Designing Fingers in Simulation based on Imprints

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Abstract: Gripper design is nowadays an area of ongoing research activity. The problem of creating a generic and automated gripper design approach tailored for a specific task is still far from solved. In this paper, we propose a new method of generating finger cut-outs aimed at simplifying the design process of doing so. This method takes root in the idea of using the *imprint* to produce the finger geometry. We furthermore provide a verification of our newly introduced imprinting method and a comparison to the previously introduced parametrized geometry method. This verification is done through a set of grasping experiments performed in simulation on two objects with geometry features based on those found in industrial setting.

1 INTRODUCTION

A large portion of industrial tasks that are (or can) be automatized through the use of robots consists of handling, manipulating, moving and placing of objects. There are some challenges that are associated with strict requirements on the process quality since the objects have to be (Honarpardaz et al., 2017):

1) grasped robustly and successfully,
2) moved rapidly in effort to reduce the cycle time, and
3) then placed precisely.

All of this is done in presence of uncertainties, which are due to factors like sensor calibration, imprecise end-effectors or the flexibility of objects and their environment. In addition, new grasping solutions have to be adopted quickly, in order to respond to changing manufacturing processes in small and medium sized productions, often encountered in the industry.

In typical industrial cases, the gripper solutions are commonly implemented starting with the selection of the gripper. The fingers are then designed by experienced engineers with the usage of heuristics, guidelines, experience and trial-and-error experiments. The finished designs are often produced by the user or system integrator, using additive manufacturing or CNC machines. The process is cumbersome and demanding in terms of the cost and the time required to establish a working solution.

The use of 3D printing as gripper manufacturing technique invites the creation of smart software solutions to produce and optimize the finger geometries. The increasing computational power available and the development of robotic frameworks (such as RobWork (Ellekilde and Jørgensen, 2010)) and physical engines, such as ODE (Smith, 2008) and RWPhysics (Thulesen and Petersen, 2016) facilitate the use of dynamic simulation to replace the arduous trial-and-error design process. The automation of design with the use of flexible software tools is indeed a current trend in industrial manufacturing and robotics.

In our previous work (Wolniakowski et al., 2017), a gripper design method was introduced which uses dynamic simulation in order to provide a quality estimate of parametrized grippers. This allows for the finger designs to be automatically optimized. This previously described method, while flexible and allowing for inclusion of task context information in the gripper optimization process, suffers from rather complex requirements on the amount of set-up and user input. In particular, the user has to provide a basic idea for the gripper structure in form of the geometry parametrization (which is then numerically optimized). An example of how a geometry parametrization can look like is seen as the left finger in Figure 1. This itself is by no means trivial, and it can be easily seen that no globally optimal gripper solution can be found when

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a insufficiently flexible parametrization is provided.

Defining the cut-out shape parametrization manually is particularly difficult and time consuming. Instead, the cut-out shape can be automatically generated based on the object's imprint in the fingers. Furthermore, the generated cut-out can be post-processed in order to eliminate the grasped object's pose uncertainty (see the right finger in Figure 1).

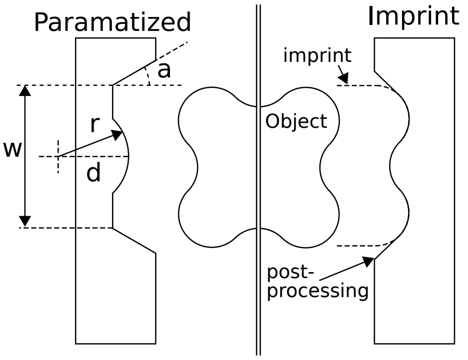
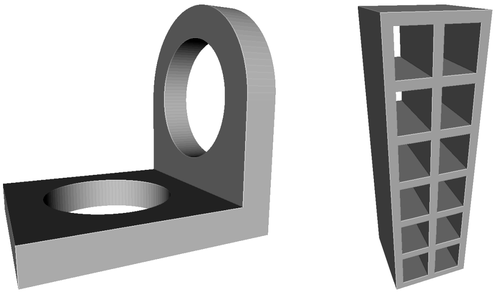


Figure 1: The two different ways to design the fingers analysed in this work. On the left: the manual parametrization method (PFO, introduced previously in (Wolniakowski et al., 2017)). On the right: the new imprint based method (IFM).

In this work, we propose a method of generating the parametrized cut-out profiles based on the grasped object imprints. The method is an extension of the previously presented idea (Wolniakowski et al., 2015) that greatly reduces the user input required in setting up the gripper optimization process. In doing so, this development marks another step in creation of a fully automated gripper design framework. The two finger design methods can be used in conjunction utilizing the synergy of the flexibility in selecting the custom optimal finger shapes, while the cut-out shape is generated automatically to match the grasped object's geometry.

