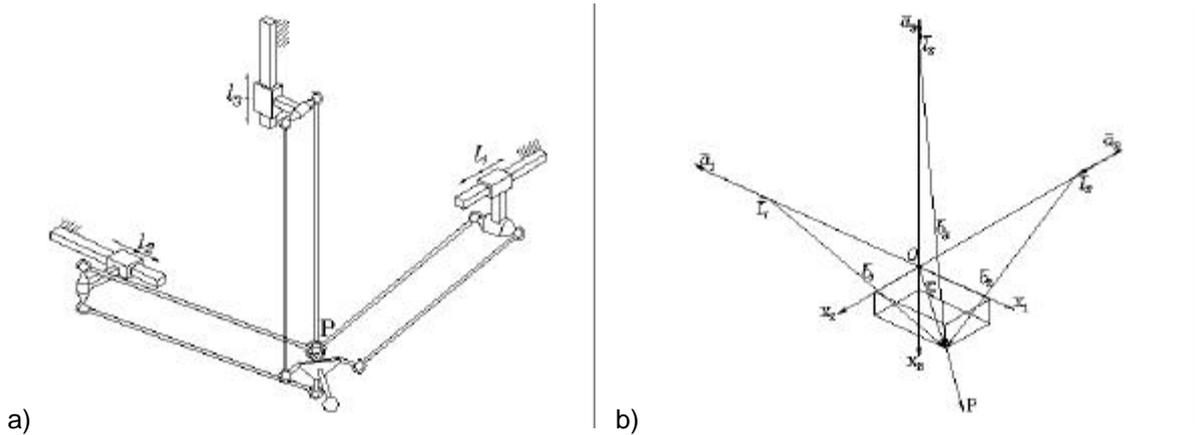
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## 1 INTRODUCTION

New technological applications of the robots need new approaches for the organization of its technological stands [4]. Measuring the geometrical shape of the surface in order to prepare its mathematical model employing classical measurement methods is a very expensive task (high cost of machinery). For realizing milling and/or polishing with the use of some new kind of robots, it needs to use three-dimensional measuring systems for the measure worked-out surfaces exactly on the stand. In some applications considerable exactness measured in micrometers is not necessary (accuracy in 0.1 mm order is enough) but it would be desirable to have a measuring device portable and relatively cheap. Known from the literature laser scanning methods are rather very expensive, while typical measurement systems used in measurement machines are rather bulky and heavy, and so its applications on the stand with the robot can be very difficult. Because of that, last time it has been invented some new approaches for the solving such a difficult task. One of them is presented in this paper. The principle of such a measuring system was derived from the class of spatial manipulators typically used as mechanical arrangements of very fast parallel robots [1,4,5]. Compared to serial manipulators, parallel systems have some advantages like a stiff mechanical structure and more precise positioning. Limited working area and reduced maneuverability of the end element are the main disadvantages of typical parallel manipulators of Stewart platform type. The main advantages of proposed system are simplicity and lightness of the construction with relatively high (good) stiffness of the mechanism, and clear concept of kinematic description of mathematical model. Adopted kinematic arrangement has very good isotropic kinematic properties. Because of that obtained results of the measure are very simple and have very clear interpretation.

## 2 POLMAN-3 MANIPULATOR FOR THE MEASURING APPLICATIONS

Good isotropy of three DOF parallel manipulator can be achieve when possible motion of the end element are determined by three identical orthogonal components of linear velocities [4]. When the use linear non-driving slides located in the base, and connected to them spatial moving parallelogram, one of possible arrangement of the manipulator could have a form shown in the general scheme in Fig. 1a. Manipulator POLMAN-3 is consist of special spatial parallelogram connected to three typical slide



**Figure 1.** General scheme of POLMAN-3 manipulator for the measure of smooth surfaces  
a) kinematic arrangement, b) kinematic model for calculation of the position

gauges located in the base in such a way, that each one slide is perpendicular to two the others. Each slide can realize translational motion. The end element of the manipulator is connected to slides with the use six identical rods in such a way, that three of them are mounted to one special spherical joint on the platform. Three the other connecting rods are located in such a way, that moving platform has the form of spatial parallelogram, and so it can only realize translational motion in the space (without any rotations). Mechanical part of the system has very high (good) stiffness, and can assure very small mechanical hysteresis. The resolution of each slide is  $\pm 0.01$  mm, so the average resolution of the measure is no more then  $\pm 0.02$  mm (approx.  $\pm 0.015$  mm) in each direction in the space.

