# DESIGN AND EXPERIMENTAL TEST OF A PNEUMATIC PARALLEL MANIPULATOR TRIPOD TYPE 3UPRR

**Ryszard DINDORF[*], Paweł ŁASKI[**]**

[*]AGH University of Science and Technology, AL. Mickiewicza 30, 31-059 Kraków
[**]Kielce University of Technology, al. Tysiaclecia Panstwa Polskiego 7, 25-314 Kielce

dindorf@agh.edu.pl, pawell@tu.kielce.pl

**Abstract:** The paper presents the design and experimental test of a tripod type-3UPRR pneumatic parallel manipulator. This manipulator consists of three identical kinematic chains (pneumatic axes) connecting the fixed base and the moving platform. The tool center point TCP of the moving platform is a resultant of relocation of three pneumatic rodless cylinders independently controlled by servo-valves. For simulation purposes a solid model of pneumatic tripod parallel manipulator in SolidWorks was constructed. Since the application of 3-CAD in modelling kinematics and dynamics of parallel manipulators is restricted further simulation was carried out by means of SimMechanics library and Matlab-Simulink package. The experimental research focused on determining the precision of positioning of manipulator's end-effector point of the moving platform during point-to-point control.

## 1. INTRODUCTION

The development of automation and robotics has increased interest in multi-axis pneumatic systems which are highly dynamic and reliable. However, due to unsatisfactory positioning accuracy of pneumatic servo-cylinder, their application in multi-axis manipulators is restricted. Pneumatic servo-cylinders used in multi-axis electro-pneumatic systems and referred to as pneumatic axes perform operations and function as supporting structure. Cartesian manipulators with pneumatic axes connected in series are classified as open-loop chain kinematic mechanisms. In serial kinematic chain elastic strains accumulate on particular pneumatic axes, which lowers the positioning accuracy of pneumatic manipulators. Parallel mechanism is a closed-loop mechanism in which the moving platform is connected to the fixed base by independent kinematic chains. Kinematic structure in the form of a closed-loop chain finds application in parallel kinematic robot (PKR) and parallel kinematic machine (PKM) (Hebsacker, 2000). Manipulators based on parallel kinematics structure can achieve better accuracy of repeatability and they can apply larger forces than conventional serial manipulators because of the higher stiffness of their mechanical structure. By using parallel kinematics in machine tools, high stiffness and high machine dynamics is achieved. With Stewart-Gough Platform as a base, numerous kinematic structures of parallel manipulators (Nonapod, Hexapod, Tripod) and hybrid manipulators (Tricept, Dyna-M, LinaPod) were formed. The names of kinematic structures of parallel manipulators are related to the kind of kinematic joint and the number of degrees of freedom (DoF). Six basic kinematic joints used in parallel manipulators were presented by Merlet (Merlet, 2000). In order to calculate degrees of freedom of parallel manipulators the formula proposed by Tsai is used (Tsai, 1999). The family of parallel manipulators includes translational parallel manipulators (TPM) based on three degrees of freedom (3-DoF) and containing at least one prismatic joint. In the group of 3-DoF TPM manipulators the most common are – spatial parallel mechanism of the structure: 3-PUU, 3-UPU, 3-UPS, 3-CPU, 3-PUS, 3-PCRR and planar parallel mechanism of the structure: 3-RPR, 3-PRR, 3-PPR, 3-RRR (Company, 2000).

## 2. PROTOTYPE PNEUMATIC PARALLEL MANIPULATOR

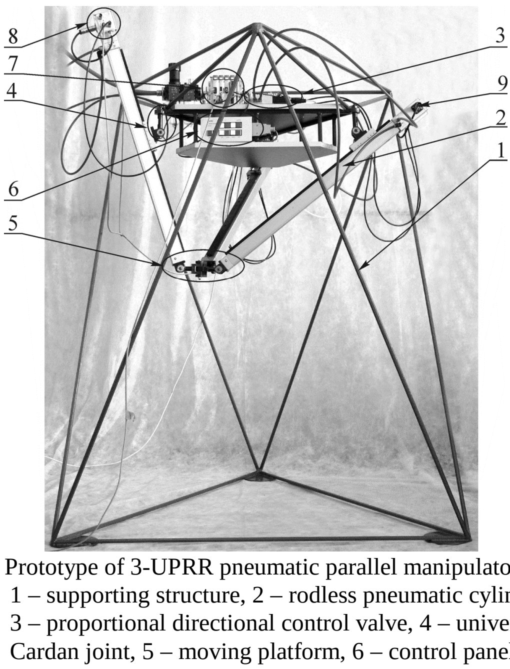



**Fig. 1.** Prototype of 3-UPRR pneumatic parallel manipulator: 1 – supporting structure, 2 – rodless pneumatic cylinder, 3 – proportional directional control valve, 4 – universal Cardan joint, 5 – moving platform, 6 – control panel, 7 – positioning axis controller, 8 – axis interface, 9 – axis connector

