Automatic Design Algorithm of a Robotic End-Effector for a set of Sheet-Metal Parts

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***Abstract*— Robotic end-effectors in automated production lines are specially designed and built for a unique task and for a particular part. An end-effector capable of grasping different parts with different geometries will expand its benefit and reduce costs. This work focuses on the grasp of sheet metal parts for the automotive industry. In order to maximize the use of a single end-effector, this paper proposes a search algorithm for a simple common grasp configuration. Such configuration imply for an end-effector design capable of grasping a set of sheet metal parts. The algorithm maps possible grasps which are candidate to be common. We define a novel quality measure estimating the distribution of the contacts across the sheet metal part. Candidate grasps which have a sufficient quality are mapped into high-dimensional feature vectors. These feature vectors parameterize the geometry of the polyhedron formed by the contacts locations and the direction of the surface normals relative to the polyhedron. Thereby, they describe the design of the end-effector compatible to the grasp. A database is generated for all possible grasps for each part in the feature vector space. A similarity join based on nearest-neighbor search and classification algorithm are used for intersecting all possible feature vectors over all sheet metal parts and finding common ones. Simulations of a 3-finger grasp on four meshed sheet metal parts resulted in a common grasp. Results of the simulations validate the feasibility of the proposed algorithm.**

I. INTRODUCTION

In automated production lines each robotic end-effector has its designated usage for a specific action and for handling a specific part. Therefore, for each part and task a robotic end-effector is specially designed and built (Figure 1a). This demands a considerable amount of engineering time and cost. Thus, the demand for multiple end effectors for each part and task requires high costs. Therefore, it has direct impact on the price of the final product.

This work addresses the problem of designing an end-effector for a robotic arm capable of grasping a set of different sheet metal parts in the automotive industry. The purpose of this work is to develop an algorithm which will find a design of a simple optimal universal end-effector for grasping a set of q sheet metal parts (SMP). The design of the end-effector is extracted from the grasp configuration defining contacts locations and force directions. SMP are curved thin and flat objects formed by bending, cutting and stamping sheet metal plates. The grasp and fixture of a SMP is usually done with clamps or suction cups. Moreover, its geometry requires well distributed fixturing points on the surface of the SMP to prevent distortion and damage. Therefore, the synthesis of such a grasp should consider some properties to be described. The proposed algorithm uses these properties to find a common grasp configuration for a given set of SMP. Given a set of q CAD models of the SMP, the goal is to design an end-effector which is universal, that is, able to hold a wide set of components. We propose a novel solution for designing simple end-effectors that can handle a class of SMP rather than a single one. This paper is an adaptation of our previous work presented in [1], [2] to SMP.

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(a) (b)

Fig. 1. (a) Grasping of a sheet metal part and (b) a sheet metal clamp.

The proposed algorithms output is a common grasp configuration which implies for the design of the industrial end-effector. The design has to be simple and low cost, thus, it has to be with minimal degrees of freedom. We search for a feasible grasp configuration which can stably grasp the object even under the application of external forces or torques due to the task being done. That is, we require force-closure grasp. As there are numerous possible grasps, we introduce a novel quality criteria termed *Variance Based Quality Measure* (VBQM) which quantify the grasp according to its distribution across the SMP. The quality measure enables filtering out inappropriate grasps. In this work we assume rigidity of the SMP and point contact by the clamps.

In the proposed algorithm, the CAD's of the SMP are discretized to a triangular mesh. We apply a mesh reduction algorithm to remove undesired areas which could not be grasped. The algorithm parameterizes all grasps (up to mesh size) that are possible candidates to be common to all SMP into feature vectors in a high-dimensional space. The feature vector implies for the end-effectors' configuration. These feature vectors construct a *Candidate Grasp Set* (CGS) for each SMP. Similarity join and classification are conducted, in order to find minimal feature vectors which cover the whole set of SMP. for finding pairs of common feature vectors in the CGS of all SMP.

The paper is organized as follows. Section III presents the grasping model used in this work. An overview of the proposed search algorithm is described in section IV. Section V presents the simulations implementing the proposed algorithm.

