



# A Review on the Kinematic Simulation and Analyses of Parallel Manipulators



Arockia Selvakumar Arockia Doss\*

VIT University, India

Submission: August 02, 2017; Published: September 14, 2017

\*Corresponding author: Arockia Selvakumar Arockia Doss, Associate Professor, School of Mechanical and Building Sciences, VIT University, Chennai, Tamil Nadu-600127, India, Email : arockia.selvakumar@vit.ac.in

## Abstract

This paper presents a detailed background of the simulation and kinematics of 3 Degrees of Freedom (DOF) Parallel Manipulators (PMs). In this work, the recent literature about the kinematic analysis, kinematic synthesis, workspace, singularity and velocity and acceleration analyses of various kinds of parallel manipulators are reviewed. This survey also focuses on the development of PMs. The various approaches adopted in the kinematic analyses are reviewed and their adoptions in the PMs are discussed. The novel design and analysis perspectives of 3-DOF parallel manipulators in general are recommended.

**Keywords:** Manipulator; Kinematics; Workspace; Singularity; Simulation

## Introduction

Generally, the robot manipulators are classified into serial type open loop chains and parallel type closed loop chains. Since decades, robot manipulators were designed and operated using the open loop serial chains. In general, Robots used in industries are all general purpose manipulators, consisting of multiple rigid links and are connected in series by means of joints such as revolute, prismatic and etc. A robot consists of a fixed support base at one end and a gripper to hold a tool at the other end for manipulating and performing various operations. Human arm is considered as an example, for Open loop manipulators. As the structure is cantilever supported, the load carrying capacity is poor but besides it has the advantage of reaching large area of workspaces and dexterous maneuverability.

Consequently, the links tend to bend at high load on one hand, while on the other, to satisfy the strength requirements, the links become bulky, which leads to vibration at high speed. Though possessing a large work space, their precision positioning capability is rather poor due to their cantilever structure. The increase in PMs begins to rise, as machine and mechanisms required higher precision, robustness, stiffness and load-carrying capacity. It all started back in 80s using parallel aligned mechanisms and the scientific studies were conducted to solve and address the real-time problems in application. After a decade, parallel manipulators became a popular research topic and in general it was addressed as

Stewart-Gough Platform. In the next section, motivations and need of parallel manipulator is discussed. In section 3, various kinematics studies of manipulators are reviewed. In sections 4 and 5, various manipulators singularity analysis and workspace generations were detailed. The study on velocity and acceleration analysis and simulation of parallel manipulators are surveyed in sections 6 and 7. Finally in section 8, the review is summarized and concluded with remarks pertaining to the approaches that are preferable for the study of parallel manipulators in general are made.

## Motivations and Need of Parallel Manipulator

In industrial automation the Parallel Manipulators were considered as an alternative to the conventional automation to achieve high load carrying capacity, good dynamic performance and precise positioning which provides higher quality and more economical processes. The latest innovation in the field of robotics is the PM, which finds its application in all areas, especially for its high load carrying capacity and superior positioning capability with greater rigidity. The interesting thing about the PM is that, the degrees of freedom vary up to six. The necessity arises for calculating the motion precisely and instructing to drive the link accordingly. Hence, the use of computers and the electronic interfacing to actuators become significant.

Industrial robots play a vital role in automation; however, the industries made an effort in the transforming automating

machining applications, such as grinding, cutting, milling, drilling, polishing etc., As this robot manipulators require to have high stiffness, rigidity and accuracy, which cannot be provided by conventional serial robot manipulators. Since, last three decades PMs found to be more attractive for the above mentioned applications and witnessed considerable research interest in this direction.

### Kinematics

Kinematics of the Manipulator deals with the study of the manipulator motion, as constrained by the geometry of the links. The structural kinematic analysis, concerns the description of the manipulator motion with respect to a fixed Cartesian reference frame, the forces and moments causing the motion of the structure were out focused. Kinematics describes the analytical relationship between the joint positions and the end-effectors position and their orientation. Differential kinematics describes the analytical relationship between the joint motions, in terms of velocities.

Kok-Meng & Dharman [1] presented the 3-DOF parallel actuated manipulator, which has 2-degrees of rotational and one degree translational freedom, with an RPS joint structure. They formulated the inverse kinematics of this parallel manipulator by ZYZ Euler approach. Two dimensional plots for work space had been created based on the simulation results. It is observed that the ball joints range of motion is limited by the maximum angle. The obtained simulation output is useful in determining the range of motion and understanding the size and shape of the work envelope.

Sukhan & Sungbok [2] presented generalized kinematic features of parallel manipulator system, in terms of deficiency, singularity and redundancy, they introduced three types of redundancies of a parallel manipulator, in which the actuators and limbs were varied in distinct ways and those three types are analyzed briefly to design a high performance parallel manipulator. Zou et al. [3] proposed a unique type of manipulator based on the Stewart-Gough platform for manufacturing a simple structure with high accuracy, by providing a new scheme of the leg mechanism. In the kinematic analysis, they found that the leg structure led to the problem of derived rotations. The authors introduced a hypothesis serial mechanism and a hypothesis branch serial mechanism, with an iteration algorithm to solve the kinematics problem.

