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GENERIC AUTOMATED FINGER DESIGN

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ABSTRACT
Finger design automation for grippers is one of the areas of highest interest for robot industries. The few studies that have been carried out in the finger design automation research area are limited to objects with specific geometrical properties (e.g. polyhedral). This paper introduces the Generic Automated Finger Design (GAFD) method that contains the essential key processes for automatic design of reliable fingers. The proposed method is implemented on two geometrically complex workpieces and appropriate fingers are designed. The results are discussed in detail and benchmarked against existing approaches.

1. INTRODUCTION
This paper presents the Generic Automated Finger Design (GAFD) method for design automation of customized fingers of industrial grippers for robots. Finger design automation of industrial grippers is one of the most important topics in robotics. Fingers for grippers are important for the success and overall performance of the workcell. As a consequence designing robust and reliable fingers is of the highest significance in the robot design (Causey, 1999).

Today, the procedure for designing fingers consists of several time consuming iterations in the design, manufacture and verification of fingers as seen in Fig. 1. This procedure begins by selecting the type of robot task, which may be a simple pick and place or assembly. The latter task requires extra information regarding the assembly process. Then the 3D model or 3D vision of the workpiece is imported to the design tool. The next step is defining the type of grasp (i.e. force and form-closure) in regard to the physical and geometrical properties of the fingers and the workpiece. Following this, the most suitable feasible grasp sets are determined in the grasp synthesis and analysis processes. Fingers are designed based on the grasp sets and their feasibility is checked in the collision detection process. This process checks for collision between the fingers and the workpiece. The final step in the design process is verifying the practicability of the fingers by conducting experiments.

Such a procedure is unable to respond to the high demand of agile manufacturing. Therefore, design automation of fingers is a promising approach that enables robot industries to comply with the agile market (Velasco and Newman, 1998).

In earlier work (Honarpardaz et al., 2015), the studies relevant to finger design automation are comprehensively reviewed, categorized and compared. The essential key processes for finger design automation procedure are identified. These key processes are *grasp synthesis*, *grasp analysis*, *finger design*, *collision detection* and *experimental verification* and in this paper they are grouped into the three major categories of *grasp*, *finger design* and *experimental verification*.

According to the conclusion of (Honarpardaz et al., 2015), the very few proposed methods in the finger design automation research area encounter two significant problems. First, the methods that are limited to taking only polyhedral objects into account. Second, the approaches that are not reliable due to omission of some key processes in their design procedure. The latter problem increases the possibility of failures of the fingers in practice which may result in damage to expensive hardware and workpieces.

This work compares the GAFD method with other relevant and available methods for finger design automation(Velasco et al., 1998; Velasco and Newman, 1998; eGrip, 2016).

This paper is divided into sections as follows, the Relevant Work section reviews the related works and the Method section

