Design and Control of 3-RRR Planar Parallel Manipulator

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Abstract:

This paper investigates the motion control of 3-RRR planar parallel manipulator through analysis, and computer simulation. An explicit nonlinear dynamic model based on CAD model is developed. The problem of inverse kinematics for the system is studied in this work. The nonlinear dynamic model resulting from CAD system is used in the simulation. A joint trajectory control is proposed; the control inputs are generated using PID controller. In order to show the efficiency of the developed model and the choosen controller gains several simulations for different paths are carried out. As a future work; further study ideas such as singularity analysis, linearizing of the dynamic model, and advanced controller strategy are required.

Keywords: Parallel Manipulator, Robot CAD Model, Inverse Kinematics

الخلاصة:

يبحث هذا العمل في التحكم في الحركة لنظام الي من النوع المتوازي في مستوي واحد من النوع الذي يحتوي على ثلاث مفاصل دورانية بواسطة التحليل الرياضي والمحاكاة الحاسوبية. تم تطوير نموذج ديناميكي غير خطي بالاعتماد على نظام CAD. تم دراسة مشكلة الكينماتيكا العكسية للنظام في العمل. تم استخدام النموذج الديناميكي غير الخطي الناتج من نظام CAD في المحاكاة. تم اقتراح تحكم مسار المفصل؛ مدخلات التحكم تم توليدها باستخدام مسيطر من نوع PID. من أجل التأكد من نجاح التصميم المقترح وعملية التمثيل الرياضي للنموذج المطور والاختيار المناسب لوحدة التحكم اجريت العديد من عمليات المحاكاة لمسارات مختلفة بها. الافكار المقدمة في البحث بحاجة إلى مزيد من العمل مثل دراسة تحليل singularity، التحليل الخطي للنموذج الرياضي، واستراتيجية سيطرة متقدمة.

الكلمات المفتاحية: انظمة الروبوت المتوازي، نظام الروبوت المعالج بالكمبيوتر، معادلات الحركة العكسية.

Introduction

This paper presents a CAD based design study for the planar parallel manipulator (PPM). Parallel manipulators are different from serial manipulators which consist of a number of links connected in series to form a kinematic chain (open chained mechanism). Parallel manipulators (PM) contain several kinematic chains parallel to each other to perform a specified task. The three degrees of freedom (3-DOF) parallel manipulator system which described in this work, the control of point (end effector) is the main target for the study. The advantages of parallel robots over the serial robots increase the system usage for many studies and applications in the recent years. The industry packaging is One of the most popular application for this tapes of robots, moreover due to their ease of construction, their light structure and the high accelerations obtained by these systems.

The main drawbacks of this type of manipulators: the complexity of the dynamic model in nature and the high chance of singularities occurrence. The behavior of the system should be mapped out in order to avoid singularities, and maintain control of the system. The dynamic model development of any robot system starts by choosing the correct parameters which are required for technical specifications. These parameters (measurement of dimensions) can be adjusted based on form of robot arms, the missing or complicated data can be estimated or replaced in simpler way in order to ease the design process. The CAD softwares offer very useful tools for the design process of robot systems. Nowadays, its capable of forming very complicated mechanical parts, calculating center of gravities and masses. Still approximation data is required to be used for when calculating not possible in the laboratory (Fedák *et.al.,* 2014). In the recent years, many researchers gave attention to the design and behavior of parallel manipulator systems studies. The kinematics analysis of 3-RRR PM is presented in (Hamduon *et.al.*, 2015). The authors in (Hamduon *et.al.*, 2015)described the inverse kinematic model for the system, the workspace reach of each kinematic chain is mapped, and simulation for the analysis is done. The forward and inverse singularities based on Jacobean matrix is presented in (Liu *et.al.*, 2017). Due to the importance of the PM workspace and path planning, in (Liu *et.al.,* 2017) the work covered all eight working modes analysis for the PPM using forward and inverse Jacobean matrix. An intelligent active force control for 3-RRR-PPM is proposed in (Noshadi *et.al.,* 2012).

