Generic Automated Multi-function Finger Design

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Generic Automated Multi-function Finger Design

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Abstract. Multi-function fingers that are able to handle multiple workpieces are crucial in improvement of a robot workcell. Design automation of multi-function fingers is highly demanded by robot industries to overcome the current iterative, time consuming and complex manual design process. However, the existing approaches for the multi-function finger design automation are unable to entirely meet the robot industries’ need. This paper proposes a generic approach for design automation of multi-function fingers. The proposed approach completely automates the design process and requires no expert skill. In addition, this approach executes the design process much faster than the current manual process. To validate the approach, multi-function fingers are successfully designed for two case studies. Further, the results are discussed and benchmarked with existing approaches.

1. Introduction
This paper aims to provide a generic and reliable method for design automation of multi-function fingers for industrial robot grippers. Multi-function fingers allow the gripper to handle multiple workpieces with the same fingers.

In most industrial assembly applications, multiple workpieces are required to be handled in the assembly process. Three solutions for multiple workpiece handling are common in the robot industry.

1. To change the gripper (tool) for each assembly task. This incurs a significant cycle time penalty and consequently reduces the throughput of the workcell.

2. To use multi-gripper (or interchangeable) end-effectors [1]. These end-effectors usually have 2-3 grippers that are attached to a rotatory wrist mechanism which activates the relevant gripper for the specific task. This solution is expensive and reduces the graspable payload of the robot considerably due to the high weight of the additional grippers and interchange mechanism [1], [2].

3. To use multi-function fingers.

Designing multi-function fingers enables the robot to handle more than one workpiece without any tool-change operation. As a result, multi-function fingers play a vital role in reducing assembly cycle time and increasing workcell throughput [3]. On the other hand, the manual design of practical multi-function fingers requires a high level of skill and experience. Besides, the current manual design process consists of several time consuming iterations which may take weeks to accomplish. Thus, automating the design procedure of multi-function fingers is highly valuable for robot industries [4].

Existing approaches for multi-function finger design automation are limited to workpieces having specific geometrical properties. Therefore, in this paper, Generic Automated Finger Design 2.0 (GAFD 2.0) is proposed to automate the multi-function finger design independent of the geometrical properties of the workpieces. GAFD 2.0 is a further development of the previous version of the GAFD.
Section 2 states the relevant work in this research area and the overview of the GAFD method is presented in section 3. Section 4 describes the methodology that is utilized in this study and Results of the implementation of the proposed approach are presented in section 5. Section 6 compares the results to existing methods and section 7 concludes the contributions.

2. Relevant Work
A review of the literature reveals that few studies [1]–[3], [5]–[11] consider the importance of multi-functional fingers in robot applications and only a couple of works [7], [11] propose approaches for the design automation of multi-function fingers [4].

In [2], [3], [9] multi-function fingers are considered to be one of the significant methods for increasing throughput of the robot workcell. Causey and Quinn [3] assert that multi-function fingers are cheaper, more effective and reliable than tool changing systems and rotary wrist mechanisms.

Pham et al. [10] present a trial and error based approach to achieve multi-function fingers. Their method begins by categorizing similar workpieces into various groups. Each group contains workpieces with similar geometrical properties (e.g. shape, mass, etc.). Then, a set of fingers are designed for a group of workpieces (e.g. group A). The designed fingers are used to grasp another group of workpieces (e.g. group B). If the fingers can grasp both groups of workpieces, they are considered as the final finger design. Otherwise, the process is repeated yet this time, the initial fingers are designed for the group B workpieces and then checked against group A. In the case of failure in both iterations, the algorithm designs a set of fingers for each group.

Velasco and Newman [7] propose a CAD-based approach to design multi-function fingers for two workpieces. In the proposed method, the geometric superposition of the workpieces is determined and assumed to be the only workpiece to be handled. In [7] finger design approach, fingers are assumed to be solid blocks from which the geometry of the workpiece is subtracted. The remaining geometry forms the designed fingers. Velasco and Newman further propose an additional hypothesis for geometrically-similar workpieces.

In this hypothesis, two sections from the grasping sides (left and right) of each workpiece are extracted and a hypothetical workpiece is created by superposing the sections extracted from all workpieces. Then the hypothetical workpiece is subtracted from the finger blocks. The result is considered as the multi-function fingers design.

3. GAFD Method Overview
The current manual procedure for designing fingers requires several exhaustive and time-consuming trial and error iterations. Earlier work [12] proposed Generic Automated Finger Design (GAFD) as a successful method to automate the finger design procedure using the customized design approach. As shown in Fig. 1, the presented design procedure consists of three stages of data arrangement, grasp and finger design.