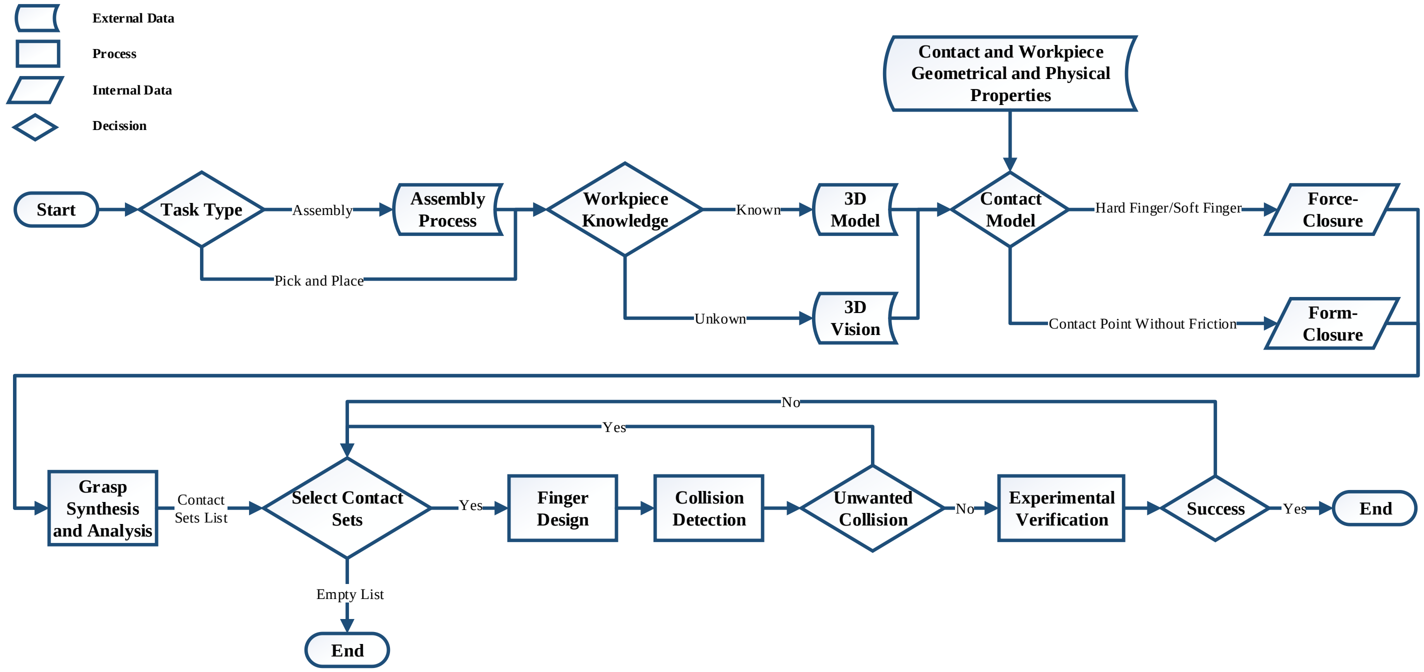

Fig. 1 - Flowchart of an example of finger design process for a known gripper. Inspired from (Nguyen, 1987, Mishra et al. 1987, Trinkle, 1992, Causey, 1999).

describes the utilized methodology. Results are presented and discussed in the Result section, and the performance of the fingers designed by considering all key processes with fingers design by existing approaches is benchmarked in the Discussion.

2. RELEVANT WORK

In the last two decades, several studies have been performed on designing fingers for industrial grippers yet very little research has been focused on automating the finger design process. Work done in the finger design research field is divided into the three groups of *modular design*, *re-configurable design* and *customized design* (Honarpardaz et al., 2015).

2.1. Modular Design Approaches

As presented in (Honarpardaz et al., 2015), some researchers believe that modular finger design is the proper approach to finger design automation (Pedrazzoli et al., 2001; Pham et al., 2007; Sanfilippo et al., 2012). Pham et al. (2007) propose a method that initially simplifies the geometry of the workpiece to a limited number of basic shapes, for instance cylinder, sphere, cube, etc. Then appropriate pairs of fingers are selected from a library of designed fingers.

While these approaches are simple and require very low computational effort, they have noticeable downsides that are pointed out as follows:

- The methods have difficulty finding solutions for workpieces with complex geometries.
- The fingers available in the finger library fit only the surface contour of simple geometries.
- The reliability of the modular design-based fingers decreases dramatically with increasing complexity of the workpiece geometry.

2.2. Re-configurable Design Approaches

Among the relevant works approaching re-configurable finger design (Brown and Brost, 1997; Brost and Peters, 1998; Balan and Bone, 2003), Balan and Bone (2003) introduce an algorithm that automatically configures the location of three simple fingers (cylindrical pins) of a parallel-jaw gripper to accomplish a task. This method considers two of the fingers as variable and located on one jaw while the third finger is constantly fixed to the second jaw.

Despite the fact that the re-configurable design-based approaches are the most cost efficient in comparison with other existing methods, the following drawbacks can be noted:

- They are computationally expensive due to their global searching method for finding grasp sets.
- They are limited to only handling polyhedral workpieces, which is not common in industry.
- They require many inputs from the user which limits the use of the algorithm to experts.