A prototype of pneumatic translational parallel manipulator (PTPM) of tripod kinematic structure was constructed in the Division of Mechatronics (Kielce University of Technology, Poland) (Dindorf and Łaski, 2005). The prototype of tripod parallel manipulator with Festo servo-pneumatic precision positioning systems is presented in Fig. 1. The manipulator possesses a supporting structure, fixed base, moving platform and three pneumatic linear motions (servopneumatic axis). Each servo-pneumatic axis consists of: rodless pneumatic cylinder type DGPIL-25-600 with integral feedback transducer (built-in Temposonic encoders for continual positioning feedback to the master control unit), 5/3 servopneumatic valve (directional proportional control valve) type MPYE-5-1/8-HF-010B, axis interface type SPC-AIF, positioning axis sub-controller type SPC-200 (the use of a sub-controller card permits control of up to four axes) and Ethernet/Can Bus interface. Kinematic structure and structure control of the prototype of 3-DoF pneumatic translational parallel manipulators is shown in Fig. 2 and Fig. 3.

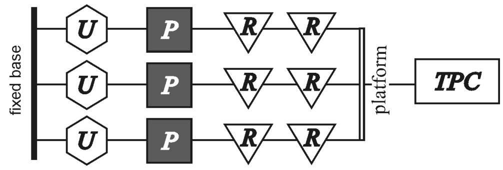



**Fig. 2.** Kinematic structure of 3-UPRR pneumatic parallel manipulator

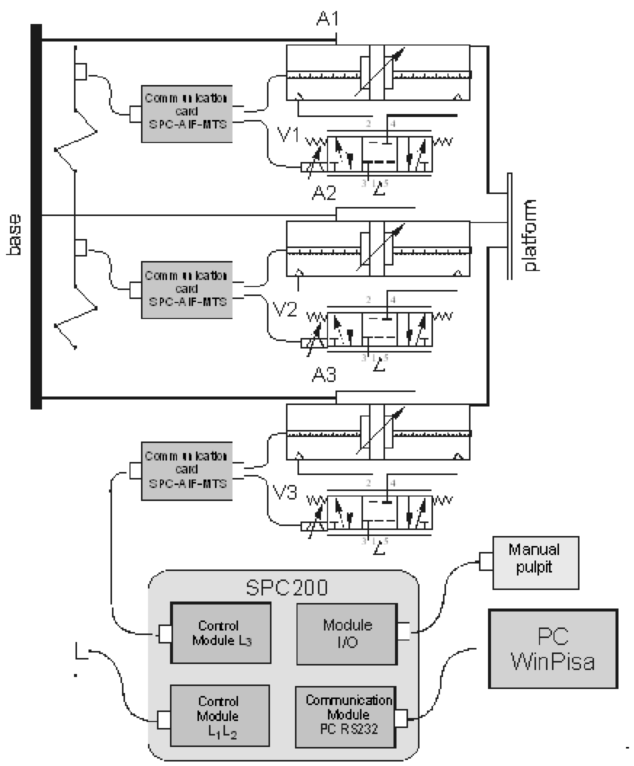



**Fig. 3.** Structure control of 3-UPRR pneumatic parallel manipulator

Each of the three identical closed-loop chains of the manipulator consists of serial kinematic chains: universal cardan joint (U), prismatic joint (P), formed by a rodless pneumatic cylinder and two revolute joints (2R) formed after universal cardan had been parted. The slide of rodless cylinder was connected with fixed base by means of articulated joints of U cardan and the end cap of cylinder were connected by revolute joint R to the moving platform. The second revolute joint R was placed in tool center point (TCP) of the moving platform. The presented construction of the parallel manipulator ensures parallel position of the moving platform to the fixed base for optional position of pneumatic cylinder. The kinematic structure of a new prototype of 3-UPRR pneumatic parallel manipulator is an interesting solution expanding the architecture of parallel manipulators, type 3-DoF TPM.

