Optimal Design for Heavy Forging Robot Grippers

Qunming Li\textsuperscript{1,2, a}, Qinghua Qin\textsuperscript{1, b}, Shiwei Zhang\textsuperscript{1, c} and Hua Deng\textsuperscript{1, d}

\textsuperscript{1}School of Mechanical and Electrical Engineering, Central South University, Changsha, 410083, China
\textsuperscript{2}State Key Laboratory of Robotics, Shenyang, 110016, China

\textsuperscript{a} liqm@mail.csu.edu.cn, \textsuperscript{b} qqh20082008@126.com, \textsuperscript{c} zsw528@163.com, \textsuperscript{d} hdeng@mail.csu.edu.cn

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\textbf{Abstract.} This paper analyzes three typical mechanisms of heavy forging robot grippers: pulling with a sliding block including short- and long-leveraged grippers and pushing leveraged grippers, and uses multi-objective evolutionary genetic algorithm to design the optimal forging robot grippers. The decision variables are defined according to the geometrical dimensions of the heavy grippers, and four objective functions are defined according to gripping forces and force transmission relationships between the joints, and the constraints are yielded by the physical conditions and the structure of the grippers. Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to solve the optimization problem. Normalized weighting objective functions are used to select the best optimal solution from Pareto optimal fronts. The Pareto fronts and optimal results are compared and analyzed. An optimal model of forging robot gripper is designed. The results show the effectiveness of the optimal design. Based on similarity theory, optimum dimensions from small scale forging grippers to large scale ones can be designed, and from model to prototype experiment to test the physical features is possible.

\textbf{Introduction}

Heavy forging robot grippers are special industrial operational robots, which can grip high-temperature work-piece from several hundred kilograms to more than 80 tons. Because of their huge sizes and heavy loads, the optimal design of the grippers is especially important. It can save huge costs and lots of delivery time by optimal design. The gripper is the interface between the forged work-piece and the forging robot, which is the key part to ensure safety and reliability. So more attentions should be given to the grippers. Most grippers installed on forging robots are designed to be mechanical two ‘V’-shape symmetrical-finger grippers, which are underactuated mechanisms for the two uncontrolled tongs, and may be considered as the simplest efficient grasping configuration. The optimization of gripping mechanisms and the method of similarity design are the main work for model design and experiments.

A lot of methods from robotic researches have been proposed to optimize multifingered robot hand grasps [1]. These methods only optimize the grasp forces, and don’t consider the fingers’ design and geometrical dimensions. Few attentions are concerned to heavy forging robot’s gripping and optimization design. The design of the two-finger forging grippers must consider multi-objective parameters of each links simultaneously. Evolutionary techniques for multi-objective optimization are currently gained significant attentions of researchers in various fields due to their effectiveness and robustness in searching for a set of trade-off solutions. Unlike conventional methods that aggregate multiple attributes to form a composite scalar objective function, EAs with modified reproduction schemes for multi-objective optimization are capable of treating each objective component separately and lead the search in discovering the global Pareto optimal fronts [2-3].

This paper aims to improve model and prototype design of forging robots, and focuses on three typical heavy forging robot grippers: pulling with a sliding block including short- and long-leveraged grippers and pushing leveraged grippers, analyzes their structure and uses multi-objective genetic algorithm to obtain the optimal design of forging robot grippers based on [4-5].
Mechanical Structures

As shown in Fig. 1, there are three typical mechanisms for heavy forging robot grippers: pushing leveraged grippers [Fig.1.a)] and pulling with a sliding block including short- [Fig.1.b)] and long-leveraged grippers [Fig.1.c)]. Each gripping mechanism of heavy duty forging grippers is composed of two tongs and two four-link mechanisms with one active driven system. When the sliding rod is driven by force $F$, the two tongs may rotate around their pivots, and the heavy forged object between the tongs can be gripped stably. Usually, the ‘V’-shape tong is designed to rotate freely around its pivot with no active driver, which can meet different shapes of workpieces. It means that it is an under-actuated mechanism, whose contact status is more complex than dexterous hands. But few researches have done on how to optimize its gripping design.