II. Related Work

Grasp planning uses the notions of force-closure and quality measure as criteria for determining and quantifying feasible grasps. A force-closure grasp is defined as a grasp that can resist any external load. Using the notion of wrenches (forces and torques), in [3]–[5] force-closure criterion is well defined and several algorithms for synthesis of a frictional and frictionless grasps were presented. Several grasp optimization methods using different grasp quality measures have been presented in the literature; Ferrari and Canny [6] and Li and Sastry [7] introduced a quality measure based on the external wrench to be resisted. A method which is based on the convex-hull of the wrenches formed by the contact forces. As we deal with grasping of large flat objects, we focus on methods which measures the distribution of a grasp over the grasped object. Chinellato et al. [8] introduced quality measures criteria for 3-finger planar objects, one based on the area of the triangle formed by the contact points. Kim et al. [9] presented the stability grasp index, which defines a polygon formed by the contact points and measures the deviation of the polygons angles from a regular polygon; this implies for the distribution of the contacts on the object.

Much work has been done in the area of grasping and end-effector design for sheet metal parts. Park and Millis [10] have dealt with the localization of sheet metal parts to acquire a precise fixture. Gopalakrishnan et al. [11] proposed an algorithm for fixturing sheet metal parts using conical grooves. Such method enables unilateral fixture avoiding tool interference at one side of the sheet metal part. Ceglarek et al. [12] introduced a method for modeling and optimization of an end-effector for SMP considering task directions and desired motion. Li et al. [13] proposed a methodology for modeling a dexterous end-effector and overcoming deformations, acquiring more precise fixturing.

To the best of our knowledge, no previous work has been done for searching common grasps or end-effectors design for a set of SMP. However, much work which has relation to ours has been done in the area of 3D shape similarity comparison algorithms, such as [14] and [15]. These algorithms are used for Internet and local storage search, face recognition, image processing or parts grasping in assembly lines. Such methods deals with parameterization of the geometry of the objects and cannot be applied for end-effector design. The work of Li and Pollard [16] is based on shape matching for finding the best grasp for a set of objects. The best grasp is found by matching hand poses from a database to each object. This is done by using a predefined parameterization of the object surface and the hand poses, a method which inspired this work.

III. Grasp Feasibility

The grasp of SMP is done using sheet metal clamps (Figure 1b). Clamping of a SMP provides two opposing forces at the contact point. In this section we present the implications of this property on the grasping model. Friction exists at the contact points between the clamps and the SMP's surface. Friction can be represented by the simple Coulomb friction model. In this model, forces exerted at a contact point must lie within a cone centered about the surface normal. This is known as the *Friction Cone* (FC). The friction model can be mathematically represented by $\left|\sqrt{\mathbf{f_{i,2}}^2 + \mathbf{f_{i,3}}^2}\right| \leq \mu \mathbf{f_{i,1}}$, where $\mathbf{f_{i,1}}$ is the normal component of the contact force, $\mathbf{f_{i,2}}$ and $\mathbf{f_{i,3}}$ are the tangential components at the contact point. The FC in this case is non-linear and to simplify the model the cone be approximated with an *s*-sided convex polyhedron and every force exerted within the FC can be represented by a linear combination (Figure 2) of the unit vectors $\hat{\mathbf{f}}_{\mathbf{ik}} \in FC$ (primitive forces) constructing the linearized friction cone,

$$\mathbf{f_i} = \sum_{k=1}^{s} a_{ik} \hat{\mathbf{f}}_{\mathbf{ik}}, \; a_{ik} \geq 0 \tag{1}$$

where a_{ik} are nonnegative coefficients. The $\hat{\cdot}$ sign denotes a unit vector. Based on the model of the grasp, we now want to define whether a grasp is feasible or not. This is presented in the following subsection.