## 3. MODEL RESEARCH ON PNEUMATIC PARALLEL MANIPULATOR

Software – CAD (*SolidWorks*, *Mechanical Desktop*, *Solid Edge*) commonly used by constructors enables designing solid models of complex mechanisms of parallel kinematics. A solid model of 3-UPRR pneumatic parallel manipulator obtained by *SolidWorks* is presented in Fig. 4.

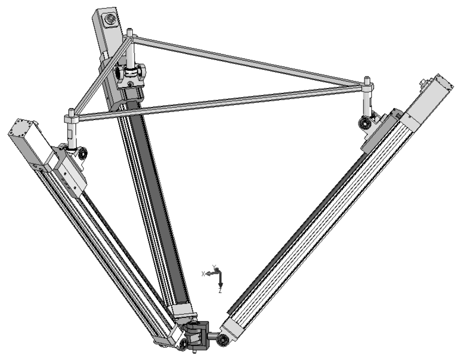


**Fig. 4.** Solid model of 3-UPRR pneumatic parallel manipulator

A revolute joint R is connecting the end cap of pneumatic cylinders with moving platform in point TCP and a U joint is connecting the slide pneumatic cylinder with a fixed base. In order to record geometric and kinematic relations holding for pneumatic parallel manipulator of 3-UPRR kinematics, its kinematic model presented in Fig. 5 was used (Dindorf et al., 2006). By means of *Dynamic Designer Motion*, which possesses graphic interface *SolidWorks* the simulation of pneumatic parallel manipulator's motion was conducted. In order to simulate the manipulator's motion it was necessary to define the basic parameters, kinematic joints and motion restrictions. For solid model a few composite relations were defined which enabled assigning them kinematic joints. In some cases it was necessary to introduce joints describing the construction's stiffness. Relying upon material properties and the shape of particular solids, the mass of the solid model was calculated. The simulation of manipulator's parallel mechanism motion was saved in avi format. The simulations conducted on a solid model aimed at position analysis of TCP point of the moving platform. The position of TCP point results from linear motion of pneumatic rodless cylinder, independently controlled by servo-valves.