Dunlop & Jones [4] presented a general 3-DOF parallel mechanism, for beam aiming applications in a closed form. The position of the platform was taken into consideration, to derive 16 forward and 8 inverse kinematic solutions by the position vector method. Wang & Zou [5] proposed a scheme of the link mechanism, to make the link structure very simple for the general Stewart platform, which is applied to the milling process. In the workspace analysis, the mobile platform radius, base platform radius, platform rotations and the link extended

range are taken into account. The kinematics algorithm was developed by considering the serial and parallel mechanism. In this work, the link structure led to the problem of derived rotations. To solve such problems, they introduced an algorithm with the hypothesis serial mechanism and the hypothesis branch serial mechanism.

Jianfeng et al. [6] presented the formulation of the inverse kinematics and dynamics of the 3-RRS parallel platform. The velocity and acceleration for the leg actuator, time histories of the driving moments of the leg actuator, the angular velocity and accelerations, were derived from the position analysis and differential motion equation constraints. Finally, they obtained the angular position of the leg actuators, velocity and acceleration for the 3-RRS parallel platform. Xin-Jun et al. [7] used three non-identical chains parallel manipulators with two degrees of translational freedom and one degree of rotational freedom. They have analyzed the velocity equation of the manipulator with three kinds of singularities and workspace simulation using MATLAB.

Feng et al. [8] proposed new kinematic structures for 2-, 3-, 4- and 5-DOF parallel manipulator designs and several types of composite pairs. The displacement of the links output was described, based on the special plucker coordinates. This paper differentiates the structure of the parallel manipulators based on their links, the joints and their kinematics constraints. Ping & Hongtao [9] determined the kinematics analysis of an offset 3-UPU (Universal-Prismatic-Universal) translational parallel robotic manipulator with an equal offset in its six universal joints, based on the zero offset in the manipulator. The manipulator was analyzed and its inverse and forward kinematics solutions were obtained, by using the position vector. It is said that the zero offset manipulator of the Tsai's manipulator has 16 forward kinematics solutions instead of two.

Yangmin L & Qingsong X [10] studied the general 3-PRS parallel mechanism along with its kinematics and inverse dynamics of the mechanism. The closed form approach was used to obtain the inverse kinematics solution and the Newton iterative method for the forward kinematics problem. The proposed model is simulated and animation results were obtained using MATHEMATICA and the MATLAB software respectively. The simulation results of the proposed dynamic models were verified with the derived dynamic equations. presented a best design of a 3-PRS spatial parallel kinematic manipulator, in consideration with the performance of a weighted sum of Global Dexterity Index and a Space Utility Ratio Index. The Jacobian matrix approached was used to solve analytically and by a numerical search method the workspace is generated. The architectural optimization of the 3-PRS parallel manipulator was implemented in a MATLAB environment and the simulated results provided the basis for the optimization of the manipulator. Finally, they concluded

that the mixed performance index is used to overcome the encountered problems of a singular free but relatively small workspace and the methodology proposed here can be applied for the architectural optimization of other types of parallel manipulators.

Vladimir [11] proposed the inverse kinematics, forward kinematics and workspace determination of a 3-DOF parallel manipulator with a SPR joint structure. An effective approach was developed for the solution of the inverse kinematics task in analytical form, for the 'given end-effectors positions. A method for workspace determination, which uses the numerical solution of forward kinematics task, is presented. Sadjadian & Taghirad [12] proposed a 3-DOF redundant parallel manipulator. A complete kinematic modeling has been performed and a closed-form forward kinematics solution was obtained for a redundant hydraulic parallel manipulator and the forward kinematics was derived using a vector approach, by considering the individual kinematic chains in a parallel mechanism. Finally, a simulation example was used as a sample trajectory in the task space of the hydraulic shoulder manipulator to validate the derived model.

Zhang et al. [13] proposed a 3-DOF PKM of a large motion range in the Z axis for machine tool application. The direct and inverse kinematics problems were solved in order to implement the real time control of the machine tool. The kinematics results were validated numerically. The singularity analysis was carried out by the reciprocal screw theory. From their work, the authors concluded that the solution of direct kinematics will be affected when the structure is in a singular position and a reasonable arrangement of geometric dimension is important to avoid singularity.

Ng et al. [14] presented the design and development of a 3-legged micro Parallel Kinematic Manipulator (PKM) for positioning in micro-machining and assembly operations. The structural characteristics were evaluated and PKMs with translational and rotational movements were identified. This paper addresses the kinematic analysis of the hybrid PKM that has been designed and developed to perform translation along the Z-axis and rotation about the X- and Y-axes. The inverse kinematics problems were solved analytically and an algorithm was implemented to control the hybrid PKMs. Based on the simulated workspace a hybrid micro PKM was developed and calibrated. Yangmin & Qingsong [15] proposed a translational parallel manipulator with fixed actuators which has a kinematic structure of 3-PRC (Prismatic-Revolute-Cylindrical).

