Force Closure Analysis for an Underactuated Robot Gripper

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Abstract. The force closure properties of the underactuated forging robot grippers are analyzed. The gripping contact forces distributed between the interface of the tongs and the work-piece are considered as an equivalent resultant force whose contact model is friction point contact, and must meet force closure equations. Then the operation theory of N robot fingers to grasp an object can be used for the analysis of the force closure and the calculation of contact forces. Based on the configurations of heavy duty grippers, where the position distribution of the resultant contact forces is optimized, the iterative algorithm of linear constrained gradient flows is used to optimize the contact forces and calculate the gripping force. The force closure properties for different forging robots and in different operation conditions and mechanisms are analyzed. Simulation and experimental results demonstrate the effectiveness of the optimization method.

Introduction

Heavy forging robots are special industrial operational robots, which have more than six degrees of freedom, and need several cylinders or hydraulic motors to cooperate to drive one action. Because of their huge sizes and heavy loads, the safety and reliability of the end effects is especially important. The gripper is the interface between the forged work-piece and the forging robot, which is the key part to ensure safety and reliability. Most grippers installed on forging robots are designed to be mechanical two ‘V’-shape symmetrical-finger grippers, which are usually underactuated mechanisms for the two uncontrolled tongs. Therefore the contact status of forging robot grippers are more complex than dexterous robotic hands to grasp an object, and the contact area between the two tongs and the object is usually a surface or a line, which leads to the contact status may be changed indefinitely to meet the requirement of force-closure. Though it is ‘simple’ to grip an object than dextrous robot hands for its only one driving system and can’t control its contact points precisely, few people studied their force-closure properties and optimization methods of heavy forging robot grippers. Its loading and gripping capacity is usually estimated by experiences. However, in order to maintain the operation stability either for an object grasped by dexterous robotic hands or for a forged object gripped by a heavy underactuated robot gripper, the force closure conditions are the same: the force and the torque balancing equilibrium must be satisfied. So the research results about dexterous robot hands can be refered to analyze the contact forces of heavy forging robot grippers. And the work on manipulation of dexterous hands has shown numerous results of theoretical, design and experimental nature[1-4].

This paper considers the contact forces between the tongs and the object are active forces transformed from the hydraulic cylinder to the ‘V’-shape contact areas of the two tongs during the forging operation, and presents an equivalent friction point gripping model to grip huge heavy loads[5]. Then the optimization calculation model of contact forces is formulated based on [2], and the method of constrained gradient flows is used to determine the force closure positions and magnitudes of contact points. Based on the results of force-closure analysis of contact forces, the optimal gripping forces can also be obtained.
Equivalence of Contact Forces between Forging Robots and Dexterous Hands

As shown in Fig.1, a typical gripping mechanism of heavy duty forging robots is composed of two tongs and two four-link mechanisms with one driver. When the rod is driven by force P, the two tongs will close and may rotate around their pivots, and the heavy forging object between the tongs can be gripped. Usually, the ‘V’-shape tong is designed to rotate freely around its pivot with no active driver. It means that it is an under-actuated mechanism, which leads to the contact status is more complex than dexterous hands.

There are three contact types of forging grippers between the objects: point contact, line contact, and surface contact. If the forging robot grips round metal object with normal temperature, the contact area is usually a point or a line. If the object is with high temperature, distortion may occur, and the contact area may be a surface when gripped. The dynamic contact model to determine which area is contated is quite complex. However, according to the compounded and decompounded rule of a force vector, the distributed forces of the contact area between the tongs and object can be composed as a resultant force. The composed method can be expressed as shown in Fig.2. Suppose that the line distribution of the normal contact forces (stresses) along the length direction of the tong is a function $p(x)$ of length $x$, then its resultant force is $F_R$ with the force action position at $\bar{x}$, where

$$F_R = \int_0^L p(x)dx, \quad \bar{x} = \int_0^L xp(x)dx / \int_0^L p(x)dx,$$

Surface distribution of the contact forces can be composed as a resultant force by the same method, where the integral cell is a differential surface $dS$.

When the gripped object is a square, the resultant forces of the gripping operation can be simplified as two or four friction point contact models. When the gripped object is a round cylinder, the gripping force must be exerted large enough and the object has to be constrained by the ‘V’-shape interface surface can the object be gripped. So the contact areas are four slant surfaces between the tongs and the forged work-piece, and the gripping and contact model between the object and the two ‘V’-shape tongs can be simplified as the four resultant forces with friction point contacts. For the forged work-piece, the gripping manipulation is the same as the dexterous robot hands to grasp an object. So the force and the torque equilibrium must be satisfied.

By the equivalent transformation, the contact stresses on the gripping interface surface don’t need to be calculated directly, and the operation theory from the research results of multi-fingered hands can be used to analyze the force-closure properties and optimization of contact forces of heavy forging grippers.
Take the forging robot to grip a round cylinder as an example, the gripping contact forces can be considered as the four resultant forces to grip the object with four friction point contacts. The calculation method of contact forces is introduced in [5].