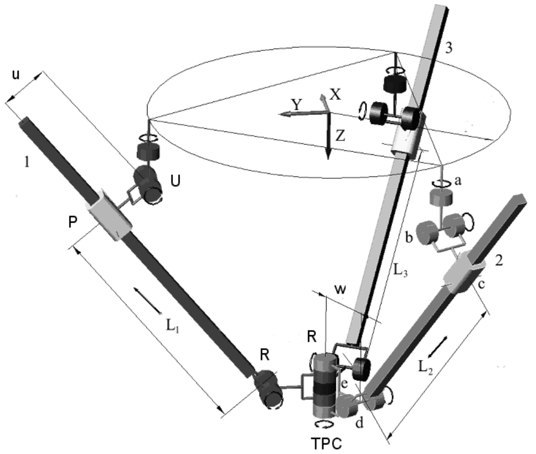



**Fig. 5.** Kinematic model of 3-UPRR pneumatic parallel manipulator

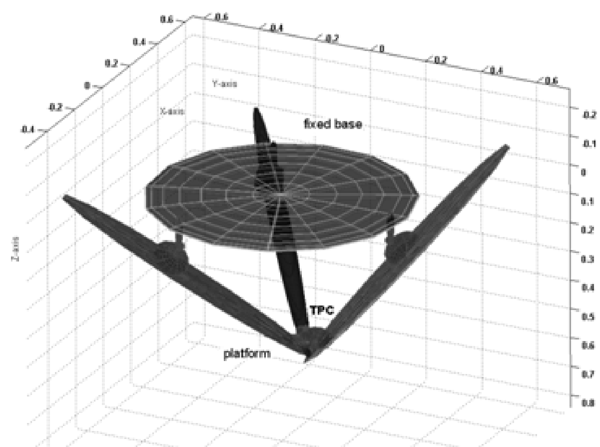



**Fig. 6.** Equivalent model of 3-UPRR pneumatic parallel manipulator

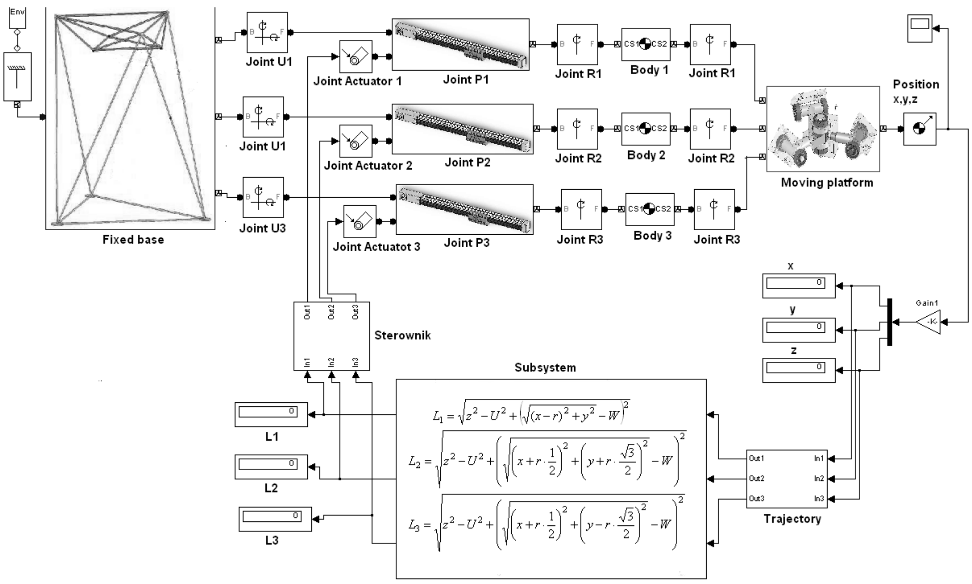



**Fig. 7.** Block-diagram of kinematic model of 3-UPRR pneumatic parallel manipulator

The solution of manipulator's kinematic reverse problem used in the design of control algorithm enabled to determine lengths of the movable links $L_1, L_2. L_3$ (displacement of linear pneumatic actuators) in relation to the coordinates of end-effector point P(*x*,*y*,*z*) of tripod parallel manipulator:

$$L_1 = \sqrt{z^2 - U^2 + \left(\sqrt{(x-r)^2 + y^2} - W\right)^2} \tag{1}$$

$$L_2 = \sqrt{z^2 - U^2 + \left(\sqrt{\left(x + r\cdot\frac{1}{2}\right)^2 + \left(y + r\cdot\frac{\sqrt{3}}{2}\right)^2} - W\right)^2} \tag{2}$$

$$L_3 = \sqrt{z^2 - U^2 + \left(\sqrt{\left(x + r\cdot\frac{1}{2}\right)^2 + \left(y - r\cdot\frac{\sqrt{3}}{2}\right)^2} - W\right)^2} \tag{3}$$

where: *x, y, z* – coordinates of end-effector point; P, *r* – ray of the circle circumscribing the equilateral triangle at the point where pneumatic servo-motors are fixed; *z, U, W* – geometric dimensions of the manipulator for the initial position of P point for the pneumatic actuators at their maximum stroke; $L_1, L_2. L_3$ - lengths of the movable links.

Since the application of *SolidWorks* in modeling kinematics and dynamics of parallel manipulators is restricted, further simulation was carried out by means of *SimMechanics* library of *Matlab-Simulink* package. The library enables the construction of complex mechanisms of parallel manipulators excluding mathematical descriptions of their kinematics and dynamics. In simulations based upon *SimMechanics* library an equivalent model of pneumatic tripod manipulator with its spatial orientation indicated was constructed. In *SimMechanics* library all the solid elements of the manipulator were described by substitute geometry by means of ellipsoids and assigned both masses and inertial tensors. In *Matlab-Simulink* environment tripod-based parallel kinematic manipulator was connected with its control system. On the basis of this scheme, the equivalent model of 3-UPRR pneumatic parallel manipulator was worked out (Fig. 6). The equivalent model retains kinematic joints and spatial orientation defined in solid model in *SolidWorks*. In order to create the equivalent model, it was necessary to define the gravity centre of solids in central and local coordinates.

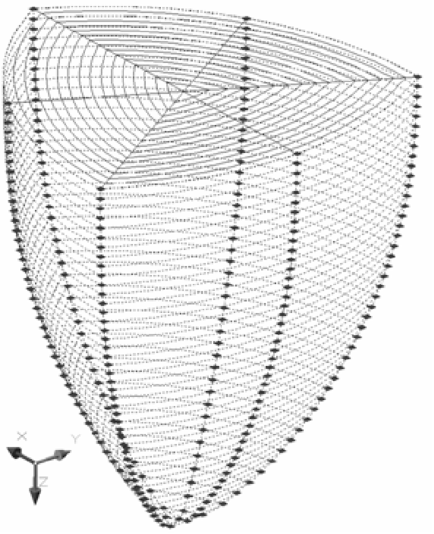



**Fig. 8.** Workspace of 3-UPRR pneumatic parallel manipulator

The kinematic model of 3-UPRR manipulator obtained by means of *SimMechanics* library is presented as simulation block in Fig.7. The kinematic model was used to analyse TCP trajectory of pneumatic parallel manipulator. The workspace of 3-UPRR pneumatic parallel manipulator in Cartesian coordinates is shown in Fig. 8.

