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Studies on Stewart platform manipulator: A review †

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Abstract

This paper presents a compilation of previous studies on the Stewart platform, which is a class of six degree of freedom parallel manipulators. The abstraction of a parallel manipulator is appropriated for the entire class of it. The paper focuses on the studies in the different fields which are closely checked to determine the direction of research and identify the solved problem areas. A significant investigation has been presented to discuss the existing methods for the analysis of the Stewart platform manipulator due to their unique applications. Studies on analysis and design of the Stewart platform manipulator using flexible joints are included. Modeling and analysis of parallel manipulators by Matlab SimMechanics environment are also highlighted.

Keywords: Flexible joint; Parallel manipulator; Robot; Stewart platform

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1. Introduction

The Stewart platform is a six-legged parallel manipulator. The need of more accurate motion of mechanical structures has been increasing in recent years. Parallel manipulators have high stiffness and have gained popularity due to accurate positioning capability. Their high level design produces superior load capacity and positioning precision over the serial ones. The potential applications of parallel manipulators include both terrestrial and space applications, including satellite antennas, telescope positioning systems and pointing devices [1]. The most important technology control and vibration isolation between the precision instrument and disturbance source have been applied to many space applications like space interferometry, spacecraft laser communications and other precision spacecraft. The Stewart platform is a locating system that includes three major parts: top or moving plate, base or fixed plate, and six identical stretchable legs. The ends of all the legs are attached to the moving and fixed plates by spherical, universal or flexible joints. It is one of the most accepted parallel manipulators known as the Stewart platform. This mechanism was first suggested by Gough in 1949 as a universal tire-testing machine [2], which was re-discovered and presented to academia in 1965 by Stewart as a flight simulator [3]. Gough was the first to realize the benefits of this mechanism and research in this area was carried out after Stewart's Paper. Therefore, the platform is generally called a Stewart platform.

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Bhaskar and Mruthyunjaya [4] presented the literature available on Stewart platform till 1998.

A brief introduction is given in Sec. 1. The analysis and characterization of the singularities and approaches towards workspace analysis is described in Sec. 2. Determination of position, orientation of the platform and kinematics of the Stewart platform is reviewed in Sec. 3. For the dynamic analysis of the parallel manipulators various methods have been implemented, but the Newton-Euler and Lagrange methods being the most popular ones and are discussed in Sec. 4. Control and vibration isolation strategy for the Stewart platform are summarized in Sec. 5. Finite element method is necessary for the detailed design of the Stewart platform system due to the complicated geometry of the Stewart platform and the necessity of modeling the joints stiffness precisely, which is described in Sec. 6. Matlab SimMechanics environment for block diagram modeling and simulation of Stewart platform is reviewed in Sec. 7. The literature on flexible joints and Stewart platform with flexible joints is discussed in Sec. 8. Finally, in Sec. 9, the review is summarized and concluded with some future scope.

2. Singularities and workspace

A parallel manipulator mechanism may attain or release one or more degree of freedom at a singular point. Many researchers have studied singularities in terms of statics [5]. The parallel manipulators cannot resist external forces and torques in definite directions due to some constraints and these constraints have to be determined. The architectures limit the

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motion and behavior of the parallel manipulator platform and generate complex kinematics singularities inside the workspace [6-8]. Bandyopadhay and Ghosal [9] determined the singularity associated with the attaining of one or more degrees of freedom. In a parallel manipulator, the analysis of constraint forces corresponding to the kinematic constraints was completed by Bandyopadhay and Ghosal [9]. They also characterized the gain singularities from the degeneracy of the constraint forces. The gain singularity actuators can lock the system, and this special phenomenon has been studied to derive the analytical criteria.

Stewart platform, which is a class of parallel manipulators, has been used due to many advantages over serial manipulators. The main disadvantage of such a parallel manipulator is the presence of singularities inside their workspace. Many researchers analyzed these singularities [10-13], and to define the singularity locus developed scalar expressions [14-17]. The scalar expressions are frame dependent, so it is very difficult to judge the effect of the parallel manipulators geometry on the singularity locus. The orientation of the reference frame used in the Stewart platform is independent from the constant-orientation singularity locus and a compact vector expression has been developed [18] for the same. Design and analysis of the Stewart platform can be more easily performed after getting the vector expression of the singularity locus, and the derivation is similar to that proposed in Ref. [19]. To determine the singularity-free region, the proposed expression [19] has been combined with interval analysis [20].