2.3. Customized Design Approaches

Different from previous groups, few researchers approach customized design fingers (Velasco et al., 1996; Velasco and

Newman, 1998; Velasco et al., 1998; Pedrazzoli et al., 2001). Velasco and Newman (1998) propose a method that designs fingers in such a way that they fit and envelop the workpiece surfaces. The algorithm begins by assuming fingers to be solid blocks. Then the geometry of the workpiece is subtracted from the blocks to leave the customized fingers.

A recently launched commercial tool, *eGrip* (eGrip, 2016), by SCHUNK (SCHUNK GmbH & Co. KG, Lauffen am Neckar, Germany) utilizes a similar approach as Velasco and Newman (1998). This tool requires three inputs from the user to be able to design fingers. First, the CAD model of the workpiece (Stereo Lithography (STL) format). Second, selecting a gripper from the library of grippers. Third, defining the planned grasp approach. When these inputs are provided to the tool, the design algorithm generates customized fingers that encompass (form-closure) the workpiece.

Unlike modular design approaches, the proposed approach for customized design is independent of the complexity of the workpiece due to its ability to fit the contour of the grasp surfaces. As a consequence the reliability of the designed fingers is independent of the workpiece geometry. Contrasting re-configurable design approaches, customized design approaches require low computational effort and few inputs. These approaches enable the user with very low experience in robotics to use the algorithm. Therefore, the proposed method in this paper (GAFD) pursues the customized design approaches to overcome the drawbacks of the modular design and re-configurable design approaches.

3. METHOD

This section describes the methodology that is employed to connect the key process to achieve GAFD. In order to facilitate the data communication between the key processes, all the key processes are implemented in the Visual Basic (VB) language

