Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 52(5) (2020) 325-328
DOI: 10.22060/mej.2019.14725.5932

Kinetostatic Performance Comparison of Spherical Parallel Mechanisms Extracted from Type Synthesis with Modeling Clearance in Passive Joints

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ABSTRACT: A spherical parallel mechanism is used to rotate a body around a fixed point. Different kinematic arrangements can be obtained for the robot with three degrees of rotational freedom. The most commonly used structure for this robot is the 3-RRR kinematic architecture which is an overconstrained parallel mechanism and causes several problems of mounting the mechanism. In this paper two non-overconstrained architectures 3-RRS and 3-RSR are compared with overconstrained one from the accuracy point of view based on the joint clearance. First, a method to obtain a model of moving platform pose (position and orientation) error based on the joint clearance is introduced which leads to a standard convex optimization problem. Then maximum values of six components of the pose error are computed in more than 1000 different configurations within their workspace. It is shown that this displacement is configuration dependent. The obtained results revealed that the 3-RRR spherical parallel mechanism has better position accuracy while in the case of orientation, the 3-RRS SPM has the lowest maximum error between spherical parallel mechanisms under study in the prescribed workspace. It can be concluded that non-overconstrained structures can be used instead of the overconstrained structure. Finally, a comparison was made between the performance indices and the presented method.

Review History:

Received: 7/26/2018
Revised: 2/7/2019
Accepted: 3/18/2019
Available Online: 3/18/2019

Keywords:

Spherical parallel manipulator
Accuracy analysis
Joint clearance
Kinematic sensitivity

1. INTRODUCTION

Spherical Parallel Mechanism (SPM) is one of the parallel mechanisms with limited degrees of freedom which is used to rotate a body around a fixed point. The most common SPM is agile eye [1] with the 3-RRR kinematic arrangement, which is overconstrained structure and needs high precision in manufacturing and its advantages are accuracy and rigidity. On the other hand, non-overconstrained structures have been proposed for spherical motion. The advantage of non-overconstrained structures is that the assembly is always possible even with the geometrical errors. In this paper, 3-RRR SPM is compared with two non-overconstrained structures 3-RRS and 3-RSR from the accuracy point of view. Given that the only difference of the mentioned mechanisms is their joints, the impact of the joint clearance on the accuracy has been studied. So far, much research was conducted on the joint clearance and its impact on the accuracy of parallel mechanisms. In this paper, the method introduced in [2-4] which is based on the screw theory is used to find the error prediction model and find maximum pose error.

To measure mechanism precision, kinetostatic indices have also been introduced. Finally, in order to determine the most suitable indicator, a comparison between these indices and the proposed method has been made.

2. METHODOLOGY

2.1. Moving platform pose error

The maximum value of each component of the pose error due to joint clearance in each limb can be found by solving the following optimization problem:

$$\max\ \delta\mathbf{E}_{i,k} = \text{maximize}\sum_{j=1}^{n}\mathbf{I}_k\,\text{adj}\left(\mathbf{T}_{i,j}\right)\delta\mathbf{e}_{i,j}$$

subject to

$$\text{R joints} \Rightarrow \begin{cases}\delta\alpha_{i,j}^2+\delta\beta_{i,j}^2\le\delta\theta_{i,j}^2\\ \delta x_{i,j}^2+\delta y_{i,j}^2\le\delta\rho_{i,j}^2\\ \delta z_{i,j}^2\le\delta\sigma_{i,j}^2\end{cases} \tag{1}$$

$$\text{S joints} \Rightarrow \delta x_{i,j}^2+\delta y_{i,j}^2+\delta z_{i,j}^2\le\delta\varepsilon_{i,j}^2$$

Where i and j represent limbs and joint's number, respectively.

$$\mathbf{1}_{6\times6}=\left[\mathbf{I}_1\ \mathbf{I}_2\ \mathbf{I}_3\ \mathbf{I}_4\ \mathbf{I}_5\ \mathbf{I}_6\right] \tag{2}$$

And the joint error can be represented by small displacement screw as following:

$$\delta\mathbf{e}=[\delta\alpha\ \ \delta\beta\ \ \delta\gamma\ \ \delta x\ \ \delta y\ \ \delta z]^T \tag{3}$$

Eq. (1) is a convex function and using the software package CVX and taking into account the constraints of the equation to be solved as follows:

$$\Delta\theta_{i,j}=0.01\,\text{rad}=0.57^{\circ} \tag{4}$$

$$\Delta\rho_{i,j}=0.1\,\text{mm} \tag{5}$$

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$$\Delta\sigma_{i,j} = 0.1\,\text{mm} \tag{6}$$

$$\Delta\varepsilon_{i,j} = 0.2\,\text{mm} \tag{7}$$

$$\Delta\omega_{i,j} = 0.01\,\text{rad} = 0.57^{\circ} \tag{8}$$

Eventually, the maximum of each of the error components of the platform is obtained as follows:

$$\max \delta\mathbf{E}_k = \min\left(\max \delta\mathbf{E}_{i,k}\right) \quad i = 1,\ldots,m \quad k = 1,\ldots,6 \tag{9}$$