The interpretation of the orientation workspace is more complicated. The orientation workspace can be represented by many aspects such as the Roll-Pitch-Yaw angles, direction cosine, Euler axis and angle tilt and torsion angles [21]. But very few works exist in the area of orientation workspace computation. The admissible work in this domain may be found in Refs. [22-24]. The determination of the orientation workspace was presented by Pernkopf and Husty [25], who used the pencil of rays from the origin because the computation accuracy was based on the density of the used rays. It is impossible to find the entire boundary of the orientation workspace due its complex shape, and this is the main disadvantage of this method. Now, at a particular position orientation workspace has been described by twelve workspace surfaces, and to find these workspace surfaces a numerical algorithm was developed by Jiang and Gosselin [26]. The determination of these workspace surfaces guarantees a singularity-free orientation workspace and the ranges for the relative leg length. Also, an iterative procedure for finding the singularity free sphere has been developed to compare the singularity free orientation workspace with sphere.

Parallel manipulators are uncontrollable due to singular configurations within the workspace. Therefore, it is essential that the workspace must be singularity free. To evaluate the performance of various parallel manipulators a variational approach is used [27]. In this approach the Lagrangian incorporates both the kinetic and potential energy term to keep the path short and singularity free. Stewart platform has complex six-dimensional workspace volume. This volume is fixed in the Cartesian space defined by six pose parameters, and it is difficult to assess and indicate because of its large size and complicated shape. The recent approach provides attractive visualizations of the orientation workspace [28], and the determined workspace is an over-estimation of the real workspace due to neglect of mechanical limits in the elastic joints. This method is only allowed to obtain the workspace component that is attainable from a known configuration and provides only a limited concept of the entire motion range of the parallel manipulator. This is the limitation of this method, as well as of those in Ref. [29]. A method was developed [30] to find the constant-orientation slice that also presents a synthesized method for determining both slices. The benefits over existing techniques cover the ability to find the workspace for all attached bodies, and any motion hurdle existing in its internal mechanism.

3. Kinematics analysis

Kinematics of the Stewart platform is concerned with the learning of the motion without considering the forces causing the motion. A method was developed [31] by using three linear sensors for analyzing the direct kinematics problem of the Stewart platform. In this method there is no integration of connection points on either the fixed or the moving plate and the linear sensors are easily attached. A five degree univariate polynomial is generated from an over-determined system of six quadratic equations. The unique solution of this univariate polynomial is evaluated by implementing an effective methodology to its solutions. The effective methodology for the solution includes the nonlinear polynomial algebra system, and to solve the nonlinear polynomial algebra system numerical iterative method was used. There is a problem for selecting iterative initial value in the numerical iterative method. Homotopy approach was used for the effective numerical iterative method because this approach requires no iterative initial value. Therefore, homotopy approach has been considered by many researchers in the discipline of engineering field [32-34]. The length of the links in parallel manipulator is determined by the solution of the bifurcation point in configuration curve [35].

In robotic field, the modeling of parallel manipulator mechanisms is the main problem because parallel manipulator mechanisms are insufficient in lower dimensional spaces. Different type of kinematic chain has been proposed with specific degrees of freedom. Plucker coordinates are used for explaining the displacement of the output link of a chain, and this principle is applied for the modeling of parallel manipulator mechanisms [36]. They also obtained different new types of 2-, 3-, 4- and 5- degree of freedom parallel manipulator mechanisms. The solution of the closed form forward kinematics of the Stewart platform was presented by Huang et al. [37] and this solution was based on a concise algebraic elimi-

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方位工作空间 22-24、25
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评价性能 27
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nation algorithm. This illustrative algebraic procedure minimizes the forward kinematics complication to a univariate polynomial equation of degree fourteen. The algorithm is analogously compact and takes moderately less computation time. However, the determinant of the univariate coefficient matrix in Ref. [38] is not in accordance with the highest degree of the univariate polynomial. Rather than using symbolical techniques, numerical technique was used to understand the univariate polynomial.

