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Design, analysis and control of a winding hybrid-driven cable parallel manipulator

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ABSTRACT

This paper is related to the design, analysis and control of a winding hybrid-driven cable parallel manipulator (WHCPM). The WHCPM has the advantages of both cable parallel manipulator and hybrid-driven planar five-bar mechanism. Design of the WHCPM is explained, and the structure static analysis is carried out by using finite element method. Dynamics and payload capability of the WHCPM are studied. The WHCPM prototype is built for precision tracking experiments. To evaluate the manipulator design, the dynamic control compensation is performed on the basis of the conventional PID controller and the adaptive fuzzy sliding mode controller. The simulated and experimental results are reported and the tracking performance of the WHCPM is significantly improved by applying the proposed control technique in comparison with the performance when applying the conventional PID controller.

1. Introduction

In the last two decades, cable parallel manipulators (CPMs) have been studied by many researchers and are employed in various applications [1,2]. The CPMs employ cables in place of rigid-body extensible legs to support and manipulate the end-effector, and have a parallel configuration [3,4]. The CPMs possess the advantages of large reachable workspace, low inertia, high acceleration capability, economical construction, and maintenance [5–7]. Given their attractive properties, the CPMs have widely used in many engineering fields, such as video capture of sporting events [8–10], large spherical radio telescopes [11], ultrahigh speed robot [12], access to remote locations, and interaction with hazardous environments [13], and robot rehabilitation [14,15].

More recently, high performance operation of the CPMs is an important task 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 [1]. The hybrid-driven planar five-bar mechanism (HDPM) is a kind of machine whose drive system consists of a constant velocity motor and a servomotor [16,17]. To realize highly nonlinear output motions with high power capacities at low costs, according to theories of mechanism structure synthesis [18], a hybrid-driven cable parallel manipulator (HCPM)exhibits certain distinct advantages in terms of the complementary characteristics of both the CPMs and the HDPM [19]. These features combine to make the drive system a good alternative to existing manipulators, in particular in modern industrial applications [20,21]. Authors have performed comparative study of kinematics and dynamics of the CPMs with and without HDPM [19], and error modeling and sensitivity analysis have been reported in [21]. However, due to the fixed length of cable connected structure, the workspace of the HCPM is mainly limited [19]. Based on the HCPM, an improved HCPM, i.e., the winding hybrid-driven cable parallel manipulator (WHCPM) with four cables was designed to enhance the performance of the HCPM, and preliminary simulation results of the kinematics and control system using fuzzy compensator are presented [22].

It is well known that dynamic performance has a great impact on the operation of the manipulator [23,24]. In order to accelerate the WHCPM from rest, glide at a constant end-effector velocity, and finally decelerate to a stop, a complex set of torque functions must be applied by the joint actuators. One method of controlling the WHCPM to follow a desired trajectory involves calculating these actuator torque functions by using the dynamic equations of motion of the WHCPM. To meet the requirement of industry applications, a certain control precision is necessary [25]. However the WHCPM is a complex nonlinear multivariable system with strong nonlinearity, time-varying characteristics and unknown disturbances, such as payload variation, external disturbances. In addition, owing to the changes in cable length and joint

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Nomenclature

l_i	length of the links
S_i	length of the cables
θ_i	angles between links and x'-axis
r	radius of the roulette wheel
Φ	rotation angle of the roulette wheel
E_p	gravitational potential energy
E_k	kinetic energy
τ_{i1}	torque of constant speed motors
τ_{i4}	torque of servo motors
$e(t)$	angular displacement error
θ_d	expected angular displacement
Θ_i	adaptive parameter of the fuzzy system
$V(t)$	Lyapunov function
G	static Jacobian matrix
J	kinematics Jacobian matrix
Δp	position deflection
PI	payload index
λ_F	Lagrange multiplier
V	volume of the overall workspace

force, the constant velocity motor of the HDPM can lead to the velocity fluctuation. Due to the lack of a control mechanism in the constant velocity motor, the velocity fluctuation cannot be attenuated by the constant velocity motor itself, yet can be propagated to the servomotor, and further to the end-effector of the WHCPM. All these characters make it very difficult to achieve good system performance, and the control problem of the nonlinear systems becomes more challenging [26–28].