In the data arrangement stage, two parallel processes prepare the required data for executing the key process in the grasp and finger design stages:

- The first parallel process imports the workpiece CAD model and the gripper properties (i.e. gripper model, maximum finger length, maximum workpiece weight, maximum jaws stroke). Then the surfaces of the workpiece are reproduced and discretized (meshed). Based on the meshed surfaces and the element nodes, a point cloud model of the workpiece is generated. In the final step, surface-normals at each point are extracted.
- In the second parallel process, material properties of the fingers and workpiece are imported to the system. Following this, the friction coefficient ($\mu$) of the contacts are extracted and the contact model is determined based on the value of $\mu$. Then the minimum number of contact points are obtained in regard to the contact model. The grasp stage begins by randomly selecting $n$ points and generating all the possible grasp sets based on the minimum number of contact points. Then the contact wrenches of all the grasp sets are determined and the convex hull of the contact wrenches for each grasp set is calculated. The stability of the grasp sets is
verified by checking the location of the origin of the wrench space [13], [14]. The grasp sets whose origins lie inside the convex hull are considered stable and listed as feasible grasp sets.

In the next step, the minimum distance between the origin of the grasp sets and the hyperplanes of the convex hull (\(\epsilon\)) are measured. The list of the feasible grasp sets are ranked based on the value of the \(\epsilon\). The larger the value of the \(\epsilon\), the more stable the grasp set [15], [16].

In the final stage of GAFD, finger design, the grasp set with the largest \(\epsilon\) is selected and the fingertips are designed. The designed fingertips mimic the contour of the surface of the workpiece at the contact point to increase the contact area and the reliability of the fingers.

Then the bodies of the fingers are designed based on the gripper properties and the grasp types (i.e. internal and external grasp). The feasibility of the designed fingers is verified by detecting whether the grasp approach is collision-free. If the approach is free of unwanted collisions, the designed fingers are considered as feasible and CAD models are exported for the production and experimental verification [12].

4. Method
This section describes the utilized methodology in this study to automate the multi-function finger design for industrial grippers. With reference to Fig. 1, point A represents the beginning of the data arrangement and point B denotes the end of the grasp stage. The data arrangement and grasp stages used in this work are identical to those presented in the earlier version of the GAFD, as described in detail in [12].

Fig. 2 demonstrates the procedure that is employed to design multi-function fingers. This procedure begins by selecting the grasp set with the highest quality and creating fingertips based on the surfaces
of the workpiece at the contact points. This feature enables the fingertips to imitate the surface contour of the workpiece. Then, the algorithm counts the number of workpieces that are required to be handled. If the number of workpieces is more than one, the area of the projection of the fingertips’ surface (A_p) is measured and the value of the measured area is listed in a database. Then the steps in the data arrangement and grasp stages (point A to point B) are repeated for the next workpiece. The best grasp set for the second workpiece is selected from the ranked list of the feasible grasp sets.

Next, the fingertips are created based on the selected grasp sets and then the A_p of the fingertips are measured and stored in the database. This process is repeated until fingertips are created for all workpieces and the A_p of the fingertips are measured and listed in the database. In the next step, the list of A_p is sorted so the fingertip with the largest A_p stands at the top of the list and the fingertip with the smallest A_p at the bottom. For cases where the areas, A_p of two fingertips are identical, the fingertip with the smaller actual contact area (not projected) (As) stands above the other fingertip in the list.

By sorting all the fingertips, the one with the largest A_p is selected as the main fingertip. The fingertip with the second largest A_p is selected and its contact surface is located on the contact point of the main fingertip. Then the contact surface of the second fingertip is subtracted from the main fingertip. The remaining geometry of the first fingertip is considered as the main fingertip and the second fingertip is removed from the list of the fingertips area. This process is repeated until the list of the fingertips area is empty. The main fingertips are used in the next step of the process to generate the finger bodies.

**Figure 2.** Multi-function Finger Design Automation Process Flowchart of GAFD 2.0.

To check the feasibility of the multi-function fingers produced by the method, the collision detection process verifies whether the grasp approach of the fingers is free from unwanted collisions for every workpiece. If the designed multi-function fingers are found to be collision-free, CAD models of the fingers are exported to be manufactured and tested in practice. Similar to the earlier version of the GAFD, this version (GAFD 2.0) is also implemented in CATIA V5 [17] and automated by implementing the described logic with Visual Basic script [12].