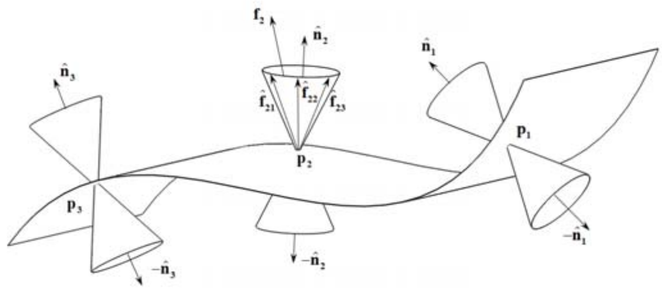

Fig. 2. Grasping of a sheet metal part.

A. Force-Closure

Forces and torques can be represented as a wrench vector in the wrench space. A wrench is a 6-dimensional vector and is denoted as $\mathbf{w} = \begin{pmatrix} \mathbf{f} & \tau \end{pmatrix}^T \in \mathbb{R}^6$ where $\mathbf{f} \in \mathbb{R}^3$ is the force vector and $\tau \in \mathbb{R}^3$ is the torque vector. Furthermore, a wrench induced by the contact force at the contact point $\mathbf{p_i}$, can be described as $\mathbf{w_i} = \begin{pmatrix} \mathbf{f_i} & \mathbf{p_i} \times \mathbf{f_i} \end{pmatrix}^T$ where $\mathbf{p_i}$ is represented in the parts coordinate frame.

A grasp is said to be force-closure if it is possible to apply wrenches at the contacts such that any external forces and torques acting on the part can be counter-balanced. In other words, a system of wrenches can achieve force-closure when any external load can be balanced by a non-negative combination of the wrenches [3]. The determination of whether a grasp is force-closure is usually done according to the following Theorem.

Theorem 1. *[5], [17] A set of wrenches $\mathcal{W}$ is said to achieve force-closure if its wrenches positively span the entire wrench space $\mathbb{R}^6$.*

To determine whether a grasp is force-closure, the Convex-Hull analysis [3] is usually done. However, it is an expensive computational method and in the next Theorem we show it is unnecessary. The following Theorem is based on the grasp method where in clamping, two opposing forces are applied at the contact.

Theorem 2. *Given $n \geq 3$ frictional contact points $\mathcal{P} = \{\mathbf{p_1}, ..., \mathbf{p_n} |\ \mathbf{p_i} \neq \mathbf{p_j}\ \forall i \neq j,\ i, j = 1, ..., n\}$ on the surface of the SMP, each with two opposed forces in direction of the normals to the surface. If there are 3 non-collinear contact points $\mathbf{p_i}, \mathbf{p_j}, \mathbf{p_k} \in \mathcal{P}$, the frictional forces at $\mathcal{P}$ positively span $\mathbb{R}^6$ and the grasp is force-closure.*

Proof: At least four frictional contact forces are needed to achieve a force closure grasp [5]. For two contact points $\mathbf{p_i}, \mathbf{p_j}$, we have four frictional forces (two opposing pairs). However, these forces cannot apply torque about the axis formed by $\overline{\mathbf{p_i p_j}}$, that is, the four frictional forces span only $\mathbb{R}^5$. Adding two more opposing forces at point $\mathbf{p_k} = \{\mathbf{p_k} | \mathbf{p_k} \neq \mathbf{p_i} + \gamma(\mathbf{p_i} - \mathbf{p_j}), \forall \gamma\}$ enables applying torque about the $\overline{\mathbf{p_i p_j}}$ axis. Hence, the three contact points $\mathbf{p_i}, \mathbf{p_j}, \mathbf{p_k}$ with six frictional forces positively span $\mathbb{R}^6$. □

Theorem 2 provides the notion that a grasp of an SMP with $n \geq 3$ clamps, where at least three clamps are non-collinear, is always force-closure. Therefore, there is no need for force closure analysis using the convex-hull method. Moreover, there is no need for modeling and linearizing the friction cones, which consumes large computation resources. This notion reduces the runtime of the algorithm drastically. However, despite all non-collinear grasps are force-closure, not all of them are equally good. There is a need for a criteria to be used to filter out undesired grasps. The next subsection defines such criteria.