The parallel manipulator based on Stewart platform has been used as a hexapod machine tool. The four necessary functions--modeling, measurement, parameter identification and implementation or compensation [39, 40]--are used to calibrate the hexapod machine tool. In parallel manipulator, kinematic parameters errors have been analyzed by a few investigators. Jokiel and Zigert [41] attempted the inaccuracies of the parallel manipulator. Parallel manipulator kinematics was optimized by Ridgeway and Crane [42]. They introduced a procedure for maximization of kinematics of the parallel manipulator after taking into account the position and orientation inaccuracies. Many researchers [43-51] have investigated the inaccuracies in the motion of the parallel manipulator mechanisms. To determine the real or near real kinematics variables, an algorithm was proposed and also used to simulate the calibration of the Stewart platform [52]. The presented [52] study concluded that the maximum observabilty of the kinematics inaccuracies, for the purpose of calibration of the Stewart platform, is delivered.

Dwarakanath et al. [53] designed and developed a force-torque sensor based on six-axis parallel manipulator design. Kang [54] explained the procedure to solve the forward kinematics in the form of closed-form solution by linearization technique. Now, this solution has been implemented on a six-axis force transducer to determine the inaccuracies in force measurement. These inaccuracies are within 0.005 % of measured forces and less than noise levels.

Gan et al. [55] investigated the forward kinematics problem of the Stewart platform. They also figured out the forty feasible different positions of the moving platform with the Grobner basis theory. Merlet [56] has given a procedure to solve the forward kinematics of the Stewart platform by interval analysis. These solutions are made after considering the physical and technological constraints. The orientation of the end effector was determined by the direction cosine matrix method [57]. However, a powerful method was introduced [58] to obtain all the suitable contour of the Stewart platform. Chiu and Perng presented [59] the solution to find the actual pose, position and orientation of the parallel manipulator with respect to the bottom plate without using sensors. A serial-parallel manipulator built by Gallardo-Alvarado [60] with two unsymmetrical fixed degree of freedom parallel manipulators brings together and connects in sequence. Kinematic parameters were optimized by Wolf and Shoham [61] of a parallel manipulator and calibrate the manipulator working operation with respect to a given instantaneous twist deformation of the Stewart platform. Alvarado et al. [62] presented the screw theory for the kinematics of a three-legged parallel manipulator with unsymmetrical link. A set of generalized coordinates was computed using a unique method based on simple geometric constraints for the forward displacement analysis.

4. Dynamics analysis

Parallel manipulator systems are closed-loop structures. Dynamic modeling and analysis of parallel manipulators exhibit fundamental complications due to kinematic constraints. Newton-Euler and Lagrange methods have been implemented in the dynamic analysis of Stewart platform due to the popularity of these methods. A closed-form dynamic model of the parallel manipulator was generated by Dasgupta and Mruthyunjaya [63] using the Newton-Euler approach. Several researchers [64-68] used this method, and Harib and Srinivasan [69] presented the dynamics of parallel manipulator, Stewart platform, mechanisms. For the analysis of the inverse dynamics of the structure, Newton-Euler formulation procedure was applied, which gives efficient results. Mukherjee et al. [70] presented the dynamic stability index of the Stewart platform. The Newton-Euler method leads to the dynamic formulation of the parallel manipulator, which includes the leg rigidity, force and torque due to adhesive friction at the hinges, inertia and gravity effects. In this approach all equations of motion must be composed for all the components of the Stewart platform. Riebe and Ulbrich [71] effectively implemented this approach for the dynamical analysis of the Stewart platform. The major drawback of this method is that it has ample number of equations and hence it has low estimation of effectiveness.

The principle of work and energy was applied in Lagrange approach to describe the dynamics of a mechanical structure. Abdellatif and Heimann [72] used Lagrangian formalism to derive explicit equations for the Stewart platform and eliminate all reaction forces and moments at the beginning. However, it is laborious to obtain the equations of motion related to the absolute generalized coordinates due to the various limitations applied by the closed loops of the Stewart platform. To simplify this difficulty new coordinates with a set of Lagrangian multipliers must be inserted. This concept was implemented by Leroy et al. [73] for general parallel manipulators.