The new cut-out shape generation method is tested by comparing its performance with the previous parametrized geometry optimization method in two scenarios of grasping objects of complex shapes: the *bracket* and the *heatshield* (see Figure 2). For each of these objects, the optimized finger geometry is generated and subsequently their alignment capability is tested in simulated grasp experiments.

The paper is organized as follows. First, in Section 2, an analysis of the gripper design problem is presented, summarizing the research published in the field, and analysing several contemporary solutions used in the industry. Next in Section 3, we present our data-driven parametrized finger geometry generation method (Wolniakowski et al., 2017) and our new method, based on the object imprint. In Section 4, the performance of the two methods is compared when designing gripper fingers for grasping two complex objects. The fingers are then tested in simulations, in order to determine the range of grasp uncertainties that the designed grippers can compensate for. Finally, we present our conclusions in Section 6.



(a) The bracket object. (b) The heatshield object.

Figure 2: The objects used in the gripper design experiments.

2 STATE OF THE ART

The most common gripper structure used in the industry nowadays is that of a *parallel finger gripper*. A parallel finger gripper consists of a base which provides the actuation (be it electric or pneumatic), which is typically selected from an array of off-the-shelf products and of two fingers. The fingers move in a linear fashion in opposite directions until a certain position or force is achieved. The reason for the widespread use of the parallel gripper design is its relative simplicity and flexibility. The adaptation to a new context is usually done by designing and mounting a new pair of fingers, tailored to fulfil the requirements of a specific task. Nowadays these fingers are often designed and manufactured (e.g. printed) by the system integrator or user. The process of gripper finger design is not a simple task, and an area of ongoing research.

An excellent literature review in the field of gripper design has been recently published by (Honarpardaz et al., 2017). They discuss the long-established solutions and recent developments critically selected from the database of thousands of articles. Other similar reviews can be found in (Boubekri and Chakraborty, 2002; Blanes et al., 2011).

The typical workflow involved in the design of a new gripper solution can be described as follows (Honarpardaz et al., 2017): 1) the requirements imposed on the task by the grasped object properties and the task context is gathered, 2) a decision is then made on whether the grasps are performed using the force-fit or form-fit method (Honarpardaz et al., 2017), and 3) the grasp sets are generated and analysed. The actual finger design is done after the optimal grasp has been found, and iterated in a trial-and-error process (testing e.g. unwanted collisions and grasp robustness) until a solution is found that is good enough.

The area of gripper design research is obviously closely connected with that of the research on grasping. As discussed above, the selection of suitable grasps is an essential component of the design process. In this field, contributions by (Borst et al., 2004; Kraft et al., 2012; Li et al., 2007; Berenson et al., 2007; Jørgensen and Petersen, 2010; Stulp et al., 2011) can be noted, in which various quality measures of the grasps space are considered. We make use of these grasp quality objectives in our gripper quality evaluation.

The process of gripper design is expensive in terms of time, cost and the expertise required. Numerous guidelines have been created, including heuristics which can be applied to assist with the process. These guidelines include, for example contributions such as (Krenich, 2014; Causey and Quinn, 1998). Many guidelines have been conveniently gathered in a work concerning agility in manufacturing (Causey, 2003).

Numerous works have been published in which the kinematic structure of the gripper that is subjected to optimization (Cuadrado et al., 2002a; Lanni and Ceccarelli, 2009; Cuadrado et al., 2002b; Ceccarelli et al., 2002). In other works, modular or reconfigurable gripper jaws systems were proposed (Zhang and Goldberg, 2006; Kolluru et al., 2000).

Recently, dynamic simulation has been proposed as a tool to facilitate the replacement of a trial-and-error process with much easier virtual experimentation. In (Ellekilde and Petersen, 2006) they proposed the design of the gripper jaws based on the convex-hull *molding*, in order to achieve robustness in terms of grasped object pose uncertainty. The results have been verified both in real-world experiments and in simulation. *Molding* and *imprinting* is taken to be the same in the cut-out generation process, the two terms are therefore used interchangeably.

In (Wolniakowski et al., 2014), we introduced a metric for the quality of a gripper design which takes into account the conditions imposed by the task context. We have subsequently worked on the formulation of gripper design parametrization and optimization methods (Wolniakowski et al., 2015), so that the gripper finger design process could be automated. This process was furthermore tested in various scenarios (Wolniakowski et al., 2017).

A new online tool by Schunk was recently made available (Schunk, 2015). This tool uses the established method of using the object *molding* on the finger, so that a new form-fit design can be created easily. The tool requires input from the user in terms of the selection of a base finger shape, the expected pose of the object and other relevant variables. This implementation is protected by a patent (Schuster et al., 2014). Molding has indeed been long used for gripper finger design (Velasco and Newman, 1998). The major shortcomings of this method is the sensitivity to uncertainties in the object shape and pose, and its inapplicability to certain classes of objects.

