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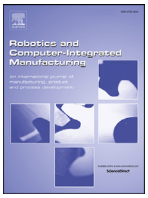

Full length Article

Geometric design optimization of an under-actuated tendon-driven robotic gripper

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ABSTRACT

The design optimization of a robotic gripper is of utmost importance for achieving a stable grasp behaviour. This work focuses on analysing the optimal design of an under-actuated tendon-driven robotic gripper with two 3-phalange fingers and a geometric design optimization method is proposed to achieve a stable grasp performance. The problem has twenty-two design variables, including three phalange lengths, three phalange widths, three radii of joint mandrels, a palm width and twelve route variables for allocation of six pulleys. First, the mathematical model between the active and contact forces is expressed in relation to the geometric dimensions of the robotic gripper. Second, the geometric model of transmission characteristics determined by the tendon routes for reducing the resistance is generated. Next, three objective functions and multiple geometric constraints are derived and integrated into two fitness models. Finally, the genetic algorithm is applied to addressing the optimization problem. Practical experiments are performed as well to validate the proposed approach. The approach is universal for optimizing any conventional under-actuated tendon-driven gripper.

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1. Introduction

The robotic grippers are required to be all-purpose and capable such as to perform stable grasps and manipulations in unstructured environments. High cost and high complexity design cannot enable robotic grippers to be refined into products. To moderate these limitations, researchers have proposed under-actuated robotic grippers with tendon-driven mechanisms (TDMs) [1–3]. Moreover, two-finger robotic grippers with single actuator are prevalent in research topics and industrial applications because of effective grasping capabilities, the mechanical simplicity and low cost [4,5]. However, robotic gripper design is a very complicated process involving modelling with many parameters [6]. The manipulation performance of an under-actuated gripper significantly depends on the design rather than the control method [7,8]. Thus, it is essential for presenting a novel versatile optimization design for two-finger grippers with TDMs so that the optimized gripper can realizing stable grasps in household and office environments.

A stable grasp is that the grasped object can withstand a range of disturbance from external forces or torques and keep the static equilibrium state [2]. It is well-known that performing a stable grasp is the most important target of gripper design. In order to achieve this target, an under-actuated tendon-driven gripper has to be optimized in the design phase. Specifically, a stable grasp should not result in an ejection phenomenon illustrated by [9]. Since all the joints driven by an active tendon are coupling dependently for each robotic finger, the ratio of the contact forces exerted on an object cannot be changed during the period of run-time. A robotic gripper may eject a grasped object and lead to a roll-back phenomenon on condition that an under-actuated robotic hand is designed incorrectly [10]. Moreover, if the grasped object can withstand a big range of disturbance from the external force/torque, it means the gripper can generate enough forces and torques to resist these disturbances as this equilibrium state is described by the resultant force and torque functions such as $\sum \boldsymbol{F} = 0$ and $\sum \boldsymbol{T} = 0$. The grasping stability is considered as a pre-condition to optimize the dimensions of grippers for the gripper to manipulate objects with a big size range. Indeed, the dimension of a gripper has an important effect on the contact force distribution [11].

A tendon route for an under-actuated robotic gripper with TDMs must be designed and optimized carefully such that forces performed on an object are controlled and the resistance of the restoration motion keeps as low as possible. The tendon-route problem is formulated as an optimization problem of the pulley allocation. The optimization of tendon routes can improve the grasping capability.

This work proposes a new practical design approach to optimizing the dimension parameters of an under-actuated robotic gripper and tendon routes based on genetic algorithm by taking account of geometric constraints. Unlike the other related works, this paper focuses on de-

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sign optimization of an under-actuated gripper with TDMs that aims at enhancing the grasping performance for the gripper by adjusting the geometric parameters. The gripper has twenty-two design variables, including three phalange lengths, three phalange widths, three radii of the joint mandrels, a palm width and twelve route variables for allocation of six pullyes. During the course of optimal design, several performance indices are involved, such as the grasping stability, transmission ratio of forces/torques. First, the mathematical model between the active force and the contact forces is extracted to determine the dimension parameters of a gripper. Second, a mathematical model is built to route the tendon with the lowest amount of resistance. Next, two separate optimization processes are presented in detail for the gripper design where three objective functions and multiple geometric constraints are derived and integrated into two fitness models. Finally, the genetic-based optimization algorithm is applied to optimizing the geometric parameters for the stable grasp behaviour and to enhance tendon routes by addressing the layout of pulley allocations. Practical experiments are performed as well to validate the proposed approach.

The rest of the paper is organized as follows. The related works are briefly reviewed in the next section. Design requirements and variables are proposed in Section 3. Section 4 builds the models of force/torque transmission between an actuator and fingers and provides the geometric analysis of the tendon routes. Section 5 constructs the optimization formulation with respect to the models given by the above section. The detail description of the optimization approach and the optimized results are illustrated in Section 6. Section 7 describes the practical grasping experiments. Section 8 gives a conclusion for the proposed framework.