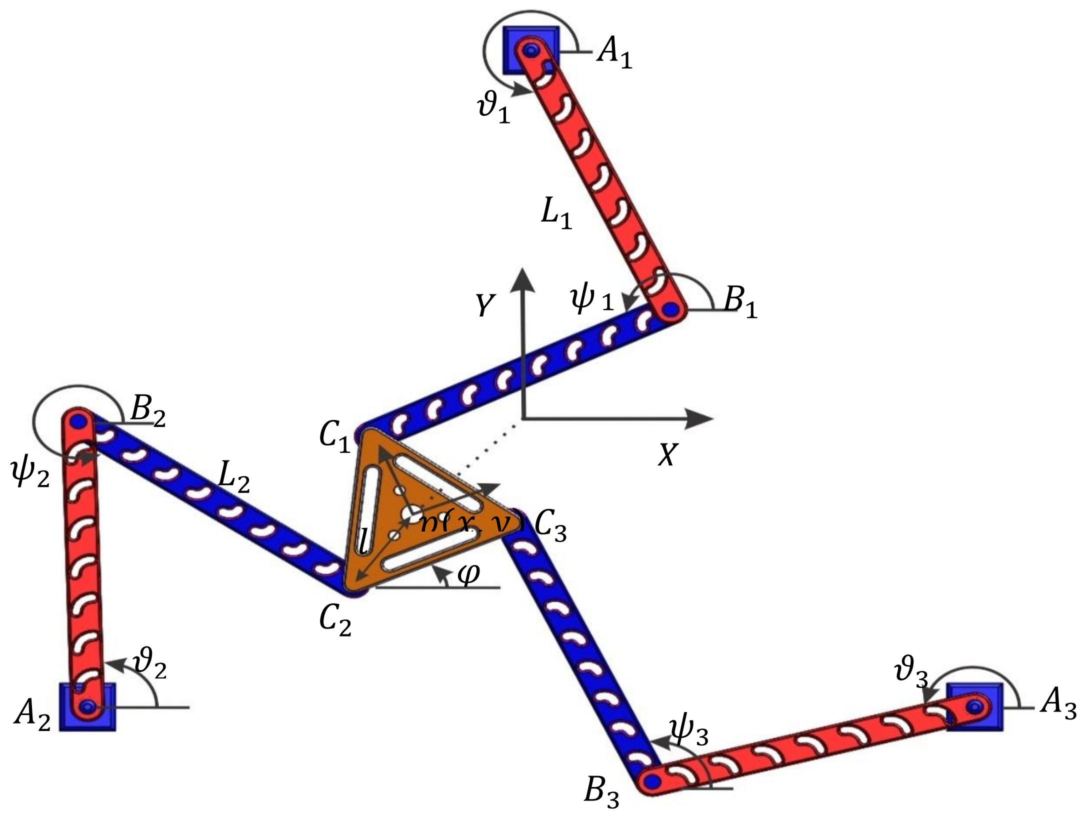

Figure 1. Planar parallel 3-RRR manipulator.

The dynamic model and the kinematics is derived and controller incorporating intelligent algorithms, which consists of iterative learning and fuzzy logic was added in series with the PID-based control scheme to produce the required driving torque for each kinematic chains. Some experimental tests are carried out in order to prove the effectiveness of the proposed controller. The CAD environment is used in (Khaled et.al., 2016) to calculate the total 3D workspace of different kind of PPM, the authors presented several approaches for solving the main problems of parallel manipulators. The approaches include separating the end effector moving platform of PPM from the rest of the kinematic chains. Then by using the vertex volumes and the vertex surfaces performing Boolean intersections relative to each limb, the 3D total workspace, and forward kinematics problems are determined.

In this work, a planar parallel manipulator which contains three (revolute - revolute - revolute) limbs and one moving platform is considered. The manipulator is designed in CAD system in order to ease the modeling process. The inverse kinematics problem is solved and simulated for different trajectories. The dynamic equations are derived using the CAD system model parameters the motion simulation is also done based on these parameters. The PID controller is used for the trajectory tracking control to follow the desired path for the end effector platform.

The rest of the paper is organized as follow: in the next section manipulator model description is presented, after that the kinematics analysis and the inverse kinematics solution is addressed. Later the workspace and working modes are explained, after this section the controller used in this work is detailed. The simulation results are illustrated after before the final section. Conclusions and future work suggestions are written in the last section.

Parallel Manipulator Model Description

A parallel manipulator can be considered as closed chained mechanism because the end effector point is eventually connected to the kinematic chains. The actuator of each chain in parallel manipulators is normally fixed at the base or close to the base of the system. The manipulator presented in this paper are 3-RRR parallel and actuated in planar way. The manipulator consists of three identical serial chains with 3-dof each connect the fixed base to the end-effector platform. Each chain includes one actuated joint and the remaining two are passive. The active and the passive joints are revolute (see figure 1). If serial chain i is RRR chain, there is an active revolute joint at A_i, the angle at B_i is variable (i.e. passive joint), and there is a passive revolute joint at C_i.

The length of the upper link in each chain (i.e. distance from A_i to B_i,) L_1, and the length of the lower link of each link is L_2. The distance from point C_i to the center point of the platform p (i.e. end effector) is l. The actuators angles for each chain are $\vartheta_1, \vartheta_2,$ and ϑ_3 respectively, furthermore the second passive joint angles of each chain are $\psi_1, \psi_2,$ and ψ_3 respectively. The kinematics analysis problem is addressed in the next section.

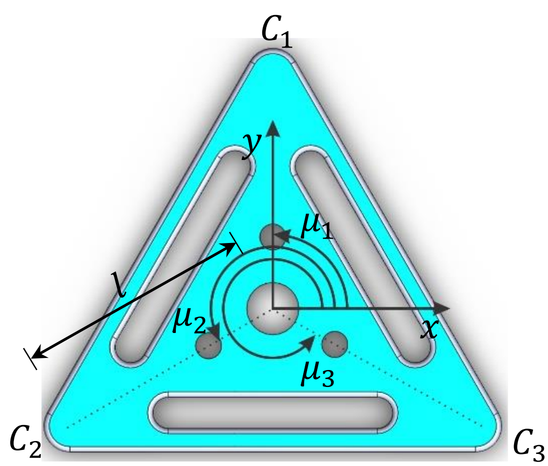

Figure 2. End-effector triangle geometry.