In this work, a new *imprinting* method inspired by the previous ideas within finger design using *molds* or *imprints* is presented. We do not only use the profile created by the inverse of the object's geometry, but also add profiles around the cut-out to facilitate the guiding of the object into a stable position when the pose uncertainties are present. Furthermore, simulations are used as a tool to verify the designs.

3 METHODS

In this section, the gripper design optimization methods used in this work a described, starting with the short primer on the parametrized geometry optimization method introduced previously in (Wolniakowski et al., 2017) (see Section 3.1). The new Imprint Finger Method (IFM) method is then introduced (see Section 3.2), which builds upon the former by greatly simplifying the process of finding the appropriate cut-out parametrization for the grasped objects.

In both methods, the general workflow is similar (see Figure 3). The common inputs required from the user are: a 3D model of the object, the expected grasp location (pose), and the task description (i.e. the object position, the environment, uncertainties, gripper structure, grasp success conditions, etc.) – see Figure 3a. In the first step, the environment representation has to be created (see Figure 3b), this was done using the RobWork (Ellekilde and Jørgensen, 2010) XML format. Next, the grasp set is generated by perturbing randomly the grasp pose specified by the user (see Figure 3c). Then, the gripper parametrization has to be provided by the user (see Figure 3d). This can be done in the form of a OpenSCAD (Kintel, 2009) script that contains a parametric model of the finger geometry or using the hereby introduced method (see Section 3.2). Finally, the simulation of the generated grasps (see Figure 3f) is done repeatedly for different gripper designs proposed by the optimization procedure (see Figure 3e). The output consists of the optimized gripper model (see Figure 3g). The dynamic simulations were in both methods implemented using the RobWork framework (Ellekilde and Jørgensen, 2010) and its simulation package RobWorkSim (Jørgensen et al., 2010). The physics engine used in simulation is the Open Dynamics Engine (ODE) (Smith, 2008).

Our new method allows for a significant reduction in user input required through automating the generation of the finger geometry parametrization, thus reducing the set-up time of the finger parametrization and improving on the ease of use.

3.1 Parametrized Finger Optimization (PFO)

In our previous work (Wolniakowski et al., 2017), a method was introduced for computing the gripper quality for a given task context using dynamic simulation as a tool. Several Gripper Quality indices were defined, capturing essential gripper properties necessary to execute the grasping tasks successfully. These quality measures are:

Success Index (S) which quantifies the overall success rate of the executed grasps.

Coverage Index (C) which provides a measure of the gripper versatility expressed as the size of the successful approach vectors.

Robustness Index (R) defining the gripper performance in presence of pose uncertainties.

Alignment Index (A) quantifying the size of pose uncertainties for which the grasped object is still forced by the gripper into a predictable pose.

Wrench Index (W) measuring the average robustness of the grasps in terms of Grasp Wrench Space metric (Ferrari and Canny, 1992).

Stress Index (T) representing structural robustness of the gripper design.

Volume Index (V) based on the time and material needed to produce the gripper fingers.

The details on the implementation of the quality index calculation can be found in (Wolniakowski et al., 2017). The quality evaluation is based on simulating a number of grasps, generated either using heuristic planning or generated stochastically with user-provided uncertainty estimations.

These metrics was used in conjunction with a gripper geometry parametrization method and an array of numerical optimization techniques in order to improve gripper finger designs automatically. The objective function for the optimization is defined as a weighted geometric average of individual indices (Equation 1):

$$Q = \left(\prod_{i=1}^{N} q_i^{w_i} \right)^{1/\Sigma_{i=1}^{N} w_i} \tag{1}$$

where $\mathbf{q} = [S, C, R, A, W, T, V]$ is the vector of the seven gripper quality indices described above and the $w_1, w_2, \ldots$ are the respective weights.

The performance of the method was showcased in several industry-based grasping scenarios (Wolniakowski et al., 2016). While this previously introduced gripper design method (which will subsequently be referred to as the ”PFO method”) is applicable and flexible, it still requires the user to provide a lot of manual input in form of a custom geometry parametrization, decide on the weights of the quality objective and the numerical optimization technique used. This problem is now targeted by automating the generation of the gripper cut-out, as described in the following section.

3.2 Imprint Finger Method (IFM)

The generation of the cut-out for a finger takes basis in the idea of pressing the object into a piece of soft clay. Using the imprint of the object directly as a cut-out is a poor solution since it requires a high degree of pose certainty to place an object into its cut-out. To improve the performance, the cut-out is modified to get the final cut-out used to generate the finger.

