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Technical note

Error modeling and sensitivity analysis of a hybrid-driven based cable parallel manipulator

Bin Zi [a,b,c,*], Huafeng Ding [c,d], Xia Wu [b], Andrés Kecskeméthy [c]

[a] State Key Laboratory of Robotics and System, Harbin Institute of Technology, 150080 Harbin, China
[b] School of Mechanical and Electrical Engineering, China University of Mining and Technology, 221116 Xuzhou, China
[c] Chair of Mechanics and Robotics, University of Duisburg-Essen, 47057 Duisburg, Germany
[d] Robotics Research Center, Yanshan University, 066004 Qinhuangdao, China

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ABSTRACT

This paper deals with the error modeling and sensitivity analysis of a hybrid-driven based cable parallel manipulator (HDCPM). The HDCPM has the advantages of both cable parallel manipulator and hybrid-driven planar five-bar mechanism. Kinematics analysis and error modeling are performed based on closed loop vector conditions and direct differential method. The error model derived for the proposed HDCPM has the ability to account for the original errors from kinematics parameters. In addition, the sensitivity analysis is also carried out to investigate the effects of 36 error sources of kinematics parameters on the end-effector of the HDCPM. A detailed example of the sensitivity of the end-effector's position coordinates for the HDCPM is presented in order to demonstrate the validity of the error modeling and sensitivity analysis developed.

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1. Introduction

Research in the topic of cable parallel manipulators (CPMs) is highly motivated and has a very strong interest as the modern engineering demand for such manipulators is growing rapidly. The CPMs are structurally similar to traditional parallel mechanisms, but differ in which cables are used instead of rigid links, which have potential advantages in terms of simple and light-weight structure, high acceleration capability, and easy reconfigurability [1–3]. For the preceding characteristics, the CPMs play an important role in many engineering fields, such as manipulation of heavy payloads for manufacturing and cargo handling, coordinate measurement, aircraft testing, super antenna, and haptic devices [4–7].

The CPMs can be classified into two main categories, i.e. incompletely restrained CPMs and completely restrained CPMs. Incompletely restrained CPMs rely on additional constraints, such as gravity, to realize all the required degrees of freedom (DOF) but completely restrained CPMs can control all DOF with the cables only [8]. This type of technology is now well known and several studies of the CPMs have been undertaken. For instance, Rosati et al. [9] studied design of an adaptive CPMs. Hassan and Khajepour [10] showed that a geometrical and systematic approach is intended for use as a convenient tool for cable tension analysis during design. Flatness-based trajectory tracking control for a kinematically undetermined three-cable suspension manipulator has been investigated by Heyden and Woernle [11]. Due to cable slippage on the drum, Baser and Konukseven developed an analytical method for predicting the transmission error [12]. Different aspects like time optimal trajectory tracking [13], workspace [14–16], control with positive tensions [17], and design of a new CPMs for large-scale manipulation [18] were also investigated extensively.

In recent years, the CPMs are finding increased use in a wide variety of modern engineering applications. Therefore, they are required not only for operations with high accuracy and high payload, but also for output with greater flexibility, which can change the law of output motion quickly and conveniently [19]. Nevertheless, the existing research on the drive system of the CPMs usually uses the low power controllable motor [20]. The low power controllable motor can not directly drive the high-loading CPMs due to the restrictions of power and torque. Hence, it is necessary to carry out for a new-type drive system for the CPMs. The hybrid-driven planar five-bar mechanism (HDPM) is a kind of machine whose drive system consists of a constant velocity (CV) motor and a servomotor [21–24], which is also a closed-loop linkage manipulator [25]. The CV motor provides main power and motion required; however, it lacks flexibility. On the other hand, the servomotor acts as a motion regulation device which suffers from the limited power

* Corresponding author at: School of Mechanical and Electrical Engineering, China University of Mining and Technology, 221116 Xuzhou, China.
Tel.: +86 18752148065; fax: +86 516 83590708.
E-mail address: binzi.cumt@163.com (B. Zi).

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Nomenclature

m	mass of the end-effector
g	acceleration due to gravity
b	side length of three pillars distributed in triangle
h	height of the cable pillar
a	distance between the joint A and the bottom of the cable pillar
L_0	length of the total cable
L	distance between cable pillar and end-effector
I	length of the Link AB
de_c	position error of the joint C
dq_c	error sources for kinematics parameters of the HDPMs
Jc	Jacobian matrix of the three groups of the HDPMs
de_0	position error of the end-effector of the CPM
dq_0	error sources for kinematics parameters of the CPM
J_0	Jacobian matrix of the CPM
de_L	length error of the cable between the pulley center and the end-effector
dq_L	12 error sources
J_L	Jacobian matrix of the driven cable
de	position error of the end -effector
dq	36 error sources for kinematic parameters
J	Jacobian matrix of the HDCPM
S	local sensitivity
$\bar{S}$	global sensitivity
V	volume of the overall workspace
S_k	sensitivity coefficient

capacity and high cost. The HDPM can, therefore, take the advantage of the complementary characteristics of both motors to generate a programmable range of highly nonlinear output motions with high power capacities at low costs [26]. On the other hand, structure synthesis can generate different types of mechanisms with specified number of links and degrees of freedom, and it is a systematic and efficient method for the design of mechanisms [27]. In this investigation, the design of a hybrid-driven based three-cable parallel manipulator (HDCPM), which combines the HDPM with the CPMs, is presented on the basis of theories of mechanism structure synthesis [28].