Kinematics Analysis

The pose kinematics deals with solving the inverse kinematics and forward kinematics. The kinematics diagram describing the geometry and configuration of the 3-RRR planar parallel manipulator is given in Fig.1. The triangular end effector Cartesian position and orientation variables are described by the vector $[x \quad y \quad \varphi]^T$. The change in the position of the end effector triangle can be controlled through the change of the actuators angles for each chain are $\vartheta_1, \vartheta_2,$ and ϑ_3. The passive joint angles $\psi_1, \psi_2,$ and ψ_3, are not required for control, can be calculated for computer simulation and/or velocity and dynamics calculations.

The inverse kinematics problem for the manipulator presented in this work requires three independent solutions (Taghirad ,2013), one for each kinematic chain. The given manipulator pose fixes the position and orientation of the end-effector triangle in the plane. From figure 2, each end effector passive joint position C_i can be determined as:

$$\begin{aligned} C_{ix} &= x + l\cos(\mu_i + \varphi) \\ C_{iy} &= y + l\,sin(\mu_i + \varphi) \end{aligned} \qquad (1)$$

The x and y represent the platform end effector position, the angle φ is between platform and the horizontal plane (see Fig. 1). The $\mu_1, \mu_2,$ and μ_3 from figure 2, are $90^\circ, 270^\circ,$ and 330°. On the other hand, the C_i based on the kinematic chain parameters (i.e. based on active and passive joints angles) can be calculated as follow:

$$\begin{aligned} A_{ix} + L_{1i}\cos\vartheta_i + L_{2i}\cos(\vartheta_i + \psi_i) &= C_{ix} \\ A_{iy} + L_{1i}sin\,\vartheta_i + L_{2i}sin(\vartheta_i + \psi_i) &= C_{iy} \end{aligned} \qquad 2)$$

By combining Eqs. (1) & (2), and rearrange the variables in vectors form gives

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} A_{ix} \\ A_{iy} \end{bmatrix} + \begin{bmatrix} L_{1i}\cos\vartheta_i \\ L_{1i}sin\,\vartheta_i \end{bmatrix} + \begin{bmatrix} L_{2i}\cos(\vartheta_i + \psi_i) \\ L_{2i}sin(\vartheta_i + \psi_i) \end{bmatrix} - \begin{bmatrix} l\cos(\mu_i + \varphi) \\ l\sin(\mu_i + \varphi) \end{bmatrix}. \qquad (3)$$

Generally, in spite of case for serial manipulators the inverse kinematics problem solution for parallel manipulators is straightforward solution, while the forward kinematics problem solution is complicated [Huang 2011]. The forward kinematics problem is not addressed in this work.

Given $[x \quad y \quad \varphi]^T$ vector the active joints angles $\vartheta_1, \vartheta_2, \vartheta_3$ calculation problem is solved [Taghirad ,2013] as:

$$E\cos\vartheta_i + F\,sin\,\vartheta_i + G = 0, \qquad (4)$$

Where E, F, G are expressed as follows

$E = 2(C_{ix} - A_{ix})\,L_{1i}$

$F = 2(C_{iy} - A_{iy})\,L_{1i}$

$G = L_{2i}^2 - L_{1i}^2 - (C_{ix} - A_{ix})^2 - (C_{iy} - A_{iy})^2$

Equation (4) lead to the solution of ϑ_i:

$$\vartheta_i = 2\,tan^{-1}\left(\frac{-F \pm \sqrt{E^2 + F^2 - G^2}}{G - E}\right) \qquad (5)$$

and the intermediate passive joint angle:

$$\psi_i = atan2\big(C_{iy} - A_{iy} - L_{1i}sin\,\vartheta_i, C_{ix} - A_{ix} - L_{1i}\cos\vartheta_i\big) - \vartheta_i. \qquad (6)$$

From Eq. (5) it is clear that there are two solution for the ϑ_i this what's the $\pm$ sign under the square root means. Consequently, the intermediate joint angle also has two different solutions.

Working Modes and Workspace

The solution from Eqs. (5) and (6) corresponds two possible configurations for each kinematics chain for the given position and orientation of end effector triangular platform, this leads to the PPM under the study has eight working modes [Liu et al. 2017]. The working modes are identified from the form of the triangle A_i, B_i, C_i, figure 3 shows all these eight working modes.

The workspace of the system is mapped out using Eq. (2), for each kinematic chain and by choosing proper joints angles. For each chain end effector C_i, the workspace will form a circle. In order to find the singularities points Eq. (4) is implemented. If the summation of the terms in (4) equal zero then the point is inside the workspace, else the $[x\ y]$ pair is singular point for the system (i.e. outside the workspace). Figure 4 shows the workspaces for each kinematic chain.

