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GRASPING OF 3-D SHEET METAL PARTS FOR ROBOTIC FIXTURELESS ASSEMBLY

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Abstract

A novel grasping strategy and gripper for fixturing 3-D sheet metal parts for the robotic fixtureless assembly application is presented. The grasping strategy combines a previously developed 2-D strategy with a unique hardware design for the fingers of the gripper. To fixture a sheet metal part, the fingers are placed within holes in the part and moved until the desired set of contact locations is achieved. The fingers are grooved at fixed angles such that the edge of the sheet metal part can be held within the grooves. The position of the sheet metal part is uniquely determined in 2-D by the geometry of the part while the non-planar dimension is controlled by the geometry of the fingers. Six frictionless point contacts are used. A computer algorithm is described that solves for suitable contact locations based on the part geometry. Four different grasps were tested on two sheet metal parts. Twenty five trials were performed for each grasp. The standard deviation of the part location prior to being grasped was 0.45 mm. After being grasped, this was reduced to 0.04 mm.

1 INTRODUCTION

Specially designed clamping devices known as fixtures are required for assembly of sheet metal parts in automotive and aircraft manufacturing. These fixtures are used to locate and immobilize the parts for spot welding and riveting. Since the number of sheet metal parts involved is large, between 300-500 per car for example, the number of fixtures required is substantial. When a new model is to be manufactured, new fixtures must be designed, built and installed in the plant. This retooling operation is very expensive. A recent potential solution to this problem is the use of two robots to assemble and join the parts without fixtures. When parts are changed for a new model, only the robot's software should have to be changed. This approach is known as Robotic Fixtureless Assembly (RFA) [4]. RFA is expected to reduce the retooling costs by 80% [5].

The issue in RFA addressed in this paper is fixturing of the parts using a robotic gripper equipped with several movable fingers. The fixturing will be performed in 3-D. Conventional robot grippers (i.e. parallel jaw and three jaw types) require frictional contacts for object immobilization. Since sheet metal parts often have very smooth oily surfaces, frictional contacts cannot be relied upon. In this work, the contacts between the fingers and the part are modelled as frictionless point contacts (FPCs). FPC's have the additional advantage of being able to slide to their desired locations.

As in conventional fixturing, the first goal is to locate the part accurately. Typically an accuracy of ±0.1 mm is required [5]. Initial errors due to robot and part positioning must be overcome to achieve this goal. The second goal is immobilization of the part at its desired location. To achieve these goals the number and location of the contacts, and a suitable finger location strategy must be determined.

With FPCs the number and location of the contacts required for immobilization may be determined by either force closure or form closure models [2] [1] [6]. For the case of FPCs, the locating strategy for force and form closure is equivalent. Nguyen shows that six contacts with independent spatial vectors are needed for grasping in 3-D [6]. Conventional fixturing designers rely on a pseudo form closure approach known as the "3-2-1" rule [3]. This rule states that a part with minimal features will be uniquely held and immobilized when it is rigidly contacting six points. Each contact point is termed a datum feature. The primary datum is a plane defined by three datum features on the most important locating surface as shown in Fig. 1. The secondary datum is a line defined by two datum features and the third is a point defined by one datum feature. The rule is not true form closure since motion is not restricted in all directions. Gravity, friction or other forces are assumed to maintain the po-