Fig. 1 Typical forging gripper mechanisms
a- Pushing leveraged gripper mechanism and geometrical dependences,
b- Short pulling leveraged gripper mechanism and geometrical dependences,
c- Long pulling leveraged gripper mechanism and geometrical dependences
Take the pushing leveraged gripper mechanism a) as an example, the design variables are depended on \(a, b, c, e, f, l, \delta\). Where \(a, b, c, e, f, l\) are dimensions of the gripper and \(\delta\) is the angle between elements \(b\) and \(c\) of the gripper. So the design decision vector is \(X = (a, b, c, e, f, l, \delta)^T\). Suppose that \(F\) is the actuation force of the cylinder, \(\phi\) and \(\beta\) are angles of links with horizontal reference lines. \(P_k\) is the gripping force exerted by fingers of robot gripper on the work piece. According to force balance equations and the geometrical relationship, the following equations are obtained.

\[
\begin{align*}
F &= R \cos(\phi), \quad R = \frac{F}{2 \cos(\phi)} \\
Rb \sin(\beta + \phi) &= P_k c \cos(\pi - \beta - \delta) \\
P_k &= \frac{Rb \sin(\beta + \phi)}{c \cos(\pi - \beta - \delta)} = \frac{bF \sin(\beta + \phi)}{2c \cos(\phi) \cos(\pi - \beta - \delta)} \\
g^2 &= e^2 + (l - z)^2, \quad g = \sqrt{e^2 + (l - z)^2} \\
tg(\alpha) &= \frac{e}{l - z}, \quad \alpha = \arctan\left(\frac{e}{l - z}\right)
\end{align*}
\]

**Optimization Problem Description**

**Objective Functions.** The definition and selection of objective functions must satisfy the forging process requirements of the forging robots. Based on equations (1)-(5), the objective functions can be evaluated as follows:

\[
\begin{align*}
f_1(x) &\text{: the function which describes the force transmission ratio between the gripper actuator and the gripper ends (tongs):} \\
\min f_1(X) &= \frac{F}{\min P_k(X, Z)} \\
f_2(x) &\text{: the function which describes the difference between maximum and minimum gripping forces for the assumed range of the gripper ends displacement:} \\
\min f_2(X) &= \left| \max_z P_k(X, Z) - \min_z P_k(X, Z) \right| \\
f_3(x) &\text{: the function which describes the shift transmission ratio between the gripper ends and the gripper actuator:} \\
\min f_3(X) &= \frac{Z_{\max} - Z_{\min}}{y(X, Z_{\max}) - y(X, Z_{\min})} \\
f_4(x) &\text{: the function which describes the length of all the elements of the gripper:} \\
\min f_4(X) &= a + b + e + c + f
\end{align*}
\]

**Constraints.** Seven constraints are considered, which refer to geometrical, physical and minimal gripping force constraints.

\[
\begin{align*}
(1) \quad &g_1(X) = y_{\min} - y(X, Z_{\max}) \geq 0 \\
(2) \quad &g_2(X) = y(X, Z_{\max}) \geq 0 \\
(3) \quad &g_3(X) = y(X, 0) - Y_{\max} \geq 0 \\
(4) \quad &g_4(X) = Y_G - y(X, 0) \geq 0 \\
(5) \quad &g_5(X) = l - Z_{\max} \geq 0 \\
(6) \quad &g_6(X) = (l - Z_{\max})^2 + (a - e)^2 - b^2 \geq 0 \\
(7) \quad &g_7(X) = (l - Z_{\max})^2 + (a - e)^2 - b^2 \geq 0
\end{align*}
\]

