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The Stewart platform manipulator: a review

Bhaskar Dasgupta [a,*], T.S. Mruthyunjaya [b]

[a] *Department of Mechanical Engineering, Indian Institute of Technology, Kanpur 208 016, India*
[b] *Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560 012, India*

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Abstract

This paper presents a state-of-the-art review of the literature on the six-degree-of-freedom parallel manipulator commonly known as the Stewart platform. The existing studies in the field are critically examined to ascertain the trends of research in the field and to identify unsolved problems. The Stewart platform being representative of the class of parallel manipulators, the concepts applicable for it have direct relevance to the entire class. The distinctions of this class from the conventional serial robot manipulators are also highlighted and the novel perspectives that are necessary for the analysis and design of the Stewart platform in particular and parallel manipulators in general are recommended. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Stewart platform; Parallel manipulators; Series-parallel duality

1. Introduction

This paper presents a state-of-the-art review of the literature on the Stewart platform, which is the most celebrated parallel manipulator. Though the manipulating structure, to which the Stewart platform owes its name, was proposed in 1965, it evolved into a popular research topic of robotics only in the 1980s. In the 1990s, there has been a steady increase in research interest in the field of parallel manipulators in general and the Stewart platform in particular, as can be ascertained from the publications in this field in technical journals and conference proceedings related to robotics. In 1995 alone, more than fifty papers have appeared in this field. Apart from that, developments in this field have motivated research in a few associated topics also.

* Corresponding author. Tel.: +91-512-597-095; fax: +91-512-597-995.
E-mail address: dasgupta@iitk.ac.in (B. Dasgupta)

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An extensive review of the literature is presented in this paper to identify the trends of research on the Stewart platform and to identify open problems in the field.

In Section 2, motivations for conceiving the idea of parallel manipulators are discussed. In Section 3, the characteristic features of parallel manipulators and their contrasts to conventional serial manipulators are brought out in the context of the series–parallel duality and the place of the Stewart platform in the class of parallel manipulators is established. In Sections 4 and 5, the phase from genesis upto maturity of the field of the Stewart platform and that of parallel manipulators in general is described. The literature on the kinematics, dynamics, singularities and workspace analysis of the Stewart platform is reviewed in Sections 6–8,10,11 while works related to the design and development for various applications are discussed in Sections 9 and 12. As the general fields of parallel and closed-loop manipulators are of relevance to the Stewart platform, a concise review of those fields also is included in Sections 13 and 14. In Section 15, open problems in the field of the Stewart platform are enumerated with projections of future trends and possibilities. Finally, in Section 16, the review is summarized and a few general suggestions pertaining to the approaches that are preferable for the study of parallel manipulators in general and the Stewart platform in particular are made.

2. Parallel manipulators

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 manoeuverability 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 importance, it is desirable to have an alternative to conventional serial manipulators. For possible solutions, one can look to the biological world and observe that (1) the bodies of load-carrying animals are more stably supported on multiple in-parallel legs compared to the biped human, (2) human beings also use both the arms in cooperation to handle heavy loads and (3) 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 positioning capability. This makes the parallel manipulators attractive for certain applications and the last two decades have witnessed considerable research interest in this direction.

Apart from classifying robot manipulators into serial and parallel types, classification into open-loop and closed-loop types is also in practice. However, it should be borne in mind that the two classifications are not identical; though open-loop manipulators are always serial and parallel ones are always with closed loop(s), it is possible to have closed-loop manipulators which are serial in nature. A robot manipulator having single-degree-of-freedom closed-loop linkages in series is essentially a serial manipulator. Examples are the two-degree-of-freedom seven-bar fractionated freedom chain and variable geometry truss manipulators. Again, there can be robot manipulators which have both open and closed kinematic loops and/or complicated series–parallel combinations of actuators. Such manipulators are called hybrid manipulators and they can be hybrid in the sense of both the classifications.

3. Series–parallel duality

Two celebrated theorems of mechanics, by Chasles and Poinsot respectively, state that a general displacement of a rigid body can be reduced to a twist about a screw and a general force system can be reduced to a wrench on a screw. Upon these two theorems was developed the monumental theory of screws of Ball [1] which provides an elegant framework for representation and analysis of mechanical systems. One of the salient features of the theory of screws is the enunciation of the duality and reciprocity between instantaneous kinematics and statics, angular and linear velocities being dual to force and moment respectively. Waldron and Hunt [2] showed that this leads to a duality between serial and fully parallel manipulators. In particular, Jacobian symmetry[1] was demonstrated between the two classes which manifests itself in the similarity of instantaneous kinematics of serial manipulators and statics of parallel manipulators.

This fact has been utilized by Collins and Long [3] in the context of twist/wrench decomposition in serial and parallel manipulators. As summarized below, the theory of series–parallel duality highlights the qualitative distinctions between serial and parallel manipulators. The direct position kinematics of serial manipulators is straightforward while the inverse position kinematics is quite complicated requiring the solution of a system of nonlinear equations. In contrast, the inverse position kinematics of parallel manipulators is relatively straightforward and the direct position kinematics is challenging. Similarly, in contrast to the simple direct instantaneous kinematics and complicated inverse instantaneous kinematics (requiring the inversion of the Jacobian) of serial manipulators, parallel manipulators exhibit more or less straightforward inverse instantaneous kinematics and complicated direct instantaneous kinematics. As is expected from the theory of duality, the situation reverses in statics. The direct force transformation of parallel manipulators is found to be simpler and the inverse force transformation is more complicated while the opposite is true in the case of serial manipulators. As a consequence of the above facts, the manifestation of the duality between the two classes of manipulators continues in the context of singularity, which is associated with the degeneracy of the input–output relationships. The singularities of serial manipulators are associated with a loss in degrees of freedom (dof) and partial locking while the preponderant

[1] The term is used in [2] to mean the symmetry of the input–output relationships, and has no implication regarding the symmetry of the Jacobian matrix, which is, in general, not symmetric.

type of singularities of parallel manipulators is associated with a gain in dof and uncontrollability.

In the general context of parallel manipulators, the above distinctions are only qualitative because the in-parallel chains of a parallel manipulator are themselves serial bringing in aspects of serial chains, though in a localized manner. Naturally, the duality with respect to serial manipulators is best exhibited by those parallel manipulators in which such aspects are minimal owing to the simple nature of the serial chains connected in parallel. Among such manipulators, the one having all the six-degrees-of-freedom (6-dof) in space is the generalized Stewart platform in which the contrast with respect to serial manipulators is manifest in the most prominent manner. This has given the Stewart platform a central status in the field of parallel manipulators making it the most celebrated manipulator in the entire class.

4. The Stewart platform

The manipulating structure now known as the Stewart platform has its origin in the design by Stewart [4] of a 6-dof mechanism to simulate flight conditions by generating general motion in space. Stewart's mechanism consisted of a triangular platform supported by ball joints over three legs of adjustable lengths and angular altitudes connected to the ground through two-axis joints. Out of the many communications in response to Stewart's paper, the one by Gough suggested the use of six linear actuators all in parallel, similar to the tyre test machine designed by Gough and Whitehall [5], and thereby making the platform manipulator a fully parallel–actuated mechanism.

Later, Hunt [6] suggested the use of parallel–actuated mechanisms like the flight simulator of Stewart as robot manipulators and mentioned that such parallel manipulators deserve detailed

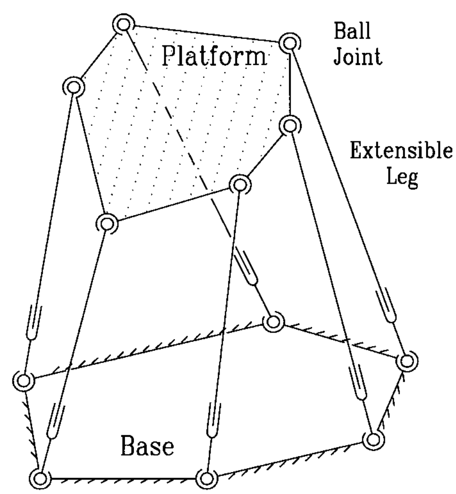

Fig. 1. The 6-SPS Stewart platform.

study in the context of robotic applications in view of their specific advantages (e.g. better stiffness and precise positioning capability) over conventional serial robots. This can be marked as the starting point of research on parallel manipulators in general and the Stewart platform in particular in robotic applications. In the course of time, the popular architecture underwent generalizing modifications. The generalized Stewart platform, as it is understood today, consists of two rigid bodies (referred to as the base and the platform) connected through six extensible legs, each with spherical joints at both ends or with spherical joint at one end and with universal joint at the other.

Though the above description somewhat departs from Stewart's original design and the mechanism of Gough and Whitehall was older and closer to this description, this manipulating structure has gained popularity among researchers as generalized Stewart platform or simply as 'the Stewart platform'. In recent years, some authors have referred to the mechanism as 'Stewart–Gough Platform'. The present authors, while crediting Gough for first realizing the manipulating structure, observe that the manipulator attracted research attention through the classic paper of Stewart and, as such, the tradition of calling it the generalized Stewart platform was established. Accepting the traditional nomenclature and for the sake of brevity, it will be referred to as the Stewart platform in this paper. In particular, the kinematic structure with spherical joints at both ends of each leg (see Fig. 1), will be referred to as 6-SPS (spherical–prismatic–spherical) Stewart platform. Similarly, the structure with universal joint at the base and spherical joint at the top (platform-end) of each leg (see Fig. 2) will be referred to as 6-UPS (universal–prismatic–spherical) Stewart platform. When neither of the qualifiers is used, it will be meant that the statement applies equally well to both the structures. It can be noticed that both the manipulating structures are actuated at the six prismatic joints of the legs and are identical to each other regarding all input–output relationships except that the 6-SPS structure possesses six passive dof corresponding to the rotation of each leg about its axis.