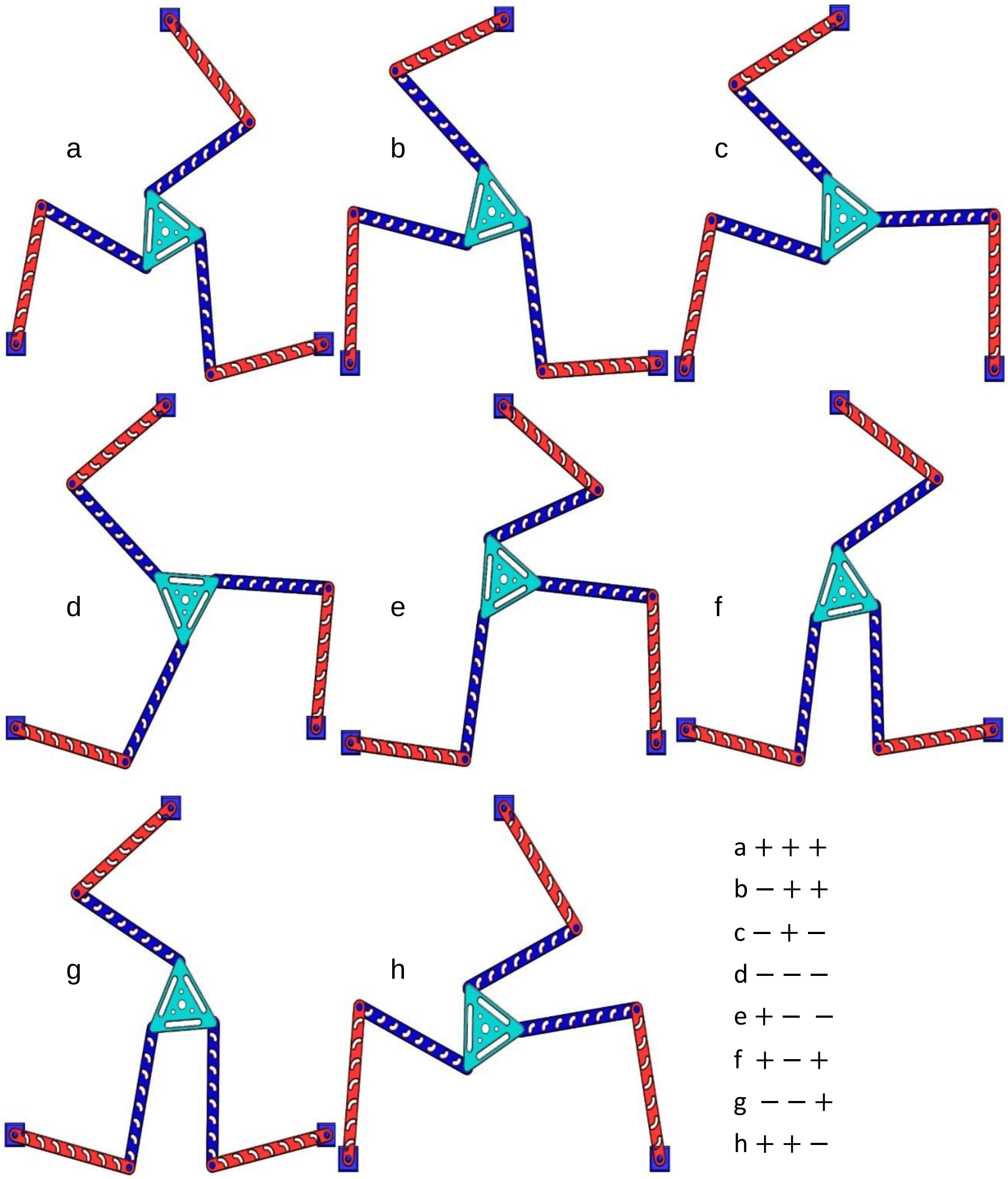

Figure 3. Eight working modes of the 3-RRR PPM.

