Embodied Computation:

Exploring Roboforming for the Mass-Customization of Architectural Components

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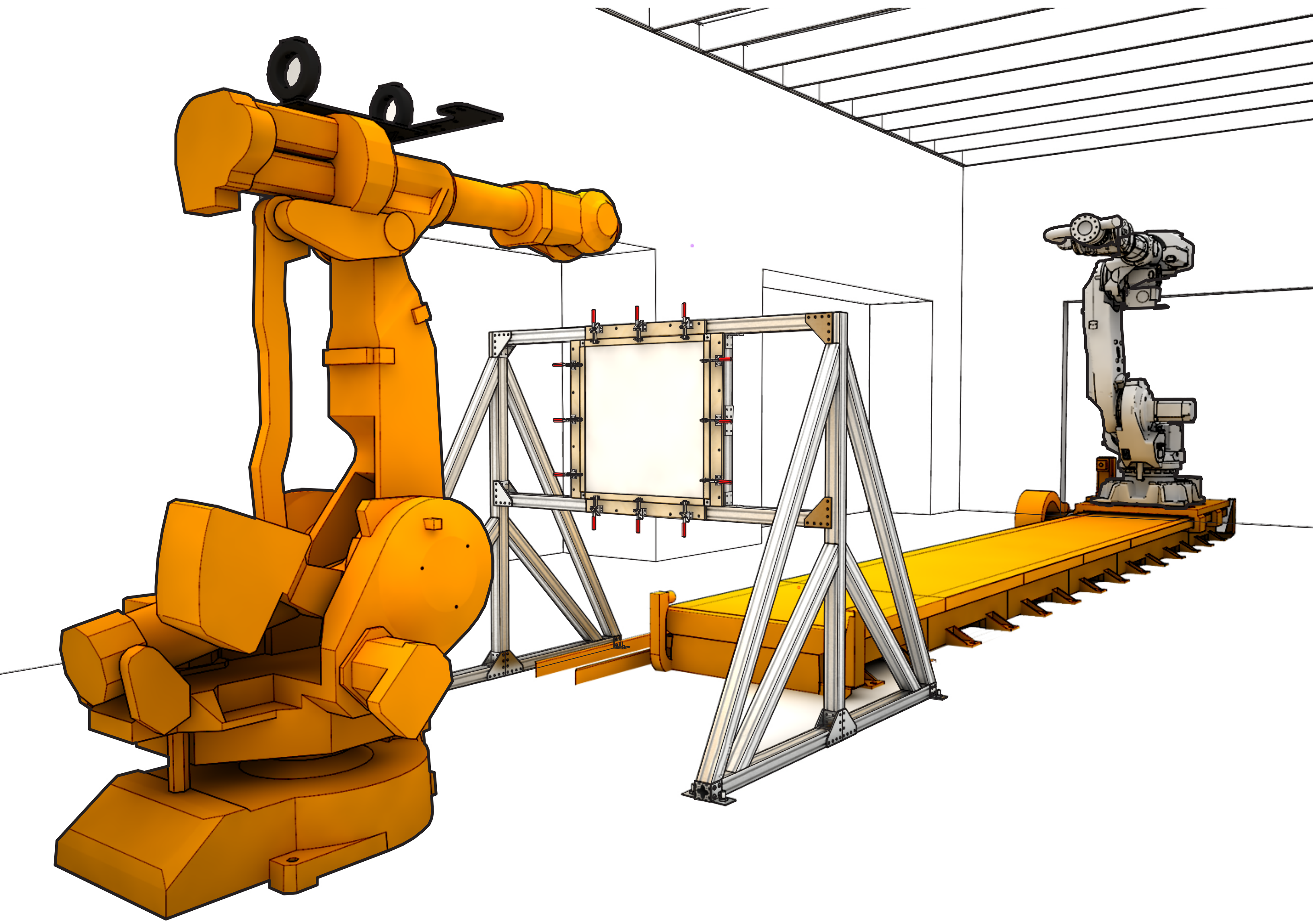
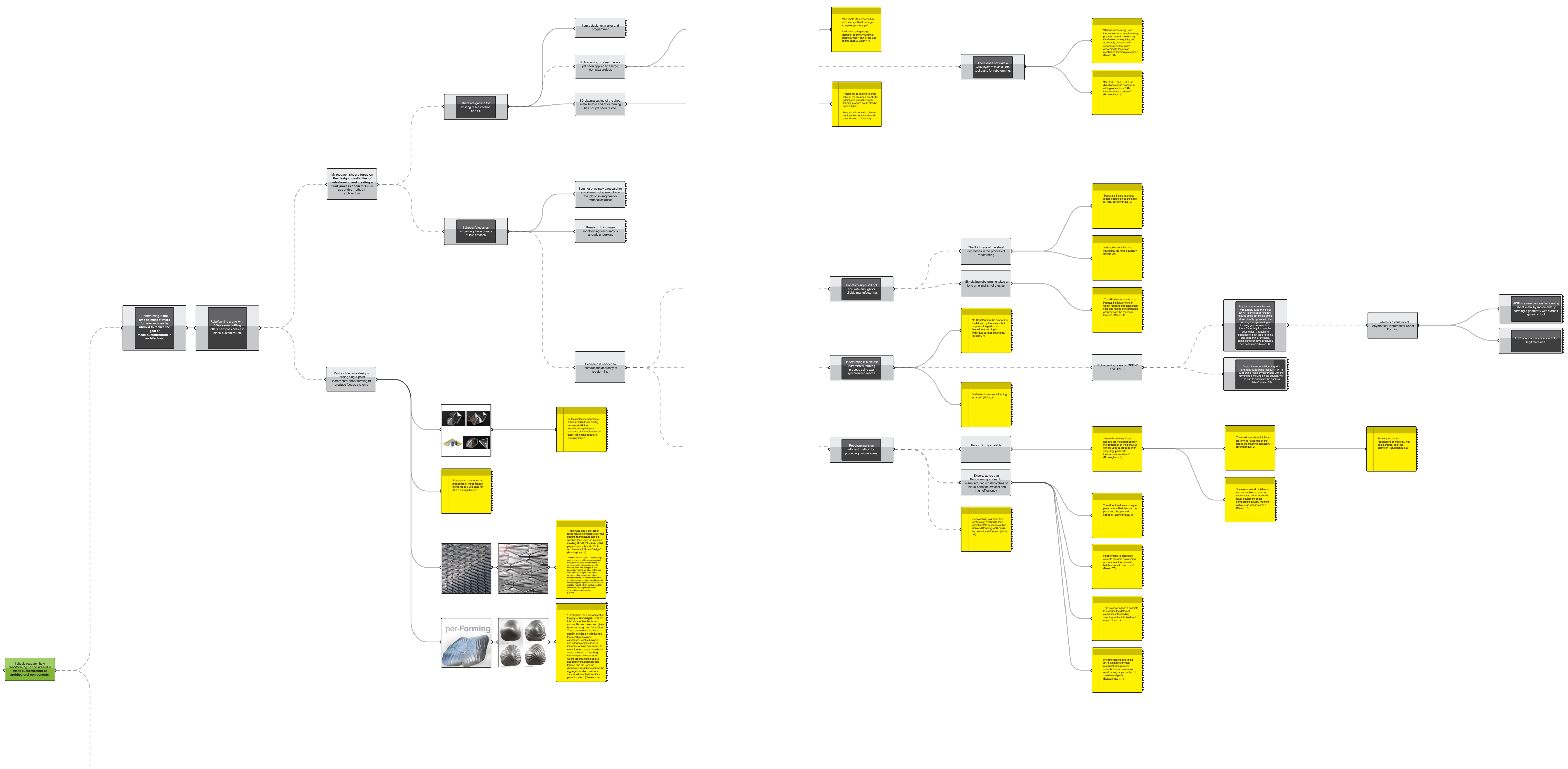
Alex J Fischer.com/thesis

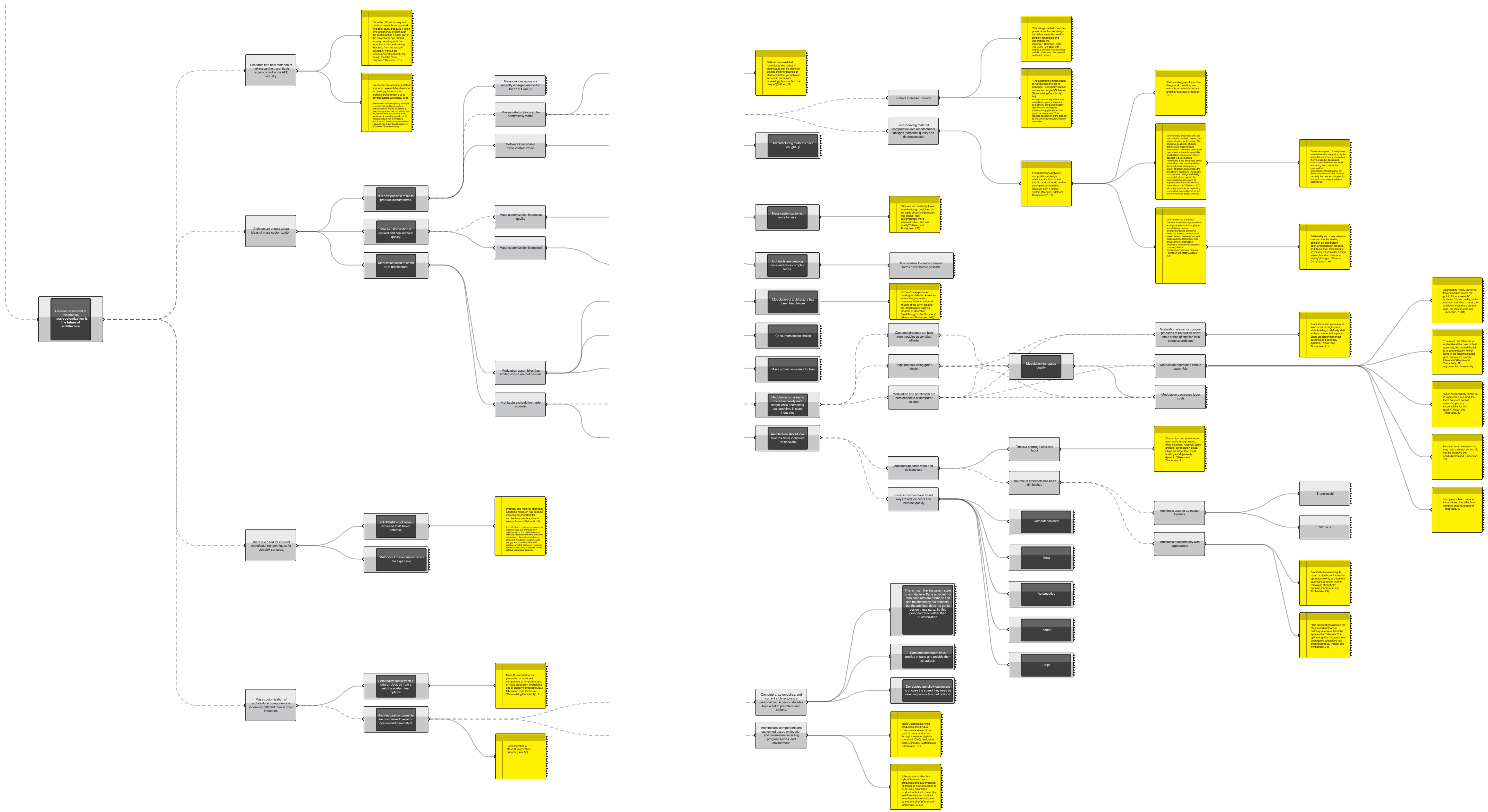


Introduction

Argument Map - Part 1/2 - Roboforming



Argument Map - Part 2/2 - Modulation and Mass-Customization



What I learned from my research:

- Designs stemming from material understanding and hands-on making will be more informed.
- There is a demand for mass-customized. architectural elements
- Roboforming is an efficient method for fabricating small batch sizes of unique parts.
- There does not exist a software for Roboforming.

Conclusion

- Design and Implement a Process Chain for Roboforming at Carnegie Mellon's Dfab Lab.
- Utilize this Process Chain to experiment and learn more about Roboforming.
- Output an best-use example of an application of Roboforming in an architectural context.

Thesis Roadmap

Research mass-customization, material computation, robotic fabrication, and designers as makers.

Write a thesis statement conveying the conclusions from this research.

Research the parameters of Roboforming.

Draw diagrams of the parameters and side-effects to understand and convey the research.

Design scripts based on these diagrams to aide in the determination of robot targets.

Design and build a frame to hold the sheet metal between the robots

Explore the process of Roboforming sheet metal using these scripts and frame.

Reflect upon the processes involved and resulting artefacts.

Hypothesize on how these processes lend themselves to the creation of architectural components.

Demonstrate the potential by fabricating an aggregate of Roboformed components.