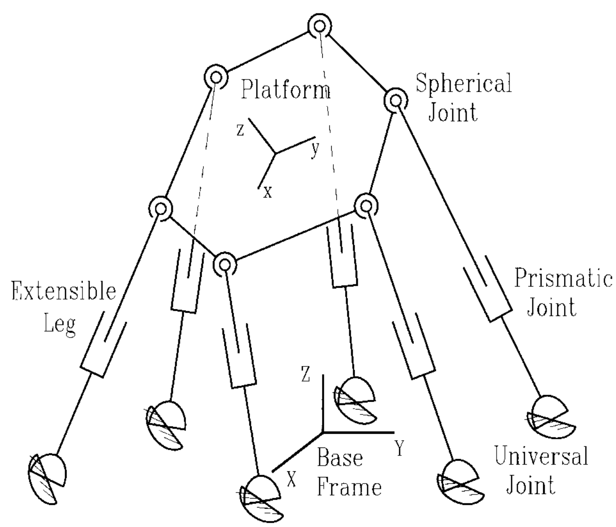

Fig. 2. The 6-UPS Stewart platform.

As stated in the previous section, the Stewart platform is found to exhibit the duality against serial manipulators in the most prominent manner. Due to this reason and also due to the fact that the studies of parallel manipulators started with the conception of this manipulating structure, the Stewart platform has found a central status in the literature on parallel manipulators.

5. Pioneering work

Among the early works on the Stewart platform, some (e.g., Refs. [7,8]) are in the context of flight simulators, the application for which it was originally proposed. The first design of a Stewart platform as a manipulator was by McCallion and Truong [9], who built such a manipulator for mechanised work-station and performed some theoretical and numerical study including its mobility analysis and iterative solution of direct kinematics. Other early designs are by Powell [10], Potton [11] and Inoue et al. [12].

Significant contributions, which carried the realm of parallel manipulators from its infancy into the status of a popular research topic, were made by the thought-provoking works of Earl and Rooney [13] and Hunt [14]. Earl and Rooney [13] analysed the kinematic structures for robotic applications and their interconnections including both serial and parallel mechanisms and presented methods for synthesis of new kinematic structures. Hunt [14] studied the structural kinematics of parallel manipulators on the basis of screw theory and enumerated promising kinematic structures. He also analysed the singularities in geometrical terms classifying them into 'stationary configurations' and 'uncertainty configurations', and discussed the assembly modes of parallel manipulators.

Fichter and McDowell [15] applied the conventional method of serial manipulators to the solution of inverse position kinematics (including passive joint variables) of individual limbs of parallel manipulators and implemented the method on the Stewart platform. Mohamed et al. [16] and Mohamed and Duffy [17] studied the instantaneous kinematics of parallel manipulators on the basis of the screw theory and presented the inverse and forward solutions. Starting from the number synthesis of n-SS, n-SPS and n-SCS platforms, Yang and Lee [18] performed a kinematic feasibility study of the Stewart platform manipulator and made the first attempt towards its workspace analysis including the physical restrictions on the spherical joints. Considering a special architecture of the Stewart platform, they developed an algorithm for finding the section of the reachable workspace on a particular plane and provided a numerical evidence to the fact that the workspace and manoeuverability of parallel manipulators (and the Stewart platform in particular) is rather poor.

During this period (till mid-1980s), most of the designs (and often analyses too) assumed two particular arrangements of legs: one having both the base and platform as triangles with legs meeting in pairs at both ends (the octahedral structure) and the other having a triangular platform with pairwise meeting of legs but with six distinct base points in a plane, which were later known as 3-3 and 6-3 Stewart platforms respectively. Soon it was realized that coalescence of spherical joints severely restricts the mobility of the manipulator; however, the 6-3 arrangement still remained popular for some more time. Another special architecture that became popular is the one having the semiregular hexagonal arrangement[2] of connection-points at both the base and the platform. This was perhaps the second choice from the viewpoint of symmetry because the most symmetrical structure, i.e., one having both the base and the platform as regular hexagons, would be uncontrollable. The recent trend is towards considering completely general disposition of connection-points.

The initial phase of development of the Stewart platform as a research field was complete through the comprehensive contributions of Fichter [19] and Merlet [20]. Fichter [19] derived the kinematic equations of the general Stewart platform, formulated the dynamic equations in a rudimentary form (by assuming massless legs and frictionless joints) and stated the condition of singularity along with the enumeration of a few singular configurations. In addition, he made some recommendations for practical construction of a Stewart platform manipulator and described a construction developed at Oregon State University which used, incidentally, an equilateral triangular platform and a semiregular hexagonal base. Merlet [20] considered the design aspects of the Stewart platform and dealt with the special architectures discussed above. He presented some description of the prototype of the Stewart platform built at INRIA, Sophia-Antipolis, France and addressed the solution of the kinematic equations, development of the Jacobian, derivation of dynamic equations with slightly more general conditions than those used by Fichter [19] and the determination of workspace sections. He also mentioned the potential of the Stewart platform as a force sensor and passive compliance device. These two works [19,20] put together embody all the basic concepts of kinematics and dynamics of the Stewart platform manipulator.

6. Direct position kinematics

During the late 1980s and early 1990s, the direct position kinematics problem enjoyed the central status in the research on the Stewart platform. The problem is to determine the position and orientation of the platform, given the six leg lengths. Geometrically, it is equivalent to the problem of placing a rigid body such that six of its given points lie on six given spheres. Denoting the i-th base point by $\mathbf{b}_i$ and the i-th platform point (in local reference frame) by $\mathbf{p}_i$, it is required to solve the kinematic equations

$$\| \mathbf{t} + \mathrm{R}\mathbf{p}_i - \mathbf{b}_i \|^2 = L_i^2, \quad \forall\, i = 1, \ldots, 6 \tag{1}$$

for the translation vector $\mathbf{t}$ and the orthogonal rotation matrix R where the leg lengths L_i $(i = 1, \ldots, 6)$ are given. As the complete solution of the problem was quite challenging, numerous approaches were made by various researchers for solutions of special cases as well as for the solution in full generality. The approaches to solve this problem fall in the following categories.

[2] Six points on a circle with each pair of alternate points subtending an angle of 120° at the centre.

6.1. Closed-form solutions of special cases

It was observed that coalescence of some of the connection-points at the platform or the base or both in groups of two or three simplifies the closed-form solution of the problem and also reduces the maximum number of possible solutions. Several special cases arising from such coalescence were solved in closed form and those special structures were often referred to by the number of distinct connection-points at the base and those at the platform. A special structure with m and n distinct connection-points at the two bodies was referred to as m–n Stewart platform, the simplest being the 3-3 case (the octahedral structure) and general structure being the 6-6 Stewart platform.

One of the approaches [21–23] is based on the use of the input–output equation of spherical four-bar mechanisms to solve the 3-3 case and extending it to more difficult (6-3, 4-4, 4-5) cases. In another approach [24–30], the platform is first removed, then the loci of the coalesced connection-points of the platform are determined and finally the constraints due to the platform are imposed to derive the equations for further simplification. In a third approach [31–35], which is slightly different from the second one, a part of the entire structure is reduced to an equivalent serial mechanism and constraints on its joint angles are imposed by the constraints of the remaining part to obtain the equations. Utilizing these specialized approaches, many different structures ranging from the simplest (3-3) to a few complicated ones (5-5 and 6-4) were solved in closed form leading to at most 40 solutions for the most complicated cases. Apart from coalescence of connection-points, other geometrical conditions like collinearity of some connection-points or similarity of the base and platform polygons[3] also facilitate the solution of the problem in closed form, as demonstrated by various authors [36–39].

Nair and Maddocks [40] suggested a decomposition scheme for the direct position kinematics into two parts, one being a linear design-dependent part where particular geometries can be exploited and the other involving solution of certain nonlinear design-independent equations. Faugère and Lazard [41] made a detailed classification of all the m–n cases of Stewart platforms with various combinations of connections and enumerated 35 distinct classes with corresponding maximum numbers of possible solutions, which are based partly on previously established analytical results and partly on conclusions drawn from computational evidence.

6.2. Numerical schemes

The numerical approaches [9,42–44] that directly resort to nonlinear-equation-solving algorithms have computational advantages in most practical situations where only one real solution is required and a good starting point is available in the form of a neighbouring configuration, but they are not suitable for a theoretical investigation aimed at determining all the possible solutions. For finding all real solutions, approaches [45–47] are employed to reduce the problem by geometrical or algebraic methods to that of solving a system of three

[3] In all these cases, there is an underlying assumption of planar base and platform that itself is a special case.

equations the solutions of which can be trapped by a three-dimensional (3D) search. A unidimensional search algorithm for finding all real solutions (closures) was also developed by Innocenti and Parenti-Castelli [48]. This algorithm temporarily replaces one of the legs of a general 6-6 Stewart platform by a fictitious leg of variable length to convert it into a 5-5 Stewart platform, solves the modified structures by the specialized method of Innocenti and Parenti-Castelli [32] and re-imposes the constraint due to the original removed leg. A predictor–corrector algorithm developed by Dasgupta and Mruthyunjaya [49] uses an efficient 3D search strategy for trapping the real solutions purely from geometrical considerations.

All the above numerical approaches are useful for finding real solutions (corresponding to actual assembly configurations or closures) only and cannot be used to predict the total (or maximum) number of solutions. To obtain the latter, it is necessary to determine all the solutions in the complex domain. The most successful numerical solution to this end was provided by Raghavan [50] who formulated the problem in the form of a polynomial system and solved it by the continuation method due to Morgan [51]. Having found 40 solutions in the complex domain, he concluded that the upper bound of the number of solutions for the general case is 40, a fact later verified by analytical works discussed below.

6.3. Analytical approaches

If the orientation of the platform is represented by the orthogonal direction cosine matrix (rather than a representation like Euler angles etc.), the six kinematic equations obtained from Eq. 1 are all quadratic and the quadratic terms appear only in a few groups thus facilitating linearization of some of those equations. A number of analytical approaches [52–55] to the direct position kinematics problem exploited this fact to reduce the total degree of the resulting polynomial system to 64, at least in the case of a planar base. However, numerical solutions of the polynomial system or numerical derivation of a univariate polynomial gave strong indication of the upper bound of the number of solutions being 40. Wen and Liang [56] followed a different approach and analytically solved the problem for the 6-6 Stewart platform with planar base and platform by the reduction of the kinematic equations into a univariate polynomial and established the upper bound of 40 solutions, but their analysis does not apply to general (non-planar) base and platform.