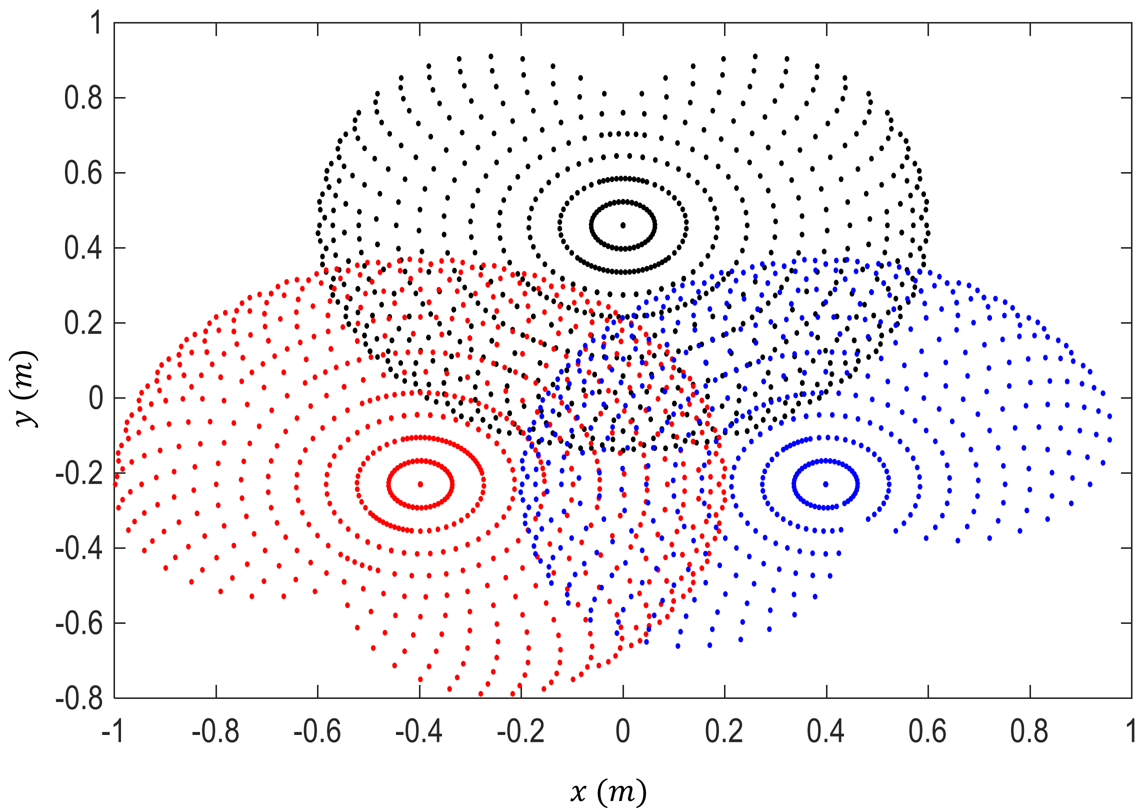

Figure 4. Workspace reach for each chain.

Controller Design

The dynamic model for the PPM in this work is derived based on the CAD parameters, in other words the CAD parameters implemented in SimMechanics in order to get the nonlinear mathematical model directly in simulation process. The Nonlinear model can also be linearized around specific point and a linear model will produce and further analysis is possible (Franklin *et.al.*, 2015). The mechanical properties for each element such as, center of gravity, dimensions, and mass inertia are imported from CAD system, this represents time saving and simplification for the mathematical modeling process. Furthermore, the forward and inverse kinematics problems can be solved inside SimMechanics environment (Russell *et.al.*, 2015).

The controller proposed for the system is a PID joint trajectory controller, and three different PID controllers are required here one for each chain. The transfer function of the PID controller used in this work (Franklin *et.al.*, 2015) is:

$$C(s) = P[1 + I\frac{1}{s} + D\frac{Ns}{s+N}]. \quad 7)$$

The motion control procedure is shown in figure 5. The desired position $[x_d \quad y_d]^T$ is provided to the system, the inverse kinematics produce the required joints trajectories. The controllers estimate the required torques $[u_1 \quad u_2 \quad u_3]^T$ in order to movie upper links which induced the change in the intermediate angles based on the inverse kinematics solution. As a result, the moving platform reaches the desired position.

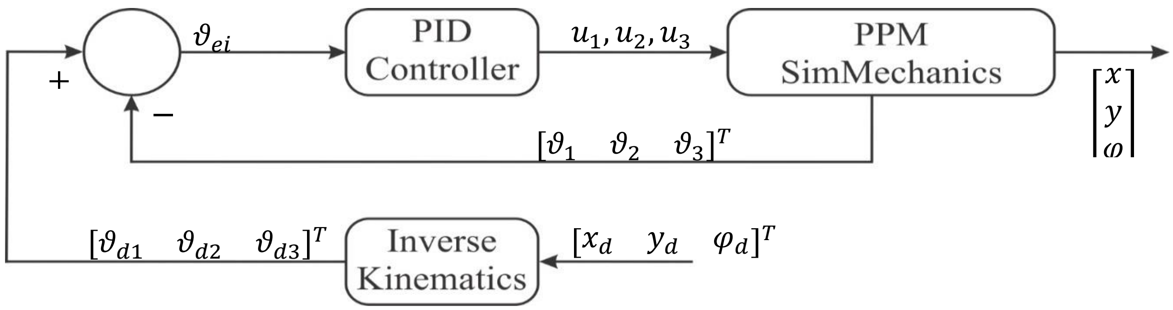

Figure 5. Control procedure block diagram.

