ISSN: 0976-3031

Available Online at http://www.recentscientific.com

CODEN: IJRSFP (USA)

International Journal of Recent Scientific Research
Vol. 8, Issue, 10, pp. 20798-20802, October, 2017

International Journal of Recent Scientific Research

DOI: 10.24327/IJRSR

Research Article

DESIGN OF KINEMATICALLY REDUNDANT PARALLEL MANIPULATOR

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DOI: http://dx.doi.org/10.24327/ijrsr.2017.0810.0962

ARTICLE INFO

Article History:

Received 17th July, 2017
Received in revised form 12th August, 2017
Accepted 04th September, 2017
Published online 28th October, 2017

Key Words:

Actuators, Jacobian Model, Manipulator, Stiffness Matrix

ABSTRACT

Parallel manipulators are a form of closed loop linkages and have a wide range of applications. Parallel mechanisms have many advantages over serial manipulator. Higher accuracy, stiffness and increased payload capacity are the characteristics of the parallel manipulator. In spite of many advantages, they have limited workspace and more singularity regions. So, redundant architectures have become popular. However, redundancy leads to infinite solutions for the inverse kinematic problem.

The current work addresses this issue of resolving the redundancy of kinematically redundant planar parallel manipulators. First, the conventional non-redundant 3-RPR planar parallel manipulator is presented. Afterwards, the kinematically redundant counterpart 3-PRPR is discussed and actuation redundant 4-RPR has been touched upon briefly. The workspace of redundant and non-redundant parallel manipulators has been obtained.

The generalized stiffness matrix has been derived based upon the Jacobin model and the principle of duality between kinematics and statics. A stiffness index has been formulated and the isotropy of stiffness index is used as the criterion for resolving redundancy. Optimum redundant parameters are obtained as a result of the analysis. A CAD model has also been designed to enhance the understanding of the mechanism workability.

INTRODUCTION

Parallel mechanisms are found recently in many applications including machine tools, robots and simulation platforms etc. Unlike serial manipulator used in most industrial robots, here, all the joint motors are located at ground level and a sort of stiffness improvising mechanism is provided in the structure. Thus, essentially, a parallel linkage provides advantages such as improved stiffness to weight ratio and more accurate path following capabilities. They are finding several applications in micro and nano level devices. More recently, planar parallel mechanisms are being employed in several application areas. Most common, planar parallel linkages are 3-RRR, 3-RPR and 3-PRR linkages. Here, the underscore denotes the actuator location in the mechanism; for example 3-RRR indicates that the mechanism has 3 chains each having three revolute joints with first revolute joint as actuation joint.

All these mechanisms drive a platform in a plane motion (3 degrees of freedom) allowing the platform point (cutting tool) to move according to a desired path/trajectory. Main disadvantages of these linkages are their relatively small workspace and huge singularities within the workspaces. At singularities, the mechanism either loses (forward) or gains (inverse) a degree of freedom and cannot perform the action as per the instructions. Such mechanisms with sufficient DOF for a specific end-effector task may not have the ability to achieve alternative paths when attempting a task due to their uniqueness of solution. In order to alleviate these problems, several efforts are made in literature. An important attempt in this direction is to provide redundancy in the mechanism.

Redundancy refers to the adding additional actuator to achieve the same three degrees of freedom at the platform point (end-effector). Additional actuators may avoid singular postures and improvise dexterity in path planning just like a serial human hand mechanism. But, the mechanism becomes more complex leading to several possible joint solutions to achieve a desired task. Resolving the complexity in kinematics and dynamics of mechanisms is one of the important issues in redundant parallel mechanisms.

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LITERATURE REVIEW

Several earlier works explained various insights of parallel redundant manipulators. These can be grouped under different headings like: workspace, singularities, dynamics and control and so on. Here, a brief literature relating to redundant parallel manipulators is described.

A systematic classification of redundancies in parallel manipulators was proposed by Lee and Kim [1] and Marlet [2]. Accordingly, there are three types of redundancies, Type I, Type II and Type III that are achieved by adding additional joint to existing limbs, replacing passive joints in current limbs with active ones and adding additional limbs. Redundancy can provide practical advantages to industrial manipulators.

Redundantly actuated linkages

Abundant literature is available on redundantly actuated manipulators since early 2000. Firmani and Podhorodeski [3] presented a study of the effect of redundant actuators on the existence of force-unconstrained configurations of planar parallel layout of joints. The 3-branch, revolute-jointed, 8-bar configuration is considered in detail. This layout is referred to as a 3-RRR configuration to denote its three branches and the number of joints per branch. Concepts of reciprocal screw quantities and kinematic geometry are used to determine the feasibility of the existence of force-unconstrained positions.