Approaches based on geometry have been most successful in the canonical formulation of the direct kinematics problem and enumeration of the maximum number of assembly configurations. In this context, mention can be made of the work by Hunt and Primrose [57], where geometrical arguments were presented in support of the upper bounds of numbers of configurations of some special structures and the upper bound for the general 6-6 structure was conjectured to be 40, 48, 54 or 64. Two recent geometrical formulations by Wampler [58] and Husty [59] employ Study's concept of representation of rigid body displacement by eight homogeneous coordinates satisfying two quadratic constraints. Both formulate the problem in the form of an intersection problem of eight quadratic manifolds in an eight-dimensional (8D) space and reduce it to a univariate polynomial equation establishing conclusively the upper bound of possible configurations for a completely general structure of the Stewart platform to be 40. The question of maximum number of real solutions or actual configurations (if there is any such bound below 40) still remains, because till now no example of 40 real solutions has been found. In this context, the correspondence of 5-SS coupler curves and assembly modes of the Stewart platform studied by Sarkissian and Parikian [60] might be a potential starting point.

6.4. Other works on direct position kinematics

Though the above formulations for finding all the closures are of great theoretical significance, for purposes of on-line control it is essential that (1) out of all possible solutions, a particular one (the actual one) is determined unambiguously and (2) the solution is fast enough for real-time implementation. To meet these two ends, redundant sensing has been proposed and analysed [61–64] for resolving ambiguity on one hand and decoupling and linearizing the problem on the other leading to fast computation. The use of a camera for obtaining extra information has also been suggested [65].

Finally, for the sake of completeness, it should be mentioned that a neural network solution was explored by Geng and Haynes [66] for the solution of the direct position kinematics of the Stewart platform manipulator.

7. Statics and rate kinematics

The forward force transformation of the Stewart platform is a straightforward linear mapping as described by Fichter [19] and Merlet [20], and denoted by the matrix $\mathbf{H}$ in the following discussion. The columns of this 6×6 force transformation matrix essentially consist of the Plűcker coordinates of the six legs. Naturally, the inverse force decomposition requires the inversion of the matrix $\mathbf{H}$ giving rise to static singularities discussed in Section 8.

The inverse velocity kinematics, derived by Fichter [19], is essentially a linear transformation given by $\mathbf{H}^{\mathrm{T}}$. The forward velocity kinematics can be obtained by inverting $\mathbf{H}^{\mathrm{T}}$, or equivalently solving the corresponding linear system. The Jacobian in the conventional sense is thus given by $\mathbf{H}^{-T}$ for the Stewart platform. The acceleration kinematics can also be easily derived from this transformation. However, Shi and Fenton [67,68] developed a variation of the formulation of the forward velocity and acceleration kinematics based on the motion of three platform connection-points. However, their method also finally requires the solution of a 6×6 linear system, hence the computational advantage of this method over the previously mentioned one is not apparent and the relevance of this alternative formulation is questionable.

As the velocity kinematics is directly applicable for differential motion (with first order approximation), the matrix $\mathbf{H}^{\mathrm{T}}$ appears in the accuracy analysis by Ropponen and Arai [69] also along with another matrix for unactuated passive joints.

8. Singularities

Unlike serial manipulators, the Stewart platform has no kinematic singularity in the strict sense (assuming that no leg length can be zero) and limitation on motion capabilities is governed by the joint limits alone. However, it does have force singularities at configurations where the force transformation matrix **H** discussed in the previous section is rank-deficient. At such configurations, the manipulator loses some degree(s) of constraint and becomes uncontrollable. An elementary analytical study of this type of singularities of the Stewart platform can be found in Gosselin and Angeles [70] where it is termed as the 'singularity of the second kind'. It can be mentioned in this context that parallel manipulators other than the Stewart platform may have kinematic singularities (singularities of the first kind as mentioned in [70]) as well depending on the complexity of the limbs, but such singularities will be localized in the sense that kinematic singularities have to be associated with individual limbs with no coupling between the limbs.

Some particular geometrical conditions for singularities of the Stewart platform were first enumerated by Hunt [14] and Fichter [19]. Later, Merlet [71,72] made extensive use of Grassman geometry to enumerate geometric singularity conditions in detail. Liu et al. [73] also made a geometric study of the singularities. Ma and Angeles [74] showed that some highly symmetrical architectures of the Stewart platform result in singularities extending over the entire workspace or significant regions of it, characterized by continuous motion capabilities with all actuators locked. They termed such singularities as architecture singularities. Though such singularities pose serious control problems, they can be eliminated at the design stage itself. Zsombor-Murray et al. [75] further investigated the various possibilities of architecture singularities on the basis of line geometry.

The important association of the conditioning of the static transformation with the stiffness of the Stewart platform was studied by Gosselin [76] through stiffness mapping and the near-singular behaviour (or ill-conditioning) leading to loss of stiffness was discussed. Takeda and Funabashi [77,78] studied the singularity and ill-conditioning in terms of a new transmission index and pressure angle, and pointed out the unusability of the ill-conditioned zones in the workspace. However, in this context, compared to the term 'motion transmissibility' used by them, the term 'force transmissibility' seems more appropriate.

A complete description and characterization of the singularities would be to parametrize the entire singularity hypersurface(s) in the task-space (6D in the case of the Stewart platform). Such an analysis would make it possible to provide boundary representations of various regions of workspace of the manipulator separated by the singularity hypersurface(s) and would describe to what extent singularities restrict the manoeuverability in the workspace. Such a description is extremely difficult for the Stewart platform and, to the best of the authors' knowledge, no such work has been reported till now. An associated question of practical significance is that of avoiding singularities in the planning of a path for the execution of a task. Bhattacharya et al. [79] developed a scheme for avoiding singularities of a Stewart platform by restructuring a pre-planned path in the vicinity of a singularity. A more general problem, posed in a global sense, is that of singularity avoidance in path planning between two end-poses. This question has been addressed by Dasgupta and Mruthyunjaya [80], who formulated the singularity-free path planning problem for the Stewart platform and developed a strategy for planning well-conditioned paths in the workspace of the manipulator. However, rigorous criteria for existence (or non-existence) of such a path is still not available.

The effects of singularities and the problem of singularity avoidance, as discussed above in the context of the Stewart platform, are conceptually similar in the case of other parallel manipulators. However, parallel manipulators, in general, may have kinematic singularities as well.

9. Sensor application

The static force transformation and singularities discussed in the previous two sections have direct relevance to the use of the Stewart platform as a force–torque sensor. As the structure has good stiffness and the reconstruction of the wrench applied at the platform from measured leg forces is quite straightforward, a Stewart platform with instrumented elastic legs can be used as a wrist force sensor. The development of the first sensor of this kind was by Gaillet and Reboulet [81] based on the octahedral structure of the Stewart platform. Kerr [82] analysed a similar structure and enumerated a few design criteria for the sensor structure. The concept of a passive Stewart platform with spring-loaded legs was used by Griffis and Duffy [83] for theoretical modelling of a compliant coupling. Nguyen et al. [84] reported the development of a Stewart platform based sensor with LVDTs mounted along the legs for force–torque measurement in the presence of passive compliance.

Theoretical and experimental investigations of the behaviour of the Stewart platform sensors were carried out by various authors [85–87]. Dasgupta et al. [88] presented a design methodology for the Stewart platform sensor structure based on the optimal conditioning of the force transformation matrix. The optimality of the condition number of the force transformation matrix (tending towards structural isotropy) has been considered by Svinin and Uchiyama [89] also while the design of Sorli and Pastorelli [90] possesses marked anisotropy with greater stiffness in the preferred direction. The former is preferable for force control with arbitrary loads while the latter is more suitable for application in assembly tasks.

10. Workspace and dexterity

The initial approaches towards workspace analysis of the Stewart platform by Yang and Lee [18] and by Cwiakala [91] were limited to the determination of some particular sections of the positional workspace with constant orientation for very specialized structures of the manipulator. Merlet [20] presented a simple method generally applicable for finding theoretical (neglecting spherical joint limits) workspace sections with constant orientation. However, that method was systematically developed and implemented by Gosselin [92] and later extended for 3D workspace evaluation by Gosselin et al. [93] through a CAD approach.

Haug and co-workers [94–97] developed a general formulation for the analysis of workspace and dexterity of manipulators in terms of rank-deficiency of the Jacobian of the constraints by incorporating inequality constraints through slack variables and analysed the working capability of the Stewart platform also. They also considered the question of free movement of the manipulator inside the workspace and predicted the barriers of internal singularities from the viewpoint of controllability. However, since their results regarding the Stewart platform are concerned with positional workspace alone (workspace with given orientation and reachable workspace), the discussion of 6D workspace is not complete. It seems that the method can be employed for a complete discussion also, but the analysis, representation and interpretation will surely be very complicated because of the strong coupling of positioning and orienting capabilities of the Stewart platform.

Masory and Wang [98] considered the problem of determining workspace sections including the constraints of joint angle limits and leg interference. The latter, however, was found to be usually inactive in their numerical studies. While most of the authors have studied the workspace with a fixed orientation, Merlet [99] developed an algorithm for computing the orientation workspace at a fixed position of the platform reference point. A fast geometry-based algorithm to generate the orientation workspace and the evidence of crucial role of link interference in limiting the orienting capability are two important contributions of this work. However, this method can take care of only two of the three possible rotations. Apart from finding the workspace, a practical question that arises from application viewpoint is that of the verification of a trajectory for containment within the workspace. This question has been addressed by Merlet [100] for straight line paths with constant orientation and with orientation varying according to linear variations of angles ϕ,θ,ψ representing the orientation, their method being exact in the former case and approximate in the latter.

One of the major difficulties in the workspace and dexterity analysis of the Stewart platform is the strong coupling of the position and orientation mentioned above. As such, a complete description of the workspace boundary is possible only in the 6D task-space which is very difficult to build and still more difficult to use in application and design. The requirement is that of a convenient representation of the workspace from which the answers to the following questions can be readily derived:

1. Given an orientation or a range (in 3D) of orientations, what is the positional workspace?
2. Given a position or a range (in 3D) of positions, what is the orienting capability?
3. Given a trajectory, whether it is completely inside the workspace?