In parallel manipulators, the Lagrangian equations of the type first must be assumed because the actuator variables are not unbiased due to the kinematic limitations. Hence the number of unknowns is increased by the Lagrangian multipliers. Such approach is not useful for the Stewart platform due to messy calculation, as mentioned in Ref. [74]. Chen [75] presented a closed form solution for the Stewart platform and considered the extending generalized coordinates to the variables of the elastic joints. The computational efficiency of Lagrangian method is much less; however, significant and basic geometry of the parallel manipulator was assumed. The coriolis terms and inertia tensors of few components were omitted and a simplified model was proposed in Refs. [74, 76]. The D'Alembert concept of virtual work [77, 78] and Jourdain's concept of virtual power [79] conveyed only an implicit and incomplete model of the inverse dynamics. Abdellatif and Heimann [80] presented the exact equations with respect to the active coordinates permitting for time optimal motion planning. The proposed methodology is a robust technique for the dynamic study of parallel manipulator mechanism. Dynamic solution of implicit models cannot be obtained directly [81]. Bai et al. [82] presented a methodology based on Lagrangian method to automatically generate three-dimensional multi-body dynamic equations. This methodology is utilized here for automated dynamic analysis, control design, and simulation of the parallel manipulator. Lagrangian approaches are more incomplete in little area as compared to the more complex Newton-Euler method [83].

All methods based on the concept of virtual work [84, 85], screw theory [86], recursive matrix method [87], and Hamilton's concept [88] were identical as they were illustrating the equivalent physical structure [89]. All approaches result in identical dynamic equations. However, these equations express the various levels of difficulty and related computational loads. The recent proposed techniques [87, 90-92] are used to reduce the number of process required in the computation of the dynamic model of the parallel manipulator. Lopes [93, 94] used the generalized momentum concept for the dynamic modeling of the parallel manipulator. This method is a powerful tool to determine the kinetic component of the generalized force acting on the all solid component of the parallel manipulator.

Graph-theory procedure for kinematics was combined with the concept of virtual work for dynamics using joint coordinates in a six-axis parallel manipulator formulation [95]. Inverse dynamic solutions can be automatically generated by the approach presented by Geike and McPhee [96] for planar parallel manipulators with three degree-of-freedom and spatial parallel manipulators with six degree-of-freedom. The natural orthogonal complement method was used for the analysis of the inverse dynamics of the Stewart platform with fixed-length legs [97]. The inverse dynamics equations were developed by this method adopted to determine the appropriate exerted actuator forces for the given movement of the parallel manipulator.

5. Vibration isolation and control

Applications of the Stewart platform in accuracy would be impracticable without the attentive vibration isolation and control of the mechanism. Selig and Ding [98] generated a geometrical model of the parallel manipulator for the analysis of vibration. For the development of this mathematical model the following assumptions were considered: Massless legs, frictionless passive joints. A dynamic stability index for the Stewart platform was proposed by Mukherjee et al. [99]. The presented dynamic stability index was validated and the model dealt with base excitations at dissimilar frequencies to study the response of the platform [99]. A mathematical model of the Stewart parallel mechanism was constructed by Gexue et al. [100] for stability analysis and control simulation. The platform is stabilized and the control performance of the platform is illustrated with the controlled and uncontrolled responses. To stabilize a platform on a vibrating base platform, workability of parallel manipulator, Stewart platform, was analyzed by Cheng et al. [101].

The vibration of intermediate linkage of the planar parallel manipulator model is effectively damped out more quickly with strain rate feedback and this model was developed [102] using the Lagrange Finite element method (FEM) formulation. Lead zirconate titanate (PZT) sensors and actuators are used to find the strain rate feedback control and this is called active vibration control simulation. Many resilient control and other control approaches have been studied [103-106].

Anderson et al. [107] developed a piezoelectric actuator based Stewart platform. A general dynamic model of parallel manipulator platform for vibration control applications based on Kane's method is presented [108] using prismatic actuator which is fixed at one of the struts. An isolator was developed [109] with six-axis Stewart platform architecture using soft actuators and multiple sensors. Zhang et al. [110] developed a Stewart platform manipulator based on magneto-strictive actuator. Chi et al. [111] presented a Voice coil motor (VCM), which is a type of electro-magnetic actuator used to convert electric energy into mechanical energy, based on Stewart platform used for active vibration isolation of the payload carried on spacecraft. The physical experiment results show that the Stewart platform based on VCM with the suggested controllers is workable in realistic applications. The Stewart platform based on voice coil type of actuator was also developed by Preumont et al. [112]. They reported a six axis vibration isolator for space applications, which used the principles of active isolation. The study includes the technology used for model design, the identification of the transmissibility matrix and the performance evolution. The main theoretical results for multiple axis decentralized control based on force feedback are summarized, which show zero gravity tests in parabolic flight.