The manipulator mobility was analyzed with the screw theory. The closed form solutions for both forward and inverse kinematics problems had been derived and the velocity analysis was performed. Based on an isotropic configuration, three kinds of singularities had been identified. The reachable workspace was calculated, based on the actuator's lay out

angles and different mobile platform sizes. The workspace of the manipulator was generated by the numerical approach. Lastly, the acquired results were compared with the simulation results. The simulation results indicate that the different objectives should be taken in to consideration and the actuator layout angle of the 3-PRC translational parallel manipulator was designed.

Cherfia et al. [16] presented a pure translational motion parallel robot model which is geometrical constrained with a PPP passive segment. From the simple geometrical model, forward and inverse kinematic solutions were derived and also they determined the reciprocal relations between the Cartesian and angular velocities of the end-effector, by solving direct geometrical expressions. Finally, the hypothetical results were verified with the simulation results. Lu et al. [17] proposed the kinematic analysis of two different 3-UPU I and 3-UPU II PKM models, in which two rotations and one translation have been discussed, along with the geometric constrained equations of a parallel manipulator. Various analytic formulae for solving the inverse displacement, inverse/forward velocity and inverse/forward acceleration of the PKMs, were derived by using the Jacobian matrix and their analytical calculation was carried out and verified by using a simulation tool.

Altuzarra et al. [18] proposed a Parallel Kinematic Machine of 5-DOF freedom, in which the output motion pattern could be obtained from the different structural topologies. The position analysis was done for the manipulator, by using the Newton Raphson method. The movement of the tool relative to the part system was defined by the corresponding transformation matrix. Translational and rotational Jacobian sub-matrices were used, to calculate the motion pattern of the PKM. Luo et al. [19] designed a new parallel robot manipulator (PRM) through the application of the constraint accession configuration method. The constraints, the degrees of freedom, the position and velocity of 3-TPS (T- hook joint, P-Sliding joint, S- Spherical joint)/RPP, 3-TPS/CP and 3-TPS/RU (T- hook joint, P- Sliding joint, S- Spherical joint, R-Rotational joint, C- Cylindrical joint, U- Compound parallelogram) were analyzed according to the kinematic theory. The velocity of the PRMs was derived from the Jacobian matrix and verified with the simulation results. From the results they concluded that the pace of the proposed parallel robots are more steady and have good controllability and the PRMs can be used in different manufacturing production lines. Ghasem et al. [20] presented an article to explain the forward kinematic problem of the 3-PRS parallel manipulator, using the homotopy continuation method. With the case study, they described the shortcomings of the traditional numerical techniques and the advantages of the homotopy continuation method. Finally, the authors concluded that the homotopy continuation method gives fast convergence to the forward kinematic problem, even with bad initial speculations over the Newton-Raphson method.

Ciprian et al. [21] recommended two approaches of forward kinematics of a 3-DOF RPS parallel manipulator for medical purposes and the methods were executed in the MATLAB/SIMULINK. The Newton-Kantorowich (N-K) method was used to solve the forward kinematics of the parallel manipulator and their prediction was close to the values that were obtained from the MATLAB simulation. The dimensional design of the robot manipulator was specified by the area of its workspace and the work space obtained was estimated, using the Lukan in method. Sun et al. [22] proposed a PRS XY serial parallel manipulator numerical analysis and simulation were carried out based on the kinematics of manipulator. The inverse kinematics was derived for the parts, the parallel part as well as the XY table. The forward kinematics was solved by using the steepest descent method. The PRS parallel manipulator was modeled and simulated, using the visual C++ 6 and the inverse and forward expressions were verified according to the path of the tool tip, using the numerical analysis and validation. Kinematics was also validated by the motion trail of the tool tip, where a graph had been developed according to the motion of the tool tip with respect to the radius of the MP.

Verdes et al. [23] presented 3-DOF Tri-Glide medical parallel robot control using a virtual reality environment. For simulation, an evaluation model was used from the MATLAB/Sim Mechanics and the motion of the mechanical system was visualized in 3D virtual space. The main advantage of this parallel manipulator was that, all the actuators were attached directly to the base platform. The forward and inverse mathematical expressions were solved by the closed form and the MP was maintained at the same position throughout the entire workspace.

### Singularity Analysis

Parallel manipulator loses its precision and control when there is a singularity condition. In this phase, it attains one or more degrees of freedom. Manipulator posture depends on the singularity of manipulator; this singularity condition changes the mobility of the manipulator which is an immediate event. These undesirable postures create challenging situations to control the manipulator, or the workspace of the manipulator is limited. Therefore, it is important to understand and study the conditions that result in a manipulator singularity. Xin-Jun & Jongwon [24] proposed a new spatial 3-DOF parallel manipulator with non-identical chains. The singularity analysis was presented with forward and inverse Jacobian matrices in closed forms. Three kinds of singularity were analyzed, based on the legs, base platform and planes. In their work, eight inverse kinematics and four direct kinematics solutions were used for the manipulator.