In addition, such an analysis should preferably be done in association with singularities because a workspace segmented by singularity barriers (as discussed in Section 8) will not be fully usable in practice. The entire problem is quite challenging, especially because posing the problem in a well-defined manner itself is quite difficult. However, it is relatively easy to pose (though difficult to solve) the corresponding synthesis problem: ‘‘Determine the kinematic geometry of a Stewart platform manipulator for a singularity-free workspace segment with the given boundary and with orienting capabilities in a given 3D region’’. In the opinion of the authors, this interesting but formidable design problem of the Stewart platform will attract research interest in near future as the trend towards optimality in design gains ground. A highly commendable approach has already been made by Merlet [101] who solved this problem under some simplifying assumptions by decomposing it into two parts, first identifying the feasible domain in the parameter space for workspace requirements and then conducting a numerical search for optimality in that domain. The approach has been applied by Merlet [102] for the synthesis of the manipulator for a required workspace described in terms of a set of geometric objects like points and segments. A generalization of this strategy, if implemented, is expected to provide true optimal workspace synthesis for the Stewart platform.

11. Dynamics and control

Compared to the vast literature on the kinematics of the Stewart platform, studies on its dynamics are relatively few. The earliest discussions can be found in Fichter [19] and Merlet [20], which are applicable if leg inertia and joint friction are negligible. Sugimoto [103] considered the inverse dynamics problem of the Stewart platform as an illustration of dynamic analysis of parallel manipulators through elimination of joint reactions. The detailed derivation of the dynamic terms was, however, omitted in his analysis.

Do and Yang [104] solved the inverse dynamics for the Stewart platform by the Newton–Euler approach assuming the joints as frictionless and legs asymmetrical and thin (i.e. the center of gravity lies on its axis and axial moment of inertia is negligible). Geng et al. [105] and Liu et al. [73,106] developed Lagrangian equations of motion under some simplifying assumptions regarding the geometry and inertia distribution of the manipulator. Ji [107] considered the effect of leg inertia on the dynamics of the Stewart Platform.

For the Stewart platform with a completely general architecture and inertia distribution, Dasgupta and Mruthyunjaya [108] developed a complete formulation of the inverse dynamics problem through the Newton–Euler approach resulting in a computationally efficient algorithm which was shown to be well-suited for parallel computation. Gosselin [109] also used the Newton–Euler formalism for the inverse dynamics and pointed out that parallel computation schemes are easily applicable to the problem due to inherent parallelism in the structure of the manipulator. Following the approach of [108] symbolically, the closed-form dynamic equations for the 6-UPS and the 6-SPS Stewart platforms have been derived by Dasgupta and Mruthyunjaya [110], incorporating the passive dof's also in the latter case. The task-space dynamic formulation through Newton–Euler approach is well-suited for parallel manipulators in general and the methodology of [108–110] can be applied to other parallel manipulators as well.

Control of the Stewart platform manipulator is almost an open field and the works reported are not rigorous. Liu et al. [106] discussed a few practical issues regarding joint-space and task-space control. A task-space control scheme was discussed by Liu et al. [111] for the control of a Stewart platform based milling cell, but the on-line applicability of their scheme is doubtful due to the involvement of computation-intensive tasks like forward kinematics and inverse statics. A preferable alternative is to plan the trajectory in task-space, which is more natural for parallel manipulators and requires only inverse kinematics.

A dynamic (model-based) control strategy was reported by Hatip and Ozgoren [112] for the Stewart platform assumed to be mounted on a ship and used as a motion stabilizer. Wang et al. [113] presented a neural network control scheme and showed its superiority over a kinematic control. Regarding trajectory planning, Harris [114] made an interesting observation that the helical path of the end-effector is computationally simpler than a straight line path and in some circumstances a screw motion of the platform between given end-poses requires less movement at the actuators.

The dynamics and control of a flexible Stewart platform manipulator (the platform assumed to be rigid) was studied by Lee and Geng [115] and Lee [116] through a simplified modelling of inertia and flexibility of the legs.

From the literature, it is apparent that research on dynamics and control of the Stewart platform has not yet been carried out thoroughly. Though complete dynamic formulation of the manipulator has been carried out, results regarding its dynamic behaviour are very few. Derivation of control strategies taking advantage of the in-parallel structure or catering to the special problems arising out of that is another important field which is almost untouched till now.

12. Design and development

Besides the pioneering works on design and development discussed in Section 5, a lot of prototypes have been designed and built based on the Stewart platform. The developments related to the utilization of the mechanism as a force–torque sensor have already been reviewed in Section 9. Other designs of the Stewart platform as robot manipulator and for specific purposes are accounted for in this section. Development of other parallel manipulators resembling the Stewart platform or related to it are briefly discussed in the relevant contexts, i.e. Sections 13 and 14.

Experimental work [117–119] on prototypes of the Stewart platform has been conducted for studying its kinematic and dynamic performance. The questions of parameter estimation, calibration and repeatability were addressed by several authors [120–128]. The fine positioning and orienting capability of the Stewart platform make it well-suited for use as a dexterous wrist and various constructions and utilizations of Stewart platform based wrists for fine manipulation have been reported [129–132]. The capability of the Stewart platform to provide 6-dof motion is attractive for motion simulation for which it was originally proposed. Salcudean et al. [133] constructed a ceiling mounted hydraulically actuated Stewart platform motion simulator. Amirat et al. [134] developed a Stewart platform manipulator and studied it for equestrian gait. The capability of giving arbitrary 6-dof motion naturally gives the Stewart platform a capability of absorbing unwanted motion also. The possible utilization of the mechanism to absorb unwanted motion for stabilizing a platform was first suggested by Meier for conducting operation on a ship (see Meier's communication in response to Stewart [4]). Control aspects of such a Stewart platform for motion stabilization were analysed by Hatip and Ozgoren [112] as mentioned in Section 11. Geng and Haynes [135] studied the Stewart platform with legs of magnetostrictive material as a vibration isolation system.

The feasibility of the platform manipulators with cable legs was investigated by Cwiakala and Langrana [136]. Viscomi et al. [137] described the construction of a cable controlled Stewart platform crane for use in integrated building systems. A simplified version of the Stewart platform (with 3-dof) with tendon actuators was built by Wendlandt and Sastry [138] for endoscopy. The challenge for such constructions lies in that the cables have to be maintained in tension. The high force-to-weight ratio and positional accuracy of the Stewart platform was made use of in the milling cell by Liu et al. [111]. An unconventional application of the Stewart platform is found in Liu et al. [139] where it is used as the carrier of a painting and repairing robot for the interior of inlet ducts. Zhang et al. [140] proposed a design of walking machine based on the Stewart platform to avoid bending loads on the legs. A special architecture of the mechanism was also proposed for pose measurement of robot manipulators (see Geng and Haynes [141]). In the context of developments related to the Stewart platform, the innovative design of concentric spherical joints with wider motion range proposed by Hamlin and Sanderson [142] can be of significant advantage over conventional spherical joints.

Compared to the works on analysis and constructions of prototypes of the Stewart platform, works on dimensional synthesis and systematic design are very few. Hara and Sugimoto [143] developed a synthesis procedure for parallel micromanipulator for which the kinematic pairs are simulated by flexural joints and synthesis essentially amounts to design of the Jacobian, considering the overall motion as small. Use of CAD/CAM in the optimum design of the Stewart platform based micromanipulator was made by Han et al. [144]. Structural synthesis and dimensional synthesis of parallel manipulators with linear drives was reported by Chakarov and Parushev [145] for optimizing stiffness. Taking stiffness and rigidity as design criteria, Bhattacharya et al. [146] developed a procedure for the optimal design of the geometry of the Stewart platform.

In the past, a number of constructions of the Stewart platform were made keeping in view the ease of subsequent analysis and control. Now, however, some of the analysis problems being solved and others under progress, it can be expected that design trends will turn towards optimality from physical and objective viewpoints. The performance measures for the Stewart platform can be derived partly on the lines of [147–152] for other (serial and parallel) manipulators and optimality criteria based on those measures can be combined with the workspace synthesis problem posed in Section 10 to formulate a geometrical synthesis problem for the Stewart platform. Designs based on such rigorous optimization are expected to offer superior performance. The isotropic design methodology of Zanganeh and Angeles [153] and the analysis of the effects of design parameters on the workspace by Ji [154] are important steps in this direction.

Another aspect of improving performance by design is through the use of redundancy. Though redundancy in parallel manipulators (including the Stewart platform) has already been suggested (discussed in Sections 14), an effective utilization of redundancy will require an understanding of the appropriate nature of redundancy applicable in this context and a thorough analysis of its behaviour and potential for optimizing performance. So far as redundancy is concerned, kinematic redundancy is not possible in parallel manipulators in the strict sense, because incorporation of more than one actuation in a particular limb of a parallel manipulator destroys its in-parallel character and it becomes a hybrid manipulator. The natural type of redundancy arising in parallel manipulators is force redundancy, i.e. the use of additional support(s) in parallel, which has been mentioned as type III redundancy by Lee and Kim [155] and discussed by Collins and Long [3] in the context of twist/wrench decomposition in serial and parallel manipulators. A fundamental approach to this issue can be found in Dasgupta and Mruthyunjaya [156], where the concept of force redundancy in the context of parallel manipulators has been studied as the series–parallel dual of the kinematic redundancy of serial manipulators and its implications to the kinematics and dynamics of parallel manipulators are examined. In particular, its utilization for reduction of force singularities and performance optimization has been explored. Merlet [157] discusses the role of various aspects of redundancy in analysis, calibration, control and optimization of parallel manipulators.

13. Lower dimensional versions of the stewart platform

The Stewart platform possesses all the sin dof's in the 3D space. Similar parallel manipulating structures in lower dimensional spaces, namely a plane and a sphere, are the 3-dof planar parallel manipulator and the 3-dof spherical parallel manipulator, sometimes referred to as planar and spherical Stewart platforms respectively. These two parallel manipulators have strong resemblance to the Stewart platform and are treated as its versions for lower dimensional spaces. As analysis and synthesis methods of these two and that of the Stewart platform are applicable to one another (with different orders of complexity, of course), a review of these two manipulators is included in the following.

13.1. Planar 3-dof parallel manipulator

The planar 3-dof parallel manipulator is an eight-bar linkage with two ternary links (frame and end-effector) connected through three in-parallel legs, each leg consisting of two links. Though a number of mechanisms are possible by different combinations of revolute and prismatic joints at the legs, two of them having 3-RRR and 3-RPR structures have attracted wide research interest, the latter (see Fig. 3) exhibiting greatest similarity to the Stewart platform.