## 4. EXPERIMENTAL RESULTS

The experimental research focused on determining the precision of positioning of manipulator's end-effector point of the moving platform during point-to-point control (Laski and Dindorf, 2007). The position and orientation of manipulator's end-effector point is dependent upon control of three pneumatic linear actuators (rodless cylinders). The maximum velocity of pneumatic actuators was $v_{max}$=1,5m/s, but their acceleration did not exceed $a_{max}$=10m/s$^2$. The exemplary trajectory of end-effector from $P_1$ point of coordinates [0,25; 0,44; 639,36] mm to $P_2$ point of coordinates [-91,46; 0,61; 408,22] mm, for the mass load $m$ = 0,2 kg, is shown in Fig. 9.

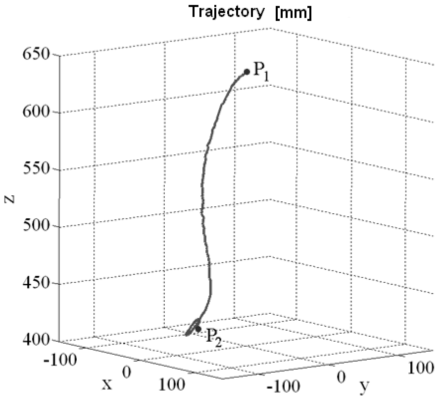
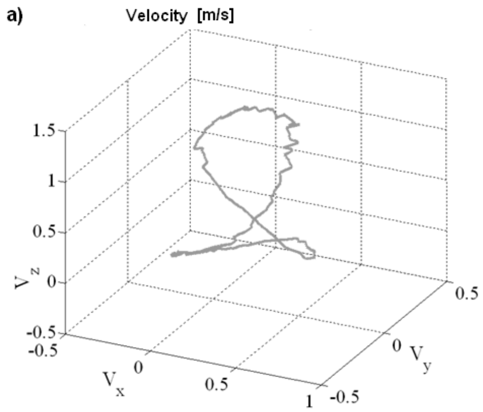



**Fig. 9.** Trajectory of the end-effector from point $P_1$ to point $P_2$

Fig. 10a and 10b presents the velocity and acceleration trajectories of the analyzed end-effector point in Cartesian space. The solution of manipulator's kinematic reverse problem was conducted by means of Matlab/Simulink package and toolbox SimMechanics. To control end effector from $P_1$ point to $P_2$ point in the Cartesian space XYZ it was necessary to control pneumatic linear actuators in order to change their positions according to the trajectory presented In Fig. 11a and the velocity corresponding to the trajectory given in Fig.11b.



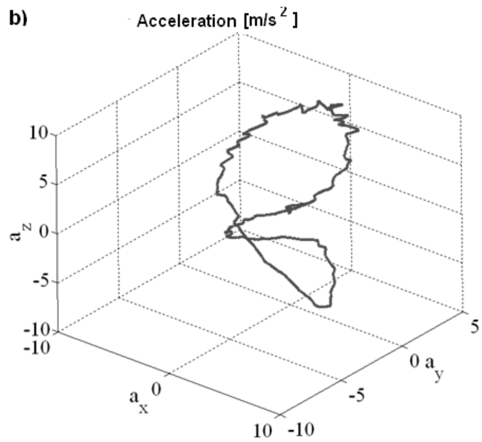




**Fig. 10.** Trajectories of velocity (a) and acceleration (b) of the end effector point of a moving platform

The positioning accuracy of 3-UPRR manipulator's end-effector point from the position selected plane to the position measurement plane for different control velocity of linear pneumatic actuators was analyzed. For the purpose of the analysis 5 measurement series of manipulator's positioning accuracy were conducted. They comprised 30 measurement points fixed on measurement plane of the dimensions of 12x10 mm with a mapped grid of 2mm. The analysis was based upon the European Standard EN 29283: 1992 (Industrial Robots - Performance Criteria and Related Test Methods), which is the equivalent of ISO 9283: 1998. Fig. 12 presents the distribution of P points on measurement plane situated at the distance $z$=490mm from the manipulator's fixed base. The points were determined at the velocity of linear pneumatic actuators $v_{15}$=0,15$v_{max}$. On the basis of computations it may be concluded the positioning accuracy of the analyzed prototype of 3-UPRR manipulator is $\Delta xy$ =2,095±1.32mm.