2. Related works

This pioneering works for under-actuated tendon-driven robotic grippers and the corresponding mathematical models are briefly reviewed here. Hirose and Umetani [12] demonstrated the capabilities of an under-actuated tendon-driven robotic hand. The under-actuated mechanism has been utilized in most of robotic hands, such as RTR2 Hand [13], SDK hand [14], and Velo gripper [15], Willow Garage hand [16], robotic gripper with soft surfaces and underactuated joints [17], GR2 Gripper [4], Soft-touch gripper [18]. In addition, there exist many classical publications describing the kinematic and dynamic models regarding an under-actuated tendon-driven gripper. Tsai et al. [19] have established the mathematical model regarding the kinematic structure of tendon-driven robotic mechanisms by the graph theory. The identification and enumeration of the kinematic structure of tendon-driven robotic mechanisms were introduced using a pseudo-triangular structure matrix by [20]. Ou and Tsai [21] proposed a methodology of driving design equations regarding kinematic synthesis of tendon-driven manipulators based on isotropic transmission characteristics. A tendon-driven mechanism (TDM) with active and passive tendons could be grouped into several classes by kinematic analyses, which was presented by Ozawa et al. [22]. However, the prior works do not present the relation between the active force and the contact forces according to the kinematic structure of TDMs and also do not present an approach to calculating the Jacobian of the structure of tendon-driven mechanism using the specific parameters.

The representative optimization methods are given for the under-actuated gripper design. The non-dominated sorting genetic algorithm version II (NSGA-II) is adopted to optimize the force extracted by the robot gripper on the surface of a grasped rigid object in [23]. Datta et al. [24] used multi-objective evolutionary algorithm to optimally calculate the dimensions of links and the joint angle of a robot gripper. Backus and Dollar [25] presented the optimization design approach of an underactuated robotic gripper by comparing the grasping performances of the cylindrical fingers and the single joint fingers. Ciocarlie et al. [26] built a function determining the size range of objects to optimize the links of the gripper. The dimension of robotic gripper was optimized via teaching-learning-based algorithm provided by [11]. The dimension optimization of the robotic gripper was presented by Dollar and Howe [27], depending on the grasping scenarios. Since it is unknown that the number and route of tendons have effects on robotic grasp quality, Inouye et al. [28] utilized a novel computational approach to quantifying grasp quality by optimizing positions of joint centres and a tendon route. Gosselin et al. [29] optimized the route of the active tendon routes by calculating the contact forces for a given configuration. The optimized method, which is based on the line constraint and the plane constraint, was proposed by Treratanakulwong [30]. Ciocarlie et al. [31] provided an approach to optimizing the tendon route such as to make the moment arms be well controlled.

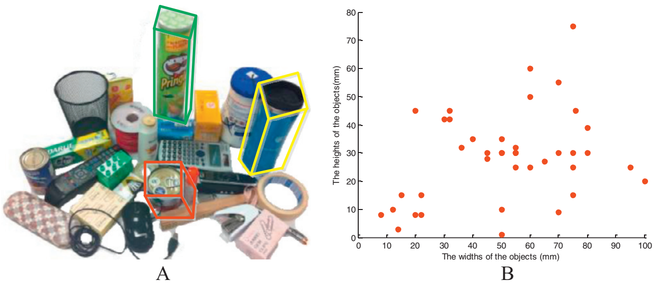

Fig. 1. Objects enclosed by bounding boxes (A) and the dimensions of a set of objects approximated by the dimensions of bounding boxes (B).

3. Desired outcome

3.1. Design requirements

The main design requirements of an under-actuated two-finger gripper with TDMs are set as follows, so as the gripper

1. can perform a stable grasp.
2. can perform both the enveloping and fingertip grasp.
3. includes two 3-phalange fingers with a single actuator.
4. can return the initial state of the gripper.
5. can grasp objects with the desired maximum width and a minimum thickness. Considering the robotic application is to manipulate objects, we defined a task of picking items with a maximum width of 100 mm.

The first requirement is the most critical condition of realizing a successful grasp. As for the second and third requirements, the enveloping mode is useful for grasping bigger objects as the enveloping grasp can exert the enclosing force in case of ejecting the object. Besides, the gripper with two 3-phalange fingers provides more contact points than a gripper with 2-phalange fingers for the enveloping grasp. Indeed, the fingertip grasp is a pivotal skill for grippers, since it is performed almost as frequently as a force grasp or an enveloping grasp. The gripper cannot exert an enveloping grasp if the object to be grasped is placed on a flat surface. In this case, the gripper uses the fingertips to pick up a small object. To reduce the resistance of restoration motion [26], the tendon routes must be designed and optimized as for the fourth requirement. Considering the robotic application is to manipulate objects, we defined a task of picking items with different shapes and size but with a maximum width of 100 mm regarding the fifth requirement. In addition, the size of some daily used objects is explored and diverse objects within the desired size range are selected to be used for performance assessment. The dimensions of a set ($n = 40$) of objects, which are used in households and offices [15], are measured approximately by that of the enclosing bounding boxes, as shown in Fig. 1.

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