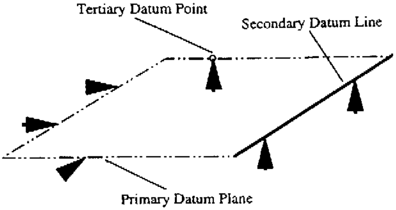


Figure 1: 3-2-1 Fixturing Principle

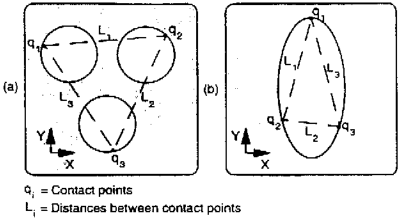


Figure 2: a) 3 Contacts, 3 Edges. b) 3 Contacts, 1 Edge

sition in three of the directions (e.g. up, right and back in Fig. 1). The "3-2-1" rule is not applicable to robotic applications since the orientation of the fixture may vary in free space. Cai et al [2] account for the flexibility of sheet metal parts during fixturing by developing an "N-2-1" principle. The scheme is based on a finite element analysis of the deformations of a sheet metal part and more contacts are added in regions of high deformation. In a robotic application, this would require a gripper with a large number of fingers, which may not be practical. Asada [1] introduced an approach for accurately locating and holding parts using reconfigurable fixtures. The contact points are selected such that the part's position relative to the fixture has a unique solution when all of the points are touching. Known as deterministic positioning, this approach is capable of significantly reducing the initial part placement errors. The final accuracy is a function of the accuracy of the part at the contact points, just as with conventional fixturing.

All of these methods can be used to determine the number and locations for the contacts but disregard how and if the contact locations can be reached. In particular they do not account for the effects of initial robot and part positioning errors, or the lack of suitability of conventional robot grippers for fixturing.

In this paper a novel fixturing method utilizing FPCs on 3-D sheet metal parts will be described. The method achieves accurate part locating and immobilization despite initial positioning errors by exploiting part edge geometry and a novel finger design. The fixturing method for 2-D is first reviewed and then extended to 3-D. A computer program is outlined for determining the desired contact locations for two sample parts. Experimental results are presented for the parts used in the computer tests for several distinct part edge geometries.

2 FIXTURING METHOD

2.1 Review of 2-D Fixturing Strategy

A brief review of the previously developed 2-D fixturing strategy (detailed in [7]) is provided in this section. This strategy will be applied to the primary datum plane.

Part edge geometry plays an important role in locating and immobilizing in 2-D. The fingers are placed within limited spaces of the object and moved until motion ceases. The limited spaces usually take the form of concave edges or holes in the object.

Consider an object with multiple edges that may contain holes. The object is grasped by a number of fingers, and the fingers provide n contacts. The number of contacts may be greater than or equal to the number of edges (m). This is illustrated in Fig. 2 for the cases (n, m)=(3, 3) and (n, m)=(3, 1).

The grasping strategy guarantees part immobilization in 2-D by utilizing the object's geometry to limit finger mobility. The solutions are based on maximizing the distances between the contact points of the grasp. For any object, the distances between two contact points belong to a set of bounded values. From this bounded set of distances there must exist at least one maximum perimeter based on a set of points. Similarly, there exists at least one set of contact locations that provide the maximum perimeter.

The contact locations are assumed to be fixed in position. In practice, the fingers will be locked when the solution locations are reached. This is analogous to the motion restrictions on the contacts in conventional fixturing. For any arbitrary displacement of the object, the perimeter at this new location is restricted to decreasing. For the perimeter to be reduced, one of the distances between contacts must decrease. Since the contacts are fixed in position, this cannot occur, all motions are restricted and form closure is satisfied.

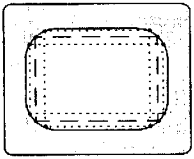


Figure 3: - - Maximum Perimeter Solution ··· Alternative Solutions

It is possible for an object to have multiple fixturing solutions based on maximizing the lengths, but not necessarily the perimeter. As the fingers move from their initial position towards solution locations, they are not permitted to decrease in length as motion proceeds. When all n sides of the polygon have reached lengths that must decrease due to any motion of the object, maximum lengths for the sides have been found. The grasp is restricted to those positions in which the lengths will not change for a possible motion of the object. If the only motion for the object is into positions in which any one of the lengths will decrease, then the object is held. This implies a successful grasp has been found that does not necessarily correspond to the points of the maximum perimeter. Examples of non-maximum perimeter solutions are given in Fig 3.