**NSGA-II Multi-objective Genetic Algorithm.** Genetic Algorithms (GA) are wildly used to solve different design optimization problems. The main advantage of the use of GA is that while running the GA program the full set of Pareto optimal solutions (non-dominated solutions) can be obtained.
and the designer has a full view of the possible compromise solutions. This paper uses Non-dominated Sorting Genetic Algorithm (NSGA-II) to solve the multi-objective optimum problem. Objectives \( f_1, f_2, f_3, f_4 \) are minimization functions. Multiple objectives from \( f_1, f_2, f_3, f_4 \) are combined into scalar objective via weight vector \( w_1, w_2, w_3, w_4 \). The function with largest range would dominate evolution. The combined objective function is:

\[
f(x) = w_1 f_1(x) + w_2 f_2(x) + w_3 f_3(x) + w_4 f_4(x)
\]

Based on similarity design theory, a downsizing experimental model which is similar to a heavy forging robot prototype is designed. The geometrical design variables of the model gripper using NSGA-II to optimize are constrained by the following data (length unit: mm):

\[
170 \leq a \leq 500, \quad 120 \leq b \leq 550, \quad 200 \leq c \leq 600, \quad 100 \leq e \leq 450, \\
50 \leq f \leq 500, \quad 200 \leq l \leq 700, \quad 90^\circ \leq \delta \leq 180^\circ
\]

The optimized parameters of NSGA-II are given as follows:

* Population size=200, number of generations=150
* Crossover rate=0.6, mutation rate=0.001

**Optimum Results of NSGA-II.** The Pareto fronts of \( f_1, f_3, f_4 \) are shown in Fig.2. The multiple objectives are combined into scalar objective via weight vector. Table 1 gives some model optimum results from the Pareto fronts, and according to the similarity design theory introduced above, when the model parameters are given \((\lambda_i)\), a prototype parameters are also derived. The results of the first row of table 1 is selected to be the optimal design parameters of the model gripper. Based on the optimum design parameters, a prototype is developed in our laboratory.

### Table 1 An optimum design parameters by NSGA-II with different weight vectors

|   | \( w_1 \) | \( w_2 \) | \( w_3 \) | \( w_4 \) | a(mm) | b(mm) | c(mm) | e(mm) | f(mm) | l(mm) | \( \delta \) (adian) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.375 | 0.125 | 0.375 | 0.125 | 224.8 | 190.7 | 391.1 | 110.1 | 70.36 | 339.6 | 2.472 |
| 2 | 0.125 | 0.375 | 0.125 | 0.375 | 276.4 | 158.5 | 266.7 | 189.9 | 63.56 | 388.3 | 2.160 |
| 3 | 0.25 | 0.25 | 0.25 | 0.25 | 231.8 | 210.3 | 302.7 | 134.9 | 59.46 | 380.01 | 2.785 |
| 4 | 0.125 | 0.375 | 0.375 | 0.125 | 236.4 | 238.3 | 401.9 | 58.79 | 150.9 | 415.9 | 1.810 |
| 5 | 0.375 | 0.375 | 0.125 | 0.375 | 272.2 | 232.4 | 467.0 | 95.2 | 131.7 | 419.4 | 2.151 |
| 6 | 0.125 | 0.375 | 0.375 | 0.125 | 251.1 | 238.1 | 462.7 | 85.59 | 124.1 | 400.5 | 2.771 |

**Conclusions**

This paper analyzes three typical configurations of heavy forging robot grippers, and proposes to use multi-objective genetic algorithm to obtain the optimal design for forging robot grippers. The decision variables are defined according to the geometrical dimensions and optimal force of the grippers, and four objective functions are defined according to forces and force transmission relationships, and the constraints are yielded by the physical conditions and the geometrical structures of the grippers. Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to solve the problem. Weighting objective functions are used to select the optimal solutions from Pareto fronts. An optimal model of a forging robot gripper is designed according to the results. Based on similarity design theory, from model to prototype experiment to test the physical features is possible. A prototype is developed in our laboratory.
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