Design and analysis of cable-driven mechanical gripper for complex manipulation

Deyang Zhang1,*, Bo Cheng1, Zhiyong Yue2

1College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, 100022, P.R. China
2Beijing Institute of Spacecraft Environment Engineering, Beijing, 100094, P.R. China
deyang@mails.bjut.edu.cn

Abstract. This paper studies the design and analysis problem of a class of cable-driven mechanical gripper for complex object manipulations. More precisely, a new structure design of mechanical gripper with cable-driven mechanism is first proposed with details for effective object grasping. In addition, an effective method is developed to prevent overload of axial rotation torque of the gripper. Based on the designed gripper, the kinematic analysis is then carried out and the caging grasp analysis is shown.

1. Introduction

In the past few years, much effort has been paid to the researches on mechanical grippers as end-effectors for robotic manipulators in many fields, such as industrial areas, medical areas, agricultural areas and other aspects [1-3]. It is worth mentioning that most mechanical grippers for industrial manipulators are usually designed with two fingers or grippers. This simple structure is always with less compliant or less flexibility designs, so that it is always difficult to well manipulate certain soft or elastic objects [4-6]. The applicable occasions of these simple end-effectors are limited to the grasping of larger solids. In particular, with the rapid development of agricultural automation, there is a considerable need for automatic plants or fruits collection [7-8]. Moreover, the desired mechanical gripper should be suitable for grasping and for some connection parts that need to be cut, such as fruit stalks. This requirement needs an additional auxiliary mechanism to perform the cutting operation. Therefore, it is reasonable to design a desired mechanical gripper for robotic manipulation.

On the other hand, it should be pointed out that recent researches on cable-driven mechanical grippers have received much attention. This is due to the fact that the cable-driven structure can obtain considerable advantages in simple structure design, easy control approach and less weight [9-11]. In addition, since the caging manipulation is very effective when dealing with irregular objects, the grasping and caging design for grippers have been widely used in many practical applications [12-15]. As a result, when dealing with the small object grasping, the caging design can be applied with the cable-driven mechanical gripper.

Based on the above discussions, in this paper, a new design of mechanical gripper is proposed for grasp and caging manipulation with soft or small objects. Compared with traditional structure design, the developed mechanical gripper is driven by cables so that the gripper manipulation can be more effective. In addition, the clamping or cutting manipulation can also be achieved with this design. Followed by the structure design, the kinematic analysis and the caging analysis are both carried out to verify the efficient mechanical design.
The following aspects are arranged as follows. The mechanical design for gripper is introduced in Section 2. The kinematic and manipulation analysis for gripper is presented in Section 3. The simulation illustration is given in Section 4 and the conclusion of the paper is provided in Section 5.

2. Mechanical design for gripper
In this section, the mechanical design for gripper will be presented with details.

2.1. Mechanical structure of the gripper
The structure of the cable-driven gripper for manipulator is shown in Figure 1.

![Figure 1: The structure of the cable-driven gripper with open and closed configuration](image)

1--Elastic rope, 2--Guide pulley, 3--Base, 4--Screw, 5--Overload prevention device, 6--Ascending screw, 7--Hollow connecting rod, 8--Wire rope, 9--Sleeve, 10--Ratchet, 11--Spring, 12--First-level housing, 13--Second-level housing.

2.2. Work principle of the gripper
It is supposed that the base of the gripper is fixed. The open and close mechanical structure driven by the steel cable is connected with the rod. The shaft of the servo motor passes through the base and the screw is fixed and the screw is coordinated by the thread. The rotation of the shaft of the servo motor drives the screw to rotate, such that the rotation of the screw can be through the thread into the up and down movement of the screw.

The first-level shell of the mechanical gripper is hinged to the base and can be rotated around the base. The second-level and first-level shells are also hinged together and can be rotated for greater flexibility. The center of the first-level shell is connected with the screw disc through a connecting rod, the connecting rod is hinged with the shell and the screw, respectively. The inner center of the second level of the shell is connected with a cable through a reversing pulley and a rotating shaft, and the outer side of the second level of the shell is connected with the base by an elastic rope. The cable wire used for driving has been in a tight state to prevent the wires from intertwining.