A unique hexapod was designed and built by Hood Technology Corporation (HT) and the University of Washington (UW). It was tested for spaceborne interferometry missions [113]. Stewart platform is used in space applications; for this purpose many critical aspects of the Stewart platform related to vibration isolation are analyzed [114]. This study includes the selection of sensor and successive control architecture, the uniformity and restrictions of the experimental system dynamics. The ultra-quiet isolation technology experiment was used to analyze the coupling of satellite by Joshi and Kim [115, 116]. The mathematical model of the parallel manipulator for vibration isolation was obtained [117] in the distinct time domain on the basis of the experimental data derived from a satellite.

Parallel manipulator mechanism can be used as machine tool, table of the machine and end effector. End effector carries the spindle of the machine. Now, for such applications, the study on the dynamics and specifically the vibration performance of these mechanisms is the primary concern. A vibration model was developed by Mahboubkhah et al. [118] for the hexapod table of milling machines. The relevant explicit equations were derived for this model and the eigenvalue problem of the top plate of the parallel manipulator was worked out to determine the natural frequencies of the manipulator. The results were verified with finite element method simulation. Yun and Li [119] presented a dual parallel manipulator for both rough positioning and active vibration isolation in a wide-range workspace. The experimental investigations carried out on the prototype of the parallel manipulator to verify the vibration control performance of the prototype.

Modified active isolation systems were developed by Xing et al. [120]. This system has an actuator in series with a spring or damper for providing the static stiffness and is used to overcome the limitations on the feedback gain of conventional active isolation systems. The performance of the active isolation system can be improved by providing a joint vibration reduction method and this method was discussed by Hongling et al. [121]. A six-axis vibration isolation system was developed by Hoque et al. [122] using active zero-power controlled magnetic suspension.

6. Finite element analysis

The finite element method is required for detailed modeling of the Stewart platform due to the complicated geometry. It is used to find the natural frequency, static stresses in the components and mode shapes of the parallel manipulators. Parallel manipulator structures with flexible joints were developed by Piras et al. [123] and the number of linear ordinary differential equations of motion was retrieved. The dynamic finite element analysis result showed that the structure has meaningful effect on the elastic vibrations for high speed motion. They also found the necessary number of constituent and their order by conducting a convergence investigation of the natural frequencies with respect to the manipulator structure. A prototype of the Stewart platform was developed by Yao et al. [124] using pre-stressed six-element. The finite element analysis was performed and the results of the finite element method validate the theoretical conclusion of the prototype.

Mahboubkhah et al. [125] performed exhaustive research on the free vibration of the parallel manipulator structure. The finite element method results displayed the identical direction of changes as the theoretical results and are near to each other. Jia et al. [126] established a finite element method model of the Stewart platform and described a procedure of six-axis load sharing. The finite element method analysis results were verified with the calculated results from the suggested procedure, which shows the performance of the procedure. The finite element model of the Stewart platform is shown in Fig. 1.

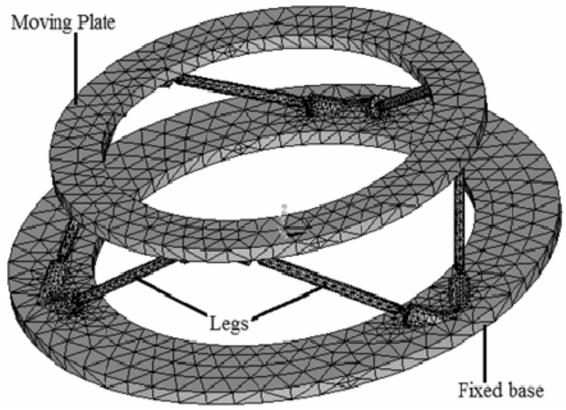

Fig. 1. FE mesh model of the Stewart platform.