### 3 KINEMATIC MODEL OF THE MANIPULATOR

Kinematic model of POLMAN-3 manipulator is derived with the use vector method. General scheme of kinematic model is shown in the Fig. 1b, where the vector  $\overline{\mathbf{w}}$  is mean as  $\mathbf{w}$ . The basic absolute reference frame is a cartesian orthogonal dextrorotary  $p_0(x_1, x_2, x_3)$ . Current configuration of the mechanism can be described equivalently with the use vectors  $\mathbf{r}_p = [x_{1p}, x_{2p}, x_{3p}]^T$ , describing current location of point  $P$  in absolute reference frame, or  $\mathbf{l} = [l_1, l_2, l_3]^T$ , describing local coordinates of the moving tables of slide gauges. Constant vectors described constant locations of slide gauges are in the form:

$$\mathbf{a}_1 = a \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{a}_2 = a \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}, \quad \mathbf{a}_3 = a \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \quad (1)$$

Vectors  $\mathbf{l}_i$  described current configuration of the manipulator in absolute reference frame:

$$\mathbf{l}_1 = l_1 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{l}_2 = l_2 \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \quad \mathbf{l}_3 = l_3 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad \text{where} \quad \begin{matrix} l_i = l_i(t), \\ l_i \in (l_{i\min}, l_{i\max}), \end{matrix} \quad i=1, 2, 3, \quad (2)$$

and vectors connected with rods  $\mathbf{b}_i$  are in the form:

$$\mathbf{b}_1 = b \begin{bmatrix} \cos x_1 \\ \cos h_1 \\ \cos z_1 \end{bmatrix}, \quad \mathbf{b}_2 = b \begin{bmatrix} \cos x_2 \\ \cos h_2 \\ \cos z_2 \end{bmatrix}, \quad \mathbf{b}_3 = b \begin{bmatrix} \cos x_3 \\ \cos h_3 \\ \cos z_3 \end{bmatrix} \quad (3)$$

Vector connected with the outrigger with ball gauge on the end of moving platform is done in absolute reference frame in the form:

$$\mathbf{c} = c \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad (4)$$

Measured trajectory of the ball gauge while its moving with the contact with measured surface in

absolute reference frame is a set of points in the form:

$${}^i \mathbf{r}_p = \begin{bmatrix} {}^i x_{1p} \\ {}^i x_{2p} \\ {}^i x_{3p} \end{bmatrix}, \quad \text{where} \quad {}^i x_{ip} = {}^i x_{ip}(t), \quad (5)$$

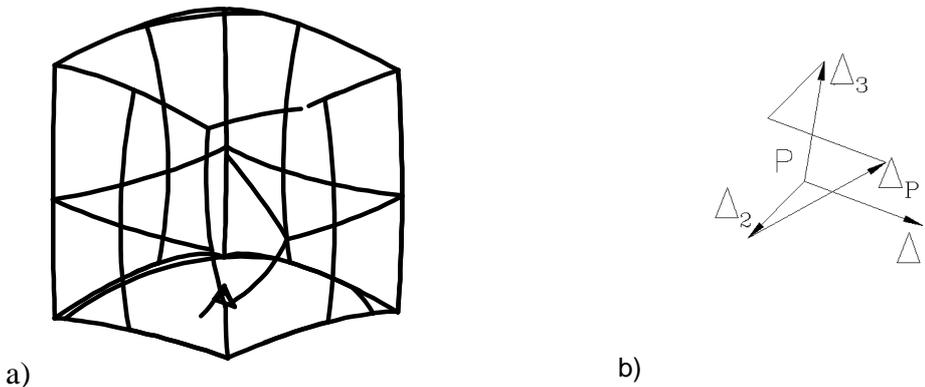
The basic kinematic relation describing mathematical model of the manipulator is:

$$\mathbf{a}_i + \mathbf{l}_i(t) + \mathbf{b}_i + \mathbf{c} = \mathbf{r}_p \quad (6)$$