2.2 Extension to 3-D

2.2.1 Novel Finger Design (Patent Pending)

The extension to 3-D is based on using the 2-D strategy to find grasping points on the primary datum and a novel finger design to locate and immobilize the secondary and tertiary datums. Each finger has a V-shaped circumferential groove (VCG) near its tip. The locating and immobilizing is achieved by the set of VCGs. A sample finger is shown in Figure 4a. Each VCG creates two FPCs, with forces normal to the direction of its surface. These forces can be broken into four independent forces in the coordinate system of the object as shown in Fig. 4b. For purposes of comparison, it should be noted that an FPC at the midpoint provides only one independent force as shown in Fig. 4c, while an edge contact with no friction provides only two independent forces as shown in 4d.

A three finger VCG grasp has six contact points and twelve independent forces. As previously mentioned, a minimum of six contacts with independent forces are needed to immobilize an object in 3-D[6]. The extra forces should result in improved dimensional accuracy as will be discussed later.

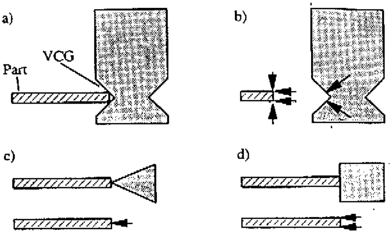


Figure 4: a)Finger with VCG b) Forces with VCG c)Frictionless Point Contact d)Frictionless Edge Contact

The fingers can be used to grasp bent parts as well as flat. They are capable of grasping any edge that is at an angle less than one half of the included angle of the VCGs. The second object used in testing shows that the edge of the sheet metal does not have to remain normal to the axis of the VCG. The VCG's limit the thickness of the sheet metal parts to be grasped to less than the height of the groove.

2.2.2 Projection into 2-D

The grasping strategy for 3-D begins by taking a projection of the part. The variable in this case is the angle of the projection. For a flat plate, the angle is normal to the primary datum. For a bent or oddly shaped piece of sheet metal, the angle should be selected so that the angles between the fingers and the surfaces adjacent to the expected contact locations are perpendicular on average. An example is shown in Fig 5. The contact locations are found by applying the 2-D strategy to the projection. The fingers are set perpendicular to the plane of projection of the object. The height of the finger from the palm of the gripper to the plane of projection can change for different grasps. The angle of the part relative to the plane of projection, the solution locations and the specific part geometry determine the finger height.

The projection onto 2-D for a 3-D object creates one complication not apparent in the 2-D theory. If all of the contact points on an object are colinear, rotation about the line of colinearity can occur that will not be detected by the 2-D grasping theory. As shown in Fig. 6, the line of colinearity is actually a narrow plane with a width equal to the thickness of the edge of the sheet metal, and in the direction of the fingers normal to the sheet metal. The moment arms created by the fingers are too short (less

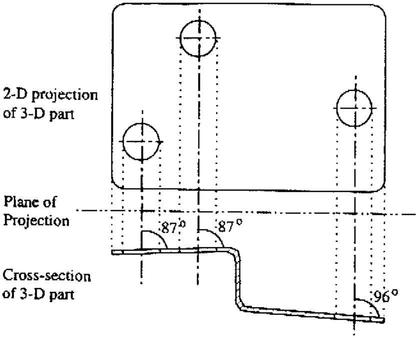


Figure 5: Example of 2-D Projection

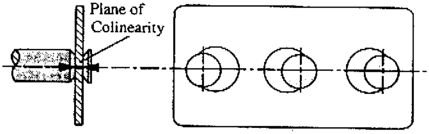


Figure 6: Colinear Grasping in 3-D

than one half the thickness of the sheet) to resist forces in the primary datum plane, leaving it free to rotate.

The strength of the maximal length theory, aside from providing form closure, is that it provides deterministic positioning and a means of convergence to the correct positions. The VCGs also provide these abilities in the secondary and tertiary datums. The position of the part within the groove is deterministic based on knowledge of the geometry of the groove, the angle of the part, and the thickness of the part.