The proposed design has a wide-range of applications in the fields of simulators and parallel kinematic machines. Anjan et al. [25] described using the clustering algorithm

and line geometry the path planning of parallel manipulators can be operated singularity-free and reachable workspace of parallel manipulators was explained using a generic numerical algorithm. The singularity points were determined inside the workspace. A Clustering method and Road map method of path planning algorithm was detailed and aided to determine a nominal path to avoid the singularities. In order to avoid scattered singularity points the local routing method based on line geometry was proposed.

Xin-Jun et al. [26] came with an idea of the HALF parallel manipulator with revolute actuators to explain the singularity analysis of the manipulator. Based on the derived inverse kinematics and Jacobian matrices, three kinds of singularities were presented. All possible singular configurations were highlighted, which shows that there are eleven cases for the singularities to arise, including one case of architectural singularity. Guanfeng et al. [27] presented a detailed geometric study on the various types of singularities in parallel manipulators using the Morse function theory and investigated their relations with the kinematic parameters and configuration spaces. The role of redundant actuation plays an important role in reshaping the singularities and improving the performance of the in this paper, the different kinds of singularities dealt with, include the actuator, end-effector and architectural singularities. Xiang et al. [28] proposed a study of 3-DOF parallel robot and considered the kinematic characteristics and singularities of the robot. The Jacobian matrix was used to formulate the inverse kinematics and then the singularity was analyzed from the velocity equation.

The Jacobian matrix was solved by the velocity polygon vector function method and the virtual mechanism method. Both methods need typical calculations. The singularity analysis was conducted by using different joint assemblies like the T joint and R joint, in order to analyze the kinematic characteristics of the mechanism. The different assembly angles for the joint were studied and the angle 90 degrees is found to be better for the motion range, when the end-effector is small.

Hengbin et al. [29] implemented the theory of singular value decomposition to study the velocity equation of the mechanism and the relationship between the generalized input and output velocities. The relationship between the singularity and the singularity values of the Jacobian matrix of a mechanism was studied. This method was used for analyzing and identifying of the singularities of the 3-DOF redundant parallel manipulators. Carme et al. [30] presented the stratification of the singularity loci of Parallel Manipulators. In this work, they identified a class of flagged manipulators whose singularity loci admit a well-behaved decomposition, i.e., stratification, derived from that of the flag manifold. Two remarkable properties were highlighted.

First, the decomposition had the same topology for all the members in the class, irrespective of the metric details of each particular robot. Thus, they explicitly provide all the singular strata and their connectivity, which apply to all the flagged manipulators without any tailoring. Next, the strata can be easily characterized geometrically, because it is possible to assign local coordinates to each stratum, which corresponds to uncoupled rotations and/or translations in the workspace.

Si-Jun et al. [31] presented the screw theory and Grassmann geometry to analyze the singularity for a 5-DOF 3R2T fully-symmetrical parallel manipulator to simulate the motion of a spinal column. The study of the kinematics inevitably leads to the problem of singular configuration. The influence of these singularities and the methods to avoid them were also illustrated. The result of this study can be used for the singularity analysis of other fully-symmetrical parallel manipulators. Daniel et al. [32] analyzed the singularity of the limited DOF Parallel Manipulators, using Grassmann-Cayley Algebra (GCA). This paper characterizes geometrically the singularities of the limited-DOF parallel manipulators. The paper describes how the GCA can be used to determine the geometric conditions associated with the singular configurations of the limited DOF parallel robots, whose legs can transmit forces and moments to the MP. This method provides a physical meaning and a geometrical interpretation of singular configurations for the family of parallel manipulators.

Flavio et al. [33] discussed the singularity analysis of planar parallel manipulators (PPMs) based on the forward kinematic solutions. An efficient approach for determining the force-unconstrained poses of PPMs, based on the concepts of the screw theory and kinematic analysis was presented. This approach is implemented for the 3-RPR, 3-PRR and 3-RRR PPMs. The forces exerted by the actuated joints were modeled with reciprocal screws. The geometrical conditions that cause singular configurations were identified and the singularity conditions obtained with the screw theory were found equivalent to the joint displacements used in the forward kinematics. Ruggiu [34] addressed the direct and inverse analysis of a 3PPS parallel manipulator in terms of analytical form. The direct position analysis was solved by an iterative procedure for each combination of actuated variables. A direct singularity occurs, when there exist motions of the MP that result in zero. The verification of the absence of singularity poses was implemented in the calculation as well. The results were proposed in terms of the position and orientation of the MP.

### Workspace Analysis

The general drawbacks using parallel manipulator is its minimal workspace compared to the serial manipulator. Thus, it is necessary to analyze the shape and volume of the workspace for enhancing the parallel manipulator's

applications. The closed-loop structure of the mechanism not only limits the motion of the platform, but also creates difficulty in development of the parallel robot and therefore it builds complex in designing, trajectory planning and kinematic singularities analysis in the workspace of the parallel manipulator.