4 RESULTS

In the experiments, the performance of the data-driven gripper design and optimization methods for grasping two different objects was compared. The two selected objects: the *bracket* and the *heatshield* are shown in Figure 2 . The objects were chosen as to highlight the pros and cons of both considered methods (PFO and IFM) and to provide a reasonable design challenge. The *bracket* object was designed in a fashion to make it difficult to generate the imprinted fingers for it, due to the necessity of using the internal grasp. The *heatshield* in turn poses a challenge for the user designed cut-out parametrization: it is not a trivial requirement to provide a simple (i.e. using only a few free variables) parametrization that is flexible enough for an object of complex geometry.

The object models were generated using the OpenSCAD software. The bounding box dimensions for the objects are 35 × 30 × 35 mm for the *bracket*

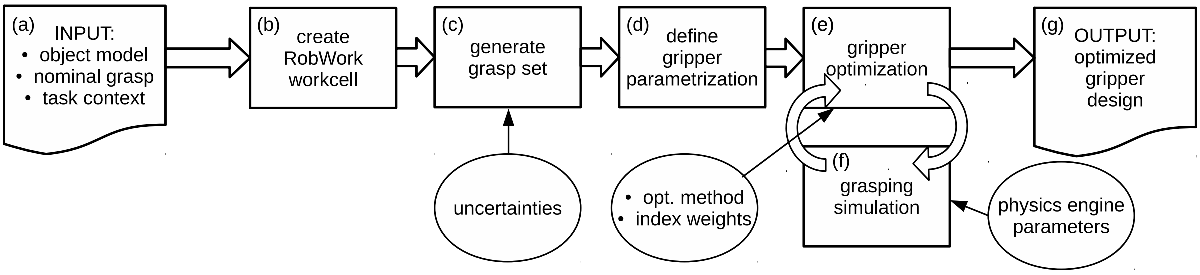
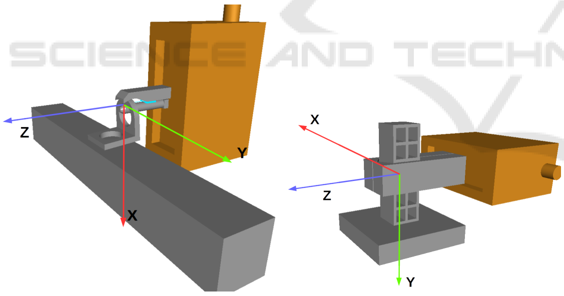


Figure 3: The workflow in using the parametrized gripper optimization methods.

object and 30 × 30 × 100 mm for the *heatshield* object respectively. For the purpose of simulation, their masses were assigned to be $m_{\text{bracket}} = m_{\text{heatshield}} =$ 50g. The friction properties of the material were set to correspond to printable plastic, with friction coefficient between the gripper fingers (also printed out of the plastic) and the object was $\mu = 0.4$. The gripper was in the simulations set to use a force of 50N for each grasp. The simulation used the Coulomb friction model.

The task context for grasping in both of the scenarios is presented in Figure 4. The objects are placed on corresponding fixtures and a *nominal grasp* (illustrated in Figure 4) is defined for both cases. The figure additionally shows the axes, which indicate the direction along which the grasps were offset during the subsequent grasp alignment experiments.



(a) The bracket grasp. (b) The heatshield grasp.

Figure 4: The nominal grasps defined for the test objects.

The grasp alignment experiments were performed in the following way. Each of the objects was grasped repeatedly with grasps offset from the *nominal grasp* along one of the major Cartesian directions: X, Y and Z and angles θ_x, θ_y and θ_z around these axes. For each of the grasps, the grasping result was assigned one of the three outcomes: *successful* – when the object was grasped and positioned correctly wrt. to the gripper in terms of translation and rotation, *misaligned* – when the object was grasped, but the position was not correct, and *failure* – when the object was not grasped (due to, e.g. collision with the fixture, the object dropping out of the gripper, simulation failure etc.).

The outcome was determined automatically in simulation, based on the object and gripper poses as well as the contact points recorded during the simulation. The grasp alignment was tested using the condition Equation 2.

$$max(d_{\text{ang}} \cdot w_{\text{ang}}, d_{\text{lin}} \cdot w_{\text{lin}}) < \varepsilon_A \tag{2}$$

where d_{ang} and d_{lin} are the angular and linear displacements from the expected pose to the grasp pose (in degrees and millimetres respectively). w_{ang} and w_{lin} are user specified weights for respectively the angular and linear displacements and ε_A is the threshold below which the grasp is considered to be *successful*.

The pose and angle weights (w_{ang} and w_{lin} respectively) are set to 0.25 and 1, and the threshold ε_A is set to 1 for both objects. The data on the performance of the grippers in object alignment was subsequently collected and processed.

