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Some Studies on Parallel Manipulator – A Review

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Abstract: **This paper presents a review of the literature on the six degree of freedom parallel manipulator commonly known as the Stewart Platform. The review, in the form of a literature survey, starts with reference to the introduction and uses of the parallel manipulator. This followed by a discussion of the kinematics, dynamics, flexible joints, finite element method, SimMechanics of the Stewart Platform. Because of their significance with respect to the current study, special attention is paid to the discussion of existing methods for the determination of manipulator workspaces.**

1. INTRODUCTION

As the science and technology of robotics originated with the spirit of developing mechanical systems which would carry out tasks normally ascribed to human beings, it is quite natural that the main thrust was towards using open-loop serial chains as robot manipulators. Such robot manipulators have the advantage of sweeping workspaces and dexterous maneuverability like the human arm, but their load carrying capacity is rather poor due to the cantilever structure. Consequently, from strength considerations, the links become bulky on the one hand, while on the other they tend to bend under heavy load and vibrate at high speed. Though possessing a large workspace, their precision positioning capability is poor. In a nutshell, open-chain serial manipulators possess both the advantages and the disadvantages of the human arm.

Hence, for applications where high load carrying capacity, good dynamic performance and precise positioning are of paramount, it is desirable to have an alternative to conventional serial manipulators.

For possible solutions, one can look to the biological world and observe that the bodies of load carrying animals are more stably supported on multiple in-parallel legs compared to the biped human, human beings also use both the arms in cooperation to handle heavy loads and for precise work like writing, three fingers actuated in parallel are used. In general, it can be expected that robot manipulators having the end-effector connected to the ground via several chains having actuations in parallel will have greater rigidity and superior and the last two decades have witnessed considerable research interest in this direction.

Although Stewart proposed his mechanism for use as a flight simulator, he also suggested other possible applications for the mechanism, including:

1. A platform held stationary in space mounted on a vessel as a ship subjected to the random movements of the sea.
2. A new form of machine tool.
3. An automatic assembly or transfer machine.

2. KINEMATIC ANALYSIS

Stewart Platform kinematics deals with the study of the Stewart Platform motion as constrained by the geometry of the links. The kinematic analysis is done without considering to the forces or torques that cause or result from the motion. Typically, the study of manipulator kinematics is divided into two parts, inverse kinematics and forward (or direct) kinematics. The inverse kinematics problem involves mapping a known position of the output link of the manipulator to a set of input joint variables that will achieve that position. The forward kinematic problem involves the mapping from a known set of input joint variables to a position of the moving platform that results from those given inputs. Unlike the inverse kinematic problem, the forward kinematic problem is much more difficult for the general class of Stewart Platforms. This is because there are many solutions, the number of solutions corresponding to the number of configurations the mechanism can be assembled into, for a given set of link lengths. Since the late 1980's forward kinematic analysis of the Stewart Platform is considered as the most challenging problem. The problem is to determine the assembly configurations when the base points, platform geometry and the link lengths are given. In other words, it is the problem of solving the following kinematic relation

$$\|T + R*p_i-b_i\|^2 = L_i^2 \text{ for, i ranging from 1 to 6}$$

where b_i denotes the ith base platform point, p_i is the ith moving platform point, R the rotation, T the translation matrices for the given link lengths, L_i. Analytical solution for the general case is quite difficult due to highly nonlinear equations with multiple solutions. Therefore, researchers constructed Stewart Platform with special geometries [1]. The analytical solutions obtained by merging of base connection points can lead to more simplified kinematic equations for a forward kinematic analysis. The platforms with special geometries are characterized by their m base platform points and n moving platform points. A 6-6 Stewart Platform is the general case, and 3-3 one is the simplified case. Although 3-3 is the simplest case, the approach which is based on solution of the input-output relations for the spherical joints makes the problem more difficult. Nauna et al. [2] uses the idea that if the joint centres of the adjacent limbs are coincident, the hexagonal structure of the platform will be reduced to a triangle and the platform can be put into a form which is isomorphic with those of triple arm mechanism. Innocenti and Parenti-Castelli [3] reduces a part of the entire structure to an equivalent serial mechanism, and the constraints on its joint angles are imposed by the constraints of the remaining part to obtain the equations for the forward kinematics.