Min [35] designed a double parallel manipulator (DPM) for enlarging the workspace and avoiding singularities, by combining two parallel mechanisms with a central axis. The geometric constraints for forward kinematics were expressed by quadratic equations, including two or three variables. Based on the DPM, a grinding robot was constructed. From the results, it was concluded that there is a remarkable advantage in the compound positional workspace of the DPM compared with the Stewart-Gough platform and no singularity arises inside the workspace.

Lung-Wen & Sameer [36] optimized the work space of a special 3-UPU (Universal-Prismatic-Universal) parallel manipulator in which the shape of the work space changes with an increase in the twist angle of the MP with respect to the base platform. It was simulated by using the MATLAB tool box. The kinematics and Jacobian matrix for the parallel manipulator were derived to achieve pure translation motion by a 3-UPU parallel manipulator; they also suggested an idea to replace the link by hollow cylindrical rods to achieve light weight. Finally, the structural characteristic associated with the parallel manipulator was investigated; the well-conditioned workspace in this work shows, that the global index is the maximum when both the moving and the base platform are symmetrical.

Dash et al. [37] presented the numerical algorithm for a reachable workspace and the singularity representation of three legged parallel manipulators. An approximate maximum workspace boundary was calculated and then the exact workspace volume was determined by the numerical integration method. The model is based on the Product-of-Exponential (POE) scheme of formulation. The algorithm was applied to the combinations of revolute and prismatic joints in the configuration of the leg. The method presented here was applied to all the combinations of prismatic joints and rotary joints of the class of parallel manipulators. Joshi & Lung [38] presented a comparative study of the well-conditioned workspace and stiffness properties of 3-UPU and tricept manipulators. The inverse kinematics and Jacobian matrix of these two parallel manipulators were analyzed to optimize the workspace. Based on the stiffness analysis they concluded that the stiffness matrix was better conditioned in the tricept than in the 3-UPU. Finally, the optimized tricept manipulator was seen to possess higher work volume than the optimized 3-UPU.

Xi et al. [39] developed four different types of tripod parametric model for machine tool applications and these tripod units were compared by considering the stiffness

and workspace. A parametric model was developed for the comparative study and the constraint equations were derived with and without a passive leg. From the workspace and stiffness analysis, the authors concluded that for the same geometric size, the configuration with the extensible legs yields the largest workspace, fixed length of legs yields the best stiffness, whereas the vertical configuration is the least optimal. Yuan et al. [40] presented the dimensional synthesis of a 3 - DOF parallel manipulator based on the maximum inscribed workspace and reciprocal of the condition number and the Golden section method is used for encountering the work space and meshing the boundary.

Finally, they concluded that the presented PM was better than the other, in order to improve the design efficiency of the parallel manipulator. Geoffrey & Juan [41] addressed the key issue of two general disadvantages of the parallel manipulator. The first one is the reduced workspace and the second is the highly singular workspace. The inclined PRS manipulator was developed to solve each of these issues, the former from an optimization standpoint. The Three degrees of freedom manipulator was constructed by means of three identical prismatic-revolute-spherical kinematic chains, where the prismatic joint was actuated. The reachable and dexterous workspace of the manipulator was discussed and the design variables which influence the volume of both the reachable and dexterous workspaces were identified.

Liu et al. [42] analyzed the workspace of the manipulator systematically by keeping the orientation of the MP constant. A constant orientation workspace was defined by the reference point of the MP and with that, the reachable workspace was calculated. At last, the rotational capability index of the MP was considered to define the third workspace of the spatial parallel manipulator. From the rotational capability index analysis results, the work shows that the parallel manipulator has high rotational capability. Zhang et al. [43] developed a computer aided analysis of the 3-DOF parallel manipulator around the axis, parallel to the horizontal plane. A type of 2PUR & PU mechanism was analyzed with its kinematic problems and singularities. The solutions of the inverse and forward kinematics were given in the closed form. The Jacobian matrix and the condition number analysis of the parallel manipulator were developed. Three limbs identical in length and with different mechanisms were developed. Each of the two kinds of limbs has specific kinematic characteristics. Three kinds of singularities and workspace analysis were presented.

Geoffrey & Juan [44] made a comparative study between 3-PRS, 3-RPS and the Tricept manipulators and lead to the use of a novel method of formulating square dimensionally homogenous Jacobian matrices and a reliable choice of independent end-effectors velocities.. This paper

quantitatively compares the dexterity of the spatial complex degrees of freedom parallel manipulators. Yi & Bo [45] solved the active forces of a 3SPU+UPR parallel manipulator. The work was carried out by simulating the mechanism and deriving the formulae for solving the inverse/forward displacement of the proposed parallel manipulator. The kinematics, the workspace and active forces are derived systematically. From the kinematic analysis they concluded, that each of the SPU-type active legs with the linear actuator is simple in structure and has a large load bearing capacity along its own axis; similarly, the UPR-type active constrained leg with a rotational actuator bears active forces and torques. The workspace of the proposed design was quite large and the orientation of the platform was increased, when the central point of the platform was closer to the side of the reachable workspace.