B. Variance Grasp Quality Measure

It has been shown that all $n \geq 3$ clamp grasps are force closure. However, not all grasps should be considered feasible. One can think of grasping a long sheet metal from one edge. Although the grasp may be force closure, large forces would have to be applied to counter balance external loads such as gravity. Hence, the criterion for defining the quality of a grasp should be based on the distribution of the clamps on the surface of the SMP. A good distribution would result in balanced and relatively low loads on the clamps.

We present a novel quality measure termed *Variance Based Quality Measure* (VBQM). It is a grasp quality measure defined for SMP and is used to filter out inappropriate grasps according to a heuristic condition to be presented. The main concept of defining the VBQM is by evaluating the distribution of the contact points on the sheet metal objects. We use variance measure to quantify the distribution.

For n clamp points $\mathcal{P} = (\mathbf{p_1}, ..., \mathbf{p_n})$, where $\mathbf{p_k} = (x_k, y_k, z_k)$. We compute the norm of the variances over all coordinates of the n points as follows

$$\mathcal{V} = \left\| \begin{pmatrix} \frac{\sum_{k=1}^{n} (x_k - \overline{x})^2}{n}, & \frac{\sum_{k=1}^{n} (y_k - \overline{y})^2}{n}, & \frac{\sum_{k=1}^{n} (z_k - \overline{z})^2}{n} \end{pmatrix}^T \right\| \tag{2}$$

where $\overline{x}, \overline{y}, \overline{z}$ are the means of the respected coordinates.

As will be shown in the following section, for each SMP, we go through all possible combination (up to mesh size) of n clamping points and find the largest variance possible among all sheet metals, that is,

$$\mathcal{V}_{max} = \max_{i,j} \mathcal{V}_j^i \tag{3}$$

where $\mathcal{V}_j^i$ is the variance of grasp j of part i.

The variance calculated is a measure of how much the grasp is distributed across the SMP. Therefore, we define the new quality measure for grasp j of sheet metal i to be normalized by the maximum variance of all SMP,

$$Q_j^i = \frac{\mathcal{V}_j^i}{\mathcal{V}_{max}} \quad . \tag{4}$$

The normalization will provide a comparative measure between SMP grasps to find a common one.

IV. SM-COG Algorithm

Given q objects to be grasped with n clamps. The Sheet Metal COmmon Grasp (SM-COG) search algorithm will output a feasible common grasp with the highest quality measure for the set of objects. The algorithm is presented in Algorithm 1.

The algorithm receives as input a set of q CAD models of the query SMP. The first step of the algorithm is the discretization of each CAD model to a mesh of k triangles. Each triangle in the mesh is characterized with its center of gravity position vector $\mathbf{p_i}$ and the normal $\mathbf{\hat{n}_i}$ (unit vector) to the surface of the triangle. Thus, the mesh of each object is defined with a set of points on the surface $\tilde{\mathcal{P}} = (\mathbf{p_1}, ..., \mathbf{p_k})$ and a set of normals at the points $\tilde{\mathcal{N}} = (\mathbf{\hat{n}_1}, ..., \mathbf{\hat{n}_k})$. The next step of the algorithm is the reduction of redundant mesh triangles as described next.

Algorithm 1 Common grasp search

Input: CAD's of SMP $B_1, ..., B_q$ and number of contact points n.

Output: A common grasp for all objects or common grasps for subsets of the objects.