Apart from the above-mentioned approaches, a decomposition scheme was proposed by Nair and Maddocks [4] for the forward kinematics problem in which one being a linear design-dependent part where particular geometries can be exploited and the other involving solution of certain nonlinear design-independent equations. Faugere and Lazard [5] classified all the m - n cases according to the combination of connection points, and found out the existence of 35 different classes with corresponding maximum numbers of possible solutions. A closed form solution of the problem is very difficult due to highly nonlinear equations with multiple solutions. It is more advantageous to use computational techniques for practical cases which need only a solution and if a good initial estimate is available from a neighbour position [6]. Numerical approaches use some algebraic and geometric elimination methods to simplify the kinematic equations to obtain all the real solutions [7]. In order to find all the real roots, Innocenti and Parenti-Castelli [8] used the analytical result of the 5 - 5 case by a uni-dimensional searches over the value of removed fictitious leg length to obtain a numerical solution for the 6 - 6 case. Dasgupta and Mruthyunjaya [9] suggested an efficient 3 dimensional searches and verification algorithm based on pure geometric constraints.

Although numerical methods have computational advantages and can be utilized to find the real solutions, they are not useful to predict total number of the roots in the complex domain. Raghavan [10] was able to find 40 solutions in the complex domain; which suggest the upper bound for the number of configurations for the Stewart Platform to be 40. In order to reduce the total degree of freedom of the final polynomial system to 64, linearization of forward kinematic equation, which includes quadratic terms (that are obtained by using a direction cosine matrix instead of Euler angles), is utilized [11]. However the results which were published by Raghavan [10] contradict the validity of this approach. Wen and Liang [12] followed a different approach by assuming the base plate as planar, the fundamental equations are reduced to establish the upper bound of 40 solutions, but their analysis does not apply to general (non-planar) base and platform.

Analytical approaches based on analytical methods have some drawbacks. They cannot be applied to obtain all real and complex solutions, and to determine the number of solutions available for 6 - 6 Stewart Platform. Despite the fact that the closed form relation based on geometrical considerations can provide some solutions, no analytical solution is constructed for the general case. A reliable and fast solution to forward kinematic problem should be suitable to reliable and real time solutions. The fast approach should satisfy the question of selecting the actual one among all the obtained results. Baron and Angeles [13] suggested a redundant sensing method to make the result procedure fast and robust to measurement noise. This produces estimates with about the same accuracy as a nonlinear procedure. In this approach, the projection of the motion of hip attachment points onto their subspaces enables conversion of the underlying direct kinematics to a linear algebraic system to resolve the ambiguity.

Bonev and Ryu [14] presented a new method for solving the direct kinematics problem of a general Stewart Platform by using three linear extra sensors for solving the DKP of general SPs (non-planar base and planar platform). The sensors are disposed at a most general way, connecting the non-planar base and the planar mobile platform at distinct points an arrangement which is the easiest to realize. A proper location of the sensors' base attachment points can eliminate any sensor interference with the legs. The extra sensory data enables to reduce the problem to the solution of an over determined system of 6 quadratic equations in 3 unknowns.

Huang et al. [15] studied the forward kinematics of a symmetrical 6-6 Stewart platform, in which both the base and the mobile platform are hexagons with joint centers satisfy some conditions. Based on the study they presented a concise algebraic elimination algorithm to solve the closed-form forward kinematics of the Stewart platform which results in reducing the forward kinematics problem to solve a univariate polynomial equation of degree at most 14. The algorithm is comparatively concise and requires fairly less computation time. Gallardo-Alvarado et al. [16] worked on the kinematics of three-legged parallel manipulator with asymmetrical limbs and investigated the decoupled motions over its moving platform by means of screw theory. The forward displacement analysis is carried out using a novel procedure which allows computation of all the feasible locations that the moving platform can reach given a set of generalized coordinates, also the velocity and acceleration analyses are carried using the screw theory.

3. DYNAMIC ANALYSIS

Dynamic analysis and derivation of dynamic formulation are quite complicated due to the closed-loop structure and kinematics constraints of the Stewart Platform manipulators. However, development and analysis of dynamic models are the important trends in various study fields on Stewart Platform. The importance of the dynamic model can be illustrated in several ways. A dynamic model can be used for computer simulation of a robotic system without the need of a real system to test various specified tasks. It is possible to achieve higher performance by incorporating more structural system information for the development of control strategies. Revealing all the joint reaction forces and moments through the dynamic analysis is also necessary for sizing the links, bearings and actuators [17].

Several different methods have been studied to model the dynamics of the Stewart Platform as a multi-body system, such as Newton-Euler method, the Lagrange formulation, the principle of virtual work, and Kane's method. Dasgupta and Mruthyunjaya [18] derived the complete dynamic equations for the Stewart Platform through the pure Newton-Euler approach. Lebret el al. [19] developed Lagrange equations of motion, and gave some insight into the structure and properties of these equations. Lee and Geng [20] studied the dynamics of a flexible Stewart Platform manipulator and using Lagrange formulation assuming platform to be rigid. Gallardo et al. [21] established the dynamic formulation by a combination of screw theory with the principle and virtual work.