The direct position and velocity kinematics of the planar parallel manipulator were solved by Pennock and Kassner [158] and an upper bound of the number of assembly configurations was shown to be six. Gosselin and Merlet [159] made an alternative formulation for the direct position kinematics problem, developed robust schemes for the solution and established sharp upper bounds (less than 6) for special geometries of the manipulator. Sefrioui and Gosselin [160,161] analysed the singularities of the manipulator and described the singularity loci as well as the singularity surface in the 3D (x,y,ϕ) task-space. Daniali et al. [162] classified the 3-dof planar parallel manipulators into various classes according to the different dispositions of revolute and prismatic joints and analysed the occurrence of different types of singularities in different classes. A systematic analytical description of the rate kinematics, statics, singularities and stiffness mapping of the planar parallel manipulator and its relationship to its dual serial 3-R manipulator can be found in a recent book by Duffy [163].

Long and Hao [164] presented a scheme for singularity avoidance by actuation redundancy

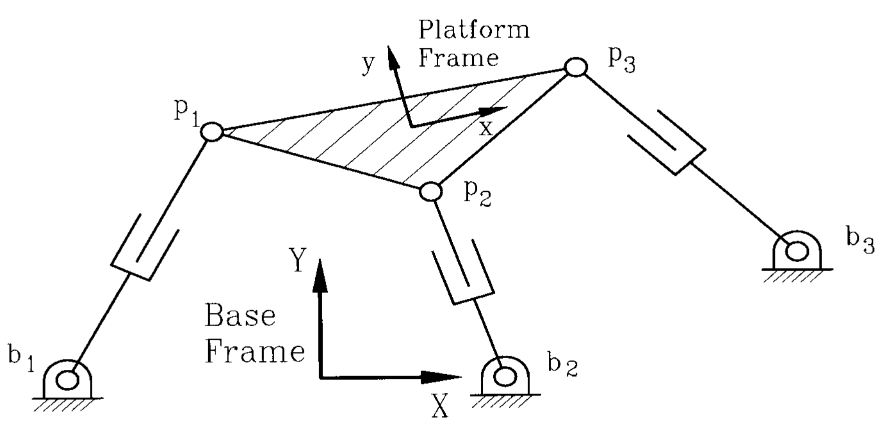

Fig. 3. Planar 3-dof parallel manipulator.

and showed that all the singularities of this manipulator are avoidable by such a measure. An example of avoidance of singularity and optimization of stiffness for the manipulator by the use of additional dof's can be found in the path optimization by Gosselin and Angeles [165] through the utilization of task-based redundancy, where the task is incompletely specified and does not need all the dof's of the parallel manipulator. The effective reduction of singularities of the manipulator through the use of static redundancy has been demonstrated by Dasgupta and Mruthyunjaya [156].

The workspace of the manipulator has been analysed by various authors [94,95,166–168] addressing three problems: (1) Workspace with a given orientation, (2) Reachable workspace and (3) Dexterous workspace. The dynamic modelling of the manipulator with 3-RRR structure was performed by Ma and Angeles [169] using the method of natural orthogonal complement while Revathi et al. [170] reported a Lagrange–Euler formulation for the 3-RPR case. The problem of optimal kinematic synthesis was addressed by Gosselin and Angeles [171]. Feng et al. [172] performed a mobility analysis of the planar parallel manipulators and made a classification of such manipulators on the basis of mobility.

13.2. Spherical 3-dof parallel manipulator

The spherical 3-dof parallel manipulator consists of two bodies connected through three in-parallel legs (mostly RRR with axes of all revolute joints passing through a point) such that any motion of the end-effector is always on a sphere. This mechanism has three rotational dof's and has applications as a wrist. Various researchers [173–177] have studied its kinematics, workspace, singularities and dynamics. Optimal kinematic design of such manipulators has also been addressed (see [178–180]) and a 3-dof wide range camera orienting device called 'the agile eye' has been constructed with such an architecture (see Gosselin and Hamel [181]).

14. Closed-loop manipulators

From the very beginning, the Stewart platform grew into a popular research topic along with a simultaneous development of the field of closed-loop and parallel manipulators in general. After the initial works on parallel manipulators discussed in Section 5, there has been a phenomenal growth in the field of parallel manipulators and a complete review of the field is beyond the scope of this paper. However, a discussion on the Stewart platform is never complete without a mention of closed-loop and parallel manipulators in general. Hence, in this section, a brief discussion of the field of parallel and hybrid manipulators is presented with emphasis on the works closely related to the Stewart platform.

General works on closed-loop and parallel manipulators [70,103,166,182–187] provide techniques for kinematic and dynamic analysis (including singularities and workspace determination) that are applicable to the Stewart platform also, though the 6-dof manipulator presents formidable computational complexity. In general, it can be seen that the realm of parallel manipulators has drawn research interest significantly towards screw theory for unified representation and better conceptual understanding. In addition, many terms earlier loosely used in the context of serial manipulators alone are getting redefined and interpreted from a direct physical standpoint.

Out of the numerous types of parallel manipulators studied and developed, a few typical ones are cited in the following. The 3-RPS parallel manipulator (see [188–193]), shown in Fig. 4, possesses three dof's and can be used as a positioning device or as a wrist or for controlling any three of the six coordinates in space. Some of the parallel manipulators are specifically designed for high speed applications like DELTA, HEXA and FALCON (see [194–197]), the last one having cable legs. A platform manipulator using pantograph mechanism similar to the design of Inoue et al. [12] has been used in the master hand controller for force-reflected teleoperation (see [198,199]). A 6-dof manipulating structure has been described by Giordano and Benea [200] which is very similar to the Stewart platform except that it possesses RUS (revolute–universal–spherical) legs rather than UPS/SPS legs. In another variation, Takeda et al. [201] designed and developed a 6-RSS platform manipulator, in which they make use of their theory of 'performance index' for optimal synthesis. Sorli et al. [202] described the mechanics of another 6-dof parallel manipulator, called the Turin parallel robot, recently developed employing three double-parallelogram mechanisms to support an active platform holding the workpiece during manufacture.

Some authors (see e.g., [203,204]) studied the number synthesis of 6-dof platform manipulators. As a matter of fact, any 6-dof chain can serve as a limb of such a manipulator and the number of such possibilities of combinations is quite large. However, a modification through the decomposition of multiple-dof joints of the Stewart platform will make the manipulator kinematically complex. In general, deviations in the kinematic structure of a parallel manipulator from the Stewart platform might be useful for workspace enhancement, but may lead to loss of rigidity to some extent. On the other hand, incorporating more than

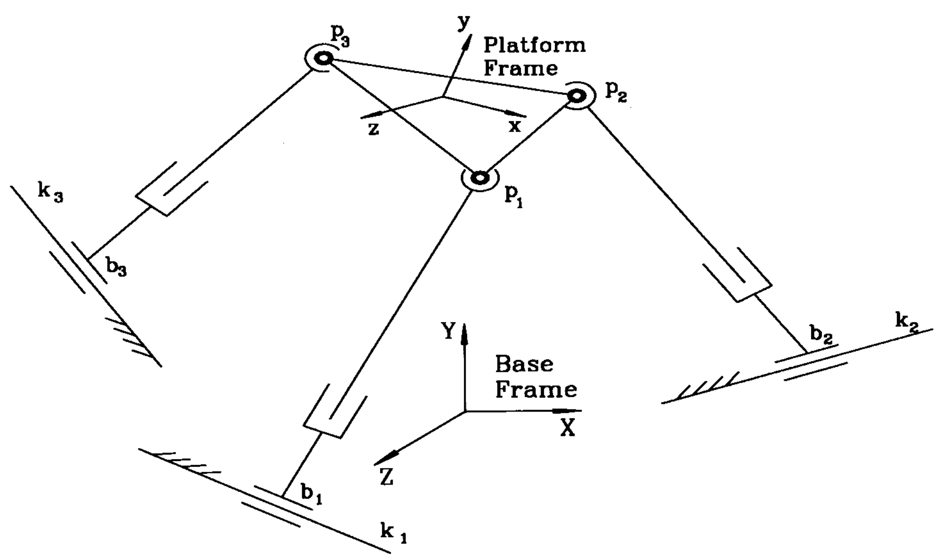

Fig. 4. 3-RPS parallel manipulator.

one actuation in a limb results in a hybrid manipulator and sometimes leads to redundancy also. Both these aspects are interesting and useful. The hybrid manipulator studied by Behi [205] has three PRPS legs with a triangular platform and is kinematically equivalent to a 6-3 Stewart platform. Podhorodeski and Pittens [206] performed a number synthesis of 6-dof platform manipulators and chose 3-2,2,2 structure, i.e. those having three limbs with two actuations each, as the one promising best performance. Direct position kinematics of a two-limbed and a three-limbed hybrid platform manipulators were reported by Husain and Waldron [207,208]. Notash and Podhorodeski [209] studied the position kinematics of all three-limbed platform manipulators with reference to sensor redundancy. A hybrid manipulator with a serial chain mounted over a parallel–actuated module has been proposed by Huang and Ling [210] while a serial manipulator with an in-parallel wrist is a more common concept. A 10-dof redundant hybrid manipulator with 3-dof 3-RPS modules in series has been developed by Mingyang et al. [211] and a manipulator with two Stewart platforms in series has been proposed by Lee [212]. The 9-dof kinematically redundant hybrid manipulator studied by Zanganeh and Angeles [213,214] also seems to hold promise, except for the difficulty of realizing the equivalent (discussed by them) of a six-link concentric spherical joint—perhaps the innovative design of concentric spherical joints by Hamlin and Sanderson [142] discussed in Section 12 might be useful.

Apart from the above, other fields of research associated with platform manipulators are cooperating robots, multifingered hands and walking machines. The techniques of kinematic and dynamic analysis of these systems are often applicable to the Stewart platform. In fact, the research on the Stewart platform and in these fields have influenced the trends of each other significantly. However, each of them is an independent field of research by itself and hence discussion of these topics is beyond the scope of the present review.

15. Open problems

From the review of the literature on the Stewart platform, it is apparent that a significant volume of work has been done on the kinematics and statics of the manipulator and those problems are well understood now. However, much less research has been done on its dynamics and control. So far as the issues of singularity and workspace analysis are concerned, partial answers to many questions are available, but a complete analysis is yet to be performed. Apart from this, there are very few works on the systematic design of the Stewart platform manipulator and study in that direction is important for the enhancement and realization of its potential.