Calculate Q_{max}, Q_{min} using eq. (3) and (4).
for $\xi = 1 \rightarrow q$ **do**
  Mesh SMP B_ξ to form $\{\tilde{\mathcal{P}}_\xi, \tilde{\mathcal{N}}_\xi\}$.
  Perform Mesh reduction.
  Generate possible n contact points grasps $\{\mathcal{P}_1, \mathcal{N}_1\}_\xi, ..., \{\mathcal{P}_\lambda, \mathcal{N}_\lambda\}_\xi$.
  for $j = 1 \rightarrow \lambda$ **do**
    Calculate Q_j^ξ of grasp $\{\mathcal{P}_j, \mathcal{N}_j\}_\xi$.
    if $Q_{min} \leq Q_j^i \leq Q_{max}$ **then**
      Map grasp $\{\mathcal{P}_j, \mathcal{N}_j\}_\xi$ to feature vector $\mathbf{e_j}$.
      Add $\mathbf{e_j}$ to set $\mathcal{E}_\xi$.
      Store pointer between $\mathbf{e_j}$ and $\{\mathcal{P}_j, \mathcal{N}_j\}_\xi$.
    end if
  end for
end for
$\mathcal{Z} = JoinCGS(\mathcal{E}_1, ..., \mathcal{E}_q)$
$\mathcal{H} = Classification(\mathcal{Z})$
if $\mathcal{H} \neq \emptyset$ **then**
  return $\mathcal{H} = (\mathbf{u_1}, ..., \mathbf{u_\sigma})$
else
  Report: No common grasps.
end if

A. Mesh Reduction

As our clamping device can only clamp near the boundaries of the sheet metal, the inner triangles of the mesh are excessive and cause tremendous calculation runtime. The redundant mesh should be removed either by the user or by a reduction algorithm. Therefore, algorithm for omitting the inner mesh was implemented. We define m as the number of layers of inner triangles from the boundary we consider as edge triangles. m is determined according to the mesh size and the desired boundary width to grasp defined by the clamp. The algorithm builds an adjacency table of the

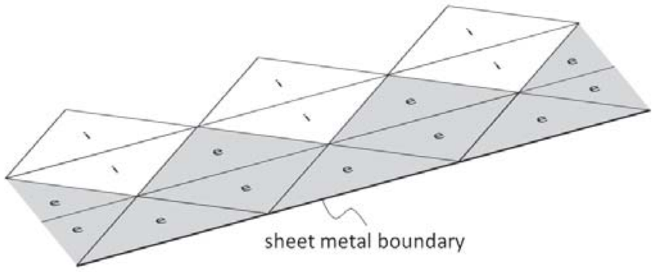

Fig. 3. The triangles of the mesh marked to be edge or inner triangles when $m = 3$.

triangular mesh. The main concept is marking the neighbors of each mesh triangle (Figure 3), those with only 2 neighbors are boundary triangles (marked with 'e') and those with 3 neighbors are inner triangles (marked with 'i'). Then, we mark as boundary triangles ('e') those which are with distance m from the boundary triangles. Finally, the inner mesh triangles are removed from the mesh.

Another optional step is for the user to manually remove areas in the mesh which are forbidden to grasp. Such areas are defined according to operational constraints, sensitive areas on the SMP, etc.

B. CGS Generation

The next step is the generation of the *Candidate Grasp Set* (CGS) for each SMP. The CGS is a set of high-dimensional vectors which represents candidate grasps. Candidate grasps are those that have the possibility to be common to all SMP. The generation of the CGS is done by mapping each candidate n-clamp grasp to a set of parameters termed *feature vector*. The CGS contains all (up to the mesh size) feature vectors of candidate n-clamp grasps. For example, a 3-clamp grasp can be represented by a triangle formed by the 3 contact points. With more than 3-clamps, the contact points form a polyhedron.

From all possible grasps, we pick only the ones which are candidate to be common it term of their quality. Grasp j of part i that is defined by n contacts $\mathcal{P}_j^i = (\mathbf{p_1}, ..., \mathbf{p_n})$ is considered to be a candidate if there are at least three non-collinear contact points and if its quality measure Q_j^i is within the bound

$$Q_{min} \le Q_j^i \le Q_{max} \quad , \tag{5}$$

where Q_{max} and Q_{min} are defined as follows. Prior to the generation of the CGS, we build a distribution graph of the quality measures for each SMP (Figure 4), this is done by sampling all possible grasps on the SMP's surface. We acquire q sets of measures Q^i. The maximum limit of the quality measure to search will be

$$Q_{max} = \min_i(\max_j(Q_j^i)) \tag{6}$$

where i is the SMP index and j is the grasp index. A boundary larger than this will be wasteful as not all SMP has grasps in that region. Therefore, grasps which has a quality measure larger than Q_{max} are not possible candidates to be common. The minimum limit of the measure Q_{min} is