For each of the scenarios, interesting ranges in offset space were determined during the preliminary simulation experiment round. The sampling and the offset bounds were subsequently defined as shown in Table 1. Altogether, 2772 grasping experiments were executed in simulation: 1246 for the *bracket* object and 1526 for the *heatshield* object.

4.1 Bracket Object Scenario

The gripper design optimization for the *bracket* scenario was performed using the predefined gripper finger shapes (a block finger with dimensions 10 × 10 × 50 mm, wrt. the coordinate axis in Figure 4(a), and a round finger with a width and length of 10 × 50 mm) with cut-outs designed using (a) the PFO method and (b) the IFM. Figure 5 shows the parametrization scheme used to design the *bracket* object grasping fingers with the use of the PFO method.

The fingers designed using the IFM were generated specifying the *bracket* as the imprint object and the *nominal grasp* pose shown in Figure 4(a) being the *imprint pose* (see Section 3.2). When designing the finger for the inner grasp using the IFM, the *bracket* was cut open. This was done because the method considers the exterior of the object and by removing the

Table 1: The sampling defined for the individual offset axes in alignment verification experiments.

Bracket scenario				
Axis	Min	Step	Max	N. of samples
X [mm]	-10	0.1	5	151
Y [mm]	-10	0.1	10	201
Z [mm]	-12.5	0.1	12.5	251
θ_x [°]	-60	0.5	60	241
θ_y [°]	-60	0.5	50	221
θ_z [°]	-45	0.5	45	181

Heatshield scenario				
Axis	Min	Step	Max	N. of samples
X [mm]	-25	0.1	25	501
Y [mm]	-15	0.1	15	301
Z [mm]	-15	0.1	15	301
θ_x [°]	-30	0.5	30	121
θ_y [°]	-40	0.5	40	161
θ_z [°]	-40	0.5	30	141

part of the *bracket* that is not in contact with the finger during grasping, the imprint can be constructed successfully.

The *chamfering* of the bracket finger was predetermined for the PFO method. The gripper used a 20 mm stroke for the grasping of the *bracket*.

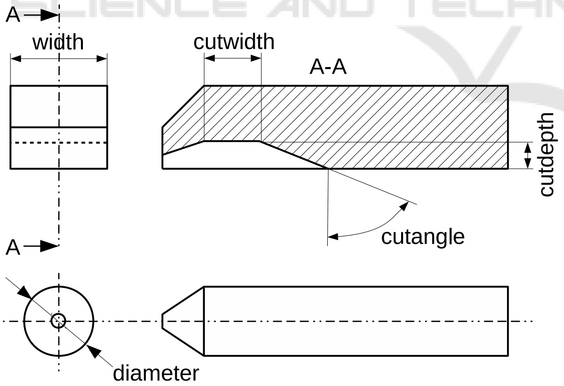


Figure 5: The brackets finger geometry parametrization.

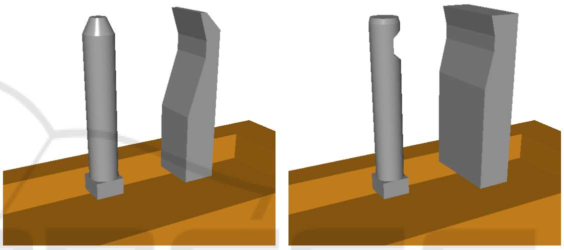
The optimization was performed with the use of Simplex optimization method (Nelder and Mead, 1965) starting from an arbitrarily chosen point in the parameter space. The objective function selected was defined as a geometric average of Gripper Quality indices (see Equation 1) with the weights defined as:

$$w_S = 1 \qquad w_R = 0 \qquad w_C = 0 \qquad w_A = 1 \tag{3}$$

$$w_W = 0.1 \qquad w_T = 0.01 \qquad w_V = 0.01 \tag{4}$$

The optimization process took 60 steps for the PFO method. The computation time was 6.5 hours for the PFO method and 7.5 hours for the IFM. The optimization was done using an 8-core i7-4702MQ CPU 2.20GHz machine with 8GB of RAM. The set-up time of the workcell and definition of the task context took about 30 minutes and is identical for both the methods. The total set-up time for the PFO method was 1-1.5 hours and 10-20 minutes for the IFM.

Figure 6 shows the fingers designed for the *bracket* object grasping scenario using both the PFO method and the IFM. The parameters of the PFO fingers before and after optimization are gathered in Table 2. The final score of the IFM fingers was found to be $Q: 0.533$. In addition to providing the basic finger shape, the user input consists of defining 6 parameters for the PFO method.



(a) The PFO method. (b) The IFM.

Figure 6: Optimized finger for handling the bracket object.

Table 2: The bracket fingers optimized parameters.

