Australian Journal of Basic and Applied Sciences, 8(15) Special 2014, Pages: 180-184

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

Comparison of Kinematic Models for Performance Evaluation of Parallel Mechanism

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ARTICLE INFO

Article history:
Received 13 November 2013
Accepted 23October 2013
Available online 30November 2011

Keywords:
Kinematics model, parallel robot, comparative studies, DH method

ABSTRACT

Background: There are a number of kinematic models available in the literature to model the mechanisms for robotic applications – the kinematic models based on Denavit-Hartenberg (DH) method or algebra method is usually adopted. However, the selection of kinematic models largely depends on the mechanism due to issues in the kinematic model. For example, DH method is might not be able to model a close loop effectively, as reported by a number of researchers. Additionally, the comparative studies are used to clarify certain issues of formulating such as two methods with one structure based on characteristics of kinematics are used but with no descriptions of performance of mechanism. Since, the performance of a mechanism, in terms of workspace analysis, which is important for robotic design. Our paper provides a strategic solution by compare the two methods with using one structure based on performance of the parallel robot. **Objective:** The main objective of this paper is to compare and analysis the effectiveness of the kinematic models based on both DH and algebra methods to model a mechanism for robotics. The focus is on a two degree-of-freedom parallel robot – which contains a close loop in the mechanism. **Results:** Our results show that the closed-form equation and workspaces shapes have similarity for both methods. The derivation is simple for Algebra rather than DH method. The result also shows that the workspaces shape is same as previous research. **Conclusion:** In conclusion, both of DH and algebra methods are able to represent a two degree-of-freedom parallel robot, in terms for their kinematics and performance (workspace). At the same time, this comparative analysis is also to validate the previous research. However, DH needs a complex derivation, and variable's initiation compared to algebra method. This provides an insight to other types of mechanisms.

To Cite This Article: Fahisal Abdullah, Sazali Yaacod and Shafriza Nisha Basah., Comparison of Kinematic Models For Performance Evaluation of Parallel Mechanism. ***Aust. J. Basic & Appl. Sci.**, 8(15): 180-184, 2014*

INTRODUCTION

Kinematics model for robot is consisting of research the motion without concern the forces or torques that cause it. Kinematics model can divide into two types of the analysis problem; direct kinematics and inverse kinematics. Inverse kinematics model is an analysis to find the actuator joint variable with given the desired position and orientations of the end effector. Then, the direct kinematics model is the reverse process of the inverse kinematics model. In robot parallel, the inverse kinematics model is easy to analysis rather than the direct kinematics model. In order to derive the kinematics model of the robot, the various formulating (Siciliano, 1999 ; Yahya, Mohamed, & Moghavvemi, 2009; Parasuraman, Chan, and Liang, 2010; Zhang and Zhang, 2013 etc) are used. Determine the appropriate formulating of the kinematics model remain a challenging issues and research activities focusing on derivation mathematical model of kinematics since it is an important aspect for develops a new robot application (Province, 2012).

In the paper, the DH method is selected since these methods more popular in serial robot. However, these methods have two opinions regarding the application mathematical models to investigate relations between actuated joint variables and location of end-effector for a specified geometry of the parallel manipulator. The first opinions as mentioned by (Tsai, 1999; Liu, X. J. and Wang, 2014) determine that the derivation of the kinematic model is complicated by existence of multiple closed loops of parallel structure. The second opinion is contrast from previous as mentioned by (Kucuk, 2010) where the mathematically modeling of the kinematic problem in parallel robot can be solving by using DH method. The authors derived the kinematics model using DH method with two planar parallel robot, 2 dof Planar Parallel Manipulators (PPMs) and a 3 dof Fully Planar Parallel Manipulator (FPPM) .The authors also determine the performances of the robot, including the analysis of workspaces, singularity, Jacobian matrix, condition number and global dexterity index. Another study by

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(Cui, 2009) solve the kinetostatic problem for 3-SPS-1-S parallel mechanism. The authors found that the DH method is using in order to derive the velocity equation of the constraining leg and velocity equation of the active parallel mechanism is using the geometric method. Besides that, (Itul and Pisla, 2006) presented the graphical visualization and the analysis elements for defined parallel robot working. The authors derived the equation of kinematics using DH method for two types of mechanism. So, this study shows that the selection of DH method is an effect to simplifying the mathematical model complexity of the kinematics problems in parallel robots. It is argued that even the workspaces and singular analysis are important to design a new robotic, the method of geometric as an example (Tsai, 1999) is not only one can be used in derived the kinematics model. Therefore, the two opinions about DH method are needed to be clarifying whether these methods acceptable to apply in the parallel robot field or not.