The 3-D grasping strategy does not encompass all 3-D objects. It is meant only for sheet metal parts. Theoretically, force closure grasps can be attained using the maximal distancing theory for any object in 3-D, but testing has not been done to verify this and it will not be addressed in this paper.

2.3 Application to Outside-In Grasps

So far, the grasping strategy has used grasps based on maximizing the lengths (which are termed "inside-out" grasps). The theory can also be applied to "outside-in" grasps. The only difference is that the lengths are to be minimized instead of maximized. The difference between inside-out and outside-in grasps is clarified with Fig. 7. An inside-out grasp is defined as one in which any motion of a finger will cause at least one of the distances between the fingers to increase (Fig. 7a). Fig. 7b shows a grasp that is on an inside surface but not an inside-out grasp since any motion of the fingers will cause the distance between the others to decrease. An outside-in grasp is defined as one in which any motion of a finger will cause at least one of the distances between the fingers to decrease (Fig. 7b).

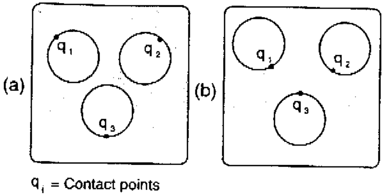


Figure 7: a) An Inside-Out Grasp b) An Outside-In Grasp

The nature of the contact between the object and fixture establishes the maximum clamping forces that can be exerted without deformation of the the object. The first form of deformation that can be induced is at the contact due to high stresses inherent with FPC's (as a result of the low contact area). The other form of deformation that must be considered for sheet metal fixturing is bending of the sheet out of the primary plane. A difference is evident between outside-in and inside-out in terms of the stresses they will apply and the deformations that will result. For a flat piece of sheet metal, an outside-in grasp will compress the material and cause it to deform out of the plane by bending, an inside-out grasp will pull the material in tension and cause little or no deformation out of the plane (and hence higher forces can be used). For a curved piece of sheet metal, this is not the case and both must be checked for deformation of the sheet.

Another difference between inside-out and outside-in grasps is the corrective forces and moments provided by each of the contacts. The forces, moments and motion of each contact are responsible for convergence to a correct grasp. An outside-in grasp will cause the object to rotate around the contact point in a direction determined by the position of the object's centre of mass and any other forces (i.e. friction or another finger). This direction of rotation may change for different grasps and may not be consistent. As an example, if the finger force changes for different grasps, the correcting moments will change and this may affect the direction of rotation. This leads to an unpredictable outcome to the affects of initial contact. An inside-out grasp will also cause the object to rotate around the contact point. The difference (as opposed to outside-in) is that the moment created by the object's centre of mass will always cause the object to be pulled into the line of action of the finger motion. This predictability is an advantage of grasping inside-out over outside in that will be proven in the testing section.

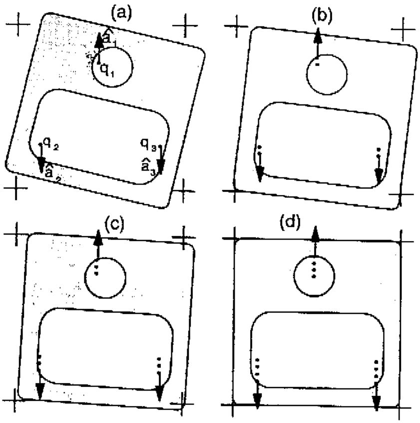
2.4 Convergence to the Solution Locations

In addition to acheiving form closure, the grasping points are located such that the object geometry will correct for initial robot and part positioning errors. This is accomplished by rolling and sliding between the fingers and the part toward the solution locations. The regions of the edges where the sliding may take place will be referred to as "convergent regions". For 2-D convergence, the convergent regions usually take the form of concave segments. An edge can have multiple convergent regions. Non-circular holes in a part are one example. In industrial parts, holes are present for a number of reasons, including fixturing purposes and weight reduction. For the non-planar convergence, the height of the VCG minus the sheet thickness represents the convergent region for the the non-planar directions. As the thickness of the sheet metal increases, the size of the convergent region decreases for that finger.