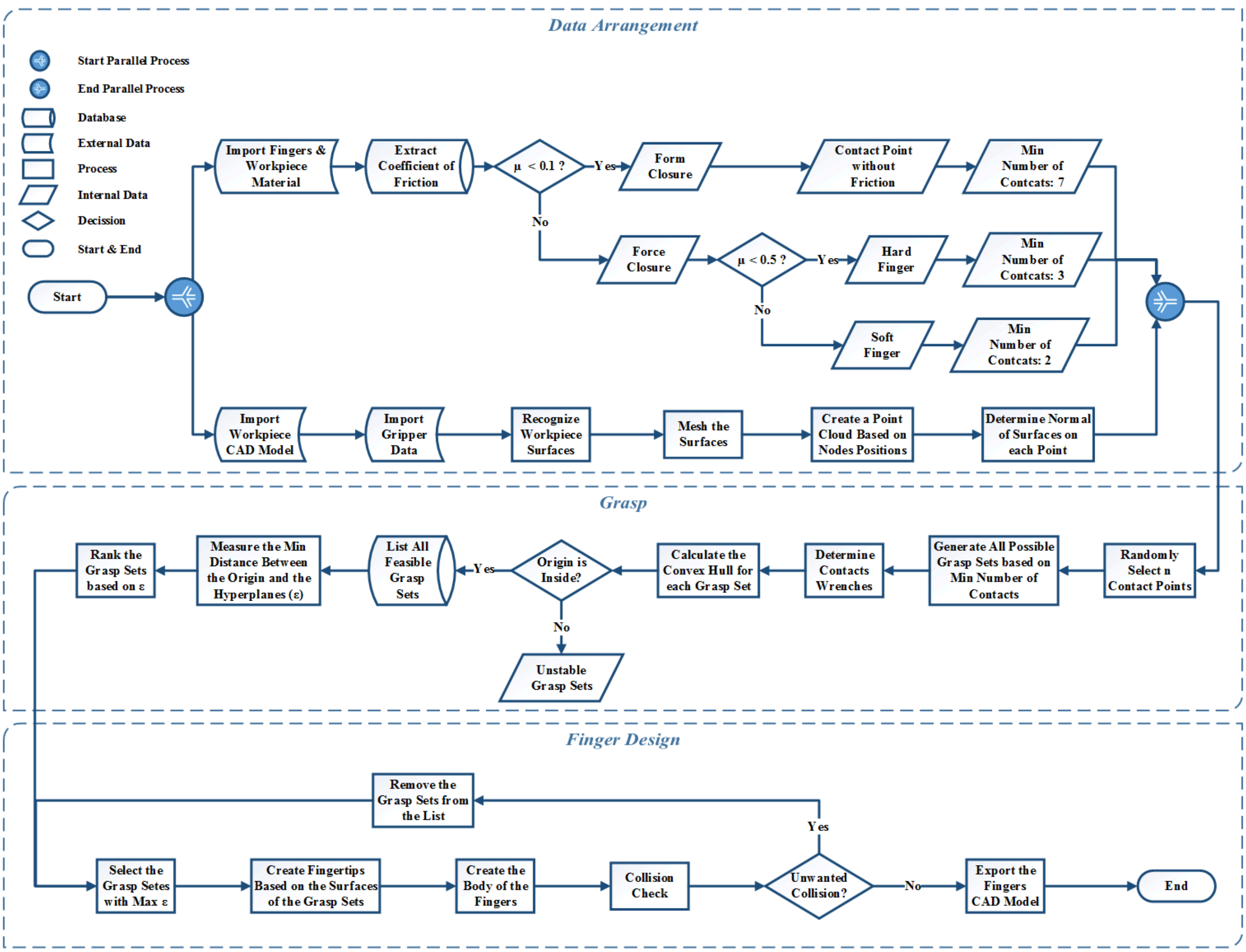

Fig. 2 – Generic Automated Finger Design (GAFD) Process Flowchart.

and merged in a commercial CAD software, CATIA (CATIA, 2016). Fig. 2 illustrates the strategy of linking the key processes together. To ease the explanation of the utilized strategy, the algorithm is categorized into three stages; *data arrangement*, *grasp* and *finger design*. Each stage consists of several steps which are described in detail in the following sections.

3.1. Data Arrangement

This part of the algorithm imports all the required inputs (i.e. CAD model of the workpiece, gripper data, and finger and workpiece materials) and prepares the input data for the other substantial stages within two major steps. As shown in Fig. 2, the data arrangement stage consists of two processes that run in parallel.

In the first parallel process, the CAD model of the workpiece and the gripper data (i.e. gripper model, maximum finger length, maximum workpiece weight, jaws stroke) are imported to CATIA (See Fig. 2). Next, surfaces of the imported CAD model of the workpiece are rebuilt. A point cloud of the model is then created by using mesh techniques. Then the normal of the surfaces at each point on the workpiece is determined.

The second parallel process begins by extracting the coefficient of friction (μ) of the contact points in regard to the fingers and the workpiece material, as illustrated in Fig. 2. Then based on the value of the μ, one of the contact models (i.e. contact point without friction, hard finger and soft finger) is selected and consequently, the minimum number of contacts for grasping an object is obtained. The reader is referred to (Trinkle, 1992) and (Nguyen, 1987) for the details of the contact models and the proof of the minimum number of required contacts for each model.

3.2. Grasp

The grasp stage is responsible for finding the most suitable grasp set to successfully accomplish the defined task. To achieve this goal, it is crucial to consider the two key processes; *grasp synthesis* and *grasp analysis*.

3.2.1. Grasp Synthesis

The role of the grasp synthesis process is to provide a list of contact sets that determines where to grasp the object to achieve a stable grasp without slippage. In this work, a similar approach that proposed by Liu and Carpin (2015) is utilized to synthesize the grasps.

After finding the minimum number of contacts, coordinates and normal directions of the cloud points, the grasp synthesizing process begins by randomly selecting a collection of points from the point cloud and generating all possible grasp sets based on the minimum number of contacts and the point collection (see Fig. 2). Then the contact wrenches of each grasp set are determined.

In order to verify the stability of the grasp sets, the convex hull of the contact wrenches of each grasp set is calculated. Salisbury (1985) and Mishra et al. (1987) demonstrate that a grasp set is considered as stable only if the origin of the contact wrench space lies exactly inside the convex hull of the contact wrenches. Therefore, all the grasp sets that contains the origin of their wrench space in their convex hull are collected and listed as stable grasps. The reader should notice that the grasp synthesis presented here finds the local optima.

