Mechanism and Machine Theory 44 (2009) 1768–1783

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

# Prediction of the pose errors produced by joints clearance for a 3-UPU parallel robot

A.-H. Chebbi [a], Z. Affi [a,*], L. Romdhane [b]

[a] Laboratoire de Génie Mécanique, Ecole Nationale d'Ingénieurs de Monastir, Tunisia
[b] Laboratoire de Génie Mécanique, Ecole Nationale d'Ingénieurs de Sousse, Tunisia

ARTICLE INFO

*Article history:*
Received 5 July 2008
Received in revised form 11 March 2009
Accepted 12 March 2009
Available online 23 April 2009

*Keywords:*
Joint clearance
Pose error
Workspace
Parallel robot

ABSTRACT

This paper deals with the singularity analysis and modeling of the effects of the clearance in the joints on the parallel robot accuracy. This model is presented in an analytical form, which allowed us to predict easily the pose error for a given external load, a nominal pose and the structural parameters of the 3-UPU parallel manipulator. Based on this model, we also developed an algorithm to map the pose error within the workspace of the robot.



## 1. Introduction

One of the main advantages of parallel robots and the translational ones in particular, is the high accuracy compared to serial robots. This accuracy can be altered by the deformation of the robot structure, the link dimension tolerance and also the joint clearance. The deviation of accuracy caused by the deformation of the robot structure can be reduced by increasing its stiffness. The link dimensional tolerance leads to predictable errors that can be corrected by calibrating the robot. However, the joints clearance can be considered as one of the most important error sources, since it affects both accuracy and repeatability. Hence, the development of a predictive model for assessing in advance the clearance effect on the parallel manipulator accuracy becomes relevant. Several methods and techniques have been used to quantify the configuration error generated by the joint clearance.

Several methods are used to identify the limits of the uncertain range of motion, generated by the joints clearance. Kosuge et al. [1] analyzed the precision of planar manipulator on silicon. They investigated the effect of the clearance in the joints on its kinematic performance. They assumed that the actuator joint angle is controlled precisely despite the existence of the joints clearance, and they expressed the inaccuracy of the manipulator as the sum of the inaccuracies introduced by the clearance of the different joints of the mechanism. Ting et al. [2] modeled the joints clearance by a small link with the length equal to one half of the joints clearance. Based on this assumption, they gave the limits of the uncertain pose of the end effector.

The stochastic methods were also used in order to predict the configuration error of mechanisms or to determine the tolerance and the clearance in mechanisms for a given precision. A synthesis procedure using stochastic model is developed in

* Corresponding author.
*E-mail address:* zouhaier.affi@enim.rnu.tn (Z. Affi).

0094-114X/$ - see front matter © 2009 Published by Elsevier Ltd.
doi:10.1016/j.mechmachtheory.2009.03.006

**Nomenclature**

| | |
|---|---|
| $R_b(O_b, \mathbf{x}_B, \mathbf{y}_B, \mathbf{z}_B)$ | reference frame attached to the base |
| $R_p(O_p, \mathbf{x}_p, \mathbf{y}_p, \mathbf{z}_p)$ | reference frame attached to the platform |
| $\mathbf{f}$ | a force acting on the mobile platform |
| $\mathbf{m}$ | a couple acting on the mobile platform |
| $\mathbf{f}_i$ $(i = 1, 2, 3)$ | the force supported by the $i$th leg |
| $\mathbf{m}_i$ $(i = 1, 2, 3)$ | the couple supported by the $i$th leg |
| $\mathbf{s}_i$ $(i = 1, 2, 3)$ | unit vector of the $i$th leg |
| $\mathbf{q}_{ij}$ $(i = 1, 2, 3$ and $j = 1, 2)$ | unit vector describing the $j$th revolute joint direction joining the $i$th leg to the base or the platform |
| $L$ | length of the prismatic guide |
| $a$ | width of the pin of the prismatic joint |
| $c$ | the magnitude of a prismatic joint clearance |
| $\varepsilon_a$ | axial clearance in a revolute joint |
| $\varepsilon_d$ | radial clearance in revolute joint |
| $\lambda$ | the half of the pin length of the revolute joint |
| $r_b$ | radius of the base |
| $r_p$ | radius of the platform |
| $\alpha_i$ | angular position of the $i$th leg |
| $l_i$ | length of the $i$th leg |
| $E_p$ | the resultant of the platform position error |
| $E_{px}$ | platform position error along the axis $\mathbf{x}_B$ |
| $E_{py}$ | platform position error along the axis $\mathbf{y}_B$ |
| $E_{pz}$ | platform position error along the axis $\mathbf{z}_B$ |
| $\theta_x$ | orientation error of the platform around the axis $\mathbf{x}_B$ |
| $\theta_y$ | orientation error of the platform around the axis $\mathbf{y}_B$ |
| $\theta_z$ | orientation error of the platform around the axis $\mathbf{z}_B$ |

[3] for the four-bar mechanism. The goal of this procedure is to allocate tolerances and clearances on different links and joints in order to restrict the output error in the path of the coupler point within specified limits. The tolerance design of a 2-DOF parallel robot is presented in [4]. In [5], Zhu et al. established a probability density function (PDF) of the robot end-point pose. The PDF is derived based on the joint deviation, which can have uniform or normal distribution and can be used in order to determine the robot pose error.

The deterministic technique can accurately determine the pose error as a function of the nominal pose of the end effector and the forces acting on the manipulator. The deterministic approach has the advantage of being based on an exact description of the occurrence in the clearance affected joints and being suitable for evaluating clearance influence in both static and dynamic condition ([6,7]). In [8], the joints clearance is treated as a virtual link. Under kinetostatic and dynamic analyses expressing the mechanism equilibrium, they performed the transmission quality of a single-loop linkage. Using screw theory, the authors generalized their method to multi-loop linkages [9]. Based on the displacement in each clearance affected joint, a model expressing the pose error of the end effector as a function of the geometrical parameters of the mechanical system is presented in [10]. A modeling of the clearance affected prismatic pair is presented in [11]. The presented model, applied to a serial Cartesian spatial manipulator, describes the displacement error in the prismatic pair and relates it to the load acting on the pair. A deterministic model, that assesses the influence of the joints clearance of a revolute pair on the pose error of a spatial mechanism at a given nominal pose, is developed in [12]. The presented model is based on six static analyses and the virtual work principal. The proposed model was improved in [6] by using a generic model of kinematic pairs of a mechanism having any arbitrary loaded links and introducing the clearance in the prismatic pairs.

The presented deterministic methods are limited to a given configuration of the mechanism where the static analysis was performed numerically. However, the designer usually prefers to have the pose error distribution of the manipulator within the workspace [13]. Hence, developing a completely analytic model expressing the pose error as a function of the external load applied on the mechanism, the joints clearance magnitude, the nominal pose of the platform and the structural parameters of the robot becomes more relevant. Therefore, this work has two main objectives: first, we develop an analytical model capable of quantifying the pose error as a function of the joints clearance magnitude, the configuration of the mechanism, and the load acting on the platform. Then, based on the developed model, we present an algorithm capable of yielding the distribution of the pose error over the workspace of the robot.

Section 2 presents the kinetostatic analysis of the 3-UPU parallel robot. In Section 3, we develop an analytical model capable of predicting the pose error of the end effector. Based on the developed model, an algorithm allowing the prediction of the pose error within the manipulator workspace is presented in Section 4. Some concluding remarks are presented in Section 5.