2.2. Performance Indices

Various indices have been introduced to measure the accuracy of the robots that are all based on manipulator Jacobian [5] which the most well-known are as follows:

Manipulability:

$$\mu \equiv 1/\sqrt{\det\left(\mathbf{K}^T\mathbf{K}\right)} \tag{10}$$

Dexterity:

$$\kappa \equiv \|\mathbf{K}\|\|\mathbf{K}^{-1}\| \tag{11}$$

Kinematic sensitivity:

$$\sigma_{r_c,f} \equiv \max_{\rho_c=1} \phi_f \ , \quad \sigma_{p_c,f} \equiv \max_{\rho_c=1} \mathbf{p}_f \tag{12}$$

One of the important weaknesses of these indices is that in robots which degrees of freedom are rotational and translational, in other words, their Jacobian is not homogeneous, the indices do not provide a significant physical quantity. Also, in robots with the same Jacobin, the situation we are facing in this paper, the indices cannot be used for comparison. Therefore, this paper presents a comparison between the proposed method and the kinematic sensitivity indices to determine the most suitable index for comparing robot precision.

3. RESULTS AND DISCUSSION

3.1. Under study workspace

In this paper, the Euler angles [ϕ, θ, ψ] is used in order to show the workspace of the manipulator which is defined by

$$\varphi \in \left[\frac{-\pi}{3}, \frac{\pi}{4}\right],\ \psi \in \left[\frac{-\pi}{3}, \frac{\pi}{4}\right], \text{ and } \theta = 0.$$

3.2. Comparison of introduced error model with performance indices

Fig. 1 shows the mentioned indices and maximum rotational error of 3-RRR SPM in the prescribed workspace. More graphs are provided in the full article. As shown in this figure, the kinematic sensitivity index is the most suitable indicator for displaying manipulator accuracy.

4. CONCLUSIONS

In this paper, an overconstrained SPM and two non-overconstrained SPMs were compared from the accuracy point of view and the results showed that the latter structures can be used and at the same time had the suitable accuracy.

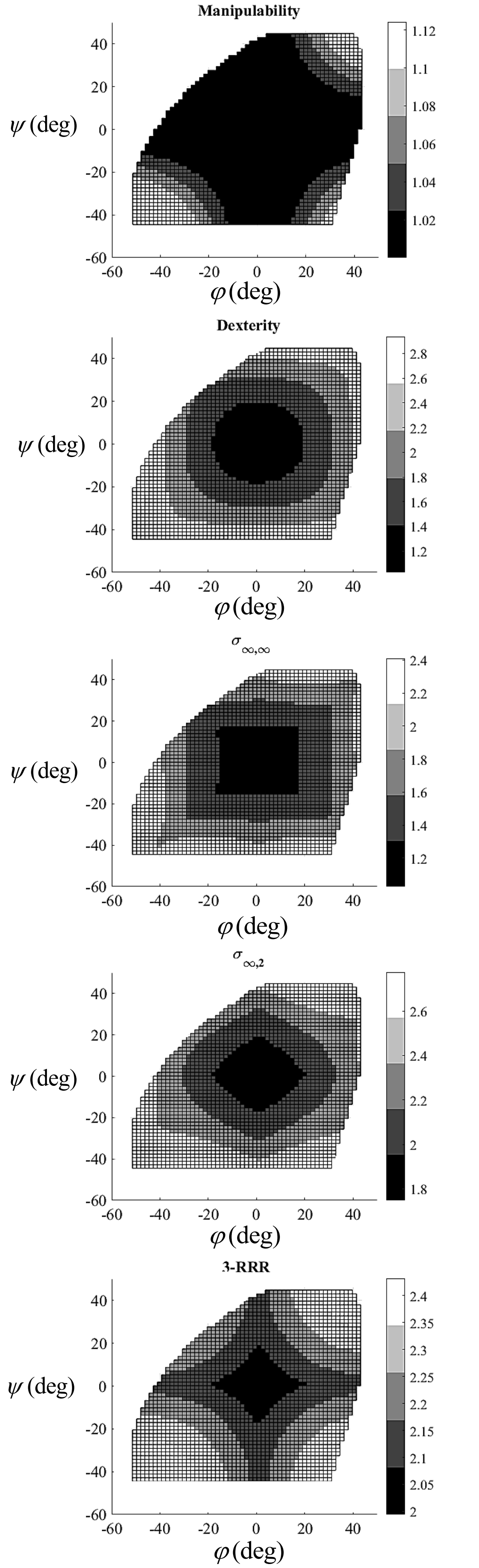

Fig. 1. Comparison of the introduced error model with performance indices

Also, a comparison was made between kinematic sensitivity indices and the error model and results revealed that the kinematic sensitivity index is the most appropriate index for expressing the accuracy of parallel manipulators.

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