3.2.2. Grasp Analysis

As shown in Fig. 2, the next key process after collecting all stable grasps is the grasp analysis. This key process measures the quality of the stable grasp sets and ranks the grasp sets based on their quality. In this study, the well-known quality metric introduced by Ferrari and Canny (1992) is employed. However, other metrics are applicable to the proposed method here. Ferrari and Canny (1992) propose a metric that uses the largest resistible disturbance wrench by grasp sets in all directions. This can be represented as the radius (ε) of the largest ball centered at the origin of the wrench space and inscribed in the convex hull of the contact wrenches (Roa and Suárez, 2014). The larger the ball (ε), the higher the quality and the more stable the grasp set. By ranking the list of feasible grasp sets based on the quality metric, the finger design stage initiates.

3.3. Finger Design

In this stage, the grasp set with the highest rank in the quality measurement is used to design fingers of the gripper. This process consists of three steps of *fingertip design*, *finger body design* and *collision detection*.

3.3.1. Fingertip Design

Designing fingertips play a very significant role in performance of the finger. This step of the finger design key process uses the coordinates of the most qualified grasp contact points and designs fingertips based on the contact points, as demonstrated in Fig. 2. In this work, fingertips are designed to mimic the contour of the surfaces of the workpiece at the position of the contact points. This customized design compensates the unavoidable position uncertainties of the workpiece and increases the reliability by enlarging the contact and friction area (Causey, 1999).

3.3.2. Finger Body Design

This step of the finger design process connects the constructed fingertips to the gripper jaw. To successfully design the body of the fingers, many important factors must be taken into consideration. For instance, the direction of opening and closing of the gripper jaws, connecting fingertips to correct gripper jaw, minimizing the finger length, etc. As a result, the construction of the body of the finger is designed by a list of defined parametric lines that connect the fingertip to the gripper jaw. Then a solid structure is built based on the parametric lines. The algorithm adjusts the parameters to ensure the design constraints are satisfied and the fingertips are properly connected to the gripper.

3.3.3. Collision Detection

The final process in designing fingers is checking for unwanted collisions while grasping the workpiece, as shown in Fig.2. While much research has focused on developing collision detecting algorithms and modules for various applications, most commercial CAD software has built-in collision detection features (Honarpardaz et al., 2015). In this work, the collision detection tool of CATIA (Clash Analysis) is utilized to check for unwanted collisions (clash).

This key process plays a significant role on detecting the feasibility of the finger designs. In the case of an unwanted collision of fingers with each other or with the workpiece, the fingers are considered as unfeasible. Therefore, a new set of contact points are selected and the process of the finger design is started over (see Fig.2). When the feasibility of the finger design is verified and approved by the collision detector, the CAD models of the fingers are exported to be manufactured and tested in practice.

4. RESULTS

In this section, results of the proposed GAFD algorithm implemented on two different workpieces are presented. The selected workpieces are an emergency lamp cap (Fig. 3 (a)) and a table tennis ball (Fig. 3 (b)). All the processes presented in GAFD are put into practice to automatically generate fingers for the example workpieces. The following sections discuss the results obtained from each stage.

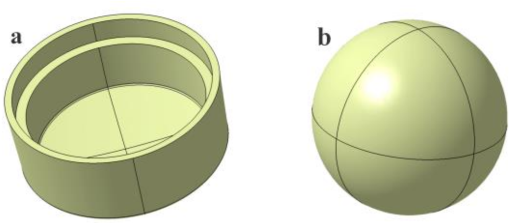

Fig. 3 – CAD models of: (a) an emergency lamp cap; (b) a ping pong ball.

4.1. Data Arrangement

According to section 3, the design procedure of GAFD begins by arranging the data for the next stages. As shown in Fig. 2, this stage consists of two parallel processes.

In the first parallel process (as seen in Fig. 2):

1. The CAD model of the workpiece in STEP (Standard for the Exchange of Product model) format are imported to CATIA.
2. A function is utilized to recognize the outer surfaces of the workpiece, as illustrated in Fig. 3.
3. The workpiece geometry is discretized by meshing techniques (Fig. 4 (a) and (b)).
4. The point cloud of the workpiece is created based on the element nodes of the generated mesh.
5. The last step in the first parallel process is to determine the normal of the workpieces at every point. Fig. 4 (c) presents the point cloud and normal generated for one of the surfaces of the ball.