7. Simulink and SimMechanics environment

The simulink is advantageous for modeling of the Stewart platform. It measures the dynamic response with non-identical variables of the Stewart platform and represents a robust tool for future research projects. It is used for the creation of new geometry of the parallel manipulator by varying the manipulator's variable, kinematics analyses and controller's validation. Molina et al. [127] demonstrated the kinematics, dynamics and control study of the Stewart platform to arrange into new configurations. They determined different types of configurations of parallel manipulator by changing the manipulator geometry and using inverse kinematics.

SimMechanics environment was used for the computer modeling [128] of spatial six degree of freedom parallel robots (Fig. 2). In this modeling, Kane approach was used to derive the integrated dynamic equations for the parallel manipulators. Brezinaa et al. [129] presented an approach which can be used for the designing of dynamic models and their control of complicated mechatronic systems. This approach was applied on the Stewart platform; simulation results proved control designed with use of the linear state space machine model. The Matlab SimMechanics used for the different phases of the design and also some general advantages of working with these environments were mentioned.

8. Parallel manipulator with flexible joints

8.1 Flexible joint

Today, flexible joints are accepted due to reduced mass of the joint and negligible backlash, friction and lubrication. They have also provided better quality of motion smoothness and virtually infinite resolution. Paros and Weisbord [130] presented design equations to determine the spring rate or compliances of the flexible joints. The static finite element analysis was implemented by Ragulskis et al. [131] to find the spring rate of circular flexible joints. A similar approach was presented by Smith et al. [132] for the elliptical flexible joint as of Paros and Weisbord [130]. The spring rate of a simple monolithic elliptical flexible joint was determined by closed-

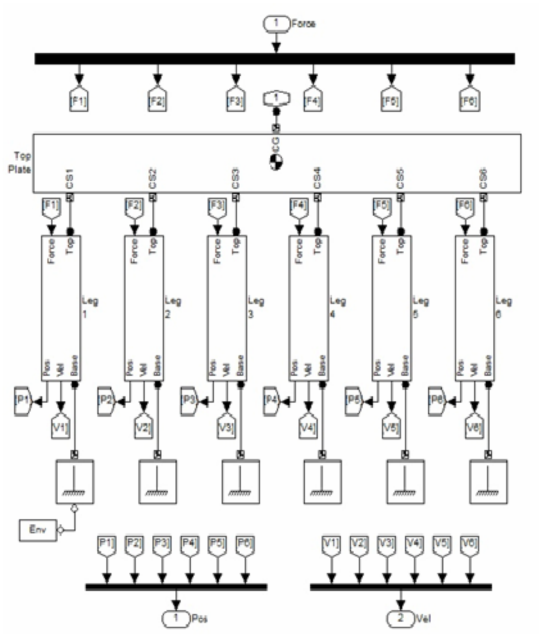

Fig. 2. Computer model of Stewart platform in SimMechanics.

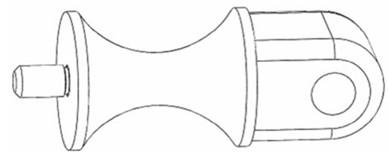

Fig. 3. Hyperbolic flexible joint.

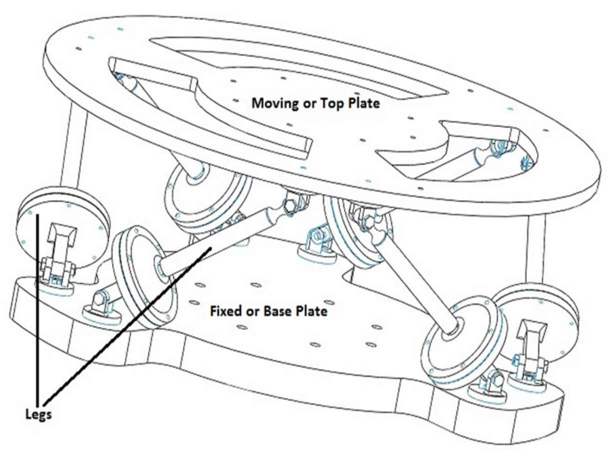

Fig. 4. Stewart platform with flexible joint.

form equations. The finite element method and experimental results were used for the model derivations. Smith [133] presented the fundamental geometry and mathematical models of two-axis flexure hinges.