Some of the open problems in the field of the Stewart platform, which are likely to get research interest in the immediate future are as follows.

1. In dynamics and control:
   - Study of the dynamic behaviour of the manipulator through extensive simulation and analytical/numerical tools for ODE systems.
   - Exploration of possibilities of specialized control strategies which will take advantage of the parallel structure of the manipulator and will offer improved performance.

- Derivation of theoretical results regarding controllability and observability issues.
- Exploration of redundancy resolution schemes for statically redundant Stewart platform.

2. In workspace and singularity:
   - A detailed easy-to-use description of the workspace.
   - Complete characterization of the singularity manifold.
   - Study of the workspace partitioning by the singularity manifold.
   - Workspace synthesis for the Stewart platform.
   - Establishment of existence criteria for singularity-free paths with given end-poses.

3. In design:
   - Optimal kinematic synthesis of the Stewart platform for well-conditioned workspace.
   - Development of statically redundant Stewart platform and study of its characteristics.
   - Comparison of non-redundant and redundant Stewart platforms regarding performance and assessment of the advantages and costs of redundancy.

Some of the above problems have relevance to the general class of parallel manipulators.

16. Conclusion

In this paper, a state-of-the-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 and design. A few unsolved problems which are highly relevant have been enumerated. 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 manipulators embodying all the distinctive features of the entire class in full generality.

As the field of robotics originated with serial manipulators and for a long time they were the only type of manipulators in existence, the techniques for kinematic and dynamic analysis of robot manipulators were developed specifically for that class of manipulators. Those techniques are often not appropriate for the analysis of the Stewart platform in particular and of parallel manipulators in general in the sense that, applied to parallel manipulators, they tend to approach the problems in a roundabout way and increase computational complexity. Hence, for the kinematic and dynamic analysis of parallel manipulators, new perspectives and methods may have to be employed keeping in view their distinctive features as compared to their serial counterparts. In addition, the new problems that arise in the parallel manipulators have to be understood and solved to pave the way for their effective application in situations where they are expected to offer better performance. First, dynamics and control should be performed in the task-space rather than in joint-space and the Newton–Euler approach should be preferred for dynamic formulation. Secondly, supporting of the payload and precise positioning have to be recognized as the primary role of a parallel manipulator and design should be based on the criteria of stiffness and rigidity. Thirdly, the role of singularities has to be understood as different from the case of serial manipulators, and redundancy of the static nature should be explored.

In general, it has to be understood that the different nature of parallel manipulators, compared to their conventional serial counterparts, calls for unconventional strategies and novel concepts for analysis and design. In a nutshell,

> "Parallel manipulator is new and different. It demands new and different viewpoints, as it promises new and different utilities."

References

[1] R.S. Ball, A Treatise on the Theory of Screws, Cambridge University Press, London, 1900.
[2] K.J. Waldron, K.H. Hunt, Int. J. Robot. Res. 10 (5) (1991) 473–480.
[3] C.L. Collins, G.L. Long, in: Proc. IEEE Int. Conf. Robot. Automn, 1995, pp. 526–531.
[4] D. Stewart, Proc. Instn. Mech. Engrs. (Part I) 180 (15) (1965/66) 371–386.
[5] V.E. Gough, S.G. Whitehall, in: Proc. 9th Int. Tech. Congr. F.I.S.I.T.A. May 1962, Instn Mech. Engrs 117, 1962.
[6] K.H. Hunt, Kinematic Geometry of Mechanisms, Clarendon Press, Oxford, 1978.
[7] M. Baret, in: Proc. AGARD Conf. 249, Piloted Aircraft Environment Simulation Techniques, 1978, pp. 22.1–22.8.
[8] P. Watson, Electron. Aust. 46 (4) (1984) 12–17.
[9] H. McCallion, P.D. Truong, in: Proc. 5th Wld Congr. Theory Mach. Mech., 1979, pp. 611–616.
[10] Powell, I.L., MTR., 81/30. Marconi Research Laboratories, GEC Marconi Electronics Ltd., Chelmsford, Great Britain, 1981.
[11] S.L. Potton, in: Proc. CIRP Conf. on Assembly Automation, 1983, pp. 126–128.
[12] H. Inoue, Y. Tsusaka, T. Fakuizumi, in: Proc. 3rd ISRR, Gouvieux, France, 1985, pp. 321–327.
[13] C.F. Earl, J. Rooney, Trans. ASME, J. Mech. Transm. Automn Des. 105 (1983) 15–22.
[14] K.H. Hunt, Trans. ASME, J. Mech. Transm. Automn Des. 105 (1983) 705–712.
[15] E.F. Fichter, E.D. McDowell, in: Proc. 6th Wld Congr. Theory Mach. Mech., 1983, pp. 1003–1006.
[16] M.G. Mohamed, J. Sanger, J. Duffy, in: Proc. 6th Wld Congr. Theory Mach. Mech., 1983, pp. 77–80.
[17] M.G. Mohamed, J. Duffy, Trans. ASME, J. Mech. Transm. Automn Des. 107 (1985) 226–229.
[18] D.C.H. Yang, T.W. Lee, Trans. ASME, J. Mech. Transm. Automn Des. 106 (1984) 191–198.
[19] E.F. Fichter, Int. J. Robot. Res. 5 (2) (1986) 157–182.
[20] J.-P. Merlet, INRIA Research Report No. 646, 1987.
[21] M. Griffis, J. Duffy, J. Robot. Sys. 6 (6) (1989) 703–720.
[22] W. Lin, M. Griffis, J. Duffy, Trans. ASME, J. Mech. Des. 114 (1992) 444–450.
[23] W. Lin, C.D. Crane, J. Duffy, Trans. ASME, J. Mech. Des. 116 (1994) 47–53.
[24] C. Innocenti, V. Parenti-Castelli, Mech. Mach. Theory 25 (6) (1990) 611–621.
[25] P. Nanua, K.J. Waldron, V. Murthy, IEEE Trans. Robot. Automn 6 (4) (1990) 438–444.
[26] V. Murthy, K.J. Waldron, Trans. ASME, J. Mech. Des. 114 (1992) 406–413.
[27] J.-P. Merlet, Int. J. Robot. Res. 11 (2) (1992) 150–162.
[28] N.-X. Chen, S.-M. Song, Trans. ASME, J. Mech. Des. 116 (1994) 61–66.
[29] Q. Liao, L.D. Seneviratne, S.W.E. Earles, Proc. Instn Mech. Engrs 209 (Pt C) (1995) 55–67.
[30] C. Innocenti, Trans. ASME, J. Mech. Des. 117 (1995) 89–95.
[31] C. Innocenti, V. Parenti-Castelli, in: Ninth CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators, Udine, Italy, 1992.

[32] C. Innocenti, V. Parenti-Castelli, Trans. ASME, J. Mech. Des. 115 (1993) 515–521.
[33] C. Innocenti, V. Parenti-Castelli, Mech. Mach. Theory 28 (4) (1993) 553–561.
[34] M. Husain, K.J. Waldron, Trans. ASME, J. Mech. Des. 116 (1994) 1102–1107.
[35] K. Wohlhart, Mech. Mach. Theory 29 (4) (1994) 581–589.
[36] C-de Zhang, S.-M. Song, in: Proc. IEEE Int. Conf. Robot. Automn, 1991, pp. 2676–2681.
[37] W. Guozhen, Robotics, Spatial Mechanisms and Mechanical Systems ASME-45 (1992) 113–117.
[38] J.P. Yin, C.G. Liang, Mech. Mach. Theory 29 (1) (1994) 1–9.
[39] S.V. Sreenivasan, K.J. Waldron, P. Nanua, Mech. Mach. Theory 29 (6) (1994) 855–864.
[40] R. Nair, J.H. Maddocks, Int. J. Robot. Res. 13 (2) (1994) 171–188.
[41] J.C. Faugère, D. Lazard, Mech. Mach. Theory 30 (6) (1995) 765–776.
[42] G. Deshmukh, M. Pecht, Computers and Structures 34 (3) (1990) 485–491.
[43] C.C. Nguyen, Z.-L. Zhou, S.S. Antrazi, C.E. Campbell Jr., in: Proc. IEEE SOUTHEASTCON, 1991, pp. 869–874.
[44] L.-C.T. Wang, C.C. Chen, IEEE Trans. Robot. Automn 9 (3) (1993) 272–285.
[45] C. Innocenti, V. Parenti-Castelli, Meccanica 26 (1991) 247–252.
[46] C. Innocenti, V. Parenti-Castelli, in: Proc. IEEE 5th Int. Conf. Advanced Robotics, Pisa, Italy, 1991, pp. 851–855.
[47] M. Ait-Ahmed, M. Renaud, M. Vidyasagar (Ed.), Proc. Int. Symp. Intel. Robot., Intelligent robotics, Tata McGraw-Hill, New Delhi, 1993, pp. 13–24.
[48] C. Innocenti, V. Parenti-Castelli, Trans. ASME, J. Mech. Des. 115 (1993) 932–937.
[49] B. Dasgupta, T.S. Mruthyunjaya, Mech. Mach. Theory 31 (6) (1996) 799–811.
[50] M. Raghavan, Trans. ASME, J. Mech. Des. 115 (1993) 277–282.
[51] A. Morgan, Solving Polynomial Systems using Continuation for Engineering and Scientific Problems, Prentice-Hall, Englewood Cliffs, NJ, 1987.
[52] S.V. Srinivasan, P. Nanua, Robotics, Spatial Mechanisms and Mechanical Systems ASME-45 (1992) 99–106.
[53] A. Dhingra, D. Kohli, Y.-X. Xu, Robotics, Spatial Mechanisms and Mechanical Systems ASME-45 (1992) 107–112.
[54] C.-de Zhang, S.-M. Song, Trans. ASME, J. Mech. Des 116 (1994) 54–60.
[55] B. Dasgupta, T.S. Mruthyunjaya, Mech. Mach. Theory 29 (6) (1994) 819–827.
[56] F. Wen, C. Liang, Mech. Mach. Theory 29 (4) (1994) 547–557.
[57] K.H. Hunt, E.J.F. Primrose, Mech. Mach. Theory 28 (1) (1993) 31–42.
[58] C.W. Wampler, Mech. Mach. Theory 31 (3) (1996) 331–337.
[59] M.L. Husty, Mech. Mach. Theory 31 (4) (1996) 365–379.
[60] Y.L. Sarkissian, T.F. Parikian, in: Proc. 9th Wld Congr. Theory Mach. Mech, 1995, pp. 1614–1618.
[61] L. Baron, J. Angeles, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 974–979.
[62] L. Baron, J. Angeles, Advances in Design Automation ASME-69-2 (1994) 467–474.
[63] L. Baron, J. Angeles, in: Proc. IEEE Int. Conf. Robot. Automn, 1995, pp. 1541–1546.
[64] K. Han, W. Chung, Y. Youm, Trans. ASME, J. Mech. Des. 118 (1996) 214–219.
[65] L. Baron, J. Angeles, in: Proc. 9th Wld Congr. Theory Mach. Mech, 1995, pp. 1925–1929.
[66] Z. Geng, L. Haynes, in: Proc. IEEE Int. Conf. Robot. Automn, 1991, pp. 2650–2655.
[67] X. Shi, R.G. Fenton, Mech. Mach. Theory 27 (3) (1992) 251–259.
[68] X. Shi, R.G. Fenton, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 3055–3062.
[69] T. Ropponen, T. Arai, in: Proc. IEEE Int. Conf. Robot. Automn, 1995, pp. 521–525.
[70] C. Gosselin, J. Angeles, IEEE Trans. Robot. Automn 6 (3) (1990) 281–290.
[71] J.-P. Merlet, INRIA Research Report No. 791, 1988.
[72] J.-P. Merlet, Int. J. Robot. Res. 8 (5) (1989) 45–56.
[73] K. Liu, F. Lewis, G. Lebret, D. Taylor, J. Intel. Robot. Sys. 8 (1993) 287–308.
[74] O. Ma, J. Angeles, in: Proc. IEEE Int. Conf. Robot. Automn, 1991, pp. 1542–1547.
[75] P. Zsombor-Murray, M. Husty, D. Hartmann, in: Proc. 9th Wld Congr. Theory Mach. Mech, 1995, pp. 1886–1890.
[76] C. Gosselin, IEEE Trans. Robot. Automn 6 (3) (1990) 377–382.
[77] Y. Takeda, H. Funabashi, JSME Int. J. Series C 38 (4) (1995) 749–755.