As compared with linear systems, the study of nonlinear control systems is imperfect. In order to reduce the effect of nonlinear uncertainties, many approaches for nonlinear systems are introduced including nonlinear adaptive control, sliding mode control, backstepping, neural network control, fuzzy logic control, robust model predictive control and so on [29–33]. Fuzzy logic has been considered to be an efficient and effective tool to manage system uncertainties since the seminal paper of Zadeh, and fuzzy controllers using fuzzy if-then rules are able to effectively incorporate nonlinear properties and unmodeled effects into its basic design [34]. Fuzzy logic control with adaptation has been utilized to learn unknown dynamics of nonlinear systems while relaxing the linear under the assumption of unknown control parameters. Model-free fuzzy logic control schemes [35] or modeling and learning capabilities of neuro-fuzzy networks [36]can efficiently eliminate or minimize both external disturbances and approximation errors with many applications [37–39]. In view of this, aiming at the strong nonlinearity, time-varying characteristics and unknown disturbances of the WHCPM system, an adaptive fuzzy sliding mode controller is designed for the precision trajectory tracking of the WHCPM closed-loop control system, and the corresponding results are compared with an existing PID controller.

The goal of this paper is to present the development and demonstration of a mechatronic systems design for the WHCPM system for high payload and high-performance output motion throughout the entire workspace. The main contribution of this study includes three aspects: 1) Design and implementation of the WHCPM with three cables are presented, 2) Dynamics and payload capability of the WHCPM are studied and the structure static analysis is carried out additionally, 3) The effectiveness of the proposed scheme is verified through experimental studies on trajectory tracking operation of the WHCPM system prototype. This paper is organized as follows. Section 2 introduces the issues involved in the design of the WHCPM. In addition, the structure static analysis of the WHCPM is studied. Section 3 covers the kinematics and dynamics of the WHCPM. Motion control system design of the WHCPM is provided in Section 4. Both simulation and experimental results are presented and discussed in Section 5. Section 6 concludes this paper.

2. Manipulator design

The WHCPM comprises of two modules: 1) the CPM consisting of three-cable tower racks, three cables, pulley struts, pulleys, girder, cargo (i.e. end-effector); 2) three groups of winding hybrid-driven planar five-bar mechanisms (WHDM). In order to expand the workspace of the HCPM and improve its work performance [19], we put forward a WHDM. The WHDM consists of pedestal, constant speed motor, servo motor, speed reducer, five-bar linkage, and the winch. The constant speed motor drives a crank with reduction gear, and the servo motor drives another crank by using a belt transmission. The connection between the cranks and the links is a revolutepair. The center of the winch is fixed on the pedestal and the five-bar linkage connects with the winch by an output point on five-bar, so that the winch can realize the circular motion.

The cables are attached to an end-effector which is considered as a point mass. The WHCPM suspends an end-effector with three cables and restrains all motion degrees of freedom for the object by utilizing the cables and gravitational force when the end-effector moves within the workspace [11]. For each cable, one end is connected to the end-effector, and the other one rolls through a winch fixed on the top of the WHDM. The cables can be shrunk and released unlimitedly through the winches, which will be easier to control. The developed WHCPM system prototype is illustrated in Fig. 1.

The WHCPM has been made according to applicable design rules and standards of the machine design. In order to study the stress distribution and the mechanical properties of each part, the finite element analysis should be done, so as to optimize the physical structure parameter of WHCPM each part. The results of the FEM analysis can be utilized for the visualization of the WHCPM deformations [40].

Firstly, the materials of the WHCPM are defined. The materials of cable tower racks and five-bar linkages areQ. 345 structural steel, whose tensile strength is around630Mpa. The cable is seal type rope, which is made of 304 stainless steel. The diameter is 3 mm, and its tensile strength is 1570 MPa.

The whole structure is meshed into 45548 elements. There are a total of 107112 nodes. The weight of the end-effector is 20 kg. The static position of the end-effector is defined at the central of the workspace. The angles between the three cables are same, and the angle between cable and the horizontal plane is 30°. According to the

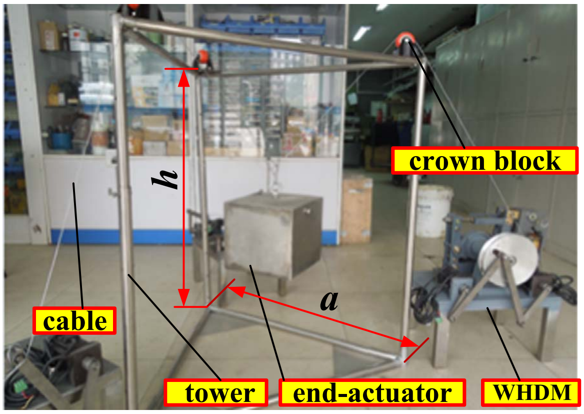

Fig. 1. The prototype of the WHCPM.