A mathematical model of corner-filleted flexible joint was developed by Lobontiu et al. [134] and implemented into planar magnification mechanisms. Static finite element analysis was conducted by Xu and King [135] of circular, corner-filleted and elliptical flexible joints. The analysis showed that the corner-filleted flexible joint has perfect profile, the elliptical flexible joint has less stress and the right circular flexible joint is the stiffest. The motion errors were caused by machining imperfections in a flexible jointed mechanism. These motions errors were modeled by Ryu and Gweon [136]. Lobontiu et al. [137] developed the parabolic and hyperbolic flexible joints (Fig. 3) for planar mechanism, and the performance of these flexible joints was measured by the flexibility, precision of the motion and stresses.

8.2 Stewart platform with flexible joint

A Stewart platform with flexible joints is shown in Fig. 4. Flexible joints are used to achieve more accurate operation of the manipulator. Kinematics and dynamics analysis of a six-axis parallel manipulator with flexible joints was presented by Wang et al. [138]. Ranganath et al. [139] presented the design and analysis of the Stewart platform formed force-torque sensor in a near-singular structure. They also showed that, by exchanging the spherical or universal joints with flexible joints, forces in the components do not amplify. Simulation results [140] showed that the gain in the degrees of freedom can be effectively overcome at singular configurations, replacing regular joints by flexural hinges in parallel mechanisms. Bhavikatti et al. [141] described the selection of the structure, design and initial experimental results of the parallel manipulator.

All-optical communication intersatellite, which has micro radian resolution and repeatability, required high-precision pointing mechanism. Such kinds of mechanism were developed [142], which employed the flexible joint as the elastic joints for precision pointing. The corner-filleted flexible joint, which is accepted after experimental test and finite element simulation, has high motion accuracy and large displacement. It is implemented in the high precision pointing mechanisms. A general control law applicable to any flexible jointed parallel manipulator was found [143], which produces a decoupled input-output response.

9. Conclusions and future scope

This paper presents a compilation of previous studies on the Stewart platform, which is a class of six degrees of freedom parallel manipulators. The paper focuses on studies in different fields which are closely checked to find the direction of research and identify the unsolved problem areas. Various methods are discussed that have the ability to determine the workspace of all connected components of the Stewart platform.

In Sec. 2, many authors were discussed who determined obstacles present and also to find the singularity-free orientation workspace for the Stewart platform. The singularities associated with the gain in the degree of freedom of a parallel manipulator mechanism are not a limitation in its usage when the regular joints are replaced by suitably designed flexible joints.

An ample amount of work related to kinematic and dynamic analysis has been done by many authors and presented in Secs. 3 and 4. From the kinematics and dynamics analysis, it is examined that at very low speed of the Stewart platform the effect of the elastic moment is comparatively high. Many authors developed a vibration model for the Stewart platform and derived the relevant explicit equations. The stability of the proposed control law was also analyzed. The theoretical and finite element method results demonstrate the validation of the prototype model or parallel manipulator. The Matlab Sim-Mechanics approach is quite complex and seems to be suitable for a dynamics modeling and a control designing of Stewart platform.

The contents of this paper can be used for the advance research and space application of the Stewart platform. The following major problems are observed for future scope.

(1) To reduce parasitic stiffness of the joints, a hyperbolic flexible joint between the legs and plates should be designed by using hyper elastic material.

(2) For the general class of parallel manipulators using a flexible joint, a well-conditioned and detailed description of the workspace should be developed with singularity-free paths.

(3) Modeling and analysis are needed using hyperbolic flexible joint to minimize the effect of elastic moment at very low speed of the Stewart platform. The use of a flexible joint, which should be made by superelastic material, reduces the parasitic stiffness and keeps the open loop zeros close to the origin while keeping the axial stiffness and the overall strength needed during the launch of the spacecraft.

(4) Harmonic and transient dynamic analysis should be done to determine the steady state response and arbitrary time-varying load response, respectively, of the Stewart platform and spectrum analysis through extensive simulation and analytically or numerical tools.

(5) Dynamics of the legs should be enhanced by minimizing and rearranging the inertia along the leg.

(6) Vibration isolation, control and simulation in Sim-Mechanics environment of the Stewart platform using hyperbolic flexible joints is needed.

(7) The Stewart platform should be developed based on quasi zero isolators.

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