Successively, a methodology of using scaling factors to determine the force capabilities of redundantly-actuated parallel manipulators was also presented This methodology allows the actuator limits to be easily incorporated into the problem of determining force capabilities of parallel manipulators. Analytical methods for determining the force capabilities of both non-redundantly and redundantly-actuated manipulators using scaling factors are derived. In addition, an optimization-based method for generating force capabilities is presented. [4]. Wu *et al*. [5], described dynamics and control of a three degree of freedom parallel kinematic machine tool with actuation redundancy. Muller and Hufnagel [6], presented computed torque control scheme in redundant coordinates to control redundantly actuated parallel kinematic machine. A 2 degree of freedom model was used to illustrate methodology. More recently, an idea of optimizing antagonistic stiffness for redundantly actuated mechanisms for resolving redundancy was proposed by Shin *et al*.[7].

Class of Parallel Manipulators

There are mainly two different types of redundancy in parallel manipulators: (a) kinematic redundancy and (b) actuation redundancy. A parallel manipulator is said to be kinematic ally redundant when its mobility is more than the degrees of freedom at the moving platform. We often use this type of redundancy for enhancing the workspace. Fig.1 shows an example of kinematic ally redundant manipulators.

The mobility or degrees of freedom M is given by $M=\lambda(L-J-1)+\sum f_j$, j=1,2,…J; with λ as motion parameter (3 in case of planar and 6 in case of spatial), L and J as total number of links and joints respectively and f_j as the degree of freedom at each joint in the linkage. In case of kinematic ally redundant manipulators, mobility M is greater than λ and is equal to the number of actuators used in the mechanism.

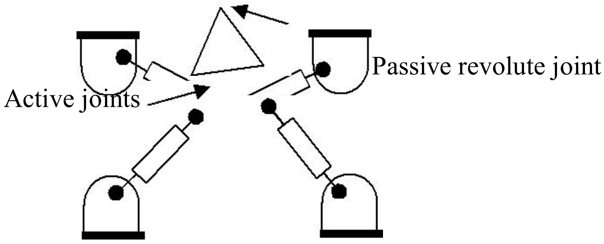

Fig Kinematic ally Redundantly actuated.

The 3-PRPR manipulator description

The mechanical architecture of the 3-PRPR parallel manipulator considered is shown in the Fig 3.5. It consists of a base platform, triangle $O_1O_2O_3$ and a mobile platform, triangle $M_1M_2M_3$. The end effector may be chosen as any suitable point on the mobile platform. The mobile platform is connected to the base platform through three parallel serial linkages called as limbs. Each limb consists of four joints, an actuated base prismatic joint along O_1L_1, a base revolute joint at L_1, an actuated distal prismatic joint along L_1M_1 and a platform revolute joint at M_1. Two prismatic joints are actuated. There are three limbs, hence twelve joints, but only six of them are actuated. The mechanism is a planar one and has three degree of freedom. But the number of actuated joints is six. So three extra joints has to be actuated through a redundancy resolution algorithm.

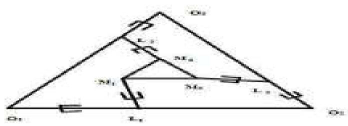

Fig The 3-PRPR Manipulator

The 4-RPR Manipulator

In order to understand the advantages of kinematically redundant linkage against redundantly actuated mechanism, in present case, we also considered 4-RPR (one extra leg) redundantly actuated linkage. The mechanical architecture of the 4-RPR planar parallel manipulator is shown in the Fig 3.7. It consists of a base platform, $L_1L_2L_3L_4$ and a mobile platform, $M_1M_2M_3M_4$. The end effectors may be chosen as any suitable point on the mobile platform. The mobile platform is connected to the base platform through four parallel serial linkages called as limbs. Each limb consists of three joints, a base revolute joint at L_1, an actuated distal prismatic joint along L_1M_1 and a platform revolute joint at M_1. The prismatic joint is actuated. There are four limbs, hence twelve joints, but only four of them are actuated. The mechanism is a planar one and has three degree of freedom. But the number of actuated joints is four. So the extra joint has to be actuated through a redundancy resolution algorithm.