Simulation Results

The parameters used in this work for the system illustrated in this work are:

$L_1 = 0.3\ m$	$m_1 = 0.41\ kg$	$A_1(0,0.46,0)$
$L_2 = 0.3\ m$	$m_2 = 0.45\ kg$	$A_2(-0.398,-0.23,0)$
$l = 0.0897\ m$	$m_3 = 0.65\ kg$	$A_3(0.398,-0.23,0)$

Here the $m_1, m_2,$ and m_3 are the masses of upper link, lower link and the moving platform respectively. The density of the material used in the design is $\rho = 7870\ kg/m^3$. The masses of the elements are calculated automatically using the CAD system, the values of the dynamic moment of inertia is also calculated in the CAD system then transferred to SimMechanics (Matlab software) for simulation.

The desired path chosen for the simulation is a circle path

$$x = 0.12\cos\left(\frac{\pi}{5}t\right),$$
$$y = 0.12\sin\left(\frac{\pi}{5}t\right), \tag{8}$$

and spiral path

$$x = 0.025\ \ t\ \ \cos\left(\frac{3\pi}{2}t\right),$$
$$y = 0.025\ \ t\ \ \sin\left(\frac{3\pi}{2}t\right). \tag{9}$$

In order to make the moving platform center to follow the desired path, the desired active joint angles ϑ_{di} are calculated using inverse kinematics procedure for each chain. The PPM motion is tested first for the circle path, in figure 6 the comparison of the desired and actual path. The controller in this simulation is a PID controller as stated earlier. The gains for the PID controller Eq. (7) use for each chain are as follow: $P = 350, I = 200,\ D = 100,$ and $N = 100$. For the same circle path simulation test he error in the joint angles ($\vartheta_{ei} = \vartheta_{di} - \vartheta_{ai}$), and the control inputs $u_{1,2,3}$ are also shown in figure 7. In figures (6 & 7), it can be noticed that the controller successfully generates the required the control inputs keeping the position of the moving platform following the desired path (8) without any abnormal behavior except some deviation from the circle path due to the approaching of the singularity region.

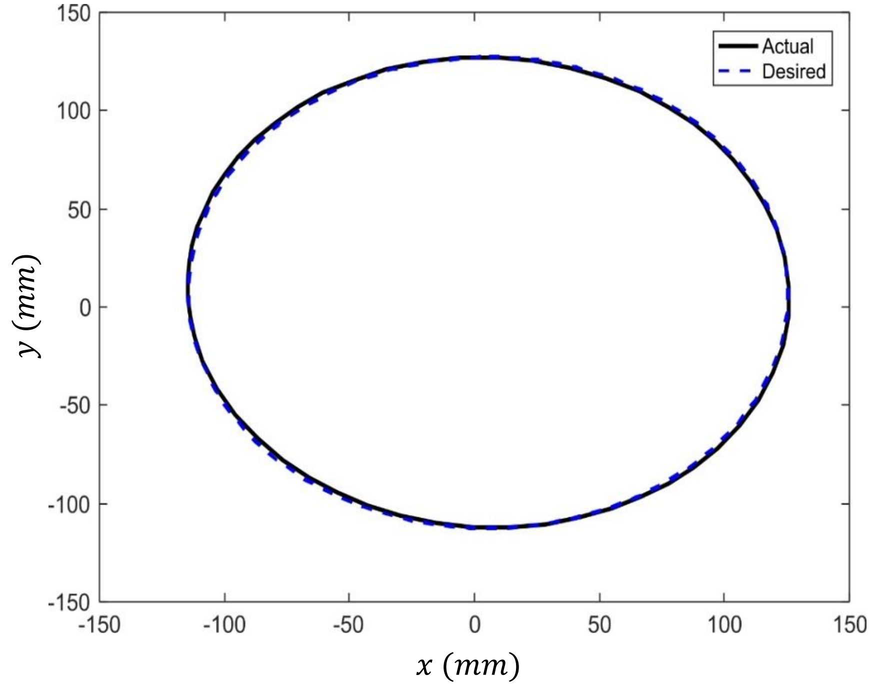

Figure 6. Desired and actual circle path for the moving platform.

The system is also simulated using more complicated path, which is the spiral path described in Eq. (9). The desired and actual moving platform position are shown in figure 8. The desired active joint angles ϑ_{di} and the generated input torques u_i are shown in figure 9. It is very clear that the controller works well based on the inverse kinematics procedure and the gains selected are detected the change in the path of the moving platform very fast. In figure 8 the same deviation from the spiral path can be seen also due to the singularity which is not addressed in this work. The simulation results represent a good progress in the study of the complex mechanical system in nontraditional way of mechanical design and controlled motion simulation. In order to bring more imagination for the motion animation of the PPM designed in this work; video is available in "youtube" as 'Three RRR planar parallel manipulator spiral motion' in the link: https://youtu.be/GEq8PbJ2kK0.

Conclusions

A simulation of 3-RRR parallel robot manipulator has been presented. Instead of deriving the dynamic model of the system, the CAD model is used for nonlinear modeling. The inverse kinematics problem is addressed, a problem solution for each chain is presented. The problem of trajectory tracking control is studied in the work. Based on the simulation for the controller; the moving platform is followed the desired path perfectly except neglected small error. It can be announced that the integrating CAD system model for complex mechanical system can be valuable method for control analysis. The presented results in this contribution can be used as a basis for experimental study and comparison with advanced control strategy. Further developments are required for the workspace analysis, singularities, and linearizing the mathematical model.