PFO Q: 0.134 → 0.616	
diameter	*width*
10.00 → 8.53 [mm]	10.00 → 14.50 [mm]
cutwidth	*cutdepth*
5.00 → 4.72 [mm]	5.00 → 5.42 [mm]
cutangle	
45.00 → 71.51 [°]	

Figure 7 presents the results of grasping the *bracket* object using fingers designed using PFO and IFM methods for increasing offsets introduced in axes defined in Section 4. It can be seen that the two methods failure regions are quite similar. However, the success range of the IFM is smaller, along some of the axis, than that of the PFO method. This is because the object is able to rotate in the cut-out of the two fingers and a large part of the result are hence classified as misalinged.

The IFM method offers a great advantage in terms of time and effort saving in the set-up phase. In this scenario it does, however, results in lower performance than that of the PFO method.

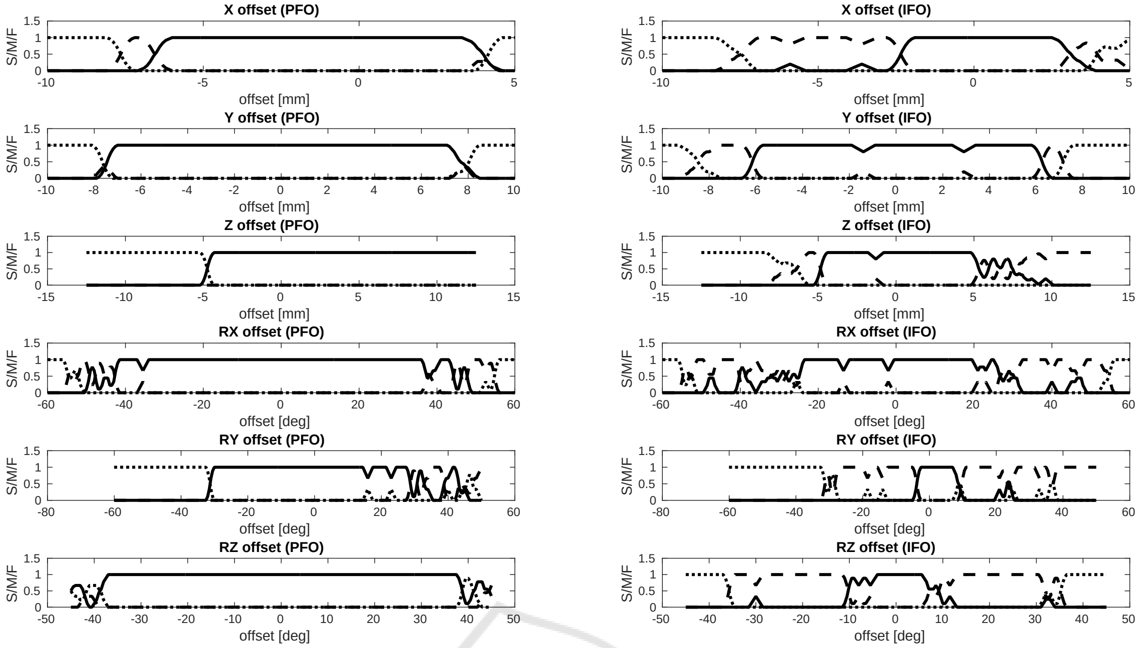


Figure 7: The comparison of the alignment results in the bracket object scenario for the parametrized gripper (on the left) and for the gripper designed using the imprint method (on the right). Solid line represents the grasp success rate, dotted line – the misalignment rate, and the dashed line – the failure rate.

4.2 Heatshield Object Scenario

In the experiments performed for the *heatshield* scenario, the gripper design optimization was performed using the predefined gripper finger shapes (a set of block fingers with dimensions $20 \times 30 \times 75$ mm, wrt. the coordinate system in Figure 4(b)) with cut-outs designed using (a) the PFO method and (b) the IFM. The parametrization scheme chosen for the *heatshield* object grasping fingers designed using the PFO method is presented in Figure 8. The grasping fingers for the IFM were designed with the *heatshield* as the imprint object and the *imprint pose* (see Section 3.2) was the *nominal grasp* pose seen in Figure 4(b).

The gripper used a 70 mm stroke for the grasping of the *heatshield*. The PFO method has a predefined *cutdepth* and *cutwidth* set to 15 and 30 mm respectively based on the *heatshields* actual size.

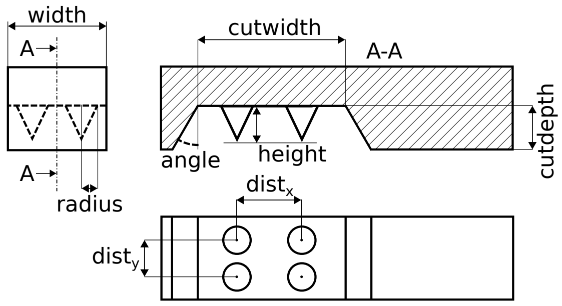


Figure 8: The heatshield finger parametrization.