**5. Results**

In this section, the results of applying the developed version of GAFD (GAFD 2.0) on two workpieces are presented. As shown in Fig. 3, the chosen workpieces are a ball (Fig. 3 (a)) and a rack gear (Fig. 3 (b, c)). To properly demonstrate the capability of the proposed approach, two different case studies are defined and the GAFD 2.0 design process (see Fig. 2) is implemented on each case study. The case study 1 consists of the ball and the gear in its first stable pose (Fig. 3 (a, b)) and in the case study 2, the ball and the gear in its second stable pose are considered (Fig. 3 (a, c)). In each case study, the presented algorithm automatically generates fingers that are able to grasp both workpieces. As stated earlier, the processes carried out in the data arrangement and grasp stages (point A to point B) are not
replicated in this work (see [12]). Thus, only the ranked list of the grasp sets is presented here as the result of the grasp stage.

![Figure 3. CAD model of the: (a) ball; (b) rack gear in stable pose 1; (c) rack gear in stable pose 2.](image)

\[A. Fingertip Design\]

Once the grasp set location is known, the finger design stage commences with the design of the fingertips. In both case studies, the ball is considered as the first workpiece and the gear as the second. However, the order of the workpieces does not affect the result. According to the design process (Fig. 2), the first step is selecting the best grasp set for the ball from the grasp set list (see Fig. 4 (a)). Then the fingertips are created in such a way that the contact surface conforms to the surface contour of the ball (see Fig. 5 (a)). To do so, a preliminarily-designed fingertip is extruded to meet the contact surface of the workpiece. As a result the contact surface of the fingertip mimics the surface contour of the workpiece.

In the next step of the process, the area of the projection of the contact surface \(A_p\) is measured and stored in a database. Then the second workpiece (i.e. the gear) is imported to CATIA and the ranked list of the grasp sets is obtained from the grasp stage. In a similar manner to the processes applied to the ball, the best grasp set for the gear is selected. Fig. 4 (b) and Fig. 4 (c) represent the best grasp sets for case study 1 and case study 2 respectively. Then the fingertips of the gear are generated and the \(A_p\) of the fingers is measured and stored in the database.

![Figure 4. Best grasp set of the: (a) ball in both case studies; (b) gear in case study 1; (c) gear in case study 2.](image)

As shown in Table 1, in the case study 1 the \(A_p\) of the ball is larger than the gear; and in the case study 2, the gear and the ball have the same \(A_p\). Thus, the actual contact surface area \(A_s\) of the workpieces are measured and the workpiece with the smaller \(A_s\) (i.e. the gear) stands at the top of the list.

The first fingertips in the list are selected as the main fingertips which are the ball-gripping fingertips for case study 1 (Fig. 5 (a)) and the gear-gripping fingertips for case study 2 (Fig. 5 (c, e)). Then the contact surface of the second workpiece is coincident with the main fingertips at the contact points. To ensure the contact surfaces of the workpieces do not fully overlap, the contact surface of the second workpiece is slightly translated towards the fingertip base along the grasp axis. Then the contact surface of the second workpiece is subtracted from the main fingertips. Fig. 5 (b) and Fig. 5 (d, f) illustrate the fingertips generated for case study 1 and case study 2, respectively.
Table 1. The area of the projection of the fingertips’ surface ($A_p$) and actual contact area ($A_s$) for the ball and the gear. Numbers with underlines represent main fingertips.

<table>
<thead>
<tr>
<th>Case Study 1</th>
<th>Fingertip 1 (right)</th>
<th>Fingertip 2 (left)</th>
<th>Ball</th>
<th>Gear</th>
<th>Selected Main Fingertip</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_p$ [mm$^2$]</td>
<td>$A_s$ [mm$^2$]</td>
<td>$A_p$ [mm$^2$]</td>
<td>$A_s$ [mm$^2$]</td>
<td></td>
</tr>
<tr>
<td>Fingertip 1</td>
<td>230</td>
<td>241</td>
<td>38</td>
<td>38</td>
<td>Ball</td>
</tr>
<tr>
<td>Fingertip 2</td>
<td>230</td>
<td>241</td>
<td>38</td>
<td>38</td>
<td>Ball</td>
</tr>
<tr>
<td>Case Study 2</td>
<td>Fingertip 1 (right)</td>
<td>169</td>
<td>174</td>
<td>169</td>
<td>169</td>
</tr>
<tr>
<td>Fingertip 2</td>
<td>160</td>
<td>165</td>
<td>172</td>
<td>172</td>
<td>Gear</td>
</tr>
</tbody>
</table>

Figure 5. Case study 1: (a) main fingertip for both fingers; (b) final fingertip design for both fingers. Case study 2: (c) main fingertip for finger 1 (right); (d) final fingertip design for finger 1; (e) main fingertip for finger 2; (f) final fingertip’s design for finger 2.