Kinematics and Jacobin Analysis of the 4-RPR Manipulator

The kinematics of the 4-RPR can be derived from the constraint equations of the four prismatic joints. The displacements of prismatic joints are t_1, t_2, $t_3$and t_4. The displacements of distal prismatic joints are constrained within the minimum and maximum joint limits. The velocity equations for the 4-RPR mechanism can be obtained as follows, Writing the displacement constraint from Fig.3.8,

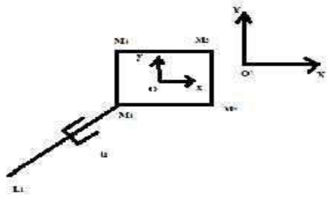

Fig Seperated limb of The 4-RPR mechanism

Generalized Stiffness Matrix

Several authors worked out on stiffness index as one of the measure of manipulator performance. A brief literature of few papers is cited below:

Simaan and Shoham [25], considered the stiffness synthesis of a kinematically redundant parallel robot. The proposed a polynomial solution for the geometric parameters in order to achieve a stiffness matrix. A six degree of freedom double planar parallel manipulator was studied and the polynomial obtained possessed 384 real solutions.

Legnani *et al*. [26], discussed isotropy and decoupling of n-dof parallel manipulators. The use of Jacobian matrix in achieving isotropy was revived. The application of these concepts to Gough-Stewart platform indicated that it can be isotropic, but not decoupled. A modification was proposed which resulted in two six degree of freedom isotropic and decoupled parallel manipulators.

Bandyopadhyay and Ghoshal [27], derived the Jacobian of Stewart platform that led an algebraic formulation in terms of an eigen value problem to obtain isotropy of the mechanism. The criterion for isotropy was expressed in terms of minimum number of algebraic equations. Two families of manipulators with isotropic form were obtained using the symbolic algebraic equations.

RESULTS AND DISCUSSION

This chapter presents the simulation results relating to kinematics of non-redundant and redundant 3-RPR parallel manipulator.

Workspace and Singularity Analysis of 3-RPR manipulator

In order to illustrate the stiffness index optimization, we considered a working zone within the manipulator reachable workspace. In general, the workspace of the parallel manipulator consists of the set of points that can be reached by the end effector through a feasible configuration of its internal parts. There are many types of workspaces, namely dexterous workspace, reachable workspace, constant orientation workspace. The constant orientation workspace consists of the set of points reachable by the end effector at a fixed platform orientation. The reachable workspace consists of all points reachable by the end effector with at least one orientation. The dexterous workspace consists of the region spanned by the end effector with any orientation of the platform. Singularities occur when the configuration of the mechanism at a point in space becomes unstable. The mechanism either becomes locked up or some degrees of freedom are lost. At such points, the Jacobian of the mechanism becomes singular. Some singularity regions are grouped around the corners i.e. near workspace boundaries only. When manipulator works around the singular points or near singular regions, its accuracy, rigidity and other performances will become worse. In order to compute the workspace, a numeric discretization process is adopted. Table 1 shows the geometric parameters considered in the kinematic analysis. To enhance workspace, often equilateral triangular platforms are considered. All the prismatic joints are having same range of sliding motion.

Simulation Results using ADAMS software

Msc ADAMS is a commercial multibody dynamic analysis tool. It stands for automated dynamic analysis of mechanical systems. It allows to create the model of complete mechanical system including kinematic pairs and constraints. With the help of Msc ADAMS, a model of 3-RPR with geometric parameters in Table 4.1 was created as shown in Fig. 4.5. The base position of the model could be varied parametrically. An inverse kinematic simulation was run for a circular trajectory within the workspace and the feasibility of motion was tested. Since, there were no direct link interferences, the solutions were feasible for the kinematic analysis of the mechanism

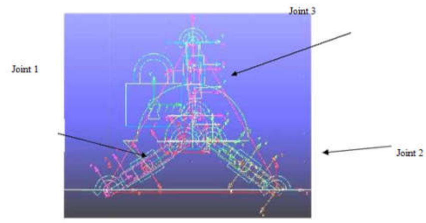

Fig. Multibody Model of the 3-RPR Mechanism

A circular path was chosen w ith following equations for the end effector, x = rcos(t), y = rsin(t);

Stiffness Index Analysis

The mechanism is useful if it is able to track any point within the desired workspace while working against some load. Since, for any useful work, the error due to deflection of the point tracing the required trajectory must be contained within limits. In case of redundancy obtained due to additional actuators in each limb of the manipulators, there exists infinite poses for achieving a target point within workspace. Hence, there is a need to resolve this difficulty. Further, the stiffness of mechanism is dependent on configuration of the mechanism; hence any strategy that takes into account stiffness as the driving factor will benefit the design procedure as a whole.