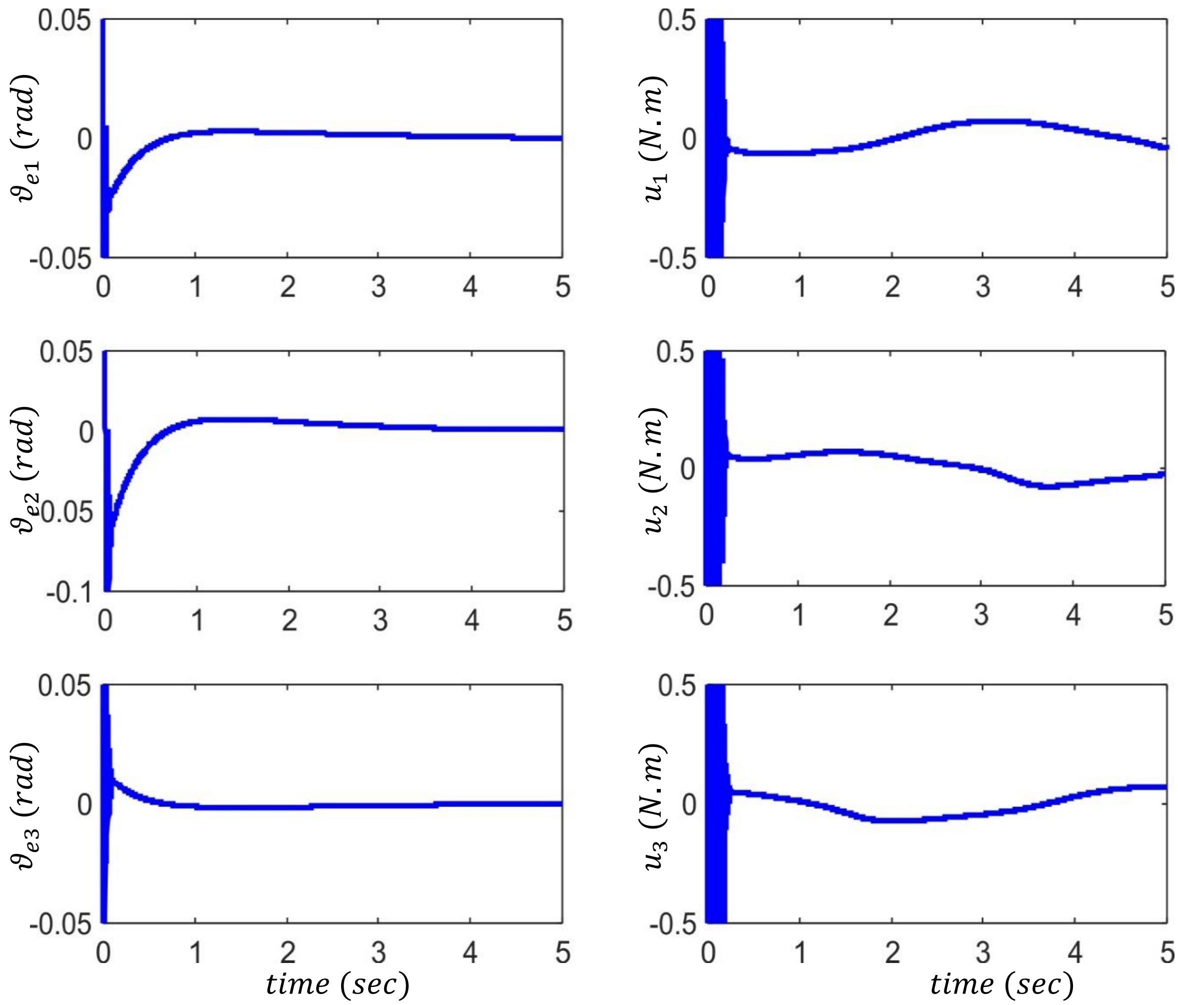

Figure 7. Error in the active joint angles ϑ_{ei} and the control inputs u_i.