Yunjiang & Guanfeng [46] proposed an optimization technique to maximize the work space of the parallel manipulator. Generally, the PM design parameters are defined in terms of the velocity relation. The distance between the two links was treated as a workspace constraint and the linear velocity and angular velocity were treated as dexterity constraints. In this paper, the controlled random search technique was used to optimize the work space between the search intervals. A design procedure to optimize the work space of the delta robot and Stewart platform was presented. Finally, they concluded that the random search technique algorithm proved to be efficient and reliable to solve the optimal design problem of the parallel manipulator. Yangmin & Qingsong [47] proposed a 3-DOF parallel manipulator, with adjustable actuator layout angles and a detailed explanation was provided for kinematic characteristic, workspace and dexterity, positional analysis by altering the arrangement of the actuators. This 3-PRS parallel manipulator resulted in reaching a maximal reachable workspace when the actuator layout angle is around 75 degrees. With variations in the actuator layout angle, the dexterity characteristics of the manipulator were investigated in detail, based on a local sense measure kinematic manipulability and on a global sense measure global dexterity index respectively.

Qimi J & Clement MG [48] focused on the singularity - free workspace of planar 3 RPR parallel mechanisms. A simple singularity equation was developed and based on that, the singularity free workspace and maximum leg length ranges were determined. Three case studies were provided to obtain the maximum singularity free workspace. The minimal leg lengths have been prescribed and the workspace depends on the physical architecture. From this assumption, the maximal lengths as well as three maximal workspace circles were determined. The singularity free workspace for the acute triangle, equilateral triangle and obtuse triangle bases were analyzed. Based on the analysis, the authors concluded that the

equilateral triangle base will have better kinematic properties, compared to the other architectures.

Bi & Lang [49] focused on the joint workspace of a parallel kinematic machine (PKM) and a tripod machine tool model with structural constraints taken as an example. The forward kinematic model was proposed to derive the workspace. A case study was presented, based on the geometric constraints of the PKM. The constraints were examined by comparing the direction of the support bar and of the guide way. Based on the joint workspace results, they reported that the structural constraints divide the domain of the joint motion into an unreachable area and a reachable area. The unconstrained joint motions of a point in joint workspace produce a reasonable end-effector motion in the task workspace. The cavities and holes presented in the joint workspace might result in a discontinuous trajectory. They concluded that the validation of the trajectory is essential to get good robot workspace. Geoffrey & Juan [50] compared the dexterous workspace of three variants of the 3-DOF manipulator. The three models were compared with the available stroke of the actuated prismatic joints which may be used to constrain the workspace. By using the optimal architectural parameters, the workspace volumes for each manipulator were determined. Finally, they concluded that the model of the 3-PRS introduced by Tsai et al. has a larger workspace volume than that of Merlet's and Carretero's Models.

Raza Ur-Rehman et al. [51] presented the multi objective design optimization of a 3-PRR planar parallel manipulator. They developed a parallel manipulator to minimize the mass of the mechanism in motion and to maximize its regular shaped workspace. The problem of the dimensional synthesis of parallel kinematic machines was addressed and its performance indices were used as the constraints for formulating the problem. Geoffrey & Juan [52] studied the kinematic and workspace analysis of a spatial 3-DOF parallel mechanism. The inverse displacement of the 3-PRS mechanism was provided. An augmented 6x6 Jacobian matrix was developed by the screw theory related to the platform velocity vectors. The workspace of the proposed mechanism was determined as the function of the inclined angle of each link and the length of the fixed link. A dexterous workspace was defined as the subset of the reachable workspace, geographically limited to poses and orientations inside an angle between the link and the MP, which corresponds to the singular condition. The work concluded that increasing the inclination angle of the link has an adverse effect on the size of the reachable workspace.

### Velocity and Acceleration Analysis

Patrick & Tatsuo [53] analyzed the maximum velocity of parallel manipulators in operational space by a graphical method. The Jacobian matrix was used to determine the

maximum velocity zones and an algorithm based on a 2D geometric model was developed, by considering the constraint inequalities to connect all the segment lines created by the delimited zone. The surface and volume of the parallel manipulator were computed from the triangle segments. The proposed method was applied to the conventional Stewart platform and the new parallel manipulator with a fixed linear actuator, to find their performance. From the comparison of the two parallel manipulators it was concluded that the conventional Stewart platform had superior high speed, whereas the new parallel manipulator had better robot position control.

Lung-Wen [54] presented a systematic methodology of formulating the dynamical equation of motion of the Stewart – Gough platform, based on the principle of virtual work and Jacobian matrices. The input forces required to produce a desired trajectory of the MP was achieved by the inverse dynamic analysis. A computational algorithm was developed for solving the inverse dynamics of the manipulator. In that, the trajectory of the MP was given as an input parameter and the rotation matrix, angular velocity and angular acceleration of the MP were considered as the output parameters. The Input forces for the proposed parallel manipulator were calculated from the calculated output parameters. MATLAB Software was used to develop the computer program and was simulated for various trajectories of the MP. Jianfeng et al. [55] proposed an inverse kinematic and dynamic analysis of a 3-DOF parallel mechanism, which represents the 3UPSUP parallel manipulator, where the dynamic equations were categorized into passive and active sub chains. Both these methods were solved by using the moment equilibrium method, the time histories of angular displacement, angular velocity and angular acceleration of the MP, generated from the obtained solution.