In more compact form it can be described:

$$\mathbf{r}_p = \mathbf{r}_p(\mathbf{l}) \quad (7)$$

Where  $\mathbf{r}_p$  in the form (5) is called now as manipulation vector, while  $\mathbf{l}$  in the form  $\mathbf{l} = [l_1, l_2, l_3]^T$  is a joint vector. Solution of equation (6) can be obtained as intersection of three spheres with constant radius of each  $b$ , and with the center in the point of the end of vector  $[\mathbf{a}_i + \mathbf{l}_i(t)]$ , located away by vector  $\mathbf{c}$  represent probe element on the end-effector with constant orientation. There exist two solutions of this task, and so it has to take only one for positive  $x_{ip}$ . Working space of the manipulator can be obtained by inspection of relations (6) according to (2). It is area between six spheres with radius  $b$  each, which centers are located in points on the ends of slides in the base. Workspace of the manipulator is shown in the Fig. 2a.



**Figure 2.** Basic features of the manipulator POLMAN-3:  
a) workspace, b) generated errors of the end-effector

Error of the position of the end-effector  $P$  is composed of three independent components generated in sliding gauges and transmitted to the end-effector. Appropriate its components can be derived from general form of differential equations (7) of kinematic model of the manipulator [6]:

$$d\mathbf{r}_p = \mathbf{J}(\mathbf{l})d\mathbf{l} \quad (8)$$

in the form:

$$\Delta \mathbf{r}_p = \mathbf{J}(\mathbf{l})\Delta \mathbf{l} \quad (9)$$

where matrix  $\mathbf{J}(\mathbf{l})$  is the Jacobian matrix of the whole system  $d(\cdot)$  is operator of differentiation, and  $\Delta$  is the first difference of actual variable. Scalar value:

$$w = \sqrt{\det \mathbf{J} \mathbf{J}^T} \quad (9)$$

is defined to be the manipulability measure at state  $\mathbf{l}$  with respect to the manipulation vector  $\mathbf{r}_p$ . In investigated kinematic model of POLMAN-3 manipulator dimensions of vectors of input and output variables are the same, and equal to 3, so the manipulability measure is simply given by:

$$w = |\det \mathbf{J}| \quad (10)$$

It means, that normalized error generated in the mechanism of POLMAN-3 manipulator can be simply obtained from equation (10) as euclidean norm of the determinant of Jacobian matrix. In 3-D space,

this error can be interpreted as is shown in the Fig. 2b, where  $\Delta_i$  are the vectors generated from sliding gauges seen in the end-effector, while  $\Delta_p$  is produced error of the end-effector. By expecting equation (10) in working space, one can show, that produced error is not exceed  $\pm 0.02\text{mm}$ .

#### 4 INITIAL RESULTS, APPLICATIONS

Motion accuracy is a very important performance goal of typical NC machine, because its relevance to milling/polishing/grinding/finishing accuracy. When use of the robot, this goal is much more complicated. Typical robot with serial-chain kinematic arrangement and harmonic gears is not appropriate to realize such tasks. For realizing technological operations, RNT robot with special serial-parallel kinematic arrangement, shown in the Fig. 3 has been used. Driving systems of the robot-arm has been designed based on ball screws in the system of motion of the arm and special tooth gears with elimination of the backlash in the wrist. But very complicated mechanical system of the manipulator and big number of joints cause errors of its end-effector. Beside of this because of the friction, real mechanical system with elasticity in joints generates mechanical hysteresis (Lost Motion).