In order to determine the suitable derivation mathematical method of the kinematics model, the comparative analysis for two methods is used. Based on previous work, the comparative analysis for two methods (DH method versus Screw method) with one structure is done in study based on a kinematics characteristic of method such as parameter identification, direct kinematics, inverse kinematics and differential kinematics (Rocha, Tonetto and Dias, 2011). The findings showed that screw-based kinematic modeling has some beneficial features when compared to DH modeling. This study as a result shows that the comparative analysis two methods for one type of serial robot based on a characteristic of method can explain some concepts related to the screw-based kinematic modeling method. Another study by (Wang, 2004) as mentioned that the comparative analysis for two structures (Tricept robot and Tricept like the robot) with using kinematics characteristic and performances of robot parallel. The outcomes show that the inverse kinematics algorithm for each robot is similar, but the performance of each robot such as workspaces and dexterity is different. Therefore, the comparative analysis of two methods with using one structure based on performance of the parallel robot will be discussed in this paper. The kinematics performance's characteristics such as workspace, singularity and maximum velocity is used since it is important in kinematics design and control for parallel robot application (H.Patrick and A.Tatsuo, 1997).

In this paper, kinematics model based on DH method for structure from previous research such as planar parallel robot is deriving. Based on inverse kinematics, the workspaces of these types of the parallel robot are analysis and compare. Workspaces shaped, and the equation forms are given to compare their performances. This paper is helpful for us to clarify certain issues regarding the formulating of kinematics model method. The idea of solution is because no comparative study for formulations of the kinematic model based on performances of the parallel robot.

This text is planned as follows. Next section descried the design robot concerning the one manipulator (planar) structure of the previous research is developed. In the following, the derivations of mathematical modeling are using the DH method. The two methods for an example structure are compared later. Finally, conclusions are presented.

Description of RPRPR medical planar parallel robot:

Kinematics of the 2 dof of RPRPR medical parallel robot was extensively presented by (Stan, 2006; Sergiu-dan Stan, Vistrian, and Radu, 2008; Szep *et al*.,2009). The RPRPR (revolute-prismatic- revolute-prismatic-revolute) structure also known as 2-RPR (revolute-prismatic- revolute) robot is shown in Figure 1. These robots consist of two RPR leg, and the inverse kinematics based on algebra method can be derived as following equations (Szep *et al*., 2009) :

$$q_1 = \sqrt{x_p^2 + y_p^2} \quad (1)$$

$$q_2 = \sqrt{(b - x_p)^2 + y_p^2} \quad (2)$$

The direct kinematics based on algebra method can be derived as following equation:

$$x_p = \frac{q_1^2 + b^2 - q_2^2}{2.b} \quad (3)$$

$$y_p = \sqrt{q_1^2 + x_p^2} \quad (4)$$

Where:
q_i: leg length (mm); x_p, y_p : coordinated of point p ; b: distances between two bases joint (mm)

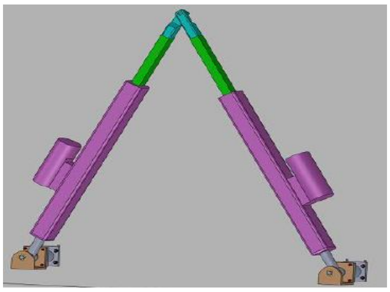


Fig. 1: CAD model of 2-RPR medical planar parallel robot (adapted from (Szep *et al*., 2009)).

Kinematics Modeling for RPRPR Medical Planar Parallel Robot Based on DH Method:

Kinematics diagram of RPRPR medical planar parallel robot is shown in Figure 2. For solving the inverse kinematics problems of this structure, the given coordinated P (x_p, y_p), the analytical expressions for the actuator length qi (i =1, 2) can be derived. The coordinated of point P can be defined by using general homogeneous transformation matrix 4x4 as given:

$$T = \begin{bmatrix} c\theta & -s\theta & 0 & a \\ s\theta c\alpha & c\theta c\alpha & -s\alpha & -s\alpha(d) \\ s\theta s\alpha & c\theta s\alpha & c\alpha & c\alpha(d) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

Where;
c: cos ; s: sin ; a: distance of the common normal ; d: distances along previous z to the common normal ;
θ: angle about previous z, from old x to new x; α:angle about common normal from old z to new z.

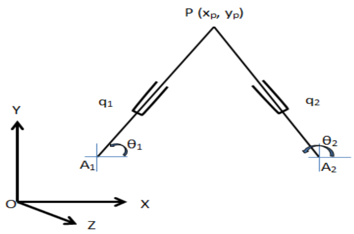


Fig. 2: Kinematics diagram of 2-RPR medical planar parallel.