Staicu & Carp [56] approach for dealing the geometric, kinematic and dynamic analyses of a Delta parallel robot was achieved by iterative matrix relations. The virtual powers method was used to obtain the solution for inverse kinematic problem. Finally, they concluded that this virtual work principle approach establishes a direct recursive determination of the variation in real time, of the moments and powers of the active couples. Yu-Wen et al. [57] proposed the Newton Euler approach to formulate the inverse dynamics of the parallel manipulator. The Inverse kinematics of the parallel manipulator was derived by using the position vector method, followed by the velocity and acceleration analyses. The manipulator was modeled and simulated and the values were verified by using the derived equations of the dynamic analysis. The external forces acting on the parallel manipulator were considered, based on the structural integrity. The actuating force that is required by the link could be derived, based on the Newton Euler method.

Zhang et al. [58] proposed a new method to develop high speed machine tools with high stiffness and dynamic performance. Lagrange's formulation was used for the dynamic modeling of the 3-DOF parallel kinematic machine. The kinetostatic analysis was used for metal cutting, which requires large forces, higher stiffness and small deformation, resulting in better surface finish and longer tool life. MATLAB was used in workspace analysis of the parallel manipulator. The authors proposed various modules like the dynamic model, design optimization module and CAD/CAM/CAE module in their work.

The Lagrangian formulation was used for dynamic modeling and the genetic algorithm for solving the design optimization module and FEA packages. Alexei & Paul [59] determined the dynamic analysis for a 3-DOF parallel manipulator with an RPS joint structure. The motion equations were obtained with an application of the principle of virtual work and with the end-effector coordinates chosen as the generalized ones. The equations were derived based on the simplified radical-free position equations. The dynamic analysis, together with the associated numerical issues for the particular case of an inverse kinematics singularity, was also considered.

Yi L & Bo H [60] formulated various formulae for solving the displacement, velocity and acceleration of PKMs, by using the Jacobian and Hessian matrices. The derived formulae were applied to the 3SPR, 4SPS+SPR and 3UPU PKMs and they concluded that the derived equations were unified and simple. The kinematic force singularity was analyzed, by using the Jacobian and Hessian matrix and the determined geometric constraints of the constrained wrench could be used to determine the poses of the various constrained forces or torques of the PKMs. Stefan [61] determined the Matrix relations in the kinematics and dynamics of the Star parallel manipulator. Knowing the translation motion of the platform, they developed the inverse kinematics problem and determined the position, velocity and acceleration of each

Robot's link. Further, the inverse dynamics problem was solved, using an approach based on the principle of virtual work, but it had been verified the results with the framework of the Lagrangian equations with their multipliers. Recursive formulae offer expressions and graphs for the power requirement comparison of each of the three actuators in the two computational complexities, namely, the complete dynamic model and the simplified dynamic model.

Yangmin & Qingsong [62] investigated the dynamic modeling and robust control of 3-PRC (Prismatic - Revolute - Cylindrical) parallel kinematic machine with translational motion. A simplified inverse dynamic model was established and the dynamic equations were derived via the virtual work principle. The dynamic model results were validated with

the ADAMS software package. Zhang et al. [63] proposed an innovative 3-DOF parallel manipulator design with a passive link to increase the stiffness of the system that can be applied to a machine tool. Both direct and inverse kinematics problems were investigated and the direct kinematic problem was solved by the polynomial equation with an order of 40. A dynamic analysis was carried out based on the Lagrangian and Newton-Euler approaches; the former one was used to describe the velocity and acceleration of the system and the latter was used to calculate the driving forces of active joints. The proposed models were compared based on the workspace and stiffness and they concluded that the passive leg undertakes most of the external loads from the tool.

Shanzeng et al. [64] presented the dynamics of the 3-DOF spatial parallel manipulator, with flexible links. In this, the model of the spatial flexible beam element was developed the kinematics and dynamics equations were derived for the 3-RRS parallel manipulator. In addition, the dynamics response of the flexible links was also analyzed. Numerical simulation was carried out in order to verify the flexibility of the links. From this study, the authors suggested, that in order to make the manipulator to carry out the desired motions, there is a necessity to develop the motion control algorithms for the flexible parallel manipulator.

Meng-Shiun & Wei-Hsiang [65] formulated the dynamic equations of the 3-DOF parallel mechanism in the bi-coordinate system. The derived system could not avoid the complex velocities transformation between different spaces; but it could allow the separate dynamics of the legs and the MP by the reaction forces. The joint forces and the internal forces of the MP were derived from the Jacobian analysis. A circular trajectory of the MP was simulated, to study the dynamic behavior of the parallel mechanism. Zhang et al. [66] proposed an Elastodynamic modeling method for a 3-PRS parallel manipulator. The architecture of the manipulator and the inverse kinematics of the proposed manipulator were presented and analyzed. Two types of dynamic equations were derived from the structure dynamics. The first one was based on the limb subsystem and the other was on the MP subsystem. The kineto-elastic-dynamics was applied to the dynamic modeling of the limb subsystem and Newton's second law was used for the MP subsystem. By solving the Eigen value problem, they concluded that the distribution of the natural frequencies over the workspace has a significant influence on the system dynamics.