[78] Y. Takeda, H. Funabashi, JSME Int. J. Series C 39 (1) (1996) 85–93.
[79] S. Bhattacharya, H. Hatwal, A. Ghosh, Mech. Mach. Theory 33 (7) (1998) 965–974.
[80] B. Dasgupta, T.S. Mruthyunjaya, Mech. Mach. Theory 33 (6) (1998) 711–725.
[81] A. Gaillet, C. Reboulet, An isostatic six component force and torque sensor, in: Proc. 13th Int. Symp. Ind. Robots, 1983.
[82] D.R. Kerr, Trans. ASME, J. Mech. Transm. Automn Des. 111 (1989) 25–28.
[83] M. Griffis, J. Duffy, Trans. ASME, J. Mech. Des. 113 (1991) 508–515.
[84] C.C. Nguyen, S.S. Antrazi, Z.-L. Zhou, in: Proc. IEEE SOUTHEASTCON, 1991, pp. 880–884.
[85] A. Romiti, M. Sorli, Sensors and Actuators A 32 (1992) 531–538.
[86] M. Sorli, N. Zhmud, Sensors and Actuators A 37-38 (1993) 651–657.
[87] J.S. Dai, C. Sodhi, D.R. Kerr, Proc. 2nd Biennial European Joint Conference on Engineering Systems Design and Analysis, ASME PD, 64(8-3), 1994, pp. 809–817.
[88] B. Dasgupta, S. Reddy, T.S. Mruthyunjaya, in: Proceedings of National Convention on Industrial Problems in Machines and Mechanisms (IPROMM)'94, Bangalore, India, 1995, pp. 14–23.
[89] M.M. Svinin, M. Uchiyama, Int. J. Robot. Res. 14 (6) (1995) 560–573.
[90] M. Sorli, S. Pastorelli, Mechatronics 5 (6) (1995) 585–601.
[91] M. Cwiakala, ASME Paper 86-DET-95, 1986.
[92] C. Gosselin, Trans. ASME, J. Mech. Des 112 (1990) 331–336.
[93] C.M. Gosselin, E. Lavoie, P. Toutant, Robotics, Spatial Mechanisms and Mechanical Systems ASME-45 (1992) 323–328.
[94] D.-Y. Jo, E.J. Haug, ASME-3, Advances in Design Automation 19 (3) (1989) 53–60.
[95] E.J. Haug, J.Y. Wang, J.K. Wu, Mech. Struct. Mach. 20 (3) (1992) 321–361.
[96] F.-C. Yang, E.J. Haug, Trans. ASME, J. Mech. Des. 116 (1994) 111–118.
[97] C.-M. Luh, F.A. Adkins, E.J. Haug, C.C. Qiu, Trans. ASME, J. Mech. Des. 118 (1996) 220–227.
[98] O. Masory, J. Wang, Advanced Robotics 9 (4) (1995) 443–461.
[99] J.-P. Merlet, J. Intel. Robot. Systems: Theory and Applications 13 (2) (1995) 143–160.
[100] J.-P. Merlet, Int. J. Robot. Res. 13 (4) (1994) 326–333.
[101] J.-P. Merlet, in: Proc. IEEE Int. Conf. Robot. Automn, 1996, pp. 3726–3731.
[102] J.-P. Merlet, Int. J. Robot. Res. 16 (4) (1997) 545–556.
[103] K. Sugimoto, Trans. ASME, J. Mech. Transm. Automn Des. 111 (1989) 29–33.
[104] W.Q.D. Do, D.C.H. Yang, J. Robot. Sys. 5 (3) (1988) 209–227.
[105] Z. Geng, L.S. Haynes, J.D. Lee, R.L. Carroll, Robotics and Autonomous Systems 9 (1992) 237–254.
[106] K. Liu, M. Fitzgerald, D.W. Dawson, F.L. Lewis, Control of Systems with Inexact Dynamic Models ASME-33 (1991) 83–89.
[107] Z. Ji, Trans. ASME, J. Mech. Des. 116 (1994) 67–69.
[108] B. Dasgupta, T.S. Mruthyunjaya, Mech. Mach. Theory 33 (8) (1998) 1135–1152.
[109] C.M. Gosselin, Trans. ASME, J. Dyn. Sys. Meas. Control 118 (1996) 22–28.
[110] B. Dasgupta, T.S. Mruthyunjaya, Mech. Mach. Theory 33 (7) (1998) 993–1012.
[111] K. Liu, G. Lebret, J.A. Lowe, F.L. Lewis, Advanced Control Issues for Robot Manipulators ASME-39 (1992) 23–30.
[112] O.E. Hatip, M.K. Ozgoren, in: Proc. 9th Wld Congr. Theory Mach. Mech., 1995, pp. 1393–1396.
[113] H. Wang, C. Xue, W.A. Gruver, in: Proc. IEEE Int. Conf. Sys. Man Cyber., 1995, pp. 2934–2938.
[114] D.M.J. Harris, in: Proc. 9th Wld Congr. Theory Mach. Mech., 1995, pp. 1565–1568.
[115] J.D. Lee, Z. Geng, Computers and Structures 48 (3) (1993) 367–374.
[116] J.D. Lee, Computers and Structures 48 (3) (1993) 375–385.
[117] K. Cleary, T. Arai, in: Proc. IEEE Int. Conf. Robot. Automn, 1991, pp. 566–571.
[118] C.C. Nguyen, S.S. Antrazi, Z.-L. Zhou, C.E. Campbell Jr., in: Proc. IEEE Int. Conf. Robot. Automn, 1991, pp. 1873–1878.
[119] D.M.J. Harris, in: Proc. 9th Wld Congr. Theory Mach. Mech., 1995, pp. 1695–1699.
[120] H. Zhuang, Z.S. Roth, Applications of Modeling and Identification to Improve Machine Performance ASME-29 (1991) 43–48.
[121] J. Wang, O. Masory, in: Proc. IEEE Int. Conf. Robot. Automn, 1993, pp. 114–120.

