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A Novel Modular Approach for Kinematic Modeling and Analysis of Planar Hybrid Manipulators

For customized design of a hybrid manipulator for a specific application, selection of an appropriate configuration is always a challenge. To assist in this foremost decision in data-driven synthesis, a novel approach is proposed for modular formation of quick configurations. Majorly, a unified methodology is presented for the development of respective kinematic models and differential relations for their performance analyses. This unified modular approach utilizes modular primitives to define planar hybrid configurations. Three types of primitives are introduced as modular components, and the pattern study is detailed. Modeling results from the proposed approach are also compared with normally used partial differentiation with respect to the computational efforts, streamlined modular implementations, and applicability in optimal design approaches. The comparison highlights how the column-wise approach is appropriate for modular methodology. The strategy will help a designer as a tool for analyzing several configurations. Two realistic case studies are demonstrated in this article for application of the methodology in the medical robotics field. [DOI: 10.1115/1.4050305]

Keywords: data-driven design, linkages, mechanism synthesis, parallel manipulators, robot kinematics

1 Introduction

Utilization of hybrid topologies for the design of robotic manipulators has been explored by several researchers. Motivation of this study lies in the fact that serially connected links are normally selected for large manipulability, and parallel manipulators are utilized for better positional accuracy. In planar hybrid linkages, closed loops offer structural stiffness and larger payload capacity and the serial links attribute toward larger workspace and maneuverability [1]. Various task-oriented designs deal with the requirements of both dexterous workspace and payload capacity, as in surgical applications and in development of robotic exoskeletons. Many researchers have explored the utility of hybrid manipulators [1–3] for such applications. Common choices of hybrid topologies include either serially connected parallelograms or a loop inserted in a serial manipulator at different locations. Normally, in this study, the number of degrees-of-freedom (dofs) is kept fixed a priori. No significant study is reported for adaptive modeling approach, which can assist in developing kinematic models with variations in the hybrid configurations. This study focuses at the development of a unified approach for kinematic modeling and performance analysis of any randomly generated topology from three 1-dof primitive modules. Since the structure of the hybrid manipulator is not fixed a priori, it is challenging to develop a kinematic model of a completely new topology by keeping in consideration the base location, various loops, loop locations, coupler location, and active joints. Here, the coupler denotes the basic terminology used for the four-bar mechanism, i.e., connecting rod of crank and follower. This study proposes a *modular methodology,* which utilizes three primitive modules of single-dof each. To compute the Jacobian for a planar hybrid manipulator, a modular algorithm has been designed, which involves the decomposition of a planar hybrid morphology into a set of serial linkages and closed-loop four-bar modules. This provides a general approach applicable to a large set of hybrid structures.

2 Background and Problem Formulation

The previous studies on hybrid manipulators have been reported where a basic morphology is selected a priori, and the required analyses are carried out for its optimal design and development processes. Wang et al. [4–6] worked out the formulation for a planar parallel manipulator to be implemented in a five-axis hybrid machine tool using the Newton–Euler approach. The structural stiffness analysis of a planar hybrid 2-dof, seven-bar linkage has been explored by Luo and Dal [7]. The aspect is similarly explored and utilized by Kim [8] through an optimal synthesis of a 2-dof, five-bar hybrid manipulator for low-power dissipation characteristics, a simplified dynamics, and a large structural stiffness with both the motors at base. Recently, studies have been reported to consider hybrid morphologies in task-oriented designs of medical robots. One such example is the optimal design of an exoskeleton based on four-bar mechanisms, which can reproduce the human finger motion for grasping simple objects [9]. Another is the kinematic model of a 7-dof medical hybrid manipulator, presented by the authors' group, based on the concept of dummy frames [10]. The kinematic study of hybrid manipulators with parallel linkages connected in series has also been reported in few studies [1,11]. Besides, a kinematotropic hybrid parallel manipulator was synthesized based on the displacement group theory and mathematical logic [12]. A method to synthesize planar motion has also been reported in recent studies, using a pseudo rigid-body model [13], a quasi-constant transmission ratio methodology [14], and a task-driven approach [3,15–18]. The task-driven approach is further utilized to animate the coupler motions of four-bar or six-bar linkages

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