Hao et al. [67] addressed the dynamic modeling of a novel 3-PSP (Prismatic - Spherical-Prismatic) spatial parallel manipulator, which was used as a tool head for high speed machining. Based on the kinematic analysis, the dynamic equation with/without considering the parasitic motions was investigated, using the Newton Euler approach. In order

to verify the results, a numerical simulation was carried out. From the simulated results, the authors concluded that the error of the actuating force between the two cases has only a minor effect on the dynamic analysis.

### Simulation

Even though Clement et al. [68] discussed the kinematic simulation and computer aided design of the spherical parallel manipulators with revolute actuators for high performance robotic systems. In this paper, the rotation matrix from the base platform to the MP was derived from the Hartenberg-Denavit convention. The inverse kinematic problem was solved by the vector approach and the direct kinematics solution was derived from the polynomial equations. Both the forward and inverse kinematics problems of a spherical parallel manipulator, lead equally to 8 solutions. SMAPS (Simulateur de Manipulateurs Paralleles Spheriques), a CAD package was used to simulate the parallel manipulator model and the Euler angles, singularity, workspace and dexterity analysis were computed. Yangnian & Clement [69] presented the design of a reactionless 3-DOF and 6-DOF parallel manipulator. In this work, two types of the actuation schemes of the parallelepiped mechanisms were designed. The counter weight and rotations were used to balance the mechanism dynamically. The ADAMS simulation software was used to simulate the motion of the mechanisms. Finally, reactionless 6-DOF parallel manipulators were synthesized, using the 3-DOF parallelepiped mechanisms and the reaction less property was verified numerically.

Neugebauer et al. [70] coupled a Broyden-Fletcher-Goldfarb-Shano algorithm with the FEM system, using GNU Octave mathematical and numerical system, to achieve an efficient optimization on a tripod PM. The Clavel's tripod structure was taken into account to demonstrate the optimization algorithm. The FEM model was created from simple pipe elements. The inner and outer diameters were parameterized as optimization variables in the first condition. The second condition was that the weight of the structure should not be increased. The authors concluded that 6% of weight was reduced by the proposed method. This paper summarized that a FEM tool was required to predict the dynamic behavior of the system and for structural optimization. Nalluri & Mallikarjuna [71] presented the dimensional synthesis of the 3-RPS parallel manipulator by the Genetic algorithm (GA)-simplex method. In this method, the output from the GA was given as an input to the simplex algorithm. The GA-simplex method was used to determine the location of the ball joints and the direction of the revolute joints; they also noted that the proposed method can be readily applied and does not require proper initial guess solutions for the design. The developed method was explained with 10 numerical examples to establish the concept.

Leon [72] presented an overview of simulation in robotics. The author explained the importance of simulation in all

fields of robotics, from kinematics and dynamics to industrial applications. He mentioned that the advanced simulation tools were the foundation for the design of sophisticated robot systems, for the application of robots in complex environments and for the development of new control strategies and algorithms. The author believed that simulation in robotics played a very significant role.

### Concluding Remarks

The kinematics, workspace analysis, singularity' analysis, velocity and acceleration analysis, simulation and structural analysis have been studied so far in the literature. Most of the studies are devoted to the kinematic and workspace analysis of parallel manipulators. The study of the work volume and structural analysis was carried out for very few of the parallel manipulators. Among the studies of the simulation, work volume and structural analysis, the 3-DOF Tripod and Tri-Glide mechanism of the parallel manipulator has not been carried out. Most of the dimensional synthesis studies of parallel manipulators, dealt with the workspace of the parallel manipulator due to geometrical constraints of its parallel structure.

The dimensional synthesis due to the initial angle between the base platform and the link is found to be limited in most of the published papers. In dimensional synthesis, to get the maximum mobility and work volume, the geometrical parameters are important to optimize the design. The papers on the singularity analysis of parallel manipulators accounted for both mobility and work space and the constraints of the parallel configurations were also considered. The studies of the singularity analysis in the simulation of parallel configurations are very few in the open literature. Most of the published works do consider the actuation (horizontal / vertical) of the parallel manipulator. To design a parallel manipulator with high rotational capability, one has to study the actuation directions, with the geometrical parameters of the manipulator as one of the primary constraints. The Vibration analysis can be carried out on the parallel manipulator to enhance the stiffness of the links.

The structural analysis using ANSYS can be compared with the derived stiffness equation to improve the performance of the PM in Angular machining applications. In PMs, by introducing parallelogram concepts instead of using identical links, the PM stiffness and performance can be improved. The dynamic analysis can be carried out using software packages (ADAMS and ANSYS) and the results of the software packages can be correlated with the derived dynamic equations [73-81].

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DOI: [10.19080/RAEJ.2017.01.555559](https://doi.org/10.19080/RAEJ.2017.01.555559)

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