Principle of virtual work formulation is based on the computation of the energy of the whole system with the adoption of a generalized coordinate framework [21]. To simplify this approach, theory of screws, which is a way to express velocities and forces in three dimensional space, combining both rotational and translational parts, was used. Wang and Gosselin [22] and Tsai [17] also used the principle of virtual work to perform the dynamic analysis of the spatial six DOF parallel manipulators with prismatic actuators.

Koekebekker et al. [23] provided the dynamic formulation of the Stewart Platform through Kane's method. As Liu et al. [24] mentioned, Kane's equation analyses the dynamics of a multibody system with N bodies using the relation

$$\boldsymbol{F} + \boldsymbol{F}^{*} = \boldsymbol{0}$$

where F demotes the generalized active force, and F^{*} is projection of active and inertial forces on the generalized velocities. The calculation of accelerations, partial velocities of mass centres, and partial angular velocities of all links are required to apply the method.

The application of Newton–Euler approach is straightforward. However, this approach needs computation of all constraint forces and moments at all joints. In addition, sometimes these computations are not necessary for the simulation and control of the manipulator. Lagrange formulation provides an orderly structure which can be expressed in closed form. However, derivation becomes quite tedious due to large amount of symbolic computations needed. Principle of virtual work is an efficient approach for dynamic analysis of a Stewart Platform manipulator. However, dynamic structure formulation is not explicit [25]. In general, deriving the equations of motion for a parallel manipulator results in a set of differential algebraic equations as mentioned in [24]. In simulation and control, this formulation can cause difficulties. Choosing the appropriate modeling method makes the dependent variables be explicit functions of the integrable differential equations to avoid the difficulties mentioned earlier. Accounting for the parallel configuration of the Stewart Platform, and combining the advantages of both Newton–Euler method and Lagrange formulation, the explicit compact closed-form dynamic equations of Stewart Platform can be derived in the task space [25].

Hou et al. [26] proposes a novel hyperstatic six-component force/torque sensor structure based on the Stewart platform, and presents the parameter optimization of the sensor structure with genetic algorithms. The dynamic analysis of the sensor's force mapping matrix is built by using the screw theory. Dynamic modeling of parallel manipulators presents an inherent complexity, mainly due to system closed-loop structure and kinematic constraints. Antonio M. Lopes [27] explored an approach based on the manipulator generalized momentum which is used to compute the kinetic component of the generalized force acting on each manipulator rigid body, and applied it to the dynamic modeling of a Stewart platform to obtain the analytic expressions for the rigid body's inertia, Coriolis and centripetal terms matrices. Gravitational part of the generalized force is calculated using the manipulator potential energy and finally evaluated the computational load of the dynamic model measuring the number of arithmetic operations involved in the computation of the inertia and Coriolis and centripetal terms matrices. This model obtained using the proposed approach presents a low computational load which will be an important advantage in obtaining a desirable fast simulation and real-time control.

4. FLEXIBLE JOINTS

Mechanically assembled joints such as universal or ball joints reduce the accuracy due to manufacturing errors. The monolithic characteristics of the flexible joints help avoid manufacturing errors. This characteristic brings easy manufacturing process and implies a very compact design that can be used in the micro-assembly workstation presented in [28-29]. From operation point of view, flexible joints clearly reduce frictional losses. Therefore, they do not require lubrication, and inaccuracies due to lubrication would be eliminated.

Flexible joints must be designed extremely carefully due to their very sensitive force-displacement relationship. Because of this, high dimensional accuracy during the fabrication and calibration after fabrication process are needed. Flexure may also be sensitive to the working temperature [30].

Wei et al. [31] stated that the flexure hinges have a lot of advantages compared to the others such as ball joints or universal ones. Because of the fact that they are manufactured monolithically, they are very compact in structurally. Besides, they have a lot of advantages like having no backlash, no friction, no lubrication and no error due to lubrication. However, they have a limited range of motion as they have to flex without sustaining any plastic deformation at the joints.

Flexure hinges with single-axis can be divided into two main categories: leaf and notch type hinges [32]. Due to relative low rotation precision and stress concentration, leaf type hinge is seldom adopted. In 1965, Paros and Weisbord [33] introduced the first notch hinge and circular flexure hinge. The common feature of these two types is ease of manufacture. Therefore, researchers turned their attention to other configurations that could provide precision rotation in an even larger angular range.