When the servo motor rotates, the screw disk rises and falls, and the first-stage housing is opened and closed through the connecting rod. At the same time, the winding wire is tightened under the rotation of the rotating shaft, which drives the second-stage housing to tighten. At the lowest point, the first level of the mechanical gripper is tightened, and the second level is also tightened for achieving the purpose...
of opening and closing the mechanical gripper. The cable wire is wound on the stepped sleeve. The stepped sleeve is part of the overload-proof ratchet. The thicker part is connected to the shaft. The shaft has protruding teeth. There is an internal gear inside the sleeve, which meshes with the ratchet teeth. The ratchet teeth are connected with the spring. When the torque reaches the limit value, the spring is extended, and the ratchet teeth swing to disengage it from the teeth of the sleeve and mesh with the next tooth to achieve the purpose of limiting torque.

When the screw turns to raise the screw disc, the connecting rod props the first-stage shell apart, and at the same time, the sleeve around the cable wire turns to relax the wire rope, and the elastic rope outside the shell makes the second-stage shell open and keeps the cable wire tight.

3. Manipulation analysis for gripper

In this section, the kinematic analysis and the caging manipulation analysis for gripper will be provided with details.

3.1. Kinematic analysis of the gripper

Based on the movement requirements of the designed gripper, the manipulation workspace of the gripper is given.

Figure 2: The manipulation workspace

The slider speed \( v_{\text{slider}} \) of the gripper is defined as:

\[
v_{\text{slider}} = \frac{S \cdot \omega_{\text{screw}}}{2\pi}
\]

where \( S \) represents the lead of the screw, \( \omega_{\text{screw}} \) represents the angular velocity of the lead screw. The calculation formula of the lead of the screw is:

\[
v_{\text{slider}} = \frac{\pi d}{\tan \alpha} \cdot \frac{\omega}{2\pi} = \frac{d \cdot \omega_{\text{screw}}}{2 \tan \alpha}
\]

where \( d \) is the diameter of the ball screw, \( \alpha \) is defined as the helix angle of the ball screw.

Due to the circular symmetry of the fingers of the mechanical claw, the following kinematic analysis will use the rotation axis of the base of the first-level link as the origin of the coordinate system. Considering that the axial deformation of the wire rope is negligible and the geometric relationship of the connecting rod of the gripper, the angular velocity of the first-level can be expressed as:

\[
\omega_1 = \frac{v_{\text{slider}}}{l_{11}} = \frac{v_{\text{slider}} \cos \theta_1 \cos \theta_2}{l_{11}}
\]

where \( l_{11} \) represents the pivot length of first link, \( \theta_1, \theta_2 \) represent the angle between the middle link and the slider and the slider and the first-level link respectively. Similarly, the angular velocity of the secondary link can be expressed by

\[
\omega_2 = \frac{v_2}{l_{22}} + \omega_1 = \frac{v_{\text{liner}} \sin \theta_3 - \omega_1 l_1}{l_{22}} + \omega_1 = \frac{v_{\text{slider}} \cos \theta_1 \sin \theta_3 - \omega_1 l_1}{l_{22}} + \omega_1
\]
where $l_{22}$ represents the pivot length of second link, $l_1$ represents the length of first link, $\theta_3$ represents the angle between the wire rope and the secondary connecting rod.

Finally, the motion formula of the end of the mechanical gripper can be obtained as follows:

$$v_{end} = \omega_2 l_2 = \frac{l_{11} v_{slider} \cos \theta_1 \sin \theta_3 - v_{slider} \cos \theta_1 \cos \theta_2 l_1}{l_{11} l_{22}} + \frac{v_{slider} \cos \theta_1 \cos \theta_2 l_2}{l_{11}}$$

(5)

where $l_2$ represents the length of second link.

3.2. Complex manipulation analysis of the gripper

It is worth mentioning that the design of the gripper determines the size of the grasped object during caging manipulation. For a convex planar polygonal object, the designed gripper can grasp the object with the end of the structure or cage the object with the closed configurations. It is worth mentioning that the object will be kept hold when the shape configuration of the gripper is given constant and the stable grasping or caging conditions should be satisfied.

