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KINEMATICS AND WORKSPACE ANALYSIS FOR A 6-DOF PARALLEL MANIPULATOR WITH COAXIAL CTUATED ARMS

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Abstract: *The article presents a kinematic model of a manipulator with a closed kinematic change, with coaxial actuated arms, Hexarot type. The structure references widely used SCARA type industrial robots. The discussed coaxial manipulator structure posses six coaxial rotation drives with active arms, to which passive drive arms are mounted via spherical joints. The work platform, to which the effector is mounted, has been designed on a regular triangle base, and connects passive arms via spherical joints. The workspace shape has been designed on the basis of sample geometric dimension.*

Keywords: Parallel manipulator, 6-DOF, Hexarot, Kinematics, Workspace.

1. Introduction

Regular SCARA (Selectively Compliant Assembly Robot Arm) robots possess a kinematic chain which includes two rotation drives and one progression drive (Zwierzchowski, 2016a, Takosoglu, 2016a). The SCARA family of robots was designed for a variety of general-purpose applications requiring fast, repeatable and articulate point-to-point movements such as palletizing, depalletizing, machine loading/unloading and assembly (Blasiak, M., 2016). Now, the main areas of use for SCARA robots are: welding, handling, assembly, painting and finishing, picking, packing, palletizing and machine tending (Blasiak et al., 2016, Koruba et al., 2013). Key markets include automotive, plastics, metal fabrication, foundry, electronics, machine tools, pharmaceutical and food and beverage (Zwierzchowski, 2016b, Takosoglu, 2016b).

There is research being conducted into finding machines which could replace SCARA robots, while retaining similar functionality, while displaying better dynamics and positional accuracy. One such machine could be a structure with a closed kinematic chain with coaxially actuated Hexarot type arms. A prototype of such machine has been built by ABB, but their robot possess a smaller number of degrees of freedom, being a 3-DOF type machine. The kinematic structure of the device has been described in an article (Brogårdh, 2007). The rotary actuators have equipped on the prototype coaxially on a cylindrical column, and the drive is transferred onto the platform using passive drive units and the joints between them. Robots with rotary drives mounted on a common cylindrical column have been analyzed in scientific works (Marlow et al., 2014) (Isaksson et al., 2012; Isaksson et al., 2013; Pedrammehr et al., 2016 and Qazani et al., 2015). An article (Isaksson et al., 2012) analyses the kinematic structure and the shape of the workspace of a 5-DOF manipulator, which possess a closed kinematic chain with coaxially actuated drive arms. Similarly to other solutions, this type of structure is based on a truss, whose columns do not transfer shear and torsion load, which means they can be produced from light, high rigidity material (Isaksson et al., 2012, Pietrala, 2016). The link structure of the octahedral Hexarot robot was inspired by the original platform designed by E. Gough. In robots of this type, cross and spherical joints have been used.

2. Kinematic analysis of a 6-DOF spatial manipulator with a rotary drive

For the analyzed 6-DOF manipulator a basic set of Cartesian coordinates has been assumed. The axes of this set have been marked with color: *x* axis – red, *y* axis – green, *z* axis – blue. Moreover, all sets used in

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kinematic analysis have been assumed as having a positive orientation. Also defined are homogenous transformation matrixes, which have been presented as matrixes (1) and (2):

$$RotX(\alpha)=\begin{pmatrix}1 & 0 & 0 & 0\\ 1 & c\alpha & -s\alpha & 0\\ 0 & s\alpha & c\alpha & 0\\ 0 & 0 & 0 & 1\end{pmatrix};\quad RotY(\alpha)=\begin{pmatrix}c\alpha & 0 & s\alpha & 0\\ 0 & 1 & 0 & 0\\ -s\alpha & 0 & c\alpha & 0\\ 0 & 0 & 0 & 1\end{pmatrix};\quad RotZ(\alpha)=\begin{pmatrix}c\alpha & -s\alpha & 0 & 0\\ s\alpha & c\alpha & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix};\quad (1)$$

$$TransX(d)=\begin{pmatrix}1 & 0 & 0 & d\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix};\quad TransY(d)=\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & d\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix};\quad TransZ(d)=\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & d\\ 0 & 0 & 0 & 1\end{pmatrix};\quad (2)$$

The analyzed structure is one of the more interesting spatial solutions using six degrees of freedom along with a rotary drive. Analogous to using delta type manipulator is utilizing rotary drives and passive arms. The structure being discussed possess six drives mounted one on top of another, creating a column with a common axis. Similarly to devices described previously, every individual kinematic chain contains a rotary drive link and passive arms with spherical joints. A single kinematic chain can be written down a 6-RSS where: (R) symbolizes a rotary joint, and (S) symbolizes a spherical joint. The device possesses a work platform based on the shape of a regular triangle with cut vertices, on which the passive arms' spherical joints are mounted. Fig. 1 presents a simplified solid model of the manipulator with six rotary drive, in which the passive arms do not receive one degree o freedom. This DOF is the rotation around the longitudal axis of the rod, which does not influence the position nor the orientation the work platform. Figs. 1 and 2 present characteristic dimension of the device, as well as views of the local coordinate systems $R_{i,1}$, $R_{i,2}$, $R_{i,3}$ $R_{i,4}$ for individual arms.