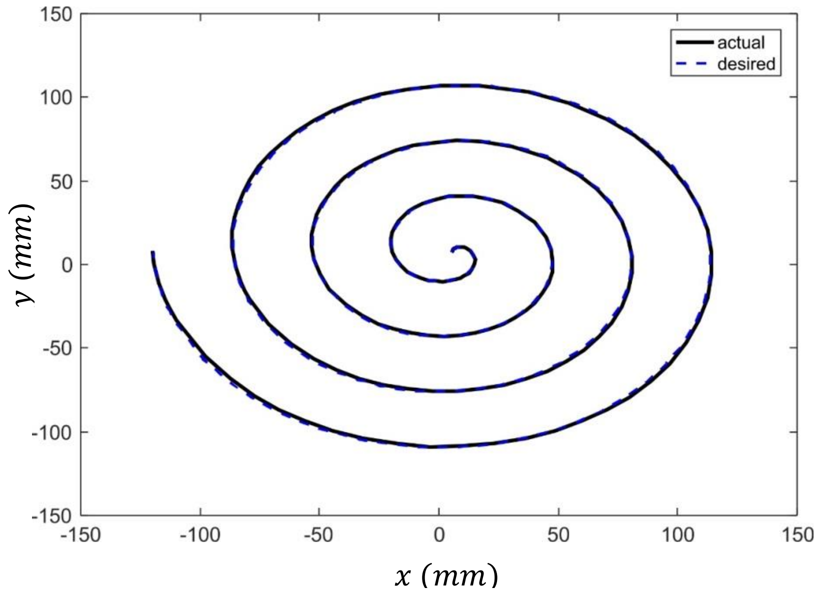

Figure 8. Desired and the actual spiral path for the moving platform.

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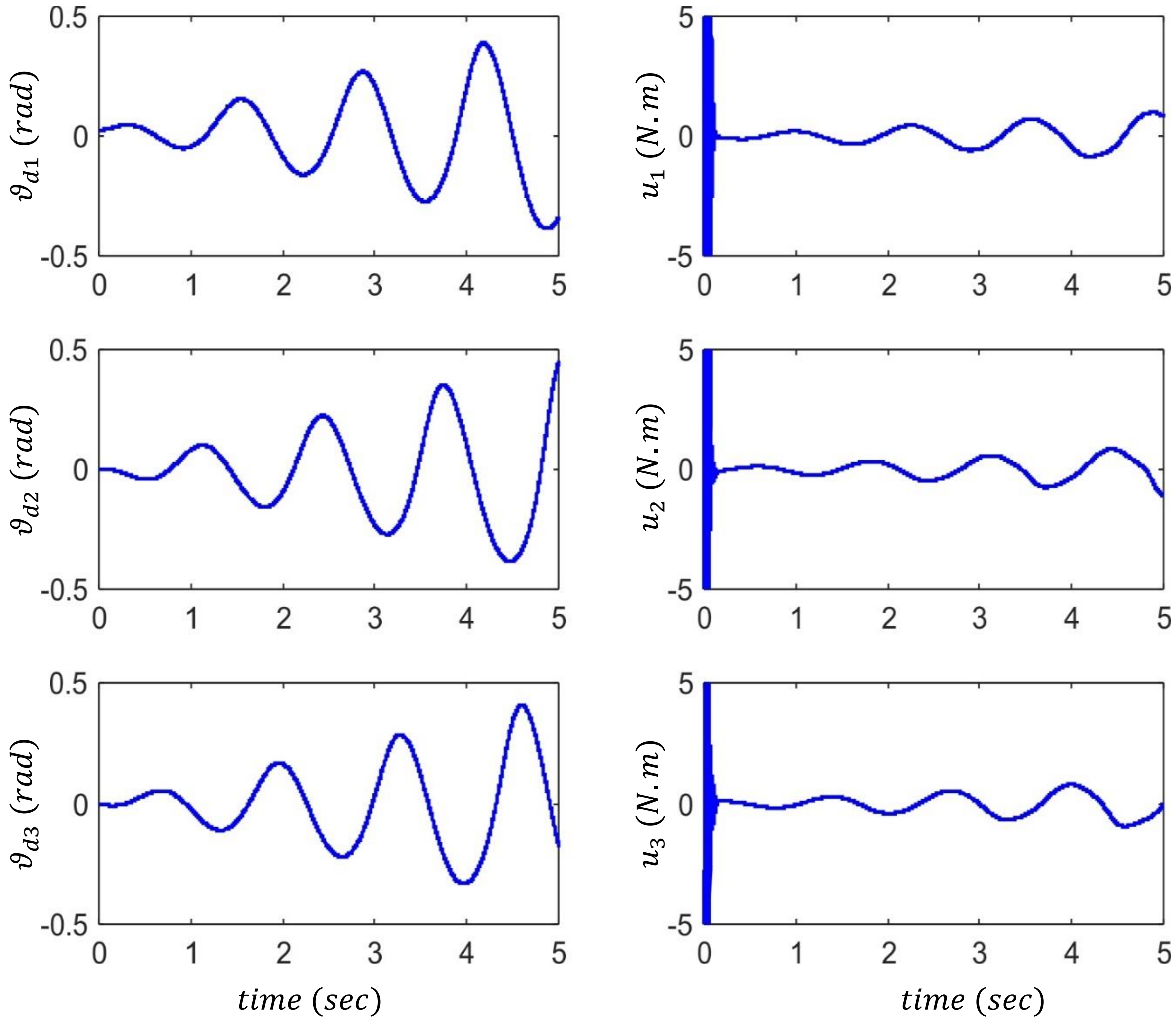

Figure 9. Desired active joint angles ϑ_{di} and the control inputs u_i.