B. Finger Body Design

The next step in the finger design process is generating the body of the finger. Considering the fact that the finger body is responsible for properly connecting the fingertip to the gripper jaw, a group of parametric lines are defined as a guideline for designing the finger body. The algorithm automatically adjusts the parameters of the lines to ensure the feasibility of the design while taking the gripper properties (e.g. maximum finger length, maximum jaws stroke, etc.) into the account. Then the Sweep feature (in CATIA) is used to follow the guideline and construct the solid finger body. Fig. 6 (a) and Fig. 6 (b) respectively represent the fingers designed for case study 1 and case study 2.

Figure 6. Designed multi-function fingers for the: (a) case study 1; (b) case study 2.
C. Collision Detection

The final step in the proposed design process is verifying the feasibility of the generated fingers. The feasible multi-function fingers should be able to grasp both workpieces without incurring unwanted collisions with the workpieces. Therefore, the inbuilt collision detection module of CATIA (Clash Analysis) is employed to this end. As shown in Fig. 7, the designed multi-function fingers for both case study 1 (Fig. 7 (a, b)) and case study 2 (Fig. 7 (c, d)) are collision free and feasible. As a result, the proposed approach shows good potential for successfully designing multi-function fingers for handling multiple workpieces. The execution time to accomplish the design process for the case study 1 and 2 is respectively 1670 and 1840 seconds on a 2.7 GHz Intel i7 with 16 GB RAM running Windows.

![Fig. 7](image)

**Figure 7.** Collision detection of the designed fingers for the: (a, b) case study 1; (c, d) case study 2.

6. Discussion

This section discusses the pros and cons of the few existing approaches for the multi-function finger design automation. Further the results that are obtained in this work are benchmarks with the existing approaches.

Pham et al. [10] propose an iterative approach for producing multi-function fingers. The algorithm uses a trial and error approach to detect whether the designed fingers for a group of workpieces are able to grasp another group. While this approach is simple and easy to implement, it has the following weaknesses and limitations:

- The approach is effective only for similar groups of workpieces.
- The approach is unable to ensure a reliable grasp as the fingertips do not fully match the surface of the workpiece.
- The efficiency of the approach falls considerably with increasing number of workpieces.

In contrast to [10] method, [7] present a CAD-based approach for designing multi-function fingers. Their proposed approach consists of two complementary methods. The first method geometrically superposes the workpieces that are required to be handled and considers the superposition result as the only workpiece to be grasped. Then the superposed workpiece is subtracted from the finger blanks. The outcome of the fingers geometry should be able to grasp all the workpieces. However, this method is inapplicable for similar workpieces with different dimensions (e.g. two spheres with different radii). As a consequence, the second method is utilized to design fingers for workpieces with similar geometries. In the second method, two sections (from the right and left side) of each workpiece are extracted. Then, all the sections of the workpieces are superposed and a hypothetical object is created. The method uses the hypothetical object and subtracts it from the finger blanks. The remaining geometries are considered as the multi-function fingers. Although [7] approach is more generic than the one presented by [10], the approach suffers the following shortcomings:

- The approach encounters difficulties finding a solution for workpieces with complex geometries.
- The presented approach lacks a logical method for superposing the extracted section.
- The approach is unable to guarantee a feasible solution. For instance, a cube and a sphere with equal length and radius, respectively.
In consonance with the results of this study, the developed GAFD process for designing multi-function fingers overcomes the limitations of the existing approaches in the literature. The elaborated design process consists of the succeeding advantages:

- The approach is generic and independent of the geometrical complexity of the workpieces.
- The approach can ensure the stability of the grasp by utilizing grasp synthesis and analysis.
- The algorithm completely automates the design process.
- The approach verifies the designed multi-function fingers using a collision detection process.
- The approach has the potential to be quicker than the current manual design process.

It should be noticed that some of time-consuming processes in the manual design procedure (i.e. fingers manufacture and experimental verification) are not considered in this benchmark, thus comparing designs lead-time cannot be precise.

7. Conclusion
This paper presents the development of Generic Automated Finger Design (GAFD) algorithm for designing multi-function fingers for industrial robot grippers. The proposed approach automates the design process for multi-function fingers to overcome the complexity and lengthy lead time of the current procedure and is able to handle workpieces with complex geometries. In addition, the approach can ensure the stability of the grasp and produces fingers with a smaller foot-print in comparison to other approaches that are therefore more suitable for assembly applications.
The future work suggestions are pointed out as follows:

- Experimental verification of the designed multi-function fingers using GAFD 2.0.
- Benchmarking the performance of the multi-function fingers designed by GAFD 2.0 with other approaches.
- Optimizing the GAFD 2.0 design process to reduce lead time.
- Developing the algorithm to be able to design multi-function fingers for the combination of internal and external grasps.

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References