The second parallel process (as seen in Fig. 2):

1. Imports the material properties of the workpieces and the fingers. In this case, the ball and the lamp cap materials are Acrylonitrile Butadiene Styrene (ABS) and the fingertip material is considered to be rubber.
2. The static friction coefficient at the contact is determined which in this case would be 0.6 (Blau, 1992).
3. The soft finger is considered as the suitable contact model.
4. According to Nguyen (1987) this proves that at least two contact points are required in order to achieve force-closure with the soft finger contact model, the grasp sets that are defined in the grasp synthesis contain two points.

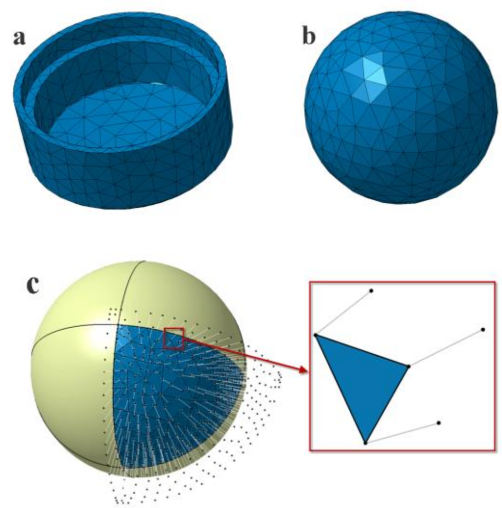

Fig. 4 – (a) meshed lamp cap (b) meshed ping pong ball (c) point cloud and normal that generated for one surface of the ping pong ball.

4.2. Grasp

The second stage of the GAFD determines the suitable grasp sets that ensure stable grasp for designing the fingers. The grasp stage consists of two key processes of *grasp synthesis* and *grasp analysis*.

4.2.1. Grasp Synthesis

By knowing the minimum number of contact points required for the grasp sets, the grasp synthesis process starts by randomly selecting 100 points and generating all possible grasp sets using selected points. Then the contact wrenches of the grasp sets are obtained. In the exampled cases here, the friction cone is approximated by an inscribed regular polyhedral with 8 faces to simplify the computations (León et al., 2014). Fig. 5 demonstrates the randomly selected points and determined contact wrenches on the lamp cap. The next step in grasp synthesis processes is to generate all the possible grasp sets and then check their stability by calculating the convex hull of the contact wrenches of every grasp set. Only grasp sets that enclose the origin of the contact wrenches in the convex hull are considered as stable (Salisbury, 1985; Mishra et al., 1987) and collected in the list of the feasible grasp sets.

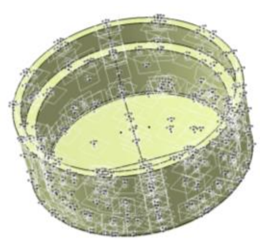

Fig. 5 – Randomly selected points and generated contact wrenches for the lamp cap.

4.2.2. Grasp Analysis

In this process, the quality of the feasible grasps that are listed in the grasp synthesis process are measured. The quality metric used in GAFD is introduced by Ferrari and Canny (1992) (also known as ball criteria). This metric measures the radius of the largest sphere centered on the wrench space origin and inscribed in the convex hull. In other words, the minimum distance between the hyperplanes of the convex hull and the wrench space origin is considered as the quality metric. Grasp sets with larger radius have higher quality (Roa and Suárez, 2014). Utilizing this quality metric, the feasible grasp sets are sorted by their quality. Table 1 shows the best five grasp sets which have the highest quality for the ball. The location of the best grasp set for the lamp cap and the ball are demonstrated in Fig. 6 and the red lines represent the grasp sets with the highest quality.