The geometric error is an utmost important consideration factor when designing a machine tool or robot manipulator [29]. The actual kinematic parameters of the manipulator deviate from their nominal values, which are referred to as kinematic errors, and the kinematic errors would result in the end-effector errors if the nominal kinematics were used to estimate the position of the manipulator [30]. Due to the above problems, kinematic parameter estimation technique, and kinematic modeling and calibration is an effective way to improve the absolute accuracy of the manipulator [31–33]. On the basis of the error modeling, it is expected that the model enables the designer to clarify those errors affecting the uncompensable position errors and they thereby should be eliminated or at least minimized with the aid of sensitivity analysis [34,35], and sensitivity analysis plays an important role in dynamic analysis of the system [36].

In this paper, aiming at a class of HDCPM, which combines the HDPM with the CPM in a way to provide a solution for moving heavy objects with high efficiency and high-performance, explicit expressions of error mapping functions in terms of position have been formulated thanks to closed loop vector chain and direct differential modeling strategy. In this investigation, a comprehensive and multifunctional error model is systematically defined to incorporate properly all possible geometric errors into a mathematic model so that it can meet the requirements for the tolerance design, assembly and kinematic calibration. Additionally, sensitivity analysis of the HDCPM is also carried out.

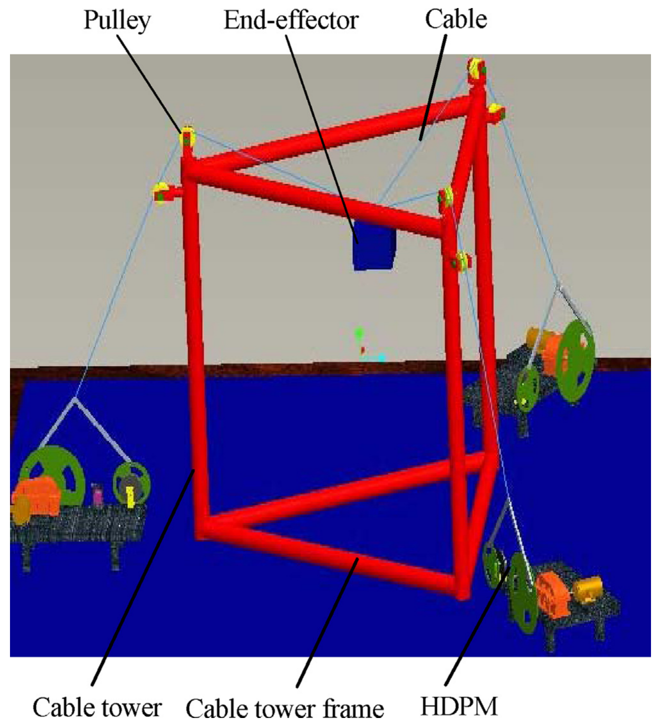

Fig. 1. Three-dimensional model of the HDCPM.

The remainder of this paper is organized as follows: Section 2 describes the design model of the HDCPM. Then, mechanics analysis and error modeling of the HDCPM is described based on the differentiation of kinematic equations in Section 3. Sensitivity analysis of the HDCPM is provided in Section 4. In Section 5, illustrative simulation studies highlight its performances. Finally, conclusions and future studies are summarized in Section 6.

2. Mechanism description

Fig. 1 presents the three-dimensional design model of the HDCPM with three translational motions. For each cable, one end is connected to the end-effector, the other one rolls through a pulley fixed on the top of the relative cable tower and then is fed into the HDPM. The HDCPM comprises of two modules: (1) the CPM consisting of three-cable tower, cable tower frame, three cables, pulley struts, pulleys, girder, cargo (i.e. end-effector); (2) three groups of HDPMs containing three-phase asynchronous motors, servomotors, reducers and double crank five-bar linkage; the asynchronous motors are connected using the pulley transmission mechanisms, while the servomotors and the reducers are linked by couplings. At the same time, the pulley transmission mechanisms and reducers are joined to the double crank planar five-bar linkage. The double crank planar five-bar linkage is made up of a large crank disk, a long connecting rod, a small crank disk, and a short connecting rod. Moreover, each cable tower is equipped with a cable guide pulley, and the radius of each pulley is assumed to be zero.

A simple kinematic sketch of the HDCPM structure model with the associated coordinate systems are depicted in Fig. 2. At the bottom of one cable tower, a global coordinate system ($OXYZ$) is established. The end-effector has location coordinates $G(x,y,z)$. The distance between each cable tower top $P_i(x_i,y_i,z_i)$ and the end-effector (load) is L_i (i = 1, 2, 3). The three cable towers have the same height and are arrayed in a triangle on the cable tower frame.

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