Journal of Mechanical Design

Guest Editorial

Spatial Mechanisms and Robot Manipulators

The subject of spatial mechanisms and robot manipulators continues to see sensational theoretical advances and exciting practical applications in fields ranging from product engineering, manufacturing, military applications, space exploration, rescue and recovery operations in hazardous environments, and of course, the rapidly growing area of medical robotics. Each new application raises numerous theoretical and experimental challenges. These open questions have attracted the attention of the best and brightest researchers, working in the general areas of mechanisms and robotics. The field of robotics, in particular, is interdisciplinary, with a constant flow of theories from many areas, including kinematics, statics and dynamics, computer graphics, control, and programming. The theories are used to provide a working and consistent approach to the interesting problem of robot manipulator control.

This special supplement attempts to share with the readership of the ASME Journal of Mechanical Design some of the exciting new advances proposed by these researchers. The Guest Editors have collected a number of recent submissions to the journal in these subject areas and attempted to include a mix of basic theoretical research and practical applications of well-known principles to new and challenging problems. To further solidify the value of this special issue, we approached several distinguished scholars to submit invited papers. They agreed to provide articles based on some of their most recent and original work. The manuscripts were peer reviewed and found to be outstanding. Therefore, we anticipate that this special issue will be a widely-sought reference for students, educators, and researchers in the areas of spatial mechanisms and robotics.

To whet the appetite of the reader, the Guest Editors will touch upon some of the highlights of the invited papers in this supplement.

The invited paper by Wampler investigates the interesting problem of the location of a rigid body such that N specified points of the body lie on N given planes in space. Variants of this problem arise in kinematics, metrology, and computer vision, including some, such as the motion of a spherical four-bar, which are not at first glance point-plane contact problems. The case $N=6$ (i.e., the minimum number to fully constrain the body) is of special interest. The paper presents an eigenvalue method for finding all solutions, which may number up to eight. For $N\geqslant 7$ there are, in general, no solutions, but if the constraints are compatible and not degenerate, the paper shows how to find the unique solution by a linear least-squares method. For $N\leqslant 5$, the body is underconstrained, having in general $6-N$ degrees of freedom; the paper determines the degree of the general motion for each case. The article also examines the workspace of a particular three-degree-of-freedom parallel-link tripod mechanism.

The invited paper by Stump and Kumar develops analytical techniques to delineate the workspace boundaries for parallel mechanisms with cables. In such mechanisms, it is not only necessary to solve the closure equations but it is also essential to verify that equilibrium can be achieved with non-negative actuator (cable) forces. The authors use tools from convex analysis and linear algebra to derive closed-form expressions for the workspace boundaries and illustrate the applications using planar and spatial examples.

The invited paper by Khan and Angeles describes the optimum dimensioning of a robotic manipulator. The design of a robotic manipulator begins with the dimensioning of its various links to meet performance specifications. However, the authors believe that a methodology for the determination of the manipulator architecture (i.e., the fundamental geometry of the links, regardless of their shapes) is still lacking. Attempts have been made to apply the classical paradigms of linkage synthesis for motion generation, as in Burmester Theory. The problem with this approach is that it relies on a specific task, described in the form of a discrete set of end-effector poses, which kills the very purpose of using robots—namely, their adaptability to a family of tasks. Another approach relies on the minimization of a condition number of the Jacobian matrix over the architectural parameters and the posture variables of the manipulator. This approach is also not trouble-free, for the matrices involved can have entries that bear different units, the matrix singular values thus being of disparate dimensions, which prevents the evaluation of any version of the condition number. As a means to cope with dimensional inhomogeneity, the concept of characteristic length was proposed. However, this concept has been slow in finding acceptance within the robotics community, probably because it lacks a direct geometric interpretation. In this paper, the authors revisit the concept of characteristic length and put it forward from a different point of view. In this vein, the concept of homogeneous space is introduced in order to relieve the designer from the concept of characteristic length. Within this space the link lengths are obtained as ratios, their optimum values as well as those of all angles involved obtained by minimizing a condition number of the dimensionally-homogeneous Jacobian. Further, a comparison between the condition number based on the 2-norm and that based on the Frobenius norm is provided. The paper also describes a formulation of the inverse problem (i.e., obtaining link lengths) and the direct problem (i.e., obtaining the characteristic length of a given manipulator). Finally a geometric interpretation of the characteristic length is provided and the application of the concept to the design and kinetostatic performance evaluation of serial robots is illustrated with examples.