Grasp Set ID	***Point-1 ID***	***Point-2 ID***	***Surface-1 ID***	***Surface-2 ID***	***Quality Measure***
GS-531	P-349	P-176	S-5	S-7	12.697
GS-84	P-128	P-24	S-3	S-6	12.602
GS-1025	P-11	P-75	S-7	S-4	12.244
GS-299	P-247	P-128	S-6	S-4	12.062
GS-1844	P-99	P-41	S-8	S-3	12.038

Table 1 – The best five grasp sets of the ping pong ball based on the ball criteria.

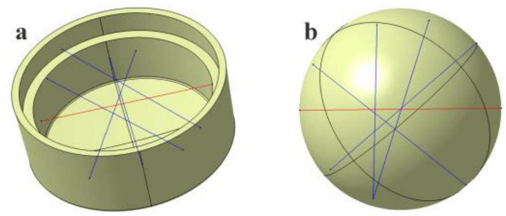

Fig. 6 – The best five grasp sets for: (a) the lamp cap; (b) ball.

4.3. Finger Design

By obtaining the best grasp sets, the finger design stage initiates. This stages consists of three processes of *fingertip design*, *finger body design* and *collision detection*.

4.3.1. Fingertip Design

This process selects the best grasp set from the feasible grasps list and utilizes the contact points coordinates to design the fingertips accordingly. The fingertips are designed to be a block with its center of mass located on the contact point. Then the block is subtracted from the workpiece and the remaining geometry is the fingertip. As shown in Fig. 7, this technique allows the fingertip to have the same surface contour as the workpiece at the contact point. Furthermore, the implemented technique enables both internal (Fig. 7 (a)) and external grasp (Fig. 7 (b, c)).

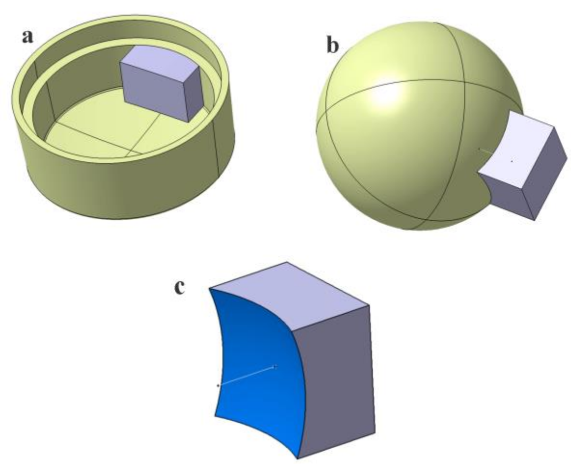

Fig. 7 – A fingertip designed for the (a) lamp cap; (b, c) ball.

4.3.2. Finger Body Design

The next process after the fingertip design is constructing the body of the finger. To design the finger body, a group of parametric lines are created and the Sweep feature is utilized to produce the solid structure of the finger body. As demonstrated in Fig. 7, the fingertip design method presented in GAFD takes both internal and external grasps into account. Therefore, the finger body process employs design procedures appropriate for internal and external grasps. Fig. 8 (a,b) represents the designed fingers for externally grasping the ball and Fig. 8 (c,d) illustrates the fingers designed for internally grasping the lamp cap.

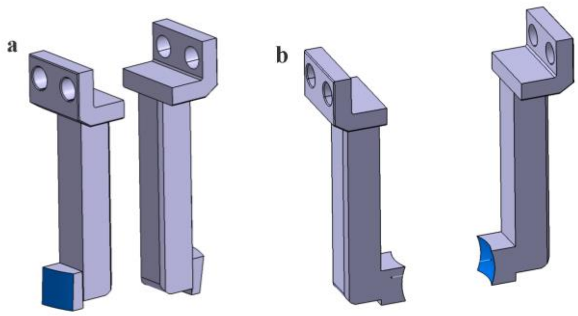

Fig. 8 – Designed fingers for the: (a) lamp cap; (b) ball.