It should be specified that the size of the convergent region in both cases must be larger than the initial position error. This is not a drawback since this error is usually much smaller than the convergent regions.

The grasp is executed by moving the fingers under position control. Each finger proceeds from a position in the vacinity of its solution location along an approach vector. The approach vectors are defined such that at least one of the distances of a finger relative to any one of the other fingers must increase (for an inside-out grasp).

It is assumed that there is no motion of the contacts opposite to the approach vector (i.e. the fingers cannot be forced back). Upon initial contact, the part will roll or slide relative to the finger(s) until immobilized. It is assumed that there is no friction between the object and the surface that the object rests upon. When any distance between two points reaches its maximum length for that solution, the corresponding fingers are fixed in position. This may occur for up to (n-1) fingers prior to immobilization. In this case, the grasp is completed by the nth finger. It is also possible to lock (n-1) fingers at their maximum lengths prior to executing the grasp. This means that a multi-fingered gripper with numerous degrees of freedom is not required for the grasping strategy. The strategy can be applied with a parallel jaw gripper as is done in the testing section.



q_i = Contact points

$\hat{a}_i$ = Approach vector

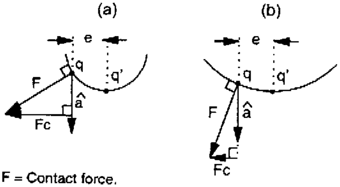
Figure 8: Sample Grasping Sequence

The issue of position control of the fingers of the gripper must be addressed. Conventional fixturing relies on precise position control of the pins of the fixture to accurately determine the part position. An error in the position of the pins for conventional fixturing will result in a positional error of the part. This is also the case for the fingers of the gripper.

The advantage of grasping in convergent regions can be qualitatively described in terms of error correction. A position error in a convergent region will have a predictable outcome with accuracy determined by the part. For the example shown in Fig 8, successive contact of the fingers will always lead to motion of the object that finishes in the position shown in Fig 8d.

2.5 Effect of Local Curvature of the Object on Error Correction

Another way to consider the error correction process is to view the response of the object to incremental motions of the finger based on



F = Contact force.
Fc = Corrective force on the object.
e = Initial error.
q = Initial contact location.
q' = Solution location.
$\hat{a}$ = approach vector

Figure 9: Effect of Curvature on Corrective Force

its shape. Irrespective of the approach angle, the response of the object will be based on the local curvature in all three dimensions. Corrective forces in the plane will be based on the curvature of the object while corrective forces out of the plane will be based on the geometry of the VCG's. As shown in Fig. 9a, a large curvature gives a larger corrective force for a displacement of the finger. The corrective forces for the VCG are constant due to its constant slope.

Realistically, friction cannot be avoided and will have an effect on the outcome. It will provide a tangential force on the edge of the object that opposes sliding. When the corrective force of the object is balanced by the frictional force of the object, motion of the finger along the edge will cease. A small curvature object or flat surface will have a smaller corrective force as is shown in Fig. 9b. Motion may cease in the direction tangential to the surface before the correct position has been reached.

The response of the object will be based on the effects of all of the contacts combined. A larger number of corrective forces in different directions created by the fingers translates to better positional control of the object. Any directions not accounted for by corrective forces will result in poor position control for that direction.

2.6 Algorithm for Finding Solution Locations

A computer program was written to give solution locations based on the theory given in Section 2.1 and 2.2. The program was run for the parts shown in Fig. 10.

The solution process for a part is an iterative process that involves three steps for analysis in 3-D. The projection of the part is calculated manually and the relevant geometric features are stored in a file. The second step is to find the 2-D solution points based on the algorithm outlined below. The final step is to find the height of the fingers from the gripper to the 2-D projection for each specific solution location. For a bent or non-flat part, the height will change for different solution locations in the projected plane. Due to limited space, only a brief outline of the algorithm is given below.