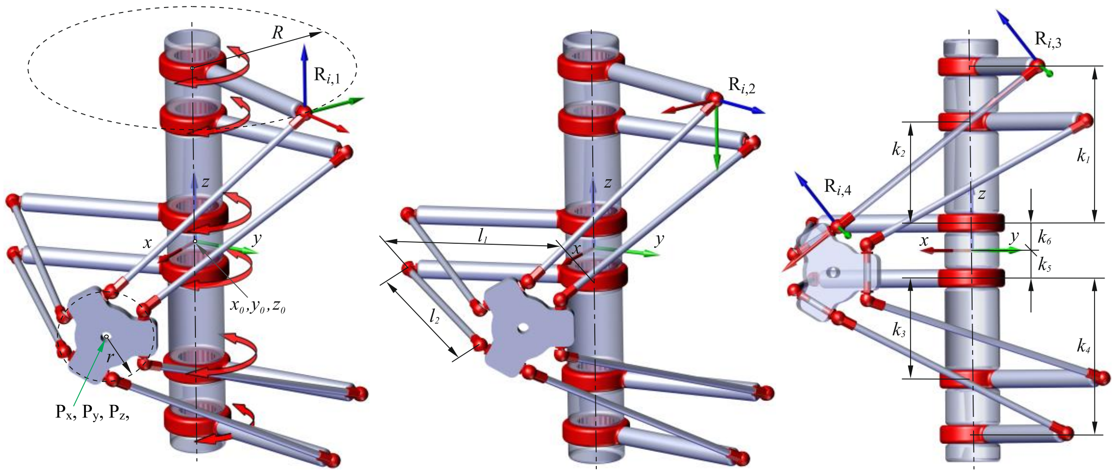

Fig. 1: . Spatial mechanism with 6 DOF – view of local coordinate systems $R_{i,1}$, $R_{i,2}$, $R_{i,3}$ $R_{i,4}$.

Kinematic equations have been determined for the structure being analyzed (3). This equations take into account the relationship tying the arms to the work platform. The analyzed kinematic structure is characterized by being symmetrical to the *xy* plane. Additionally, the distances $k_1 = 500$ mm, $k_2 = 350$ mm, $k_3 = -350$ mm, $k_4 = -500$ mm, $k_5 = -75$ mm, $k_6 = 75$ mm on the z axis have been determined and represent the height at which each (*arm number symbolized by i)* is mounted. In other words – the distances at which all of the rotary drives are place along the z axis. Kinematic equations have been determined for the arms, with *i* marking the arm number, and their corresponding work platform point, placed in a circle with a radius of r =125 mm and spaced at the following angles: $\zeta_1 = \zeta_0$, $\zeta_2 = 120^o - \zeta_0$, $\zeta_3 = 120^o + \zeta_0$, $\zeta_4 = 240^o - \zeta_0$, $\zeta_5 = 240^o + \zeta_0$, $\zeta_6 = -\zeta_0$. An additional base angle for the platform has been introduced at $\zeta_0 = 36.8699^o$. It determines the placement of joint in the circle, and is equal to half of the angle between two platform joints in one coupling.

$$f(\theta_{i,1},\theta_{i,2},\theta_{i,3}) = \begin{pmatrix} -P_{i,x} + \cos\theta_{i,1}(l_1 + l_2 \sin\theta_{i,3}) + l_2 \sin\theta_{i,1}\cos\theta_{i,2}\cos\theta_{i,3} \\ -P_{i,y} + \sin\theta_{i,1}(l_1 + l_2 \sin\theta_{i,3}) - l_2 \cos\theta_{i,1}\cos\theta_{i,2}\cos\theta_{i,3} \\ -P_{i,z} + k_i - l_2 \sin\theta_{i,2}\cos\theta_{i,3} \end{pmatrix} = 0 \tag{3}$$

3. Workspace of the 6-DOF manipulator

The workspace has been determined for the mechanism being analyzed, assuming geometrical constraints and physical constraints for the range of movement of the joints. The working range for the rotary drives has been assumed at $-2\pi/3 \div 2\pi/3$ while the working range of the joints has been assumed at $-\pi/2 \div \pi/2$ for ball joints on the first axis, indexes i = 1, 2, 3, 4 and $\pi/2 \div 3\pi/2$ for arms with indexes i = 5, 6, as well as $-\pi/6 \div \pi/6$ as the working range for ball joints on the second axis. Figs. 2 and 3 present the shapes of the workspaces for zero orientations of the work platform.