Based on Figure 2, the equation of geometric can be derived as below:

$$OA + AP = OP \tag{6}$$

The transformation matrix T^1 and T^2 based on Figure 2 can be represented as follows:

$$T^1 = \begin{bmatrix} 1 & 0 & 0 & OA_x \\ 0 & 1 & 0 & OA_y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\theta_i & -s\theta_i & 0 & 0 \\ s\theta_i & c\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & q_i \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c\theta_i & 0 & s\theta_i & OA_x - s\theta_i(q_i) \\ s\theta_i & 0 & -c\theta_i & OA_y + c\theta_i(q_i) \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

$$T^2 = \begin{bmatrix} 1 & 0 & 0 & x_p \\ 0 & 1 & 0 & y_p \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

The position vector of transformation matrix T^1 and T^2 are equal, and then the equation is obtained as below:

$$\begin{bmatrix}-s\theta_i(q_i)\\ c\theta_i(q_i)\end{bmatrix}=\begin{bmatrix}x_p-OA_x\\ y_p-OA_y\end{bmatrix} \quad (9)$$

Next, the equation of (9) is summing the squares of both side of this equation and then simplification is done for solving the inverse kinematics problems of this robot, the analytical expressions for the actuator length q_i can be established:

$$q_i=\sqrt{(x_p-OA_x)^2+(y_p-OA_y)^2} \quad (10)$$

The passive joint variable θ_1 and θ_2 can be derived from equation of (10).

$$\theta_i=a\tan 2\left(\frac{-x_p+OA_x}{q_i},\frac{y_p-OA_y}{q_i}\right) \quad (11)$$

The direct kinematics based on DH method is found by rearranging the equation 10 as follow.

$$x_p=\sqrt{q_i^{\,2}-(y_p-OA_y)^2}+OA_x \quad (12)$$

$$y_p=\sqrt{q_i^{\,2}-(x_p-OA_x)^2}+OA_x \quad (13)$$

The passive joint variable θ_1 and θ_2 can be derived from equation of (9).

$$\theta_i=a\tan 2\left(\frac{-x_p+OA_x}{q_i},\frac{y_p-OA_y}{q_i}\right) \quad (14)$$

Comparisons between the DH Method and the Algebra Method:

Table 1 shows workspace shapes produces by the RPRPR Medical Planar Parallel Robot Based on DH and Algebra Method. The shapes of workspaces implement the parameters qmin = 6 mm, qmax = 9.6 mm and b= 5 mm into the equation (1),(2) and (10). Based on the equation of both method seen a similarity in terms of close form equation. The equation shows that derivation of Algebra method is simpler than DH method. However, the performance characteristic of the parallel robot is as showing the similarity of workspace for both kinematics models. The shapes of workspaces have to produce by this robot is same as stated in (Szep *et al*., 2009). As shown in Table 2, we can give a summary comparison of both method with apply to the same structure. Hence, we can learn that the ability of DH method in derivation of the kinematic model by using comparative studies based on performances of the parallel robot.

Table 1: Workspaces shape for DH and Algebra methods.

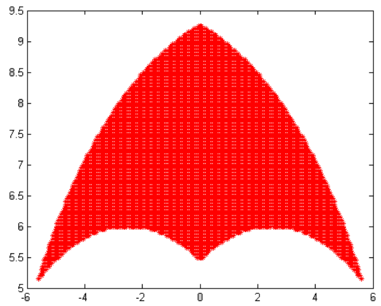
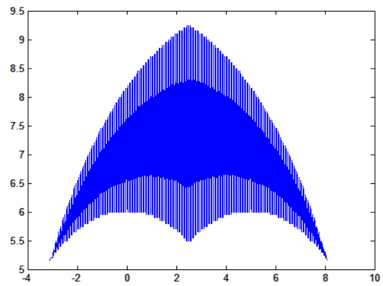
DH method	Algebra method
	
Parameters: q_{min} = 6 mm , q_{max} = 9.6 mm , b= 5 mm	

Table 2: Kinematics modeling using DH and Algebra methods.

Characteristics	DH method	Algebra Method
Inverse Kinematics	Close form solution	Close form solution
Direct Kinematics	Close form solution	Close form solution
Workspaces Shapes	Similar	Similar

Conclusion:

In this paper, we provided a brief introduction to the study related to formulating based kinematics model issues, especially applications of DH method in parallel robot. As we observed, the ability of this method applied in parallel robot filed regarding certain researchers is a doubt to use in their study. This is because of existence of multiple closed loops of parallel structure. The comparative analysis of two methods with one structure is without discussing the performance of the parallel robot. Here we purposed a solution. Our idea is to compare the two methods based on performance of mechanisms. Though the idea is simple, it gives an answer to the severe problem. The results show the closed-form equation and workspaces shapes have a similarity for both methods. The derivation is simple for Algebra rather than DH method. The result also shows that the workspaces shape is same as previous research. At the same time, this comparative analysis is as well to validate the previous research. Further comparison analysis can be added such as singularity and maximum velocity studies in order to verify the performance of method. And the additional study is also needed such as other's structure and method to validate of this approach.

ACKNOWLEDGEMENT

The authors / researchers want to express a great appreciation and gratitude to my supervisor and co-supervisor, including School of Mechatronic, University Malaysia Perlis (UniMAP) administrators and staffs, which enabled the progressing of this development. Thanks a lot to those are given a good support and their time to provide useful information that made this research possible.

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