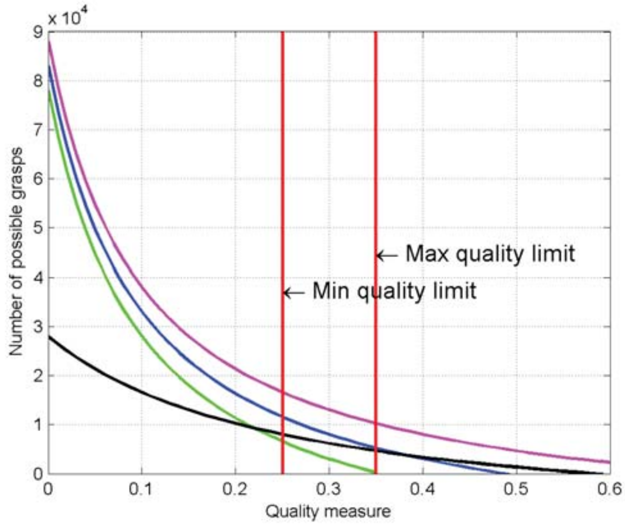

Fig. 4. Distribution of the quality measure for each SMP and the search limitations.

defined by a maximum allowed number β of points in a set. Therefore, we choose Q_{min} to be

$$Q_{min} = \max_i(Q_{min}^i) \tag{7}$$

such that each Q_{min}^i maintains the condition

$$\int_{Q_{min}^i}^{Q_{max}} f_i(Q^i)dQ^i \le \beta \cdot (Q_{max} - Q_{min}^i), \forall i = 1, ..., q \tag{8}$$

where $f_i(Q^i)$ is a polynomial fit of the distribution points acquired previously. The choice of the number of points β to be in the set affects the runtime.

Next, the candidate grasps are parameterized to feature vectors in the feature space. That is, we define transformation map T to map grasp j represented with $\mathcal{P}_j$ and $\mathcal{N}_j$ into a d-dimensional feature vector $\mathbf{e_j}$:

$$T : \{\mathcal{P}_j, \mathcal{N}_j\} \to \mathbf{e_j} \in \mathbb{R}^d \quad . \tag{9}$$

Transformation T forms a feature vector which injectively represent the grasp configuration invariant of any coordinate frame. The feature vector of a grasp is a set of parameters which constrain the size and shape of the polyhedron formed by the contact points. Moreover, parameters in the feature vector constrain the normals directions at the contact points relative to the polyhedron itself. For details and examples of the algorithm for parameterization of a grasp to a feature vector see our previous publication [18]. The dimensionality of the feature vector is determined according to the number of contact points n which defines the number of vertices in the polyhedron. The feature vectors of object B_i which are considered to be feasible are added to the CGS of the compatible SMP, denoted as $\mathcal{E}_i \in \mathbb{R}^d$.

Once all feasible grasps of all objects are mapped to the CGS sets $\mathcal{E}_1, ..., \mathcal{E}_q$, we would like to intersect the CGS's to find common feature vectors which imply for common grasps. Therefore, we define function *joinCGS* which is a similarity join algorithm to find common points over the sets. Hence, nearest-neighbor search is utilized to find pairs of common vectors among the sets. Pairs of common vectors found are checked to satisfy tolerance demands derived from the friction cones angle, accuracy demands and hardware capabilities. Basically, two feature vectors over two sets are considered to be the same if they are both inside an hyper-rectangle with predefined edge lengths.

Two vectors which are considered to be the same are further added to a registry set $\mathcal{Z} \in \mathbb{R}^d$ of common vectors. The set $\mathcal{Z}$ is a d-dimensional database of vectors taken from $\mathcal{E}_1, ..., \mathcal{E}_q$. The vectors inserted to $\mathcal{Z}$ are the ones which exists in two or more sets of $\mathcal{E}_1, ..., \mathcal{E}_q$, i.e., those which are common to two or more sets. For each feature vector added to $\mathcal{Z}$, it is marked from which CGS sets they originated.