Initially local correction of kinematic model of the robot RNT was realized with the use very simple but time consuming method shown in the Fig. 3. For determining of the position and orientation of the end-effector typical slide gauges equipped with special balls have been used. By the measure of six distances between three constant points in absolute reference frame in the table, and three points on the end-effector in local reference frame, it was determined correction of nominal kinematic model of the robot for improve its absolute accuracy. It was shown, that the model has been improved approx. 4 times from absolute error approx. 4 mm to 1 mm.



**Figure 3.** First investigation of the measure of the end-effector of RNT robot in absolute reference frame

On the basis of the idea described in the paper a number of prototypes of similar measure systems has been designed and made. One of such a system with rotational incremental encoders and with three/six DOF's is shown in the fig. 4a.

POLMAN-3 manipulator can be used as a measuring machine for the measure of smooth surfaces after technological operations. It has been used in the stand with RNT robot. Typical technological application of the robot RNT milled wood is shown in the Fig. 4b. Tool trajectory has been prepared with the use spline functions in GRIP program and UNIGRAPHICS system. Input trajectory of the tool, transformed in the system of control of the robot to motions of actuators is transformed to real trajectory of the robot end-effector with machine tool. Of course in real situation they are the difference between output and input trajectories. In first applications of POLMAN-3 manipulator, it has been used to the measure of milled surfaces. It has been realized from point to point with actual acquisition of the data. In order to prepare visualization and for calculate average errors, in the next step it have to be calculate new coordinates of the measuring surface by smoothing the data, and prepare collection of coordinates of regular or irregular meshes for presentation on the monitor and for correction of the robot trajectory. It has been observed several conclusions:

- (1) results of the measure are accurate and stable,
- (2) proposed method is able to measure most items of the motion accuracy of the robot,
- (3) measuring results characterized of good repeatability.



a)



b)

**Figure 4.** Application of POLMAN-3/6 manipulator on the test stand  
a) manipulator POLMAN-3/6 for the measuring applications,  
b) the end-effector of the robot RNT on the test stand while milled wood.

After a number of initial tests, it was decided to use this same arrangement to on-line measure of the position of the end point of end-effector with ball in the place, where the tool is mounted. Procedure of local correction of kinematic model in such a case is based on deriving and implementing an algorithm for improvement kinematic calculating of position and orientation of the robot. It was realized in such a way, that in investigated subspace of working space of the robot the vector of the difference between position and orientation calculated from corrected kinematic model and measured sized of them are minimal in the sens of its euclidean norm.

POLMAN-3 manipulator has been realized with the use electronic slide gauges with working range 300mm and measure resolution 0.01mm, They have been connected exactly to the computer. The other characteristic lengths of the system are  $a=b=450\text{mm}$ . Ball multijoint of the structure has been mounted exactly to the tool at the end of the manipulator. As a result of the correction of kinematic model of the robot, it was improved approx. 8-9 times from 4mm in the beginning to 0.45mm. For better measure the fragments on the back side of the measured element, the device can be equipped with the special equidistance element. For improving absolute accuracy of the measure it is profitable to equippe it with special calibration element in the form of spatial corner with very well measured distances. For achieve improved in such a way absolute accuracy of the system, special fixture has been designed and implemented. Worked-out parallel manipulator POLMAN-3 has been implemented in real stand with RNT robot. It has been shown, that because of good kinematic properties and enough accuracy, it can be implemented on the other real stands.

## 5 SUMMARY

Worked-out parallel manipulator POLMAN-3 for the measurement applications has been designed, constructed and built. Because of compact structure, good isotropic kinematic properties and good appropriate accuracy it can be used for some measurement applications after technological operations. With application of very simple driving system, it can be used as automatic measuring system. It is very convenient for the use it as a portable system. Manipulator can be used exactly in technological process without changing any its functional components. Mechanical part is modular and very simple, its cost is very low. Another advantage of the proposed solution is the fact, that it is easy to change parameters of the measurement system (e.g. characteristic linear or angular dimensions) for individual necessity.

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