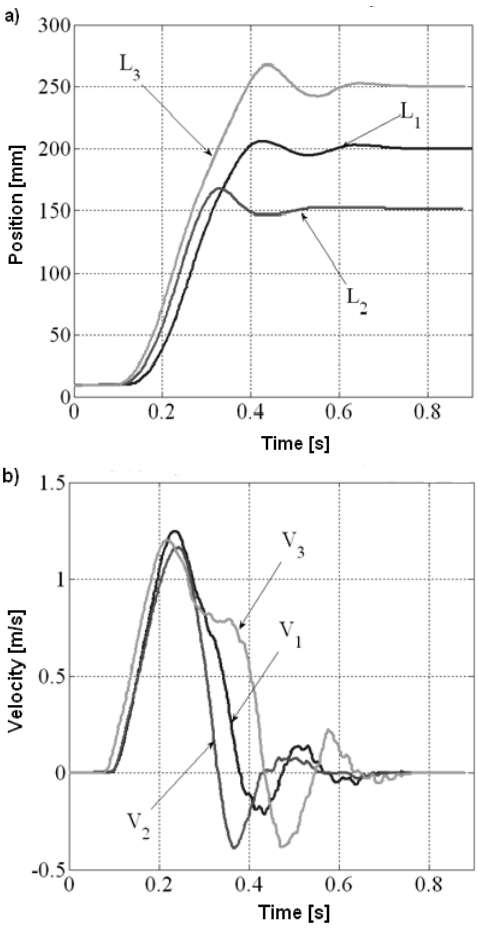



**Fig. 11.** Trajectories of position (a) and velocity (b) of pneumatic linear actuators

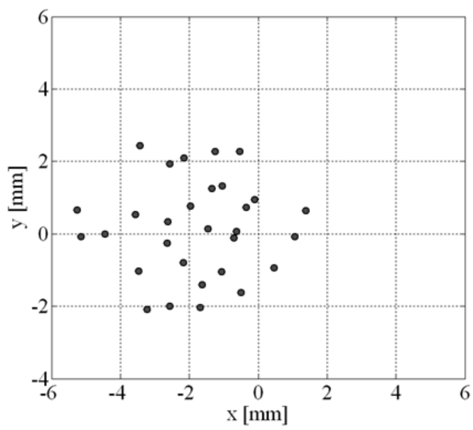



**Fig. 12**. Distribution of points on measurement plane at the distance *z* = 490mm from the fixed base

The results of positioning accuracy obtained for different trajectories of end-effector point for the control of linear pneumatic actuators with $v_{15}$ velocity were very similar. The differences in positioning accuracy result from different velocities of linear pneumatic actuators, for example for the velocity $v_{10}$ the positioning accuracy is $\Delta xy = 1.397 \pm 0.893$ mm, while for the velocity of $v_{30}$ the positioning accuracy reaches $\Delta xy = 3.616 \pm 2.025$ mm.

## 5. CONCLUSIONS

The paper presents the prototype of tripod pneumatic parallel manipulator of 3-UPRR kinematic structure. The tripod pneumatic manipulator consists of a supporting structure, fixed base, moving platform, prismatic joints (P-joints) – three servo-pneumatic axes, Cardan joints (U-joints) and rotary joints (R-joints). The single servo-pneumatic axis of the manipulator is composed of rodless pneumatic cylinder integrated with magnetostrictive measurement of position, proportional directional control valve, axis interface and axis connector, positioning axis controller. The aim of the project was to carry out model tests and simulations on a virtual model of tripod manipulator as well as conduct experimental research on a prototype of pneumatic parallel manipulator of 3-UPRR kinematics. Both the model tests and the experimental results show that the pneumatic parallel manipulator of 3-UPRR type fulfils the constructional assumptions and has satisfactory kinematic and dynamic properties. Further research will be directed towards improving the control accuracy of end-effector's trajectory by means of fuzzy logic control system (FLC) with real time interpolator and dSPACE software. The research conducted on the prototype of the pneumatic parallel manipulator of tripod kinematic structure is an original contribution towards development of parallel kinematic structures of pneumatic manipulators. The presented prototype of pneumatic parallel manipulator will find its application in both manufacturing and rehabilitation manipulators.

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