[122] O. Masory, J. Wang, H. Zhuang, in: Proc. IEEE Int. Conf. Robot. Automn, 1993, pp. 725–731.
[123] C.W. Wampler, J.M. Hollerbach, T. Arai, IEEE Trans. Robot. Automn 11 (5) (1995) 710–724.
[124] O. Masory, Y. Jiahua, J. Robot. Sys. 12 (12) (1995) 821–832.
[125] H. Zhuang, O. Masory, J. Yan, in: Proc. IEEE/RSJ Int. Conf. Intel. Robots Systems, 1995, pp. 329–334.
[126] S. Bhattacharya, H. Hatwal, A. Ghosh, Mech. Mach. Theory 32 (1) (1997) 79–89.
[127] H. Zhuang, L. Liu, in: Proc. IEEE Int. Conf. Robot. Automn, 1996, pp. 994–999.
[128] H. Zhuang, IEEE Trans. Robot. Automn 13 (3) (1997) 387–397.
[129] K. Machida, Y. Toda, T. Iwata, T. Komatsu, J. Guidance Control Dyn. 15 (1) (1991) 10–16.
[130] C.C. Nguyen, S.S. Antrazi, Z.-L. Zhou, C.E. Campbell Jr., Computers Elect. Engng 17 (3) (1991) 191–203.
[131] W.F. Smith III, C.C. Nguyen, in: Proc. IEEE SOUTHEASTCON, 1991, pp. 875–879.
[132] S.E. Salcudean, S. Bachman, D. Ben-Dov, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 2444–2450.
[133] S.E. Salcudean, P.A Drexel, D. Ben-Dov, A.J. Taylor, P.D. Lawrence, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 2437–2443.
[134] Y. Amirat, C. Francois, G. Fried, J. Pontnau, M. Dafaoui, Mechatronics 6 (2) (1996) 227–239.
[135] Z.J. Geng, L.S. Haynes, IEEE Trans. Control Sys. Tech. 2 (1) (1996) 45–53.
[136] M. Cwiakala, N.A. Langrana, ASME-DE 15-3 (1988) 97–103.
[137] B.V. Viscomi, W.D. Michalerya, L.-W. Lu, Automation in Construction 3 (1) (1994) 35–43.
[138] J.M. Wendlandt, S.S. Sastry, in: Proc. IEEE Int. Conf. Decision Control, 1994, pp. 357–362.
[139] K. Liu, R. Glenn, T.J. Lawley, F.L. Lewis, in: Proc. IEEE Int. Conf. Robot. Automn, 1993, pp. 106–113.
[140] S.-J. Zhang, D. Howard, D.J. Sanger, D.R. Kerr, S. Miao, Proc. 2nd Biennial European Joint Conference on Engineering Systems Design and Analysis, ASME, 64(8-3), 1994, pp. 849–855.
[141] Z.J. Geng, L.S. Haynes, Robotics and Computer-Integrated Manufacturing 11 (1) (1994) 23–34.
[142] G.J. Hamlin, A.C. Sanderson, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 1267–1272.
[143] A. Hara, K. Sugimoto, Trans. ASME, J. Mech. Transm. Automn Des. 111 (1989) 34–39.
[144] C.-S. Han, A.E. Traver, D. Tesar, Proc. Int. Comp. Engng Conf. Exhibit, ASME, Computers in engineering, 1989, pp. 251–256.
[145] D. Chakarov, P. Parushev, Mech. Mach. Theory 29 (7) (1994) 917–932.
[146] S. Bhattacharya, H. Hatwal, A. Ghosh, Robotica 13 (1995) 133–140.
[147] C. Gosselin, J. Angeles, Trans. ASME, J. Mech. Transm. Automn Des. 113 (1991) 220–226.
[148] J.R. Singh, J. Rastegar, Int. J. Robot. Res. 11 (6) (1992) 538–548.
[149] C.M. Gosselin, Robotics and Autonomous Systems 9 (1992) 213–226.
[150] J.R. Singh, J. Rastegar, Mech. Mach. Theory 30 (4) (1995) 569–580.
[151] K. van den Doel, D.K. Pai, Int. J. Robot. Res. 15 (1) (1996) 92–111.
[152] K. van den Doel, D.K. Pai, IEEE Trans. Robot. Automn 13 (2) (1997) 278–289.
[153] K.E. Zanganeh, J. Angeles, Int. J. Robot. Res 16 (2) (1997) 185–197.
[154] Z. Ji, Trans. ASME J. Mech. Des. 118 (1996) 526–531.
[155] S. Lee, S. Kim, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 77–82.
[156] B. Dasgupta, T.S. Mruthyunjaya, Mech. Mach. Theory 33 (6) (1998) 727–742.
[157] J.-P. Merlet, Lab. Robot. Automn 8 (1) (1996) 17–24.
[158] G.R. Pennock, D.J. Kassner, Trans. ASME, J. Mech. Des 114 (1992) 87–95.
[159] C.M. Gosselin, J.-P. Merlet, Mech. Mach. Theory 29 (8) (1994) 1083–1097.
[160] J. Sefrioui, C.M. Gosselin, Robotics and Autonomous Systems 10 (1992) 209–224.
[161] J. Sefrioui, C.M. Gosselin, Mech. Mach. Theory 30 (4) (1995) 533–551.
[162] H.R.M. Daniali, P.J. Zsombor-Murray, J. Angeles, Mech. Mach. Theory 30 (5) (1995) 665–678.
[163] J. Duffy, Statics and Kinematics with Application to Robotics, Cambridge University Press, Cambridge, 1996.
[164] G.L. Long, F. Hao, in: Proc. 9th Wld Congr. Theory Mach. Mech., 1995, pp. 1734–1739.
[165] C. Gosselin, J. Angeles, Trans. ASME, J. Mech. Des. 112 (1990) 494–500.
[166] V. Kumar, Trans. ASME, J. Mech. Des. 114 (1992) 368–375.
[167] G.R. Pennock, D.J. Kassner, Trans. ASME, J. Mech. Des. 115 (1993) 269–276.
[168] C.M. Gosselin, M. Jean, Robotics and Autonomous Systems 17 (1996) 129–138.
[169] O. Ma, J. Angeles, ASME DE 32-2 (1993) 313–320.

[170] V.P. Revathi, B. Dasgupta, T.S. Mruthyunjaya, in: Proc. 7th National Conference on Machines and Mechanisms (NACOMM) 95, Durgapur, India, 1996, pp. B1–B7.
[171] C. Gosselin, J. Angeles, Trans. ASME, J. Mech. Transm. Automn Des. 110 (1988) 35–41.
[172] G. Feng, Z. Yong-Sheng, Z. Zhi-Hui, Mech. Mach. Theory 31 (2) (1996) 161–171.
[173] C.M. Gosselin, J. Sefrioui, M.J. Richard, Trans. ASME, J. Mech. Des. 116 (1994) 587–593.
[174] C.M. Gosselin, J. Sefrioui, M.J. Richard, Trans. ASME, J. Mech. Des. 116 (1994) 594–598.
[175] R.I. Alizade, N.R. Tagiyev, J. Duffy, Mech. Mach. Theory 29 (1) (1994) 125–137.
[176] C.M. Gosselin, J. Sefrioui, Robotics, Spatial Motion and Mechanical Systems ASME-45 (1992) 329–336.
[177] C.M. Gosselin, M. Gagne, in: Proc. 9th Wld Congr. Theory Mach. Mech., 1995, pp. 2032–2036.
[178] C. Gosselin, J. Angeles, Trans. ASME, J. Mech. Transm. Automn Des. 111 (1989) 202–207.
[179] C.M. Gosselin, E. Lavoie, Int. J. Robot. Res. 12 (4) (1993) 394–402.
[180] Y. Takeda, H. Funabashi, Y. Sasaki, JSME Int. J. Ser C 39 (3) (1996) 541–548.
[181] C.M. Gosselin, J.-F. Hamel, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 781–786.
[182] K. Sugimoto, Trans. ASME, J. Mech. Transm. Automn. Des. 109 (1987) 3–7.
[183] Y. Nakamura, M. Ghodoussi, IEEE Trans. Robot. Automn 5 (3) (1989) 294–302.
[184] V. Kumar, Trans. ASME, J. Mech. Des. 114 (1992) 349–358.
[185] S.K. Agrawal, B. Roth, Trans. ASME, J. Mech. Des. 114 (1992) 564–568.
[186] D. Zlatanov, R.G. Fenton, B. Benhabib, Trans. ASME, J. Mech. Des 117 (1995) 566–572.
[187] B. Dasgupta, P. Choudhury, The Newton–Euler approach for the dynamic formulation for parallel manipulators, Mech. Mach. Theory 34 (6) (1999) 801–824.
[188] K.-M. Lee, D.K. Shah, IEEE J. Robot. Automn 4 (3) (1988) 354–360.
[189] K.-M. Lee, D.K. Shah, IEEE J. Robot. Automn 4 (3) (1988) 361–367.
[190] M. Hashimoto, Y. Imamura, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 2457–2462.
[191] Z. Huang, W.S. Tao, Y.F. Fang, Mech. Mach. Theory 31 (8) (1996) 999–1007.
[192] D. Basu, A. Ghosal, Mech. Mach. Theory 32 (3) (1997) 375–389.
[193] Y. Fang, Z. Huang, Mech. Mach. Theory 32 (7) (1997) 789–796.
[194] F. Pierrot, A. Fournier, P. Dauchez, in: Proc. IEEE Int. Conf. Robot. Automn, 1991, pp. 1288–1293.
[195] K. Miller, in: Proc. IEEE Int. Conf. Robot. Automn, 1995, pp. 532–537.
[196] J. Hesselbach, H. Kerle, in: Proc. 9th Wld Congr. Theory Mach. Mech, 1995, pp. 1935–1939.
[197] S. Kawamura, W. Choe, S. Tanaka, S.R. Pandian, in: Proc. IEEE Int. Conf. Robot. Automn, 1995, pp. 215–220.
[198] G.L. Long, C.L. Collins, in: Proc. IEEE Int. Conf. Robot. Automn, 1992, pp. 390–395.
[199] C.L. Collins, G.L. Long, IEEE Trans. Robot. Automn 11 (5) (1995) 661–669.
[200] M. Giordano, R. Benea, in: Proc. 9th Wld Congr. Theory Mach. Mech., 1995, pp. 1729–1733.
[201] Y. Takeda, H. Funabashi, H. Ichimaru, JSME Int. J. Ser C 40 (2) (1997) 299–308.
[202] M. Sorli, C. Ferraresi, M. Kolarski, B. Borovac, M. Vukobratovic, Mech. Mach. Theory 32 (1) (1997) 51–77.
[203] H. Funabashi, M. Horie, T. Kubota, Y. Takeda, JSME Int. J. Series III 34 (3) (1991) 382–387.
[204] L. Yufeng, Y. Tingli, in: Proc. 9th Wld Congr. Theory Mach. Mech., 1995, pp. 1795–1799.
[205] F. Behi, IEEE J. Robot. Automn 4 (5) (1988) 561–565.
[206] R.P. Podhorodeski, K.H. Pittens, Trans. ASME, J. Mech. Des. 116 (1994) 908–914.
[207] M. Husain, K.J. Waldron, Mech. Mach. Theory 28 (6) (1993) 763–775.
[208] M. Husain, K.J. Waldron, Trans. ASME, J. Mech. Des. 116 (1994) 924–929.
[209] L. Notash, R.P. Podhorodeski, Mech. Mach. Theory 30 (3) (1995) 391–404.
[210] M.Z. Huang, S.-H. Ling, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 2180–2185.
[211] Z. Mingyang, G. Tong, C. Ge, L. Qunming, T. Dalong, in: Proc. IEEE Int. Conf. Robot. Automn, 1995, pp. 221–226.
[212] M.K. Lee, in: Proc. IEEE Int. Conf. Robot. Automn, 1995, pp. 234–240.
[213] K.E. Zanganeh, J. Angeles, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 3043–3048.
[214] K.E. Zanganeh, J. Angeles, in: Proc. IEEE Int. Conf. Robot. Automn, 1994, pp. 3049–3054.