Contact Force Closure Properties of Heavy Forging Robot Grippers

Now consider the forging robots gripping the heavy work pieces. The simulation is a 3 tons forging robot to grip a steel cylinder with 1.915T and an 80 tons forging robot to grip an 80T steel cylinder. **Distribution of force-closure.** Consider that the position of the four contact points may be changed along the direction of contact length, the results of simulation calculation show that when the tong is on different positions, not all the contact positions along the direction of contact length can meet the force-closure conditions. For the 3T forging robot, the effective gripping length of the tongs is 460mm. If define the position that the surface through the two pivots of the tongs is vertical to the floor as 0°, now let the forging robot gripping an object and keeping in horizontal direction, and let the gripper rotate from 0°~90°. At any given angle, a fixed acting point is set on each tong, and the other two contact points will be iteratively searched along the direction of contact lines according to the force-closure conditions, the number of iterative calculation is 225, then we obtain the distribution of contact points of force-closure which is shown in Fig.3. It shows that the trend of the numbers of contact distribution meeting force-closure gripping are increasing gradually and then decreasing, when the rotating angle is from 10° to 20°, the points of force-closure are the maximum, and at 90° are the least.

When the distribution is changed, the optimal contact forces and driven force also are changed. So at any given position, the more the numbers of force-closure contact points, the more uncertain the magnitude and distribution of contact forces are. It makes against the stable gripping by control the driven force of the gripping cylinder. **Positions of force-closure.** For the underactuated tongs, when the gripper grips an object and rotate $\alpha$, after the above distribution analysis, it shows that there are lots of distribution status meeting force-closure conditions. But by the limit of driven power system and mechanical constraints, the distribution of contact points to stably grip an object is unique at any operation moment. For the gripper with totally underactuated tongs, because of its indefinite energy distribution, the iterative searching algorithm is quite complex. In the past work[5], the simulation has been assumed some preconditions such as kinematic constraints (at 0 or 90° position) or geometrical constraints (the position and orientation of the gripper at any moment) are known for the constrained tongs. When the contact status is changed dynamically, the objective function is to minimize the summation of all the four normal forces, and each contact force meets the friction cone constraint. Then the optimal contact point distribution with minimal driven power can be obtained. However, for the under-actuated gripper, the tongs of the gripper are under-constrained, and the objective function of the under-constrained tongs must add two additional subjected equations.

Suppose that the gripper gripping a forged object can keep on horizontal direction all the time during the forging operation, and let the gripper rotate continuously in lower speed. The calculation results of the distribution of the contact points of the underactuated tongs are shown in Fig.4 a) and b). It shows that the optimal distribution of the force-closure contact points is changing when the gripper rotates from 0~360° continuously. It shows that the positions of the contact points may change greatly in some angle ranges, and the other angle ranges may change linearly from. When passing 180°, the contact status of the top and down tong may exchange, one contact point on the top tong may move to the opposite side, and the one on the down tong also move to the opposite side, and on range 150~210°,
some fluctuation occurs. It also demonstrates the complexity of the distribution of contact points. Changing tongs with other spanning angles, the distribution trend is similar to Fig.4.

The optimal gripping forces. After the positions of the resultant contact forces are determined, the optimal contact forces and gripping forces can be calculated according to gradient flow algorithm[5]. Fig.5 is the simulation results of the resultant contact forces that the tongs act on the object and the driving force from the hydraulic cylinder needs to provide for 3T forging robot gripping a 1.915T object and 80T forging robot gripping an 80T object. Where $f_{x_i}$ and $f_{y_i}$ (i=1~4) are two tangential friction forces of contact points $C_i$, $f_z$ is the normal forces, $PP_{jcs}$ and $PP_{jcx}$ are the reverse contact forces of the upper and lower tongs from the tong to the object, $PP_{jc}$ is the composition of upper and lower resultant contact forces, $PP_{jc}=|PP_{jcs}|+|PP_{jcx}|$, and $Power$ is the driving force exerted by servo hydraulic cylinder. For the 3T forging robot gripping 1.915T object as shown in Fig.5(a), when the open direction of the gripper is horizontal (90º), the maximum gripping force of the hydraulic cylinder is $4.1 \times 10^5$N, and in vertical direction, the required minimal driving force is $2.6 \times 10^5$N. The two driving forces at these special positions were measured in an actual 3T forging manipulator which gripped a rigid steel cylinder, keep the object with a small dropping angle, and the results are $5.6 \times 10^5$N and $4.2 \times 10^5$N respectively. The force changing trend of simulation and experimental results are very approximate. It demonstrates that the optimal algorithm is quite effective. It is just some initial experimental results and is evaluated manually, so tolerances are large. Now a one ton loading capacity forging robot prototype with whole servo-controlled hydraulic systems is being developed, where the gripping forces, speed, positions, angles and pressure can be measured and controlled in real time. And in the near future, more experiments will be done to test the force closure properties.
Conclusions
The paper considers the resultant force of each contact surface as a contact force with an equivalent friction point, and uses the operation theory of N robot fingers to grasp an object for the analysis of the force-closure properties and the optimization of contact forces. In order to obtain the closed-form solutions of contact forces, the gripping calculation model of the underactuated V-shape tongs can be simplified as a grasp with N robot fingers including four contact points. The position distribution of contact forces of heavy duty forging gripper is analyzed. Contact forces and gripping force at different positions are demonstrated by simulation and experiment. This is helpful for the optimal design and online control of the grippers for large-scale heavy forging robots.

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