The final step of the algorithm is the classification of the vectors in $\mathcal{Z}$. After a set of vectors common to two or more of the sets $\mathcal{E}_1, ..., \mathcal{E}_q$ were acquired, classification is needed to find the minimal number of grasp configurations which can grasp subsets of the objects. We search for a minimum set $\mathcal{H} \subseteq \mathcal{Z}$ of vectors from the registry set which covers all of the CGS sets. Basically, we search for a single feature vector from $\mathcal{Z}$ which exists in all of the sets $\mathcal{E}_1, ..., \mathcal{E}_q$. Such a vector represents an end-effector design which can grasp all of the objects. If a single vector is not found, we seek for a minimal number of grasps which can grasp subsets of the objects. That is, we divide the set of objects to subsets, where for each subset there is a compatible end-effector.

As we go through all possible n-clamp grasp combinations (up to mesh size), therefore, the algorithm will certainly find a common grasp or a set of common grasps if such exist. Thus, if a single grasp for all SMP or a set of grasps for subsets of the SMP exist, the algorithm will find them. If failed to do so, the algorithm reports that common grasps do not exist.

V. SIMULATIONS

For simulations of the proposed algorithm, it was implemented in Matlab on an Intel-Core i7-2620M 2.7GHz laptop computer with 8GB of RAM. The running of the algorithm was done using MATLAB[1] parallel computing toolbox in order to decrease runtime. The following simulations present an example of the algorithm operation with 3-clamp frictional grasps of four sheet metal car doors. The four SMP are shown in Figure 5. The objects were meshed using COMSOL Multiphysics[2] to triangular meshes with average size of 10,368 triangles. However, with the mesh reduction algorithm the mesh size was reduced to an average of 2,181 triangles per SMP (Figure 6).

The boundaries of the VBQM were calculated according to conditions (6)-(8) with β chosen to be $2 \cdot 10^6$ points. Thus, the boundaries were calculated to be $Q_{min} = 0.6504$ and $Q_{max} = 0.7208$. Figure 7 presents the distribution of the grasps with respect to their VBQM and the boundaries to be used to generate the CGS.

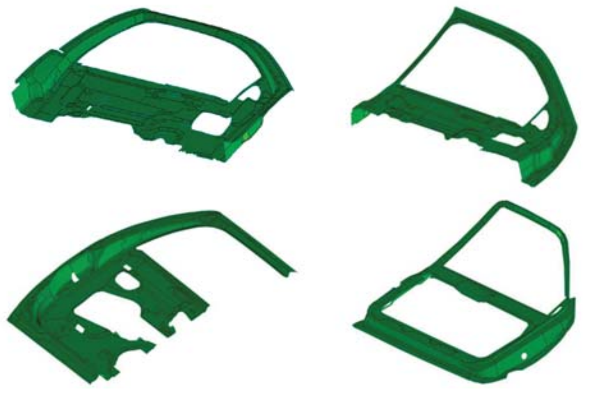

Fig. 5. CAD's of four sheet metal parts.

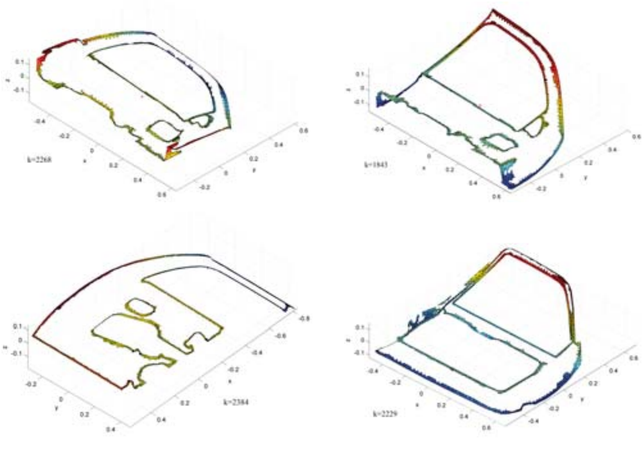

Fig. 6. Four boundary meshes of the sheet metals.