4.3.3. Collision Detection

This step is the last and the most important process in the GAFD design procedure. To approve the feasibility of the designed fingers, it is crucial to ensure that the designed fingers are collision free while approaching the workpiece. The Clash Analysis feature of the CATIA is utilized to detect unwanted collisions. The results from the collision detection shows that the designed fingers for the lamp cap and the ball are collision free and feasible. Based on these two cases, the proposed GAFD method for the finger design automation has potential to successfully design fingers for industrial grippers, although further work is required to verify its performance for a general case.

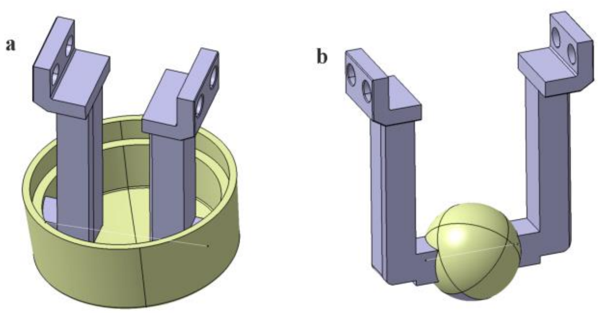

Fig. 9 – Collision detection of the designed fingers for the: (a) lamp cap; (b) ball.

5. DISCUSSION

In this section, the results of the utilized GAFD method from previous section are compared with the other existing methods in customized finger design automation research field.

The few existing works on customized finger design automation use similar approaches (Velasco et al., 1996; Velasco and Newman, 1998; Velasco et al., 1998; eGrip, 2016). Velasco and Newman (1998) utilize CAD software to design fingers in such a way that the fingers envelop the workpiece and obtain the form-closure. The design process of current methods usually begins by defining initial fingers as solid blocks and subtracting the geometry of the workpiece from the finger blocks. Then the remaining geometry of the fingers is modified to facilitate collision-free workpiece access. The web-based finger design tool, eGrip (eGrip, 2016), uses a very similar approach as proposed by Velasco et al. (1998).

The existing customized design approaches do not consider grasp synthesis and grasp analysis processes in their design procedure since the fingers enclose the workpiece and achieve the form-closure grasp. Hence, they are computationally inexpensive. On the other hand, these approaches have the following substantial weaknesses:

- They are unable to gain form-closure for workpieces with axi-symmetric geometries.
- The design process faces difficulties in completely enveloping large workpieces and ensuring a form-closure grasp. Therefore, the stability of the grasp is unknown since no grasp synthesis and analysis are performed in the design process.
- The designed fingers based on the current approaches generally have large foot-prints which reduces the approach-space and consequently causes failure due to collision with the work environment or other workpieces.

According to the results of this research, the sophisticated GAFD process overcomes the problems of the existing approaches in the customized finger design automation research area. The introduced process (GAFD) has the following benefits:

- Aiding users to have a tangible knowledge on the stability of the fingers.
- The algorithm can ensure that the grasp is either in form-closure or force-closure, depending on the contact friction coefficient.
- It is completely independent of workpiece geometric properties (e.g. size, shape, symmetricity, etc.).
- The method enables the internal grasps as well as external ones.
- The designed fingers have much smaller fingers and foot-prints in comparison with other Customized methods that encompass the workpiece.
- The method designs fingers that have large approach-spaces and are more suitable for assembly applications.

6. CONCLUSION

This paper presents the Generic Automated Finger Design (GAFD) as a method to automate the design process of fingers for industrial grippers. Finger design automation is a means of reducing lead time and development complexity in a market where robot industry demand for agile product development is increasing. However, existing approaches are unable to fully fulfill the industry requirements due to their inability in handling complex or axi-symmetric workpieces. As a result, this work proposes the Generic Automated Finger Design (GAFD) method, which successfully produces fingers for workpieces with complex geometry.

In addition, GAFD considers form and force-closure as well as internal and external grasps, regardless of the geometrical shape of the workpiece. Furthermore, GAFD designs fingers have a notably smaller foot-print and larger approach-space in comparison with other automated fingers design approaches.

The following is suggested for future work:

- Practicability of the designed fingers by GAFD are required to be verified in experiment.
- Different grasp synthesis and analysis methods to be implemented on GAFD in order to improve the performance of the grasp.
- Improving the GAFD to design fingers that can grasp multi-objects.

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