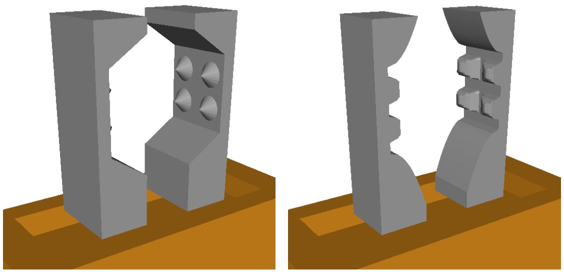
The finger optimization was performed with the use of Simplex optimization method starting from a point selected in the parameter space. The objective function used was defined as a geometric average of Gripper Quality indices (see Equation 1) with the following weights:

$$w_S = 1 \quad w_R = 0 \quad w_C = 0 \quad w_A = 1 \tag{5}$$

$$w_W = 0.1 \quad w_T = 0.01 \quad w_V = 0.01 \tag{6}$$

The optimization process took 53 steps for the PFO method and 7.1 hours to computeand the IFM took 16.7 hours of runtime in total The algorithms were run on a Intel Core i7-3610QM CPU 2.30GHz with 8GB of RAM, the program was run single threaded. The total set-up time of the workcell and task context took approximately 30 minutes. And the time to design the fingers for the PFO method took 1-1.5 hour and less than 10 minutes for the IFM.

Figure 9 shows the comparison of the fingers designed for the *heatshield* object grasping scenario using both the PFO method and the IFM. The parameters of the gripper before and after optimization are presented in Table 3. The final score of the gripper using the IFM was $Q : 0.46$. The user has to provide the basic finger shape for both of the methods. Additionally, the required input consists of defining 6 parameters for the PFO method.



(a) The PFO method. (b) The IFM.

Figure 9: Optimized fingers for the heatshield object.

Table 3: The heatshield fingers optimized parameters.

PFO Q: 0 → 0.44	
angle	*width*
20.00 → 32.91 [deg]	30.00 → 29.99 [mm]
$dist_x$	$dist_y$
13.00 → 13.00 [mm]	13.00 → 15.81 [mm]
radius	*height*
5.00 → 5.00 [mm]	5.00 → 5.01 [mm]

Figure 10 presents the results of grasping the *heatshield* object using fingers designed using PFO and IFM methods for increasing offsets introduced in axes defined in Section 4. Both the fingers found offer a similar level of performance. The IFM has on average a larger number of successful grasps along the six axis, but overall similar performance is obtained. The PFO method clearly has the advantage of obtaining its result faster than the IFM, since less than half the simulation time is needed. However, using the IFM does offers an advantage in terms of time and effort saving in the set-up phase.

5 DISCUSSION

In Section 4 the experiments in simulation where presented aimed at comparing the quality of grippers produced using both methods in terms of the grasping alignment capabilities achieved. The alignment capability of a gripper was quantified as a measure of the degree at which it can compensate for grasping pose uncertainty, while still achieving the predictable pose of the grasped object wrt. the gripper.

The averaged results for both position and angle offsets is presented in Table 4. The *linear* and *angular* offsets are grouped together in the table, and the total percentage of the grasp outcomes is shown as well. Overall, the results are comparable for both methods grasping the *heatshield*, see Section 4.2, with the IFM performing a little better than the PFO. However, the results for the *bracket* are largely different. With almost twice the success of the IFM, the PFO method shows a significant advantage. This is due to the unforeseen objects interaction with the cut-out shape that allows for rotation along $\theta_y$in the grasp of the IFM gripper, and the gripper performance hence drastically falls during the tests.

It is also worth noting that the gripper designed for the bracket using the PFO method grasps the object at a different pose wrt. the TCP than that designed using the IFM. This is because the PFO gripper was parametrized with a cut-out located only on the exterior grasping finger, while the IFM generates a cut-out in both fingers. The choice of when to apply a cut-out to a finger is an option that can be explored in further IFM research.

Table 4: The averaged grasp experiment results for the PFO and IFM methods used in the bracket and the heatshield scenarios. The columns indicate: S – the successful grasp rate, M – the misaligned grasp rate and F – the failure grasp rate.