Figure 3 and Figure 4 depict the grasping and the caging manipulation of the designed cable-driven gripper, respectively.

![Figure 3: The illustration of grasping manipulation](image1)

![Figure 4: The illustration of caging manipulation](image2)

4. Simulation illustration

In this section, the manipulation simulation illustration of the designed gripper is given.

The simulation is carried out with SolidWorks and it can be seen from Figure 5 and Figure 6 that the designed gripper can well achieve the manipulation task.
5. Conclusions
In this paper, the design and analysis for cable-driven mechanical gripper for object grasping and caging manipulations is concerned. The cable-driven mechanical structure together with the design of avoiding overload of axial rotation torque is proposed for the gripper. Furthermore, the complex manipulation analysis is given and the simulation results are given to show the correctness of the designed cable-driven mechanical gripper.

References
[1] Montambault, Serge, and Clément M. Gosselin. “Analysis of Underactuated Mechanical Grippers.” Journal of Mechanical Design, vol. 123, no. 3, 2001, pp. 367–374.
[2] Monkman, Gareth J., et al. Impactive Mechanical Grippers. 2007, pp. 75–159.
[3] Verotti, Matteo, et al. “A Comprehensive Survey on Microgripp ers Design: Mechanical Structure.” Journal of Mechanical Design, vol. 139, no. 6, 2017, p. 60801.
[4] Lanni, Chiara, and Marco Ceccarelli. “An Optimization Problem Algorithm for Kinematic Design of Mechanisms for Two-Finger Grippers.” The Open Mechanical Engineering Journal, vol. 3, no. 1, 2009, pp. 49–62.
[5] Pipattanasomporn, P., and A. Sudsang. “Two-Finger Caging of Nonconvex Polytopes.” IEEE Transactions on Robotics, vol. 27, no. 2, 2011, pp. 324–333.
[6] Schroefler, Andreas, et al. “An Automated Design Approach for Task-Specific Two Finger Grippers for Industrial Applications.” 2019 IEEE International Conference on Robotics and Biomimetics (ROBIO), 2019, pp. 184–189.
[7] Tedford, J. D. “Developments in Robot Grippers for Soft Fruit Packing in New Zealand.” Robotica, vol. 8, no. 4, 1990, pp. 279–283.
[8] Manochithra, V., and S. Karthika. “Design of Robot for Scrambling on Tree and Clutching Fruit Using Foundary Design.” International Journal of Scientific Research in Computer Science,
[9] Xiong, Ya, et al. “Design and Evaluation of a Novel Cable-Driven Gripper with Perception Capabilities for Strawberry Picking Robots.” 2018 IEEE International Conference on Robotics and Automation (ICRA), 2018, pp. 7384–7391.

[10] Bohg, J., et al. “Data-Driven Grasp Synthesis - A Survey.” IEEE Transactions on Robotics and Automation, vol. 30, no. 2, 2014, pp. 289–309.

[11] Bosscher, P., et al. “Wrench-Feasible Workspace Generation for Cable-Driven Robots.” IEEE Transactions on Robotics, vol. 22, no. 5, 2006, pp. 890–902.

[12] Voglewede, P. A., and I. Ebert-Uphoff. “Application of the Antipodal Grasp Theorem to Cable-Driven Robots.” IEEE Transactions on Robotics, vol. 21, no. 4, 2005, pp. 713–718.

[13] Tian, Li, et al. “Nature Grasping by a Cable-Driven under-Actuated Anthropomorphic Robotic Hand.” TELKOMNIKA Telecommunication Computing Electronics and Control, vol. 17, no. 1, 2019, pp. 1–7.

[14] Gouttefarde, M., and C. M. Gosselin. “Analysis of the Wrench-Closure Workspace of Planar Parallel Cable-Driven Mechanisms.” IEEE Transactions on Robotics, vol. 22, no. 3, 2006, pp. 434–445.

[15] Hong, Huajie, et al. “A Review on Topological Architecture and Design Methods of Cable-Driven Mechanism.” Advances in Mechanical Engineering, vol. 10, no. 5, 2018, pp. 1–14.