Algorithm 1: Finding Solution Locations for 3-D Objects

1. Obtain a 2-D image of the object based on the projection angle. Discretize each edge of the object such that the distance between points along the edge is constant. Number the points such that each point of each edge has a unique number.
2. Find the distance of each point to all of the other points and store as magnitudes in a two dimensional array.
3. For an n finger grasp, find n magnitudes such that a change in any one of the numbered points to an adjacent point does not cause any of the corresponding magnitudes to decrease (decrease is for an inside-out grasp, increase for an outside-in grasp).
4. A check must be made for cases in which the magnitudes for adjacent points remain constant. These are not solution locations, and should be discarded.
5. Perform steps 3. and 4. for each possible combination of edge points.

Fig. 10 shows the results from the algorithm for the two parts analysed. The solution locations whose perimeters are at least 80% of the maximum perimeter are shown.

3 RESULTS

Four different grasps were performed on the two parts shown in Fig. 10. The desired contact locations for the four cases were as shown. Cases 1-3 are inside-out grasps and case 4 is an outside-in grasp. A parallel jaw gripper with two fingers attached to one jaw and the third attached to the other jaw was used for the tests. A photo of the gripper is given in Fig. 11. The position was measured using six dial gauges as shown in Fig 12. The positions of the dial gauges were converted to a coordinate system at the centre of mass of the part. The standard deviation of the part's position and orientation were calculated based on twenty five sample grasping sequences. Each grasping sequence consisted of grasping and ungrasping the object and measuring the position before and after. Each time the part was ungrasped it was given a positional displacement to represent robot or part positional error. The results for the tests are summarized in Tables 1-4.

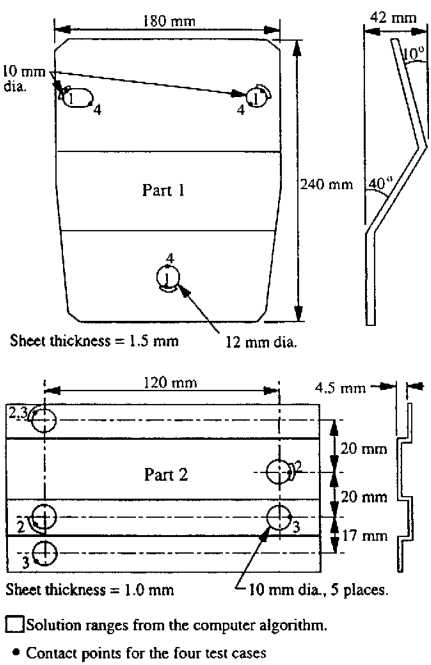


Figure 10: Testing Objects

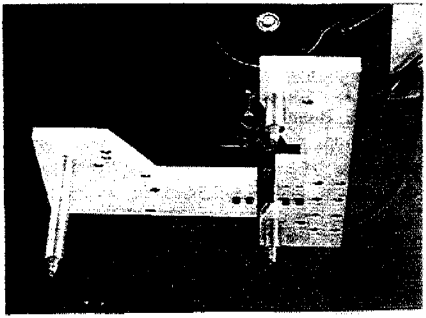


Figure 11: Customized Parallel Jaw Gripper

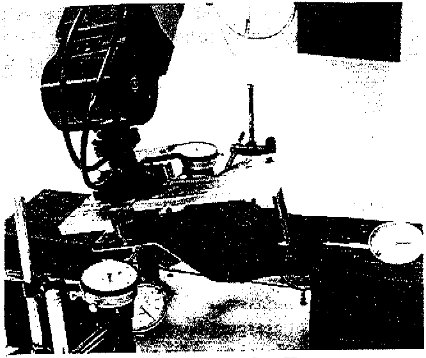


Figure 12: Testing Set-Up

Table 1: Standard Deviation(mm): Case 1

	Planar			Non-Planar		
	X	Y	Rot Z	Z	Rot X	Rot Y
Before	0.34	0.45	0.04	0.26	0.07	0.07
After	0.07	0.04	0.00	0.02	0.01	0.01