Smith et al. [34] presented a flexure hinge of elliptic cross-section, the geometry of which is determined by ratio of the major and minor axes. Likewise, Lobontiu et al. [35] introduced an analytical model for corner-filleted flexure hinges that are incorporated into planar amplification mechanisms. Later, they also introduced the parabolic and hyperbolic hinges configurations [36]. Closed-form equations are formulated to characterize their compliance both for the active rotation and all other in and out-of-plane motions.

According to Lobontiu and Garcia [37], the flexure needs to be compliant in the bending direction and rigid for all other axes and deformations. Constructively, a flexure hinge may have several sensitive axes. These sensitive axes define the rotations and motions.

Apart from these, Paros and Weisbord [33] presented two-axis circular flexure hinges which are designed in serial configuration. The serial design preserves the convenience of having each flexure hinge designed according to the standard-axis geometry. However, it also requires the extra-length that is necessary to locate the two flexures in a serial manner.

Two-axis flexure hinges with symmetric and axially-collocated notches are presented in [37]. The compliance based formulation is solved with an emphasis on the capacity of rotation. Stress, precision of rotation and efficiency in terms of strain energy are calculated. Later, all the calculations are performed again for the two axis flexure hinges with parabolic notches. The parabolic profiled two-axis flexure is also compared with its constant rectangular cross-section counterpart in terms of several performance criteria. Based on the analytical model the results show that parabolic profiled two-axis flexures give better performance than their rectangular cross-section counterparts.

5. FINITE ELEMENT METHOD ANALYSIS

The finite element method is employed for the analysis of the static and dynamic characteristics of the Stewart Platform. The finite element model of the Stewart Platform is built and the stress distribution of the elastic legs of the Stewart Platform is achieved. The natural frequencies and the natural vibration mode shapes of the Stewart Platform are obtained, which provide a reference basis for the sensor's dynamic analysis. The relative systematic analysis of a novel pre-stressed six-component Stewart Platform based force/torque sensor. The analysis of the characteristic of the structure indicates it is suitable to be used as six-component force sensor [38].

Dohner et al. [39] proposed an FEM model for chatter analysis of the spindle of a specific brand of milling machine mounted on a hexapod platform. In an attempt to actively control the chatter of the spindle, they added flexible actuators on the periphery of the spindle in their model. They did not present the explicit relations governing the vibration behavior of the hexapod. In addition, their findings cannot be extended to other hexapods such as those being used as the table of the machine similar to that developed by the authors.

Finite element method is adopted by many authors for analysis of the force/torque sensor. Nicholas Krouglicof et al. [40] optimised the sensor geometry and determined the force transformation matrix through finite element analysis. Tao Liu and Yoshio Inoue et al. [41] optimized the mechanism dimension of a six-component parallel force sensor for human dynamics analysis by finite element method. Jie Zhao et al. [42] analysed dynamic and static characteristic of a six-dimension stiff force/torque sensor elastomer for robots by finite element analysis.

6. ANALYSIS USING BY SIMMECHANICS

Matlab SimMechanics for the designing of Stewart platform model of dynamics and its control. Matlab SimMechanics was used as a tool for the multi body dynamics modeling of the mechanism. The advantage of working within this computational environment is the possibility of the model linearization at a specified operating point and receiving linear state space model. Another benefit is the option of designing of the machine control and also the control simulations may be performed in the same environment [43].

Fabian Andres Lara Molina et al. [44] presented the simulation environment proposal, analysis and control of a Stewart Platform manipulator and presented the kinematics, dynamics and control study of the Stewart Platform as a reconfigurable architecture. The simulator is a useful tool for designing and studying the dynamics response when changing different parameters of the platform. Chifu yang et al. [45] derived the integrated dynamic equations for the spatial parallel robots using Kane approach and according to the dynamic equations, the computer model of the spatial parallel robots is built with the software of Simulink and the computer model of the spatial parallel robots is established with SimMechanics in terms of the physical relationship of the spatial parallel robots.

7. CONCLUSION

In this paper, a state of art review of the literature on the Stewart Platform has been presented with critical examination of the solved and unsolved problems in various aspects of kinematics, dynamics, flexible joints, finite element methods and simmechanics. Though the focus of the discussion has been the Stewart Platform manipulator alone, many of the concepts and problems discussed have relevance to the general field of parallel manipulators, because the Stewart Platform acts as the representative of the class of parallel manipulator embodying all the distinctive features of the entire class in full generality.

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