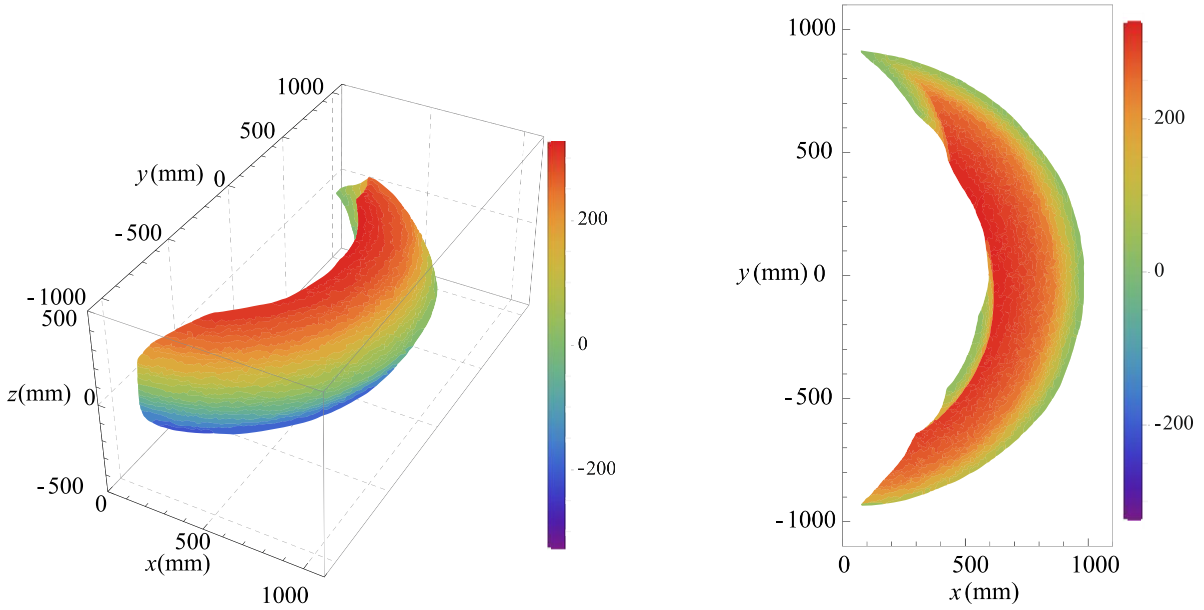

Fig. 2: Workspace: a) axonometric view; b) x, y plane view.

Fig. 3 shows the view of the workspace of the mechanism with rotary drives, in view for x ,z and y, z planes for the zero orientation of the work platform.

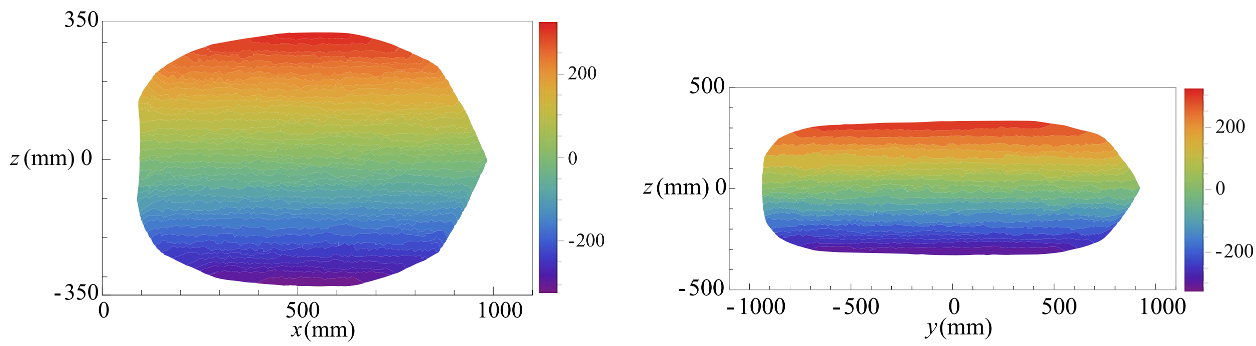

Fig. 3: Workspace – view of x,z and y,z planes for the zero orientation of the work platform.

4. Conclusion and future work

Fully parallel manipulators with a large range of platform rotations are unusual, even more so if combined with a large positional workspace. This article describes a new type parallel Hexarot manipulator. The analyzed structure possess significant potential, in relation to the shape and (large) volume of the workspace. The Hexarot type structure possess six active drive arms, which can be rotated around the column, which at the same time is a cylindrical base. All of the drives rotate on a common axis. The passive arm system transmits the drive form active units to the work platform via spherical joints, while the platform is the mounting point of the effector. The complicated system of passive arms presents a significant risk of collisions occurring between the element of the manipulator and other objects. The characteristic of the 6-DOF Hexarot manipulator, including the size of the workspace and working ranges, are highly reliant on the parameters of the kinematic structure. The lengths of the arms and axis ranges achievable by the spherical joints have the most impact on the shape of the workspace. Simulations indicated, that no inconsistencies have appeared in the volume of the workspace. However, a factor exists, which limits the possibility of achieving full rotation of the work platform, which is the collisions between the parts of the manipulator. However, such a limitation does not impact on the already wide functionality of the manipulator. In the future, optimizing the length of the passive and active arms as well as other geometric dimensions of the manipulator will be necessary, to achieve a possibly large (in terms of volume) workspace. Moreover, the shape of the workspace is significantly changed along with the orientation of the work platform changing. The achieved workspace shape shows significant potential in industrial applications of such a manipulator, similar to that of SCARA robots.

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