Table 2: Standard Deviation(mm): Case 2

	Planar			Non-Planar		
	X	Y	Rot Z	Z	Rot X	Rot Y
Before	0.59	0.16	0.25	0.25	0.10	0.16
After	0.07	0.02	0.06	0.03	0.01	0.02

Table 3: Standard Deviation(mm): Case 3

	Planar			Non-Planar		
	X	Y	Rot Z	Z	Rot X	Rot Y
Before	0.34	0.63	0.30	0.26	0.25	0.28
After	0.04	0.03	0.03	0.04	0.05	0.06

Table 4: Standard Deviation(mm): Case 4

	Planar			Non-Planar		
	X	Y	Rot Z	Z	Rot X	Rot Y
Before	0.98	0.28	0.32	0.82	0.45	0.52
After**	0.05	0.05	0.01	0.03	0.02	0.02

** For the 19 of 25 tests which grasped successfully

The first three cases show the the effectiveness of grasping inside-out with the VCGs. In all cases, the standard deviation is within 0.1 mm. The positional error in the plane was consistent with results from previous tests in 2-D [7]. This shows that the VCGs can fixture the parts repeatably in the plane. The positional error out of the plane was better than in the plane. This demonstrates the effectiveness of the VCGs for grasping sheet metal parts in 3-D. The improved accuracy out of the plane is due to the stronger corrective forces provided by the edges of the VCGs.

The fourth case shows the results of grasping outside-in. In a set of twenty five trials, the gripper failed to locate and hold the object six times. By failure, it is meant that the gripper did not provide force closure for the object. This demonstrates the greater unpredictability of grasping outside-in due to the non-correcting moments. When the grasp was successful, the positional error after the grasp was consistent with the accuracy of the grasping inside-out cases. In terms of grasp repeatability, the testing showed no difference between grasping inside-out and inside-in. The difference as demonstrated by the testing is the instability of grasping outside-in.

The positional error for all cases was reduced from an average of 0.45 mm to an average of 0.04 mm. The final error can be attributed to a number of sources. The dimensional accuracy of the gripper and the testing object is about 0.025 mm and is unknown for the industrial object. It was assumed that there was no part bending for any of the grasps. In reality the parts may have deformed slightly due to the grasping forces. Friction between the gripper and the sheet metal also likely accounted for a small error. It stopped the sliding of the fingers before they reached their solution locations. As determined in [7], the finger tends to finish on the same side of the theoretical solution location that it started on. This was not explicitly tested for here, but was evident.

4 CONCLUSION

One of the demands of RFA is a fixturing strategy for a gripper that can be applied with real robots with limited accuracy. The grasping strategy presented succeeded in reducing the initial robot and positional errors from 0.45 mm to 0.04 mm for dimensions in and out of the plane. This was done without full position control or a multiple degree of freedom gripper. The testing illustrated the dependence of positional repeatability on the local geometry of the object and VCGs. The testing also proved that the fingers will move until stopped by the part. This fact, coupled with the ability to predict where the fingers will stop, gives a consistent grasping strategy that is independent of the positional error of the robotic manipulator. The grasping strategy is limited to objects with internal or external concave edges, but this is not a significant disadvantage since most sheet metal parts contain holes. The VCG's also limit the thickness of the sheet metal parts which can be fixtured to less than the height of the groove.

Future work will continue in two directions. Firstly, the theory must be tested with a multiple degree of freedom gripper with full position control. Secondly, the algorithm for finding grasp solutions must be expanded to a higher resolution while maintaining computational time. Lastly, the algorithm should be altered to weigh solutions based on a variety of criteria including predicted accuracy,stiffness of grasp and proximity to disturbance forces.

5 ACKNOWLEDGEMENTS

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