The tolerances for the similarity join were chosen such that the distance between the contact points will not extend or shorten by more than 5% of their original length. These tolerances are continuously computed during the simulation execution. Moreover, tolerances were defined to ensure that the normals at the contact points will be inside a friction cone where the coefficient of friction is $\mu = 0.7$. Under these conditions, with runtime of 14.13 hours, the search algorithm provided 6 grasps which are common to all SMP. The output of the algorithm is a single grasp, out of the 6, with the

[1]Matlab is a registered trademark of The Mathworks, Inc.

[2]COMSOL Multiphysics is a registered trademark of COMSOL AB.

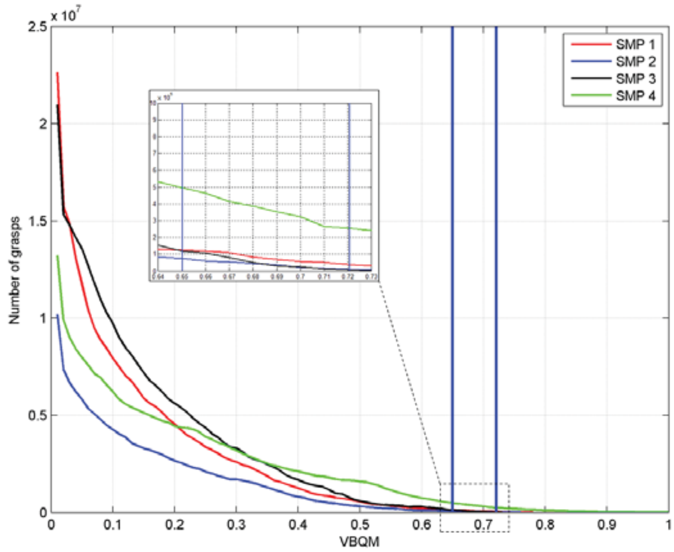

Fig. 7. VBQM distribution of the SMP grasps.

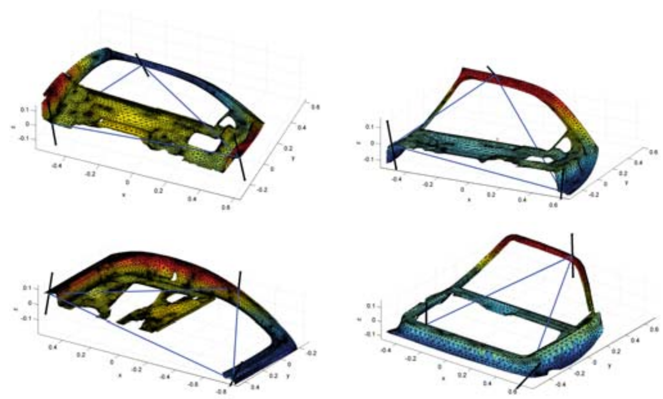

Fig. 8. The common grasp configuration on the four SMP.

highest quality measure. Figure 8 presents the best grasp configuration which has a quality measure $Q = 0.7114$. This grasp is the best common 3-clamps grasp for the four SMP. Notice that some contact points are on the outer boundary of the parts and some are on the inner boundary. And because of that, there is a different approach angle for each part. This can be solved by a rotary degree of freedom added to the certain clamp and will be addressed in future work.

VI. Conclusions

The proposed algorithm discussed in this paper provides a feasible solution for designing a robotic end-effector for automotive production lines able to grasp a set of different sheet-metal parts. The algorithm intersects possible grasps of SMP's and provides a common grasp. If fail to find one common grasp, it will try to divide the SMP to a minimum number of subsets where each subset has its own grasp. The results achieved during simulation shows the feasibility of the algorithm. The overall complexity of the algorithm is in the order of $O(k^n)$ where k is the mesh size of the SMP.
Future work will involve searching for possibilities to add degrees of freedom to the end-effector in cases where a solution could not be found because of significant scale variance between parts. Moreover, we are currently working on a full size experimental setup to verify the simulation results.

Acknowledgments

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