	PFO			IFM		
bracket object						
	%S	%M	%F	%S	%M	%F
Pos.	71.5	3.5	25.0	48.5	29.0	22.5
Ang.	75.0	9.0	16.0	28.3	50.3	21.4
Total	**73.3**	**6.3**	**20.5**	**38.4**	**39.7**	**22.0**
heatshield object						
	%S	%M	%F	%S	%M	%F
Pos.	62.0	31.3	6.7	69.7	27.0	3.3
Ang.	68.7	7.7	23.7	69.0	13.7	17.3
Total	**65.4**	**19.5**	**15.2**	**69.4**	**20.4**	**10.3**

6 CONCLUSION

In this paper a new method to generate optimized finger cut-outs was presented (IFM). The method uses the idea of using the *imprint* to produce the finger geometry. Furthermore the method introduces a profile surrounding the cut-out.

The IFM was compared to a previously developed method (PFO) in terms of set-up and run time and grasping experiments performed in simulations. Compared to PFO, the IFM design method proved to require considerably less set-up time, on average 15 minutes compared to 1-1.5 hours for the PFO. This is offset by a longer computation time (on average 12.1 hours using IFM and 6.8 hours for the PFO method). This is however not an important factor, considering that the reduction in required man-hours greatly outweighs the increase in cheap computational power.

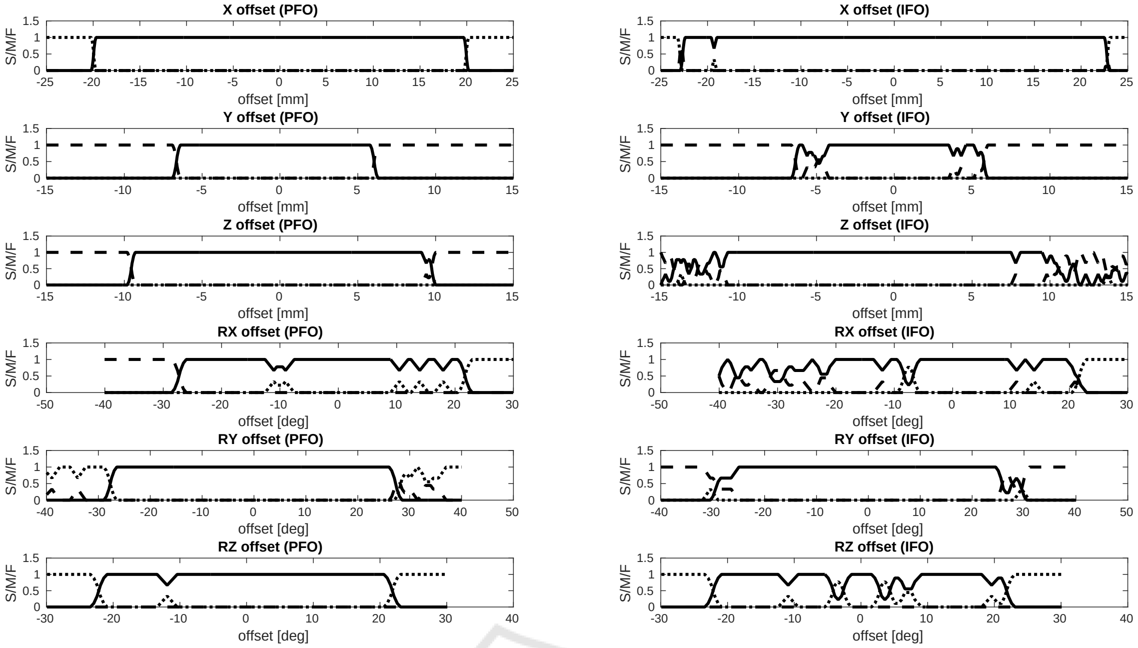


Figure 10: The comparison of the alignment results in the heatshield object scenario for the PFO gripper (on the left) and for the gripper designed using the IFM (on the right). Solid line represents the grasp success rate, dotted line – the misalignment rate, and the dashed line – the failure rate.

The IFM requires far less manual user input, particularly in cases (such as *heatshield*), where it is difficult to conceive a parametrization scheme that suits the grasping of a complicated geometrical shape. The propose IFM therefore simplifies the gripper design proses significantly. Even in the case of the simpler objects (such as *bracket*), it is of great advantage to have the grasping profile generated automatically. The *bracket* object provides a challenge for the IFM, since due to the necessity of using an internal grasp. The general dimensions and external features of the internal grasping finger (which is not generated through imprinting) are of high importance in cases like these.

Additionally, the IFM seems to produce cut-out profiles which more closely resemble the geometry of the object. This in turn allows for more robustness in the grasps performed, due to larger contact surfaces. This is also important in terms of the reduction of the forces exerted on the objects, which is of importance in the tasks of handling fragile and flexible materials.

It can be concluded, that using both of these methods in conjunction would utilize their synergy: the PFO method is best suited for the choice and optimization of the external finger profile (e.g. with the parametrization chosen from a pre-defined library of finger shapes), while the IFM is used to facilitate the parametrization of the cut-out.

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