The invited paper by Shai and Pennock describes a recent study of the duality between the statics of a variety of structures and the kinematics of mechanisms, in general, and spatial mechanisms and manipulators, in particular. To provide insight into this duality, two new graph representations are introduced; namely, the flow line graph representation and the potential line graph representation. The authors discuss, in some detail, the duality that exists between these two representations. Then they investigate the duality between a static pillar system and a planar linkage by using the flow line graph representation for the pillar system and the potential line graph representation for the linkage. A compound planetary gear train is shown to be dual to the special case of a statically determinate beam and the duality between a serial robot and a platform-type robot, such as the Stewart platform, is explained. To show that the approach presented in the paper can also be applied to more general robotic manipulators, the authors introduce a two-platform robot and the dual spatial linkage. The dual transformation is then used to check the stability of a static system and the stationary, or locked, positions of the linkage. The paper shows that two novel platform systems, comprised on concentric spherical platforms interconnected by rigid rods, are dual to a spherical six-bar linkage. The dual transformation, as presented in the paper, does not require the formulation and solution of the governing equations of the system under investigation. This approach provides an alternative technique to the synthesis of structures and mechanisms. To simplify the design process, the synthesis problem can be transformed from the given system to the dual system in a straight-forward manner.

The invited paper by Gosselin is a study of adaptive robotic mechanical systems. The goal of this paper is to develop a general framework for the use of the concept of adaptive mechanical systems in the design of advanced robotic devices. First, the paper formalizes the concept of adaptive mechanical systems. Then a design methodology is proposed in order to formulate the associated design paradigm, based on the fundamental principles of mechanics. Finally, the paper includes examples of adaptive robotic mechanical systems that are taken from the literature. These examples help to illustrate the application of the general design methodology.

Although the concepts of Jacobian matrix, manipulability and condition number have existed since the very early beginning of robotics, their real significance is not always well understood. In the invited paper by Merlet, the author revisits these concepts for parallel robots as accuracy indices in view of optimal design. The author shows that the usual Jacobian matrix derived from the input-output velocities equations may not be sufficient to analyze the positioning errors of the platform. He then examines the concept of manipulability and shows that its classical interpretation is erroneous. He considers various common local dexterity indices, most of which are based on the condition number of the Jacobian matrix. It is emphasized that even for a given robot in a particular pose there is a variety of condition numbers, and that their values are not coherent between themselves but also with what we may expect from an accuracy index. Global conditioning indices are then examined. Apart from the problem of being based on the local accuracy indices that are questionable, there is a computational problem in their calculation, which is neglected most of the time. Finally, the author examines what other indices may be used for optimal design and shows that their calculation is most challenging.

The Guest Editors would like to take this opportunity to thank all the reviewers of the six invited papers. The editors and the authors of these papers appreciate the time and effort that was invested by the reviewers in critiquing and providing constructive criticism of this research.

In addition to the invited papers, the Guest Editors have also included several outstanding papers in this supplement, covering a wide-variety of open problems in mechanism analysis and synthesis. For example, three-legged manipulators, overconstrained parallel mechanisms, Stewart platforms, parallelism measures, multi-limbed robots, cable-driven robots, robotic workspaces, platform manipulator mobility, and three-dimensional assembly synthesis are investigated in these research papers.

The paper by Akcali and Mutlu is a good example of an original contribution to this body of literature. The paper focuses on the kinematic analysis of two rigid bodies connected to each other by six legs through the use of six double spherical joints. New methods have been implemented both in the formulation and solution phases of the problem. The three-dimensional problem have been viewed, in fact, as a multitude of two-dimensional works on several planes, the intersections of which yield relationships allowing transition between adjacent planes. Therefore, the formulation is based purely on the geometric structure consisting of eight planes of interest, culminating in three fundamental equations involving three angles between the base and the side triangular planes. Extensions of the theory have been shown to include the analyses of other Stewart platform models.

The paper by Rao is noteworthy because it deals with the amorphous subject of parallelism in kinematic chains and attempts to quantify the extent of parallelism. The author shows that parallelism can be associated with every closed kinematic chain or its representative graph. Parallelism throws light on workspace, rigidity, and speed ratios (i.e., mechanical advantage), and is of great help in selecting multiple degree-of-freedom chains for robotic applications. Numerous distinct chains with the same number of links and degrees-of-freedom exist. The extent of parallelism differs from chain to chain and hence a numerical measure is necessary to quantify the same, so that the designer can gain insight simply based on the structure without having to actually design all the distinct chains before selecting the best chain for the specified task. The author's work is an attempt to develop a usable measure to quantify the extent of parallelism in any given mechanism concept.

Hong and Cipra present a novel approach to the visualization of the contact force solution space for multi-limbed robots. They present an analytical method for determining, describing, and visualizing the solution space for the contact force distribution of multi-limbed robots with three feet in contact with the environment in three-dimensional space. The foot contact forces are first resolved into strategically defined foot contact force components to decouple them, and then the static equilibrium equations are applied. Using the friction cone equation at each foot contact point, the problem is then transformed into a geometrical one. Using geometric properties of the friction cones and by manipulation of their conic sections, the entire solution space which satisfies the static equilibrium and friction constraints at each contact point can be obtained. Two representation schemes, the "force space graph" and the "solution volume representation," are developed for describing and visualizing the solution space which gives an intuitive visual map of how well the solution space is formed for the given conditions of the system.

The Guest Editors believe that the audience of the Journal of Mechanical Design will take great pleasure in reading the fascinating material in this supplement. The editors hope that this may provide the motivation for many to delve even deeper into the wide and wonderful world of spatial mechanisms and robotic manipulators.

Very happy reading.

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