Thesis Statement

Embodied Computation is an investigation of Roboforming as it applies to design, fabrication, and architecture. Roboforming is a new rapid prototyping technique for forming sheet metal efficiently that allows the fabrication of complex unique surface geometries without the need for expensive dies by utilizing two industrial robots. (Bruninghaus, 1) There is sigificant potential in this forming process in the context of architecture which at its most base level can be applied to ideas of mass-customization and at its most abstract, a rethinking of how architecture is designed and concieved of. Mass-customization offers production of individual components at almost the price of mass production. (Scheurer, "Materialising Complexity.", 91) Roboforming, which follows this paradigm, is still largely unused in other manufacturing industries since it is not appropriate for mass-production in large quantities. (Meier, 37) However, I argue this trait makes Roboforming perfect for the production of architectural components, which are custom to their site.
This thesis' role in the advancement of Roboforming is to fill gaps in the research of engineers and material scientists, who admit there is no existing software to easily output tool-paths for Roboforming and thus, Roboforming "has not been applied to a large complex geometry yet." (Meier, 4) In addition, 3D plasma-cutting of Roboformed parts has not been explored, and could offer new possibilities. (Meier, 4)
This project will be realized through a feedback loop, as Menges describes or a Persistent Model as Ayres of sixteen*(makers) describes, of computational and physical tool-making, robotic fabrication, and analysis. This reseach differentiates itself from the work of engineers and material scientists, who mainly study methods to increase the accuracy of Roboforming, by focusing on issues of customized design and haptic responses that a formed part can generate in the context of architecture and at an architectural scale. Rather than seek to decrease deviations in the formed part, this project embraces the inaccuracies and side-effects and incorporates them in the design. The uniqueness of a formed part due to the inherent inaccuracy of Roboforming can actually add value to it. The materiality and method of manufacture play a tacit role in the response by the user. (Ayres, 221) Achim Menges argues that architecture attains its relevance "through the articulation of material arrangements and structures," thus, "the way we conceptualize these material interventions- and particularly the technology that enables their construction - presents a fundamental aspect in how we (re)think architecture." (Menges, "Integral Formation and Materialisation", 198)

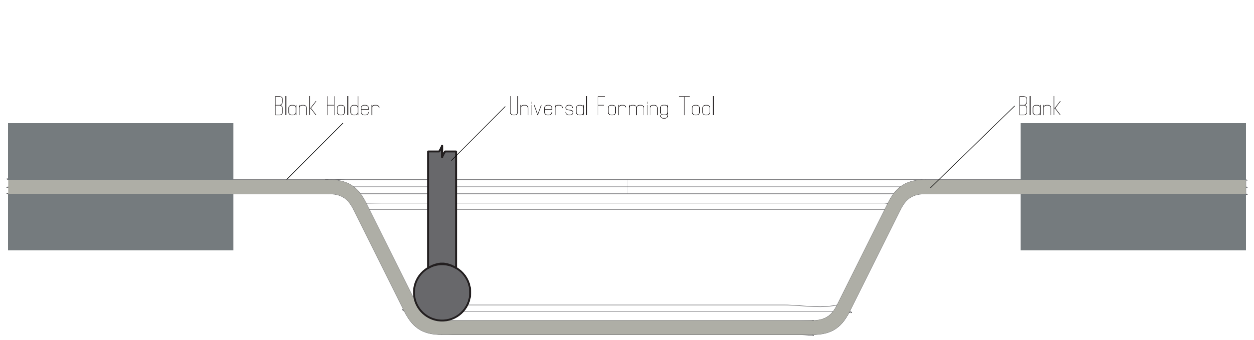
The interest in Roboforming stems from a broader scope of research that addresses ways to improve architecture's specificity and offer architects more choice and thereby more control. Roboforming should not be dismissed from serious investigation out of nonconformity to the current ideals of dimensional accuracy and fully predetermined outcomes before a thorough evaluation of its potentials and implications. (Ayres, 222)

My background in robotic fabrication, architecture, and computational design will enable me to design a process chain for Roboforming which includes: constructing the blank holder, writing scripts to output tool-paths based on geometrical input, synchronizing two 6-axis industrial robots, and outputting an example of what Roboforming in capable in relation to customized architectural components.

A more detailed examination of Roboforming and its parameters and side-effects will provide useful insight into how the process works and lead to a richer, more informed design.

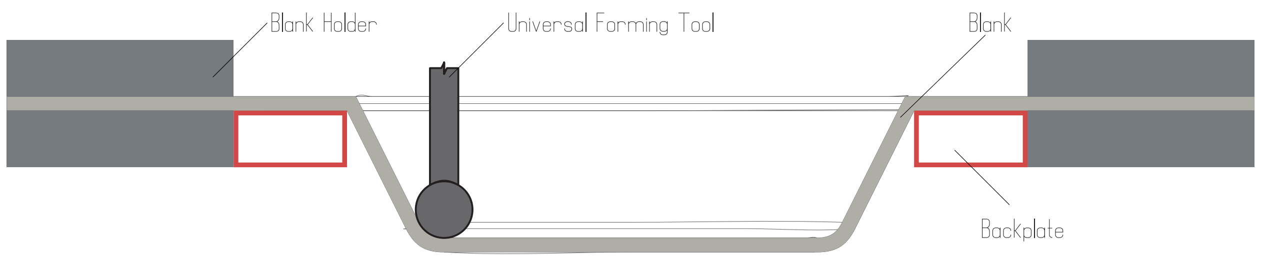
Roboforming Parameters

Types of Incremental Forming



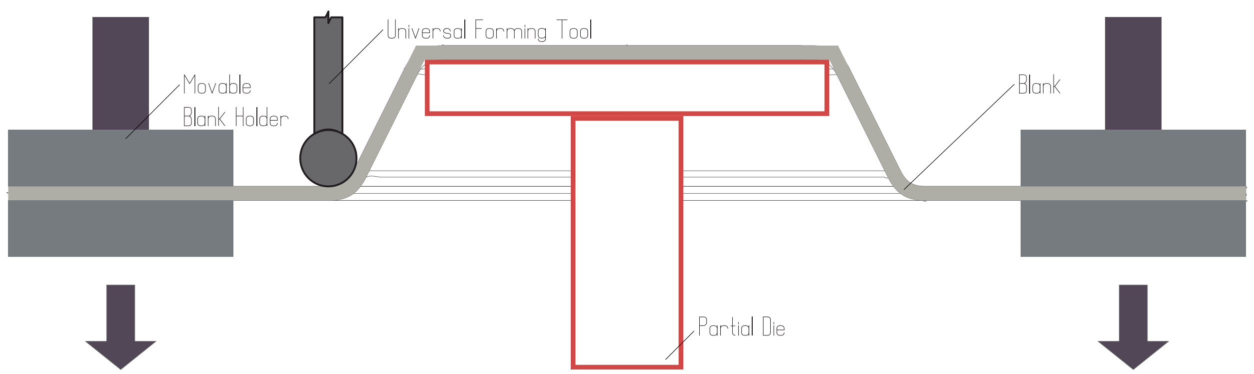
Asymmetric Incremental Sheet Forming (AISF):

A flat sheet of metal or plastic, known as a blank, is secured in a blank holder. A universal forming tool with a spherical head, follows the contours of the geometry to be formed, causing the sheet to be deformed along the tool-path. This is an efficient method, but causes inaccuracies and deviations from the desired geometry due in large part to the springback of the sheet.



Single Point Incremental Forming (SPIF):

A variation of AISF in which a backplate with the outlines of the desired geometry are fixed to the sheet on the opposite side of the tool-head. The backplate provides leverage at the initial crease of the form, reducing some of the deviations caused by springback. However, this method increases accuracy mostly at the periphery of the shape.



Two Point Incremental Forming (TPIF) with Partial Die:

A specialized tool or mold, known as a die, is located on the opposite side of the sheet from the forming tool. In this case a partial die is used, meaning it is not the exact shape of the desired geometry. Either the blank or the partial die is movable and synchronously forced in the opposite direction as the infeed direction of the tool. Inversely from SPIF, this method increases the accuracy at the apex of the form.

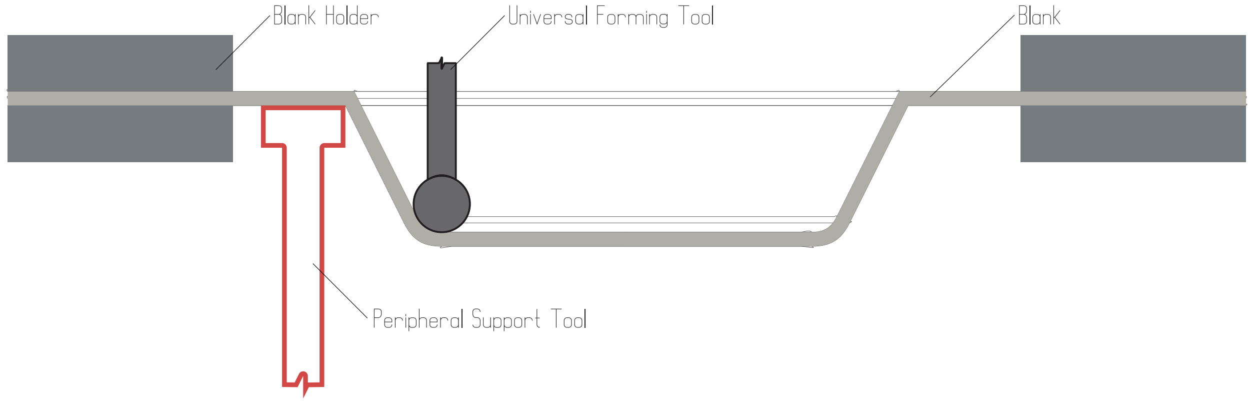
Two Point Incremental Forming (TPIF) with Complete Die:

A specialized tool or mold, known as a die, is located on the opposite side of the sheet from the robot, allowing the metal to be formed according to the die's shape. This method enables higher geometric accuracy but at a higher cost and longer manufacturing time for each part.

Sources:

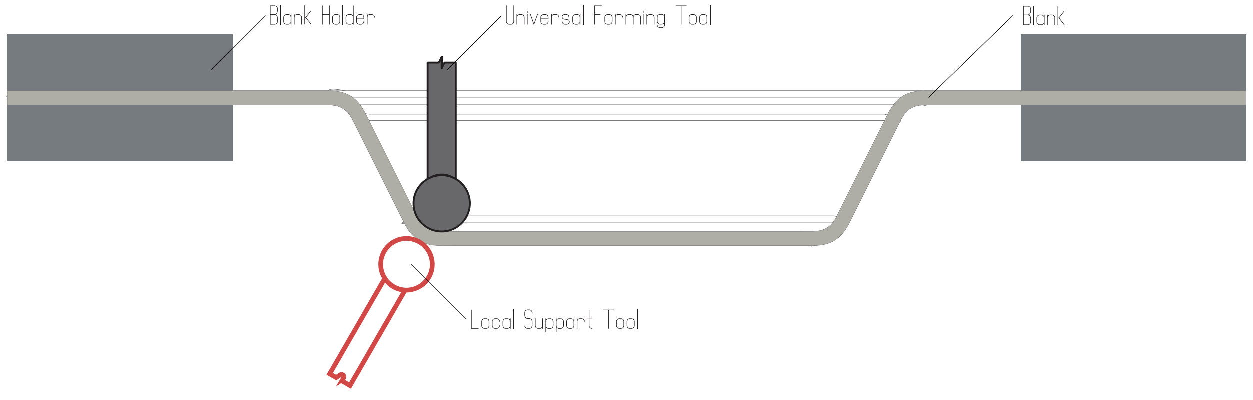
Bruninghaus, 1
Meier, 38-39

Types of Roboforming



Duplex Incremental Forming with Peripheral Supporting Tool (DPIF-P):

Two industrial robots are placed on either side of the blank sheet, secured in a sturdy frame. The 'master' robot holds the forming tool and the 'slave' robot holds a support tool. The master robot pushes incrementally on the sheet, forming the sheet in the shape of the tool-path. The slave robot moves the support tool along the boundary of the part, acting like a backplate, providing leverage on the opposite side of the sheet for the master robot to push against.



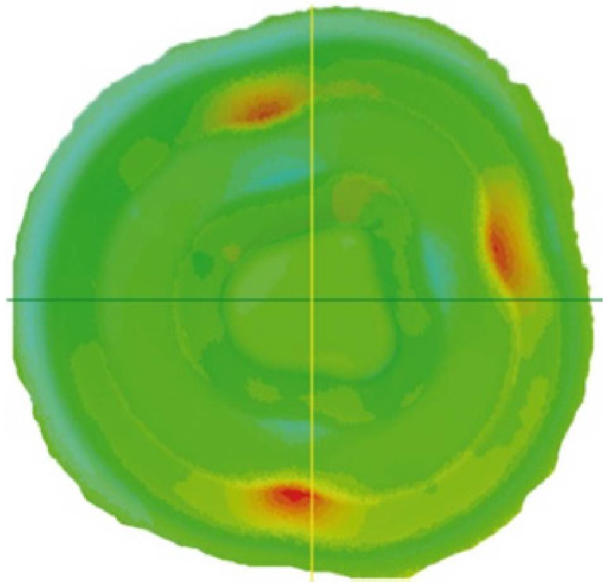
Duplex Incremental Forming with Locally Supporting Tool (DPIF-L):

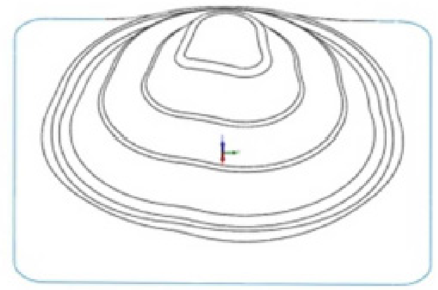
A blank sheet is secured between the two robots in a sturdy frame. Each robot is with a universal forming tool. The 'master' robot is supported by the 'slave' robot. The master robot pushes incrementally on the sheet, forming the sheet in the shape of the tool-path. The slave robot's tool follows directly opposite the forming tool, creating a forming gap between the tools. By interchanging the master and slave roles of the robots, concave and convex forms can shaped within the same part.

Sources:
Bruninghaus, 1
Meier, 38-39

Advantages and Disadvantages of DPIF-L vs DPIF-P

DPIF-P





Advantages of DPIF-P

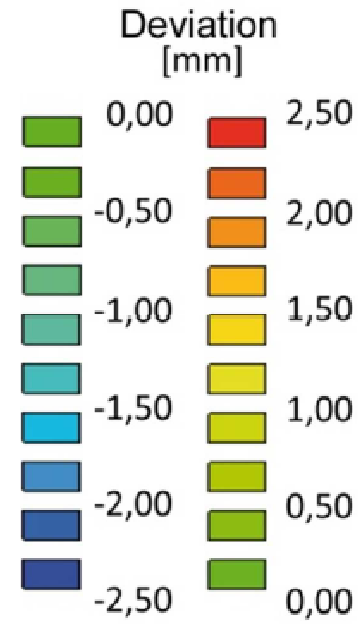
- Smaller deviation in areas of greater wall angle since the peripheral support acts as a backing plate against which the forming tool can push.
- Smaller elastic deformations occur at the boundary of the geometry due to the support at the boundary.
- The side not directly acted upon by the forming tool will have a matte finish.

Disadvantages of DPIF-P

- Larger deviaions in concave areas.
- Non-uniform deviations.
- The two sides will have different finish qualities.

Conclusions

Appropriate for mostly symmetrical concave surfaces.



DPIF-L

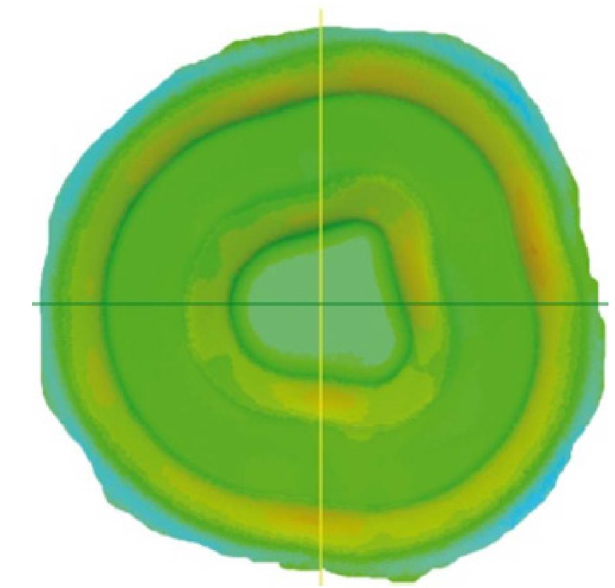


Image credit: Kreimeier, CAM, 895

Advantages of DPIF-L

- Overall uniform deviation.
- Smaller deviations in concave areas due to the ability of the support forming tool to form these areas..
- Both sides have a glossy finish.

Disadvantages of DPIF-L

- Greater deviations in areas of greater wall angle due to the increased force needed when compared to flatter areas. This force causes the sheet to buckle inwards without the periphery support.
- Greater elastic deformations occur at the boundary of the geometry, which can lead to insufficient forming in other areas.

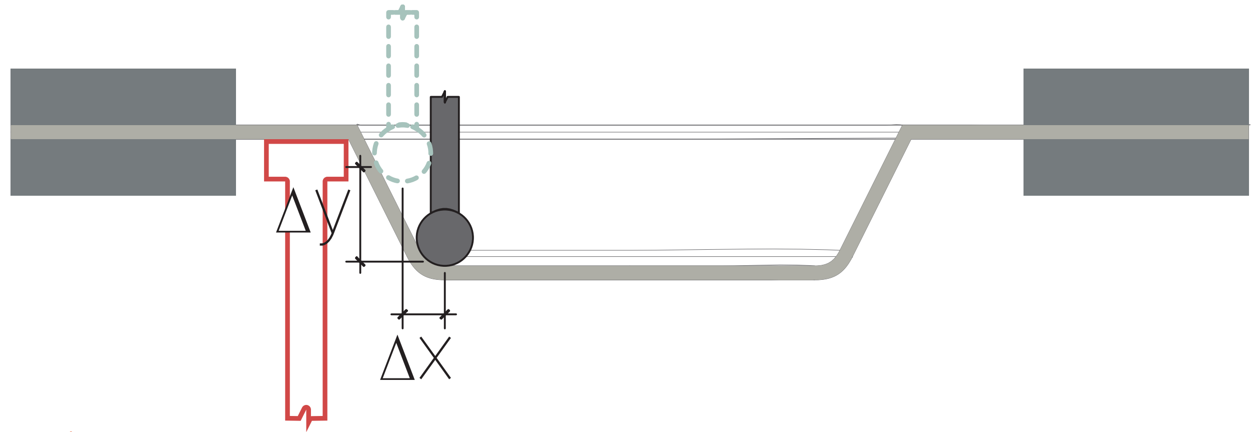
Conclusions

Appropriate for complex geometries with concave and convex areas.

Sources:

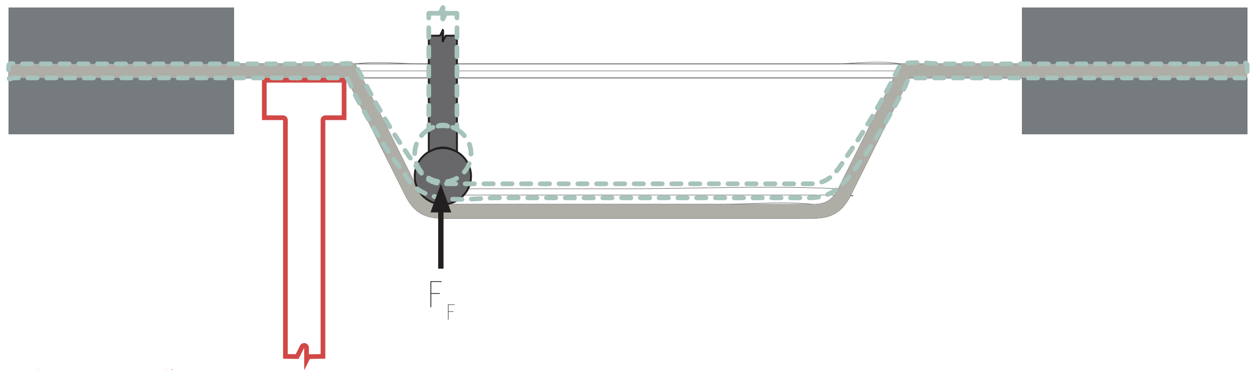
Kreimeier, CAM, 895

Causes of Deviations



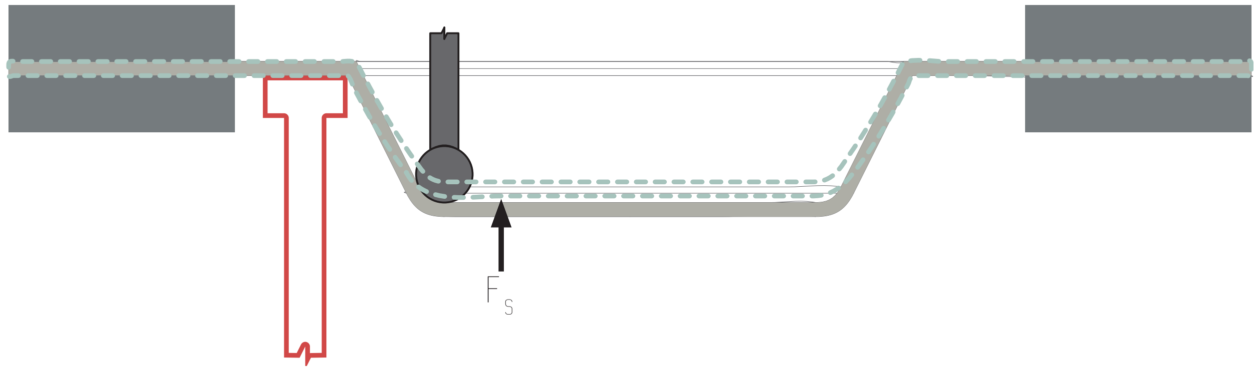
Forming Parameters

Material, forming geometry, infeed, velocity, stepdown, stepover, and tool-path type (contoured, stepped, or helical) affect the accuracy of the part.



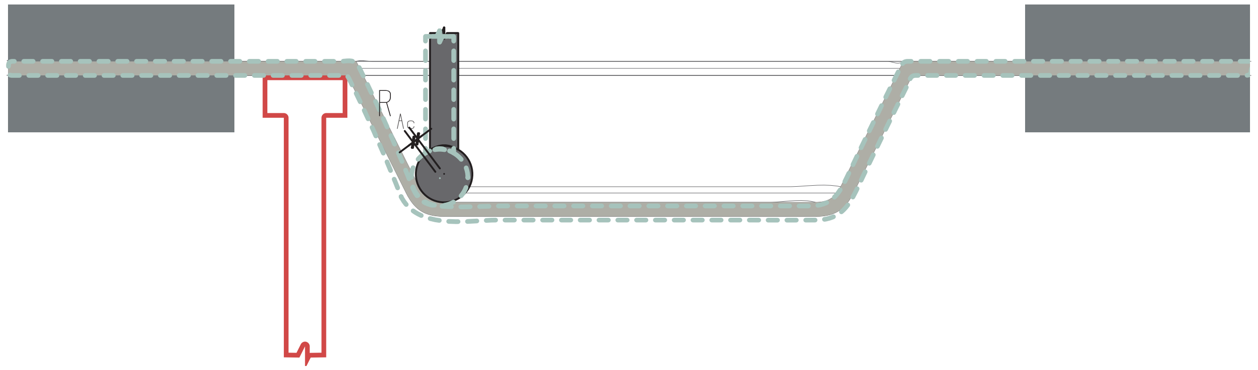
Robot Compliance

Forming forces, F_F, acting on the tool cause the robot to deflect from its predetermined path. If a robots detects enough force against its tool-head, it will pull-back to reduce the forces.



Springback

Due to the regression of the elastic forming ratio, the formed sheet will rest in a state somewhere between the desired geometry and the original flat sheet. This springback force, F_S, is inherient in the thickness of the material.

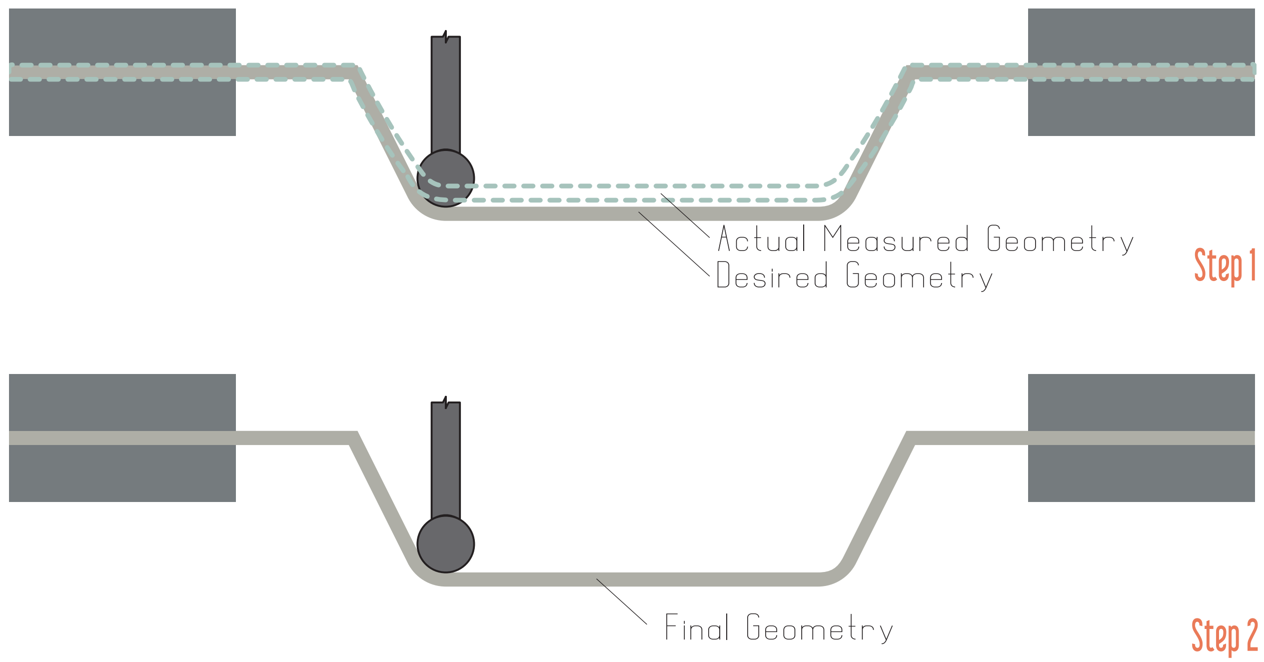


Positioning Accuracy

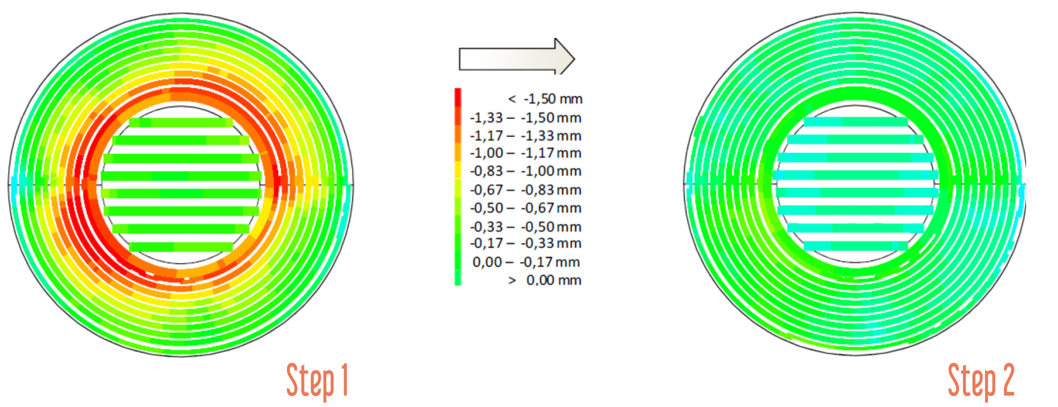
Due to the 6 joints of the robot the tool-tip does not always end up exactly where it was planned. The domain of the positioning accuracy, $R_{Ac.}$ can be as much as several tenths of a millimeter. This is determined by the resolution of the kinematic solvers and the accuracy of the robot's many joints.

Sources:
Meier, 161

Methods for Increasing Part Accuracy



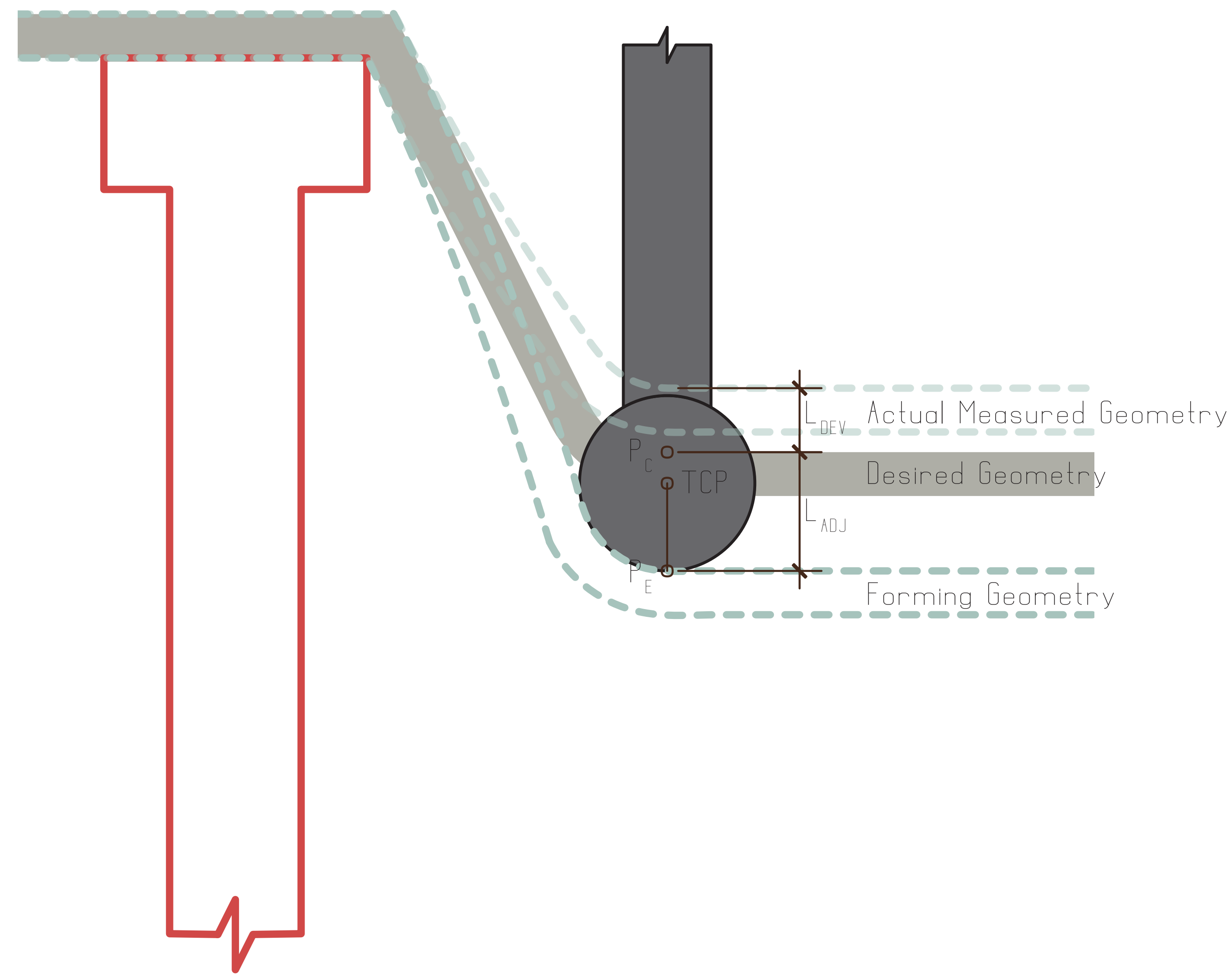
Deviations in normal direction of a truncated cone



(Meier, Accuracy, 7)

Multiple Forming

To increase the accuracy of the final formed geometry, run the forming process twice. This is effective because on the first round, the forming forces can get very high, depending on the depth of the part. These high forming forces and robot compliance cause the robot to pull back and ultimately the tool tip ends up not as far as described in the program code. Once the sheet has been formed, the second forming process will have significantly lower stresses since the sheet is already deformed close to the desired result. This allows the robot to follow it's input path more accuractly. The metal is also hardened in the first forming process due to strain hardening, so the metal is less able to bow and avoid the forming tool.

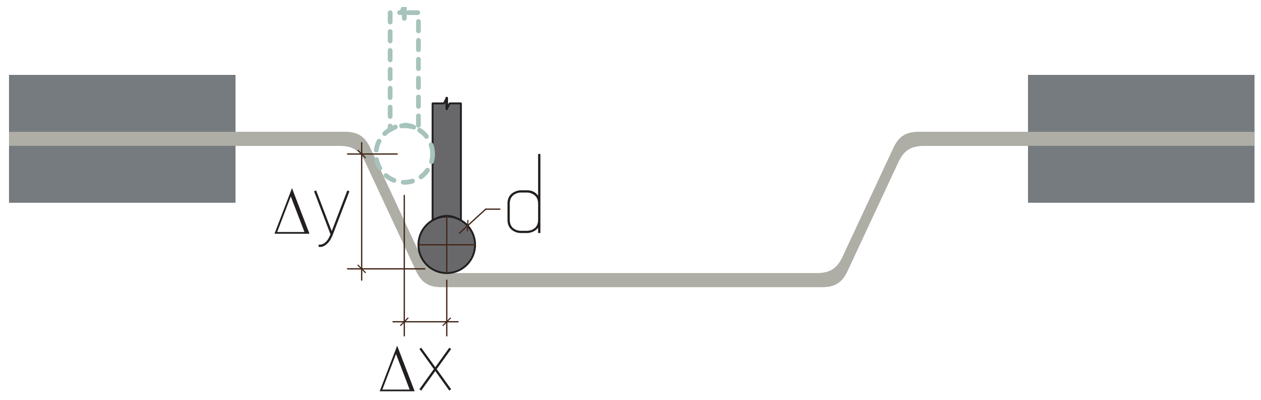


Adjustment Vector

This methods requires a feedback loop between sensors on the robot and tool-generation software. This could be done with finite element simulations of the forming process to predict deviations, but this is a time-consuming process, to the point where it is not viable with current software and hardware capabilities. Instead, a process of forming, scanning, adjusting the tool-path based on deviations, and forming again must be used. Rather than regerated the CAD geometry, it makes more sense to apply a spicific adjustment vector to each tool-path point. Ultimately, this means forming the part further out than the CAD geometry to accont for springback.

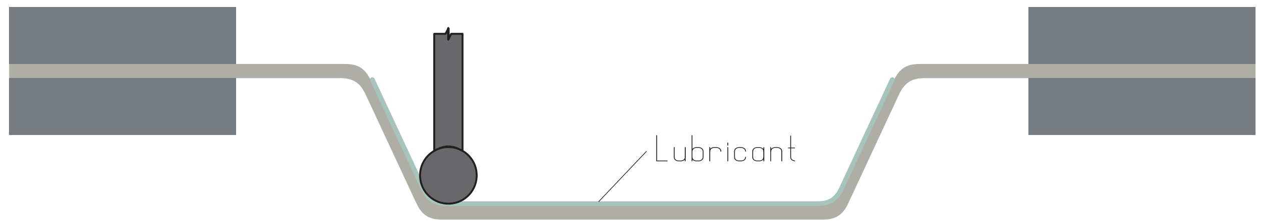
Sources:
Meier, Accuracy, 1-7

Maximizing Surface Quality



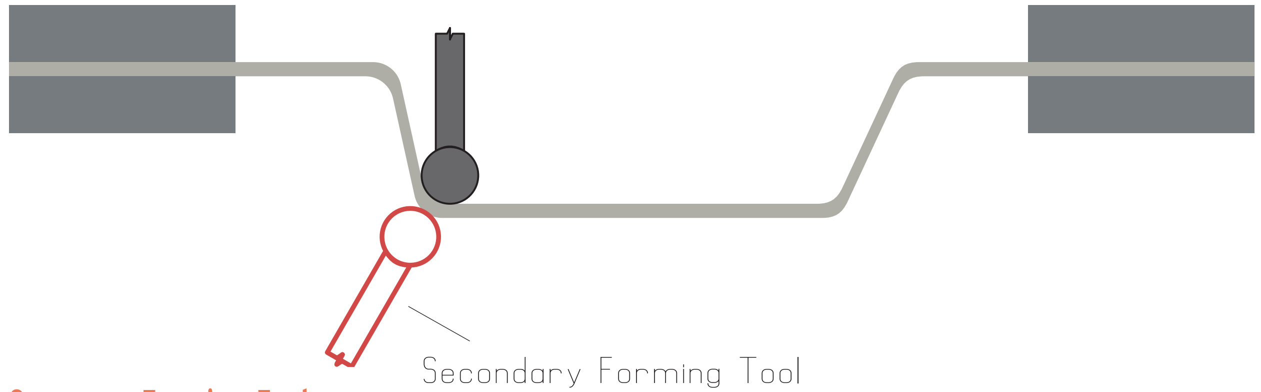
Forming Parameters

The appearance and roughness of both sides of the surface is dependent on the tool the forming tool's diameter, d, stepdown, y, and stepover, x. There is a direct relationship between the the tool diameter and the smoothness of the surface. In addition, there is an inverse relationship between the infeed parameters, x and y, to the surface smoothness.



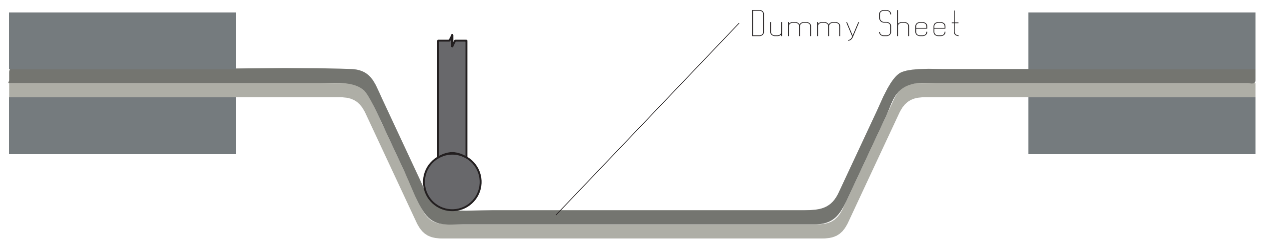
Lubricant

Friction caused by the interaction between the forming tool and sheet is a main component of the surface quality. By applying lubricant such as tapping fluid, the friction forces are reduced and scratches are minimized.



Seconary Forming Tool

In AISF, the side of the surface which is acted upon directly by the forming tool has a glossy appearance. This side also has grooves and stratches due to the movement of the tool. The other side, which is not in direct contact with the forming tool, has a bumpy matte finish with an 'orange peel' effect caused by the stretching of the sheet. So in DPIF-L, where there is a forming tool on each side, the result is both sides have a glossy finish.

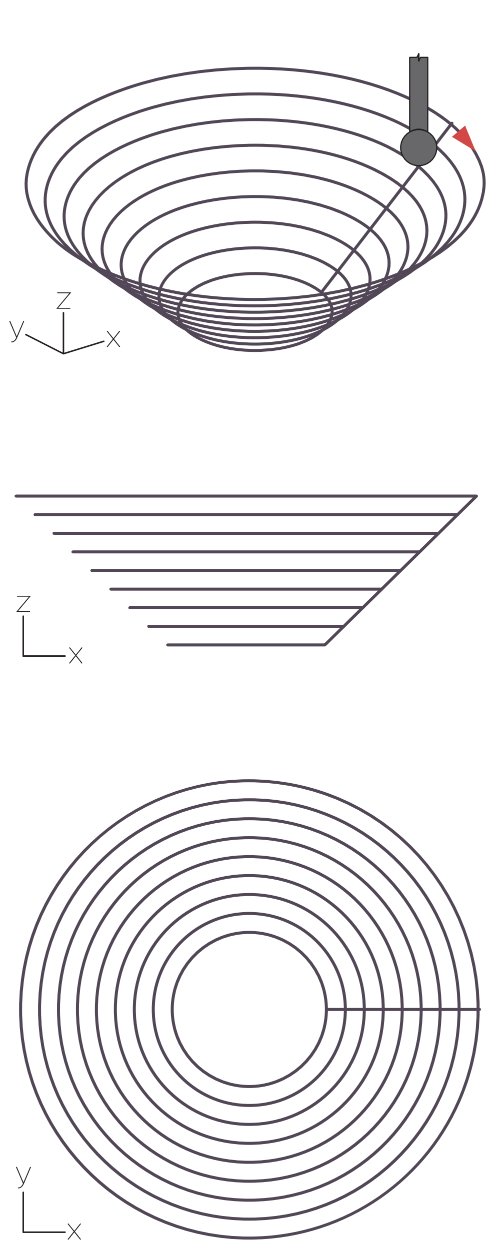


Dummy Sheet

Grooves caused by the tool can be prevented by layering an additional sheet on top of the sheet you wish to keep. This top sheet is known as a 'dummy sheet' and picks up all the tool marks while the lower sheet is formed indirectly by the deformation of the dummy sheet. As a result, the dummy is glossy on both sides and the lower sheet has a matte finish on both sides.

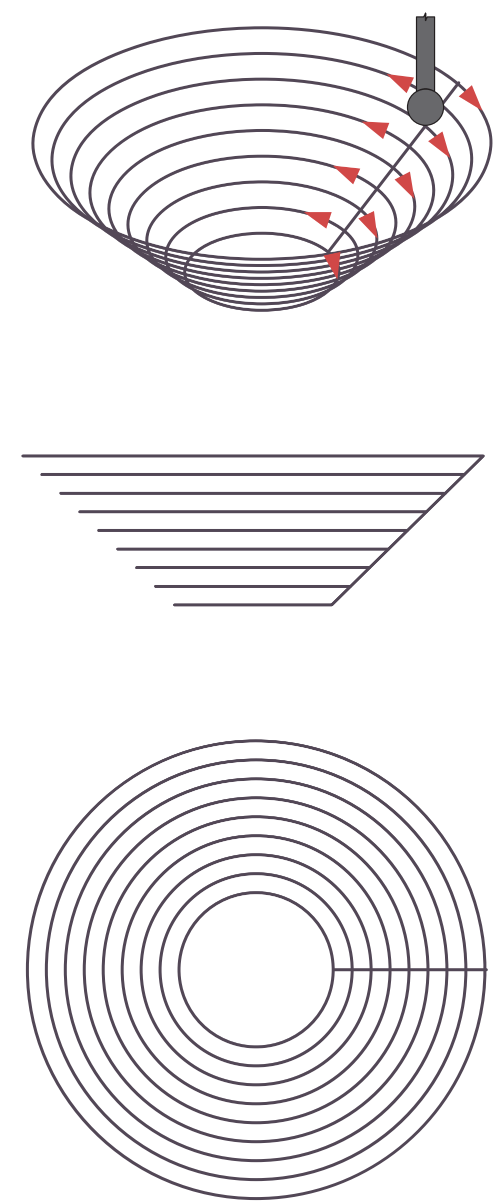
Sources:
Bruninghaus, 2
Meier, DPIF-L, 327

Tool-Path Types



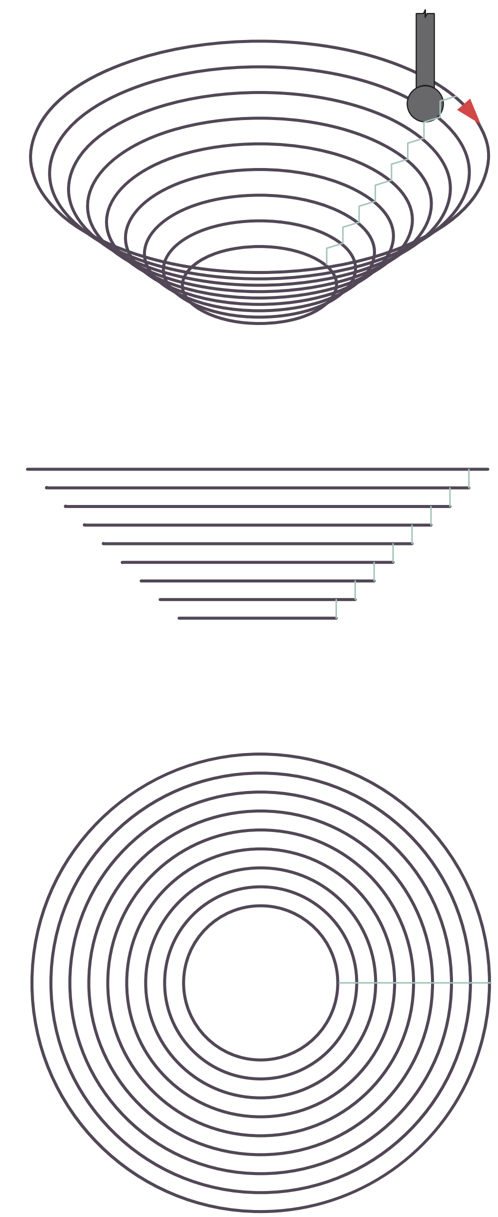
Contoured

The tool-head follows the contours of the geometry. As it moves to the next level on the z axis, it moves diagonally in the xz axes. This creates a line where the tool moved from level to level.



Alternating

The tool-head follows the contours of the geometry. The direction of each contour alternates. As it moves to the next level on the z axis, it moves diagonally in the xz axes. This creates a line where the tool moved from level to level.



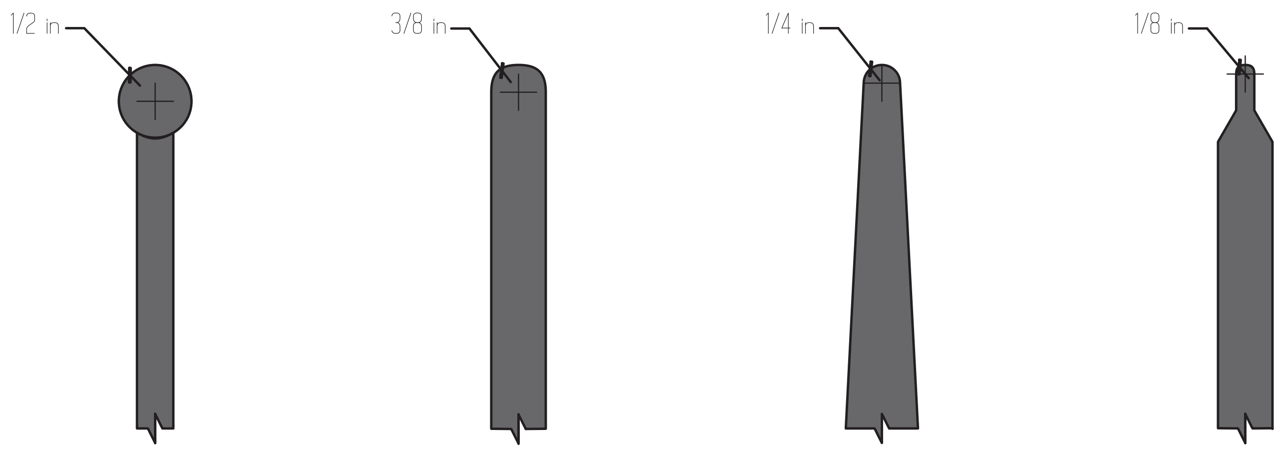
Stepped

The tool-head follows the contours of the geometry, but when it steps to the next level, it moves in the xy, then z axes, removing the line created by the tool as it moves from level to level.

Helical

The tool-head follows a continuous path outlining the shape of the geometry. The tool is always moving in the x, y, and z axes, creating a helix pattern in the formed part.

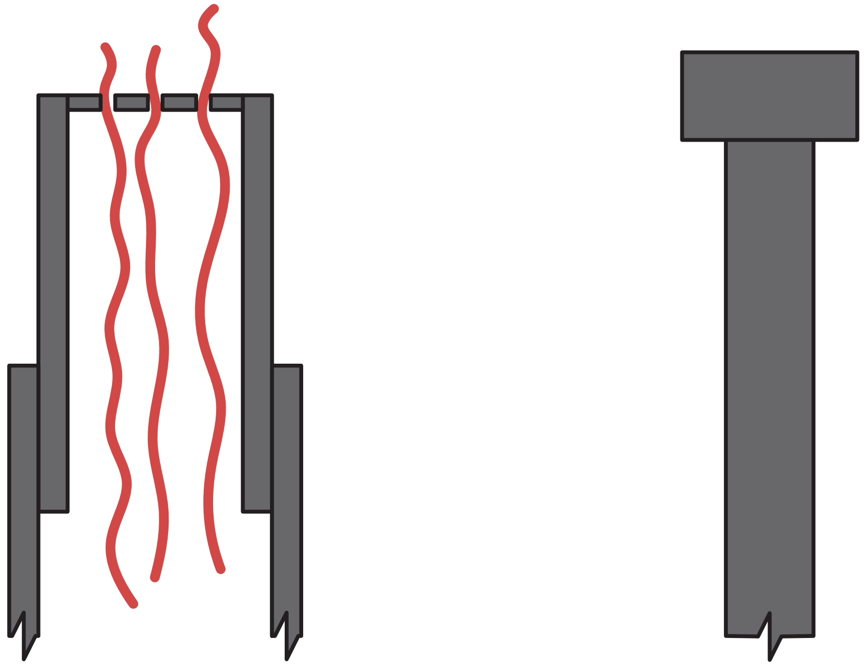
Tool Options



Dapper Punch Straight Tapered Tipped

UNIVERSAL FORMING TOOLS

A small, mostly spherical, tool is attached to the master robot. This tool can come in many forms. A **dapper punch** is a ball-ended tool used for stamping half-spheres in metal, but can be repurposed for Roboforming. However, since dapper punches are not made for uses where forces are applied laterally, the tool can fail and bend as it is forming. A **straight** profiled tool is stronger, since it does not have a thin joint where the ball connects to the shaft as with the dapper punch. The **tapered** variation is even stronger and allows for smaller radii since the shaft is not the same width as the head. The **tipped** tool is ideal for small radius tools as it provides a small tip with a wide enough shaft to prevent excessive bending.



Heat Support

SECONDARY TOOLS

On the slave robot, opposite the forming tool, there are two common tools that are used. A **heat** gun can be used to follow the path of the forming tool on the other side of the sheet, causing the material to heat up and become more malleable. This allows for a great maximum forming depth and sheets with increased thickness to be formed. Heat application can also aid in increasing the accuracy of the formed part. The other option is a generic **support** tool with a flat head and a thick body. This tool provides leverage at the periphery of the shape, increasing the accuracy of the forming process.

Maximum Wall Angle

Cosine's Law

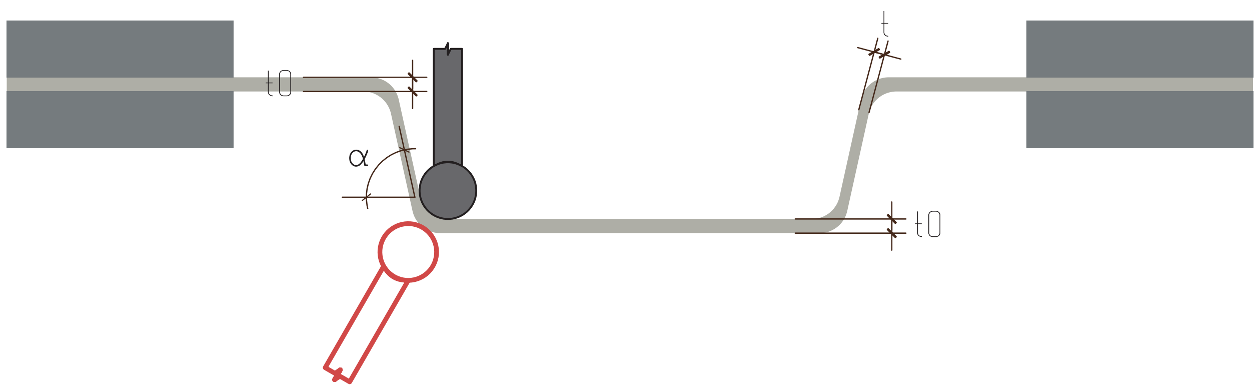
Since the sheet is stretched by the forming process material thinning occurs. So there is a maximum wall angle, α_{max} that can be formed in a single step. Beyond α_{max} the sheet will tear. As the draw angle, α, of the forming tool increases, the sheet thickness at the formed point, t, decreases. For most materials, angles up to 65° can be formed. The thickness can be approximated by cosine's law, defined as:

$t = t0 \times \cos\alpha$

t = thickness at formed point

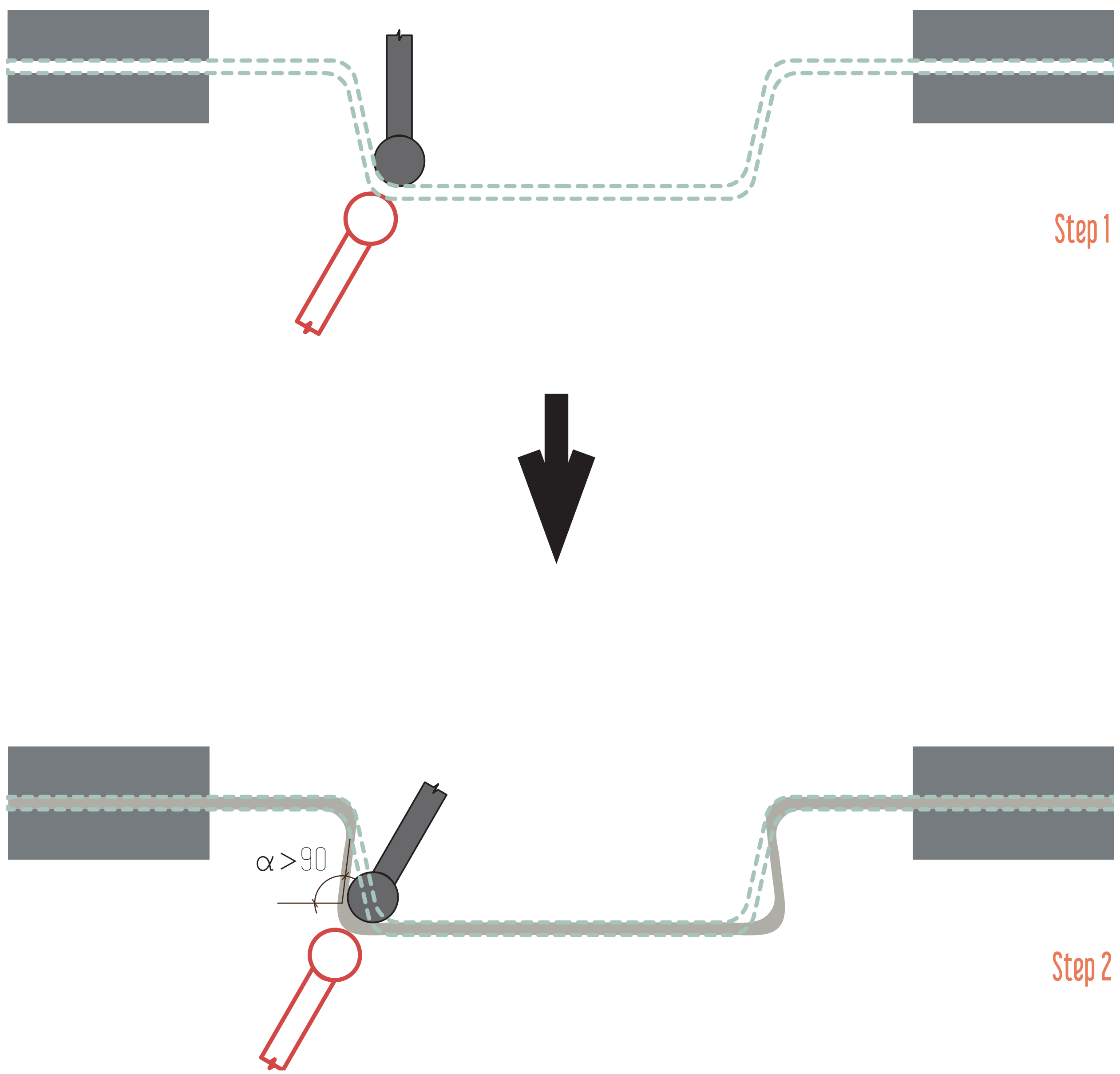
$t0$ = initial sheet thickness

α = draw angle



DPIF-L

One way to increase the maximum wall angle is to use a secondary support tool local to the forming tool. This provides additional force applied to the formed point, and greater leverage to form the sheet. Consequently, α_{max} increases by about 12.5° for a new α_{max} of about 77.5°.



Multiple Forming

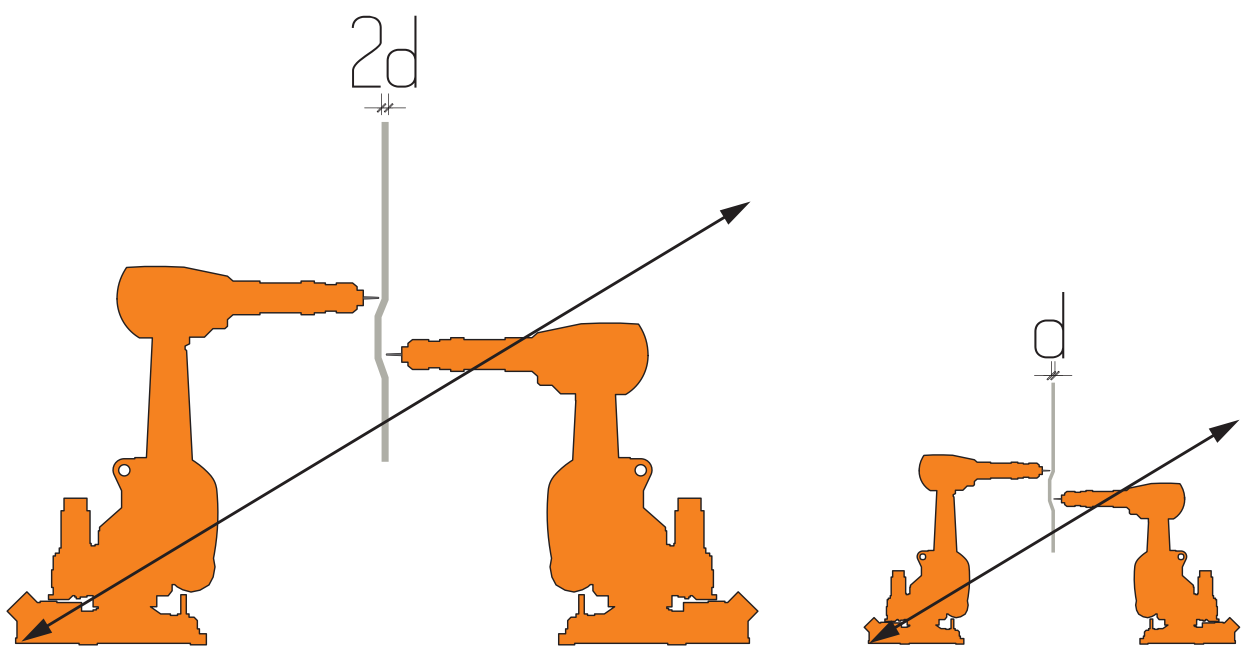
If angles greater than amax need to be formed, a process known as multiple forming can be utilzied. In this process formed areas are formed twice by non-identical paths. The first pass forms the material up to the amax of the material. The second pass forms the desired final angle. This process even allows for angles greater than 90° to be formed, creating what would be considered undercuts in a milling process.

Sources:

Bruninghaus, 2

Meier, DPIF-L, 327-328

Roboforming is Scalable

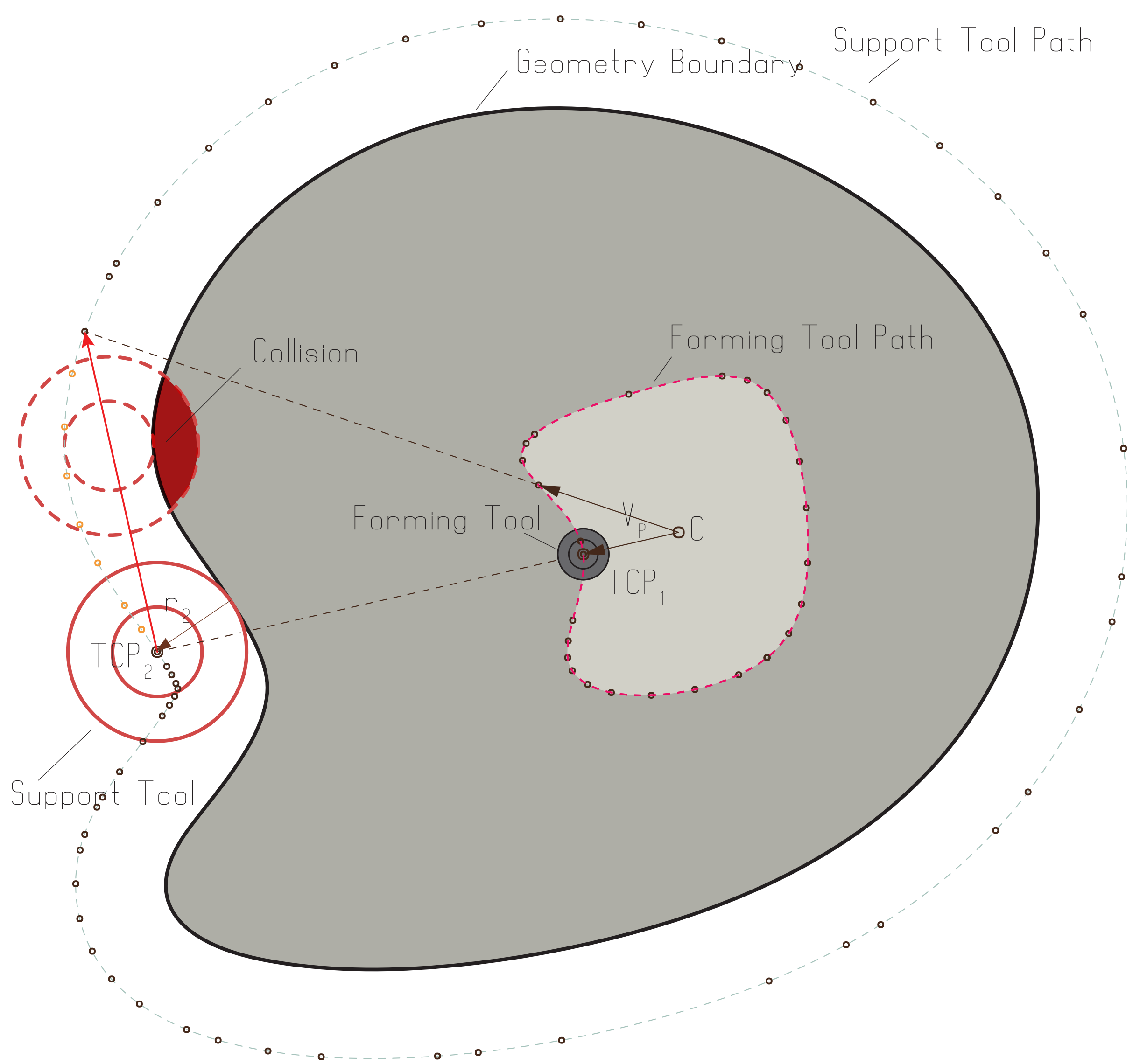


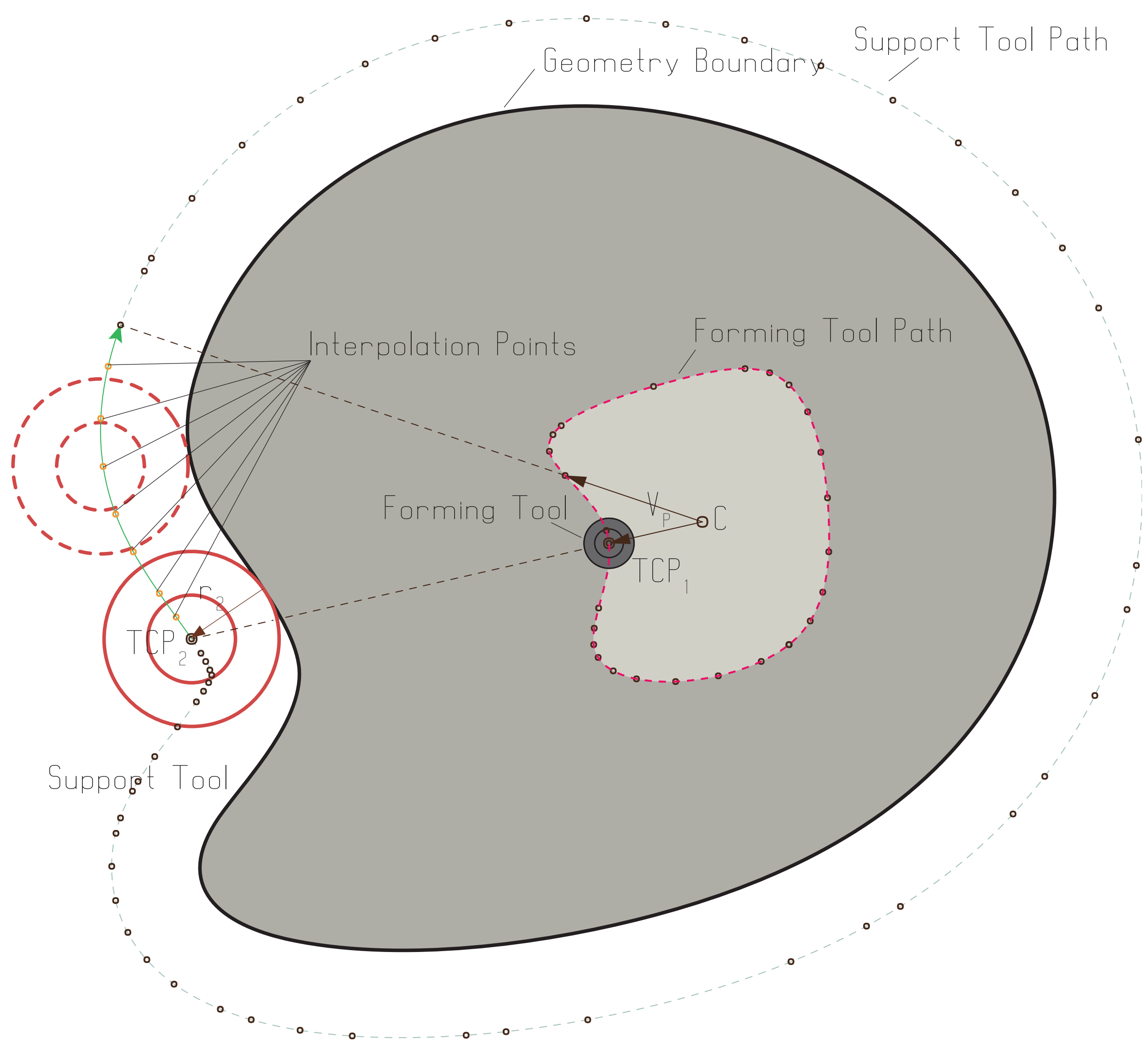
Maximum Sheet Thickness is Dependent on Forming Forces

Roboforming is scalable. The maximum thickness d for roboforming is an equation on the maximum force f the robot can apply. So the thicker the material you wish to form, the stronger the robot needs to be. However, the width x and height y of the sheet are not a factor. The forces resulting from forming an $x \times y$ sheet are the same as the ones from a $2x \times 2y$ sheet. This makes industrial robots more cost effective, since a robot is generally less expensive than a CNC-machine with a comparable work area. This makes roboforming appropriate for applications at many scales.

Sources:
Bruninghaus, 1-2
Meier, 37

Calculating Support Tool Position - Peripheral Support





The Problem

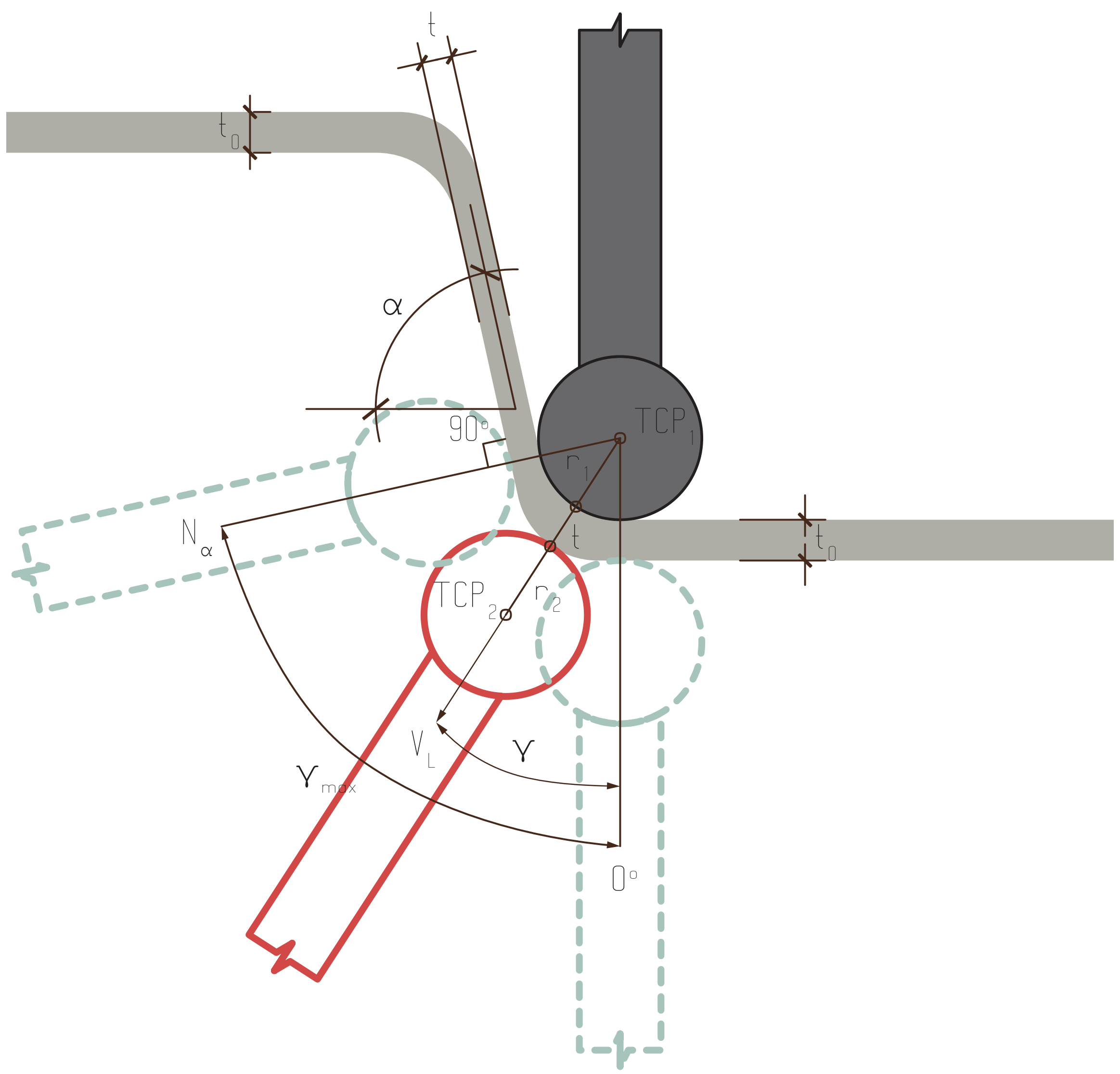
In DPIF-P, the support tool moves repeatedly in a constant plane along the boundary of the forming geometry. The support tool's position, TCP_2, is calculated based on the forming tool's position, TCP_1, relative to the centroid of the geometry, C. The centroid is typically the center of the final contour of the forming tool's path. The resulting vector, V_p, is extended until it intersects the support tool's path. The center point of the support tool, TCP_2, is located at the center of the base of the tool and it's path is simply an offset of the geometry boundary with a magnitude of the tool's radius, r_2. However, since the contour paths later in the run of the file have fewer targets than the border curve, there is a danger of the support tool running into the formed geometry on its way to the calculated next target.

The Solution

To solve this problem a series of interpolation targets along the border curve from the current tool target to the next tool target. will need to be inserted into the Support Tool Path. What this ends up meaning is that the Support Tool Path will have more targets than the Forming Tool Path. This complicates the calculation of the synchronized times. However, a function can be written to calculate the new times based on this interpolation method.

Sources:
Kreimeier, CAD, 6-7

Calculating Support Tool Position - Local Support



Zone for Local Support

The center point of the supporting forming tool, TCP_2, needs to be along the vector, V_L, from the center point of the master forming tool, TCP_1, to the point of contact, Pc. TCP_2 is translated from TCP_1 along V_L with a magnitude, M_v, of:

$M_v = r1 + t + r2$

$r1$ = radius of master forming tool

t = thickness of formed sheet

$r2$ = radius of supporting forming tool

This allows the supporting forming tool to be in a variety of positions and orientations. The shifting angle, γ_{max}, is bound between 0°, when the tools are directly opposite eachother, and N_α, the angle normal to the wall angle, α.

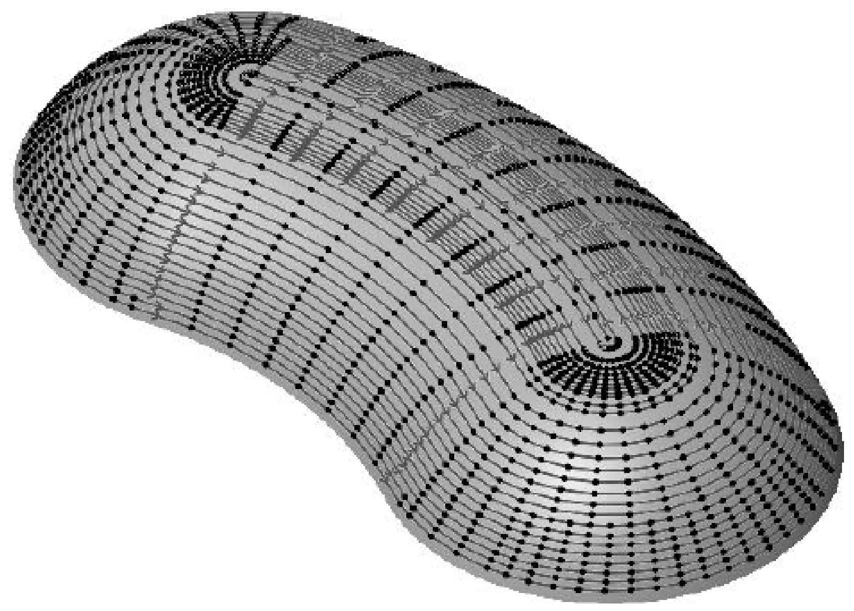


Image credit: Meier, Accuracy, 5

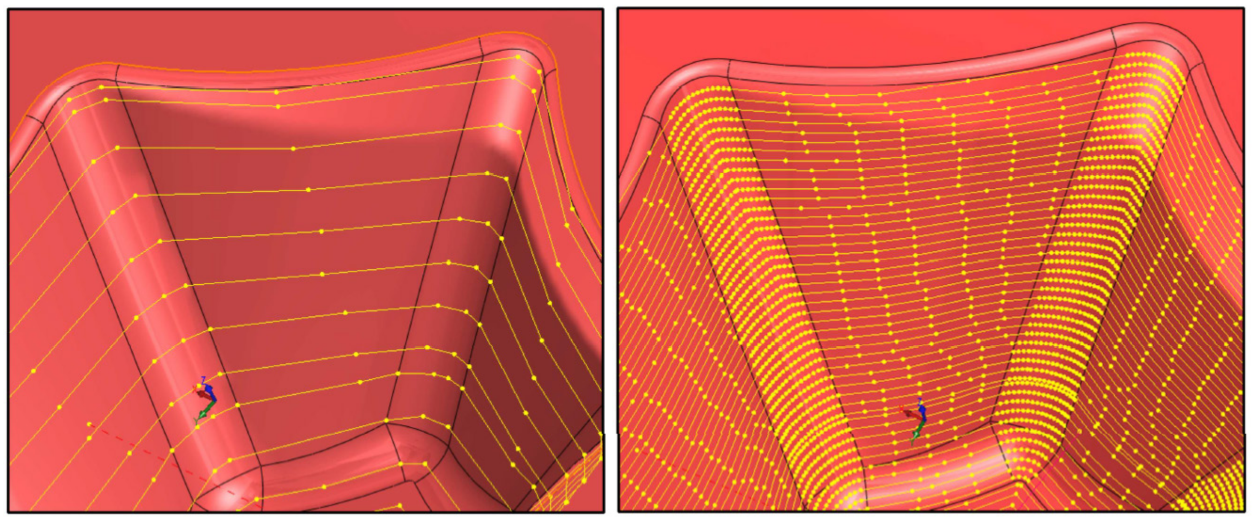


Image credit: Kreimeier, CAM, 892

Divide by Curvature to Increase Computational Efficiency

The robots do not follow paths or curves but rather are instructed to go to a series of targets. The tool-head can only move is a straight line between two targets. Therefore, the resulting toolpath is a faceted polyline. To increase the accuracy and surface quality of the forming, a smaller step size is desired. The more targets, the higher the accuracy. However, it is a waste of the computer's resources to place targets at every small interval as inevitably targets would be placed where they really were not needed. Ideally, there should be more targets in areas of high curvature, and fewer where the curvature is less.

Sources:

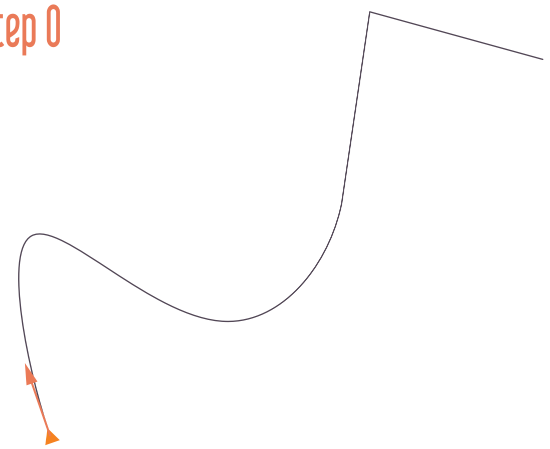
Meier, Accuracy, 5

Kreimeier, CAM, 892

Scripts

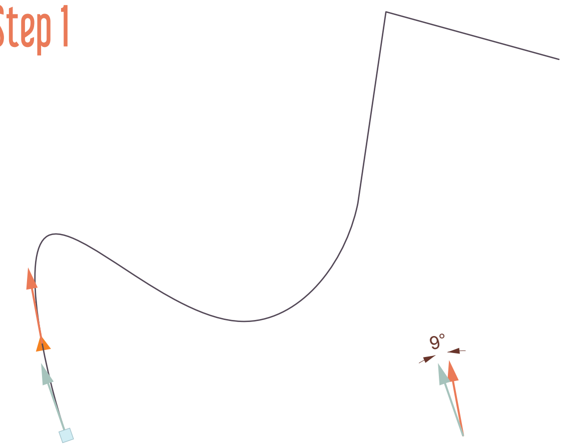
Divide by Tangent - Concept

Step 0



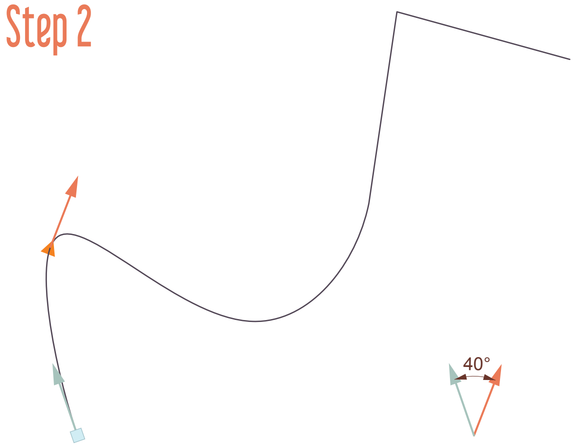
A rover travels along the path, saving the tangent vector at each point. The rover places a point at the start of the curve.

Step 1



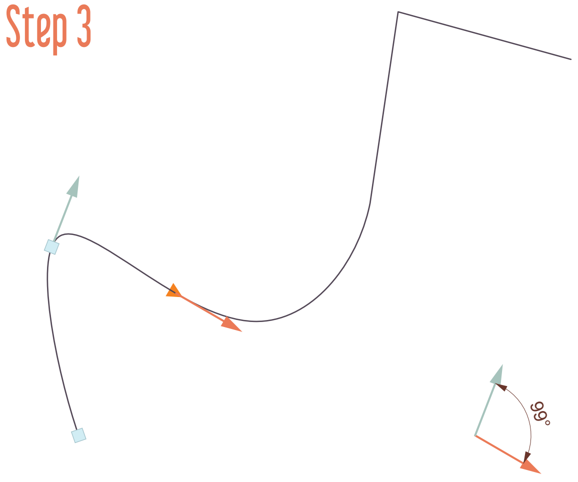
The rover steps by a given step size and compares the previous tangent to the current tangent. Here, the change in tangent angle is less than theta, so the point is not created.

Step 2



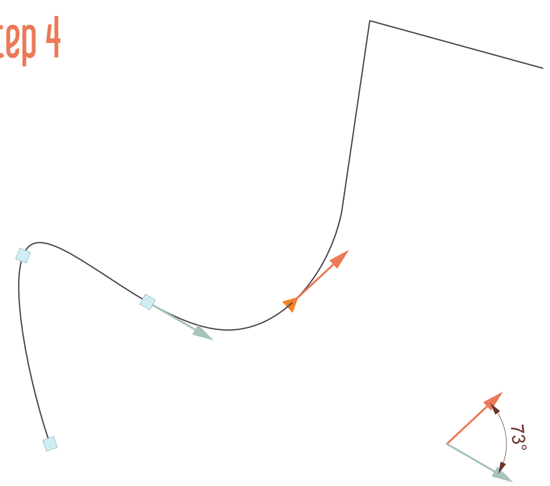
The rover takes another step and compares this new tangent to the original tangent at the start of the curve. Since the angles changes by more than theta, a point is placed.

Step 3



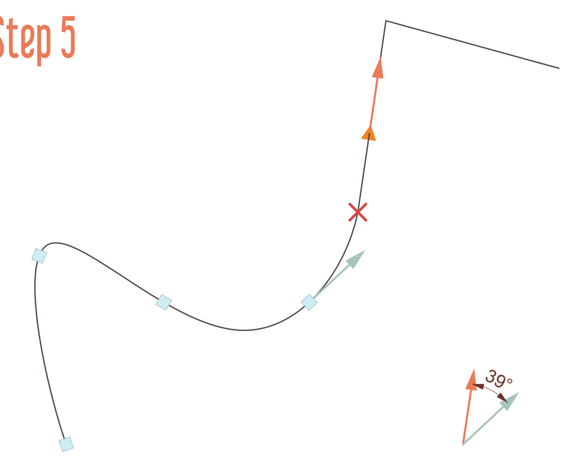
The rover steps and determines that a point should be created.

Step 4



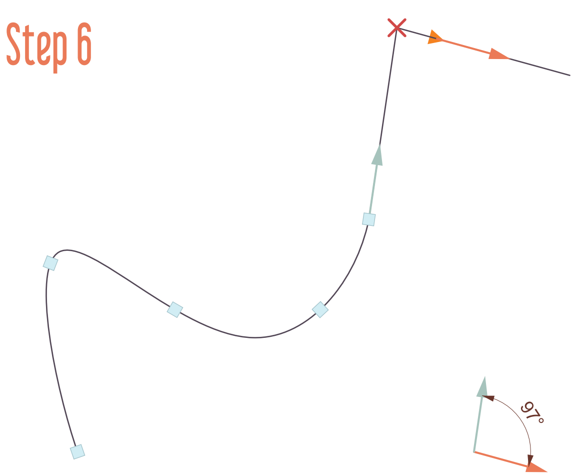
The rover steps and determines that a point should be created.

Step 5



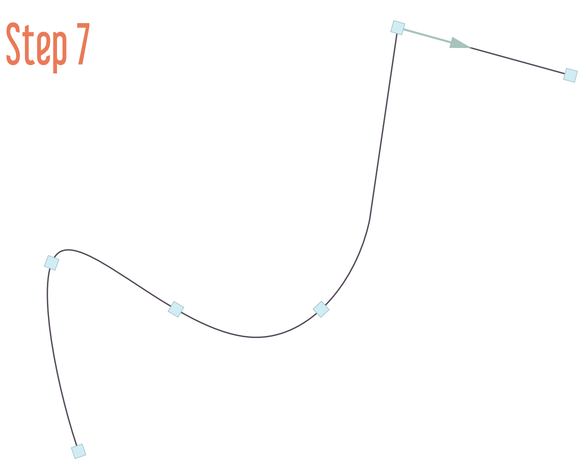
The rover steps and determines that a discontinuity exists between the previous point and the new point. So the rover places at point at the discontinuity and updates the previous tangent.

Step 6

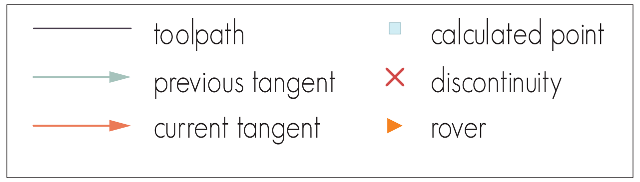


The rover steps and determines that a discontinuity exists between the previous point and the new point. So the rover places at point at the discontinuity and updates the previous tangent.

Step 7

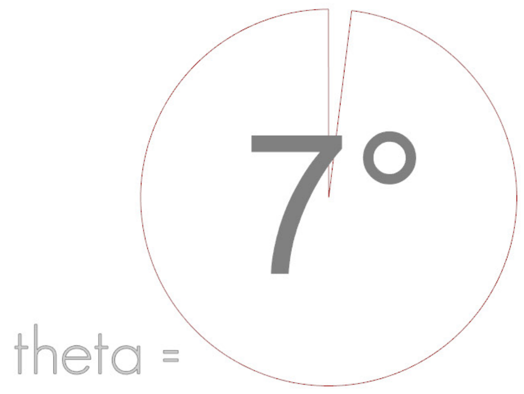


The rover places a point at the end.

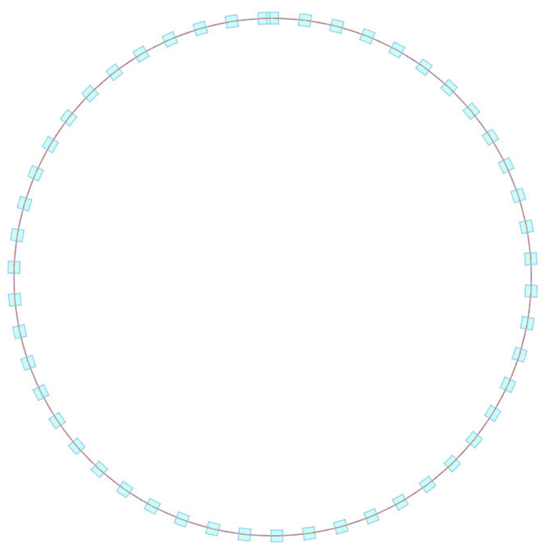


Divide by Change in Tangent Vector - Demonstration

Theta: the minumum change required

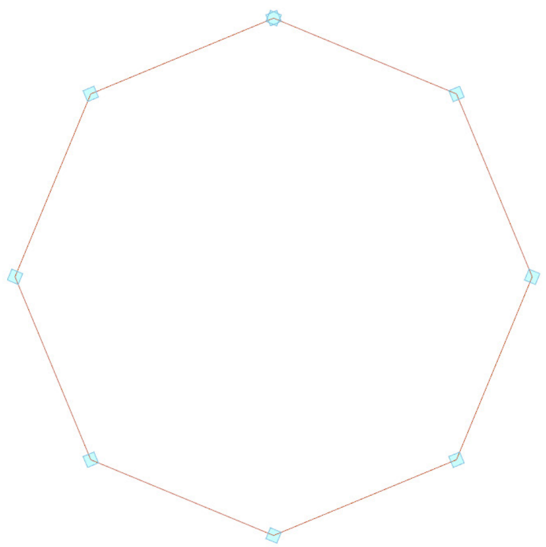


Circle



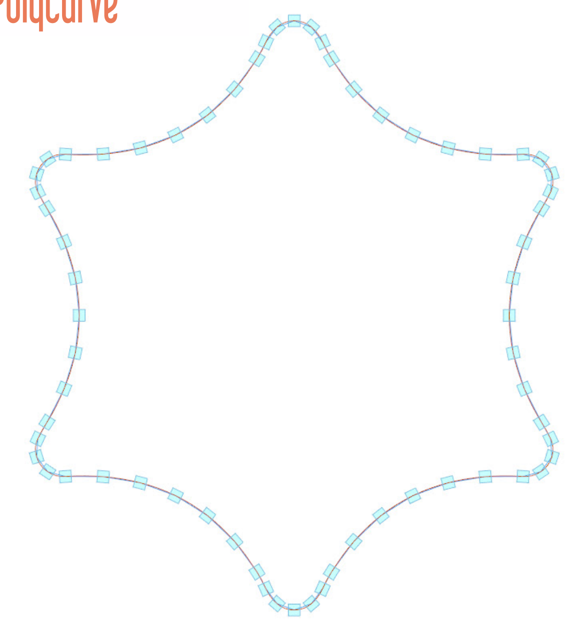
pts: 52 accuracy: 100%

Polygon



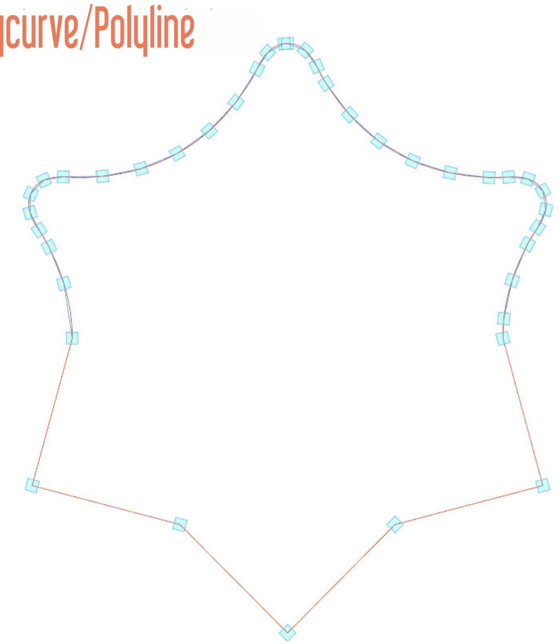
pts: 9 accuracy: 100%

Polycurve



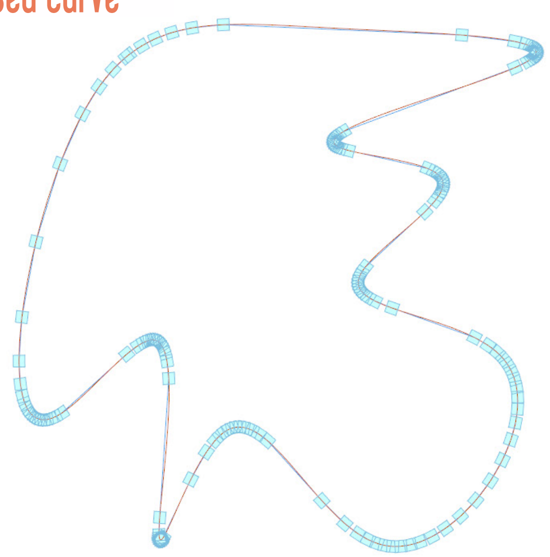
pts: 65 accuracy: 100%

Polycurve/Polyline



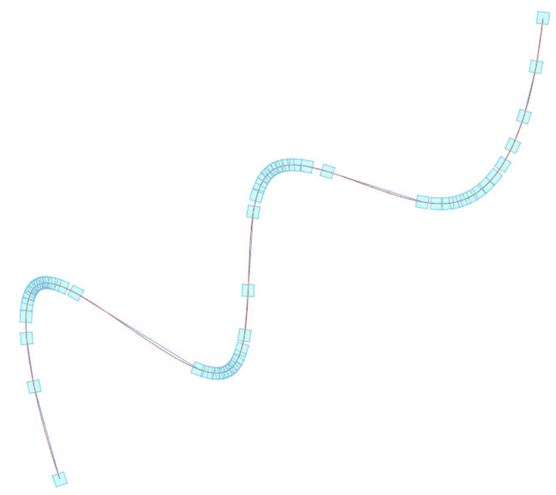
pts: 40 accuracy: 100%

Closed Curve

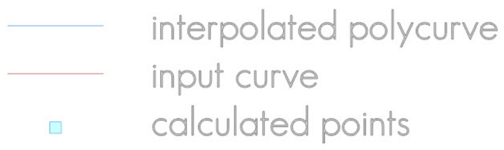


pts: 168 accuracy: 100%

Open Curve