Envelop of usable workspace acts as a primary constraint and all the computations are performed on selected checkpoints within this space. It is seen that in manufacturing industry, many components are required to be fabricated on same machine. Majority of components consists of various features with standard shapes as circles, boundaries, triangle etc. In order to fabricate such components, the workspace of the device include should contain the desired feature boundary.

As a next case, 3-PRPR mechanism is considered with the specified range of redundant base slider actuator positions (0 to 5 cm). The maximum possible workspace with symmetrically laid base sliders is likewise computed as equivalent 3-RPR mechanism. Within the workspace, some region in the form of circular and square shapes is separately considered as the working path of mechanism to present the optimization analysis. Objective is to achieve a maximum stiffness close to unity at the boundaries of these shapes and at interior choosen points. So the program employs Jacobian analysis at every Cartesian location of work shape compute the stiffness matrix and finally the stiffness index. This analysis involves nonlinear terms and requires some efficient optimization scheme.

Since, it is difficult and time taking to perform computation at each point within the workspace, certain selected points are used for the purpose of optimization. These points are referred to as checkpoints. Checkpoints may lie within or on the boundary of the workspace.

There are two work envelopes, a circular and a square. The checkpoints are marked on the boundary as well as on the inside. All points cannot be considered as it would form an exhaustive, but a very time consuming search and computational cost would go up. Hence, it is wise to discretize or mesh the workspace. Only, selected checkpoints need to be computationally verified for obtaining the optimal solution.

Case Study I

A circular workspace is chosen first for the purpose of illustration. The workspace is discretized into twelve checkpoints: Eight checkpoints are on the boundary and four checkpoints lie inside the workspace. At each and every check point with specified (x,y) coordinates, we require to find the Jacobian and stiffness at some pre-set values of base prismatic joint locations using simple 3-RPR kinematics. The convergence of the stiffness index is plotted against number of iteration cycles for first checkpoint.

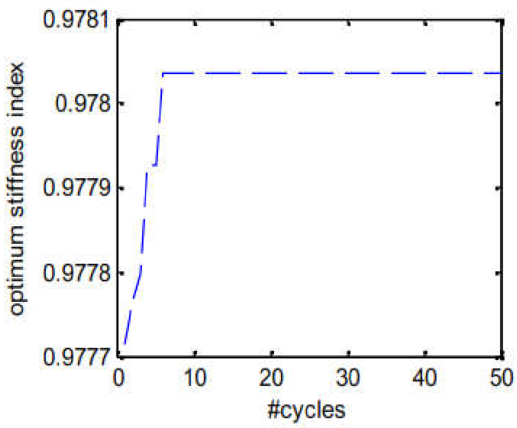

Fig Convergence of the Optimal Index at First Checkpoint

In order to test the validity of the obtained solution, one can test the mechanism for a set of joint forces, to see whether the output forces and moments are reasonable or not. A force of 10 Newton is applied at each distal actuator at fixed optimal base slider positions for each check point and the corresponding end-effector forces are computed through static analysis. Fig.4.10 shows the outputs. The values obtained are of reasonable levels.

CONCLUSIONS

- In this work, the redundancy resolution for the 3-PRPR kinematically redundant parallel manipulator has been achieved to obtain the isotropic stiffness index inside a work region by proper selection of base slider positions.
- The optimum base slider positions has been obtained for the mechanism at selected checkpoints of a usable workshape defined within the maximum workspace of the kinematically redundant mechanism.
- Circular and square workshapes were considered, where twelve checkpoints distributed over the boundary and inner region of the workshape were selected in order to minimise the time and cost of computations while maintaining the accuracy of the results.
- The workspace and singularity regions of 3-RPR linkage has been obtained and it is found that an enhancement can be obtained with the help of kinematic redundancy.
- The case of 4-RPR actuation redundant manipulator was briefly discussed and its workspace was analyzed. The solid model of the mechanism analysed in ADAMS software has given some interesting inverse kinematics outputs.
- After achieving optimal locations, forward kinematic analysis was carried out to verify the closeness of selected work shape and also the corresponding output forces were obtained from a given joint torques.
- A CAD model of the mechanism was designed and attempted to verify the workspace features. In overall sense, the present study aids in the analysis and design of kinematic ally redundant manipulators effectively.

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How to cite this article:

Samala Sridhar.2017, Design of Kinematically Redundant Parallel Manipulator. *Int J Recent Sci Res.* 8(10), pp. 20798-20802. DOI: http://dx.doi.org/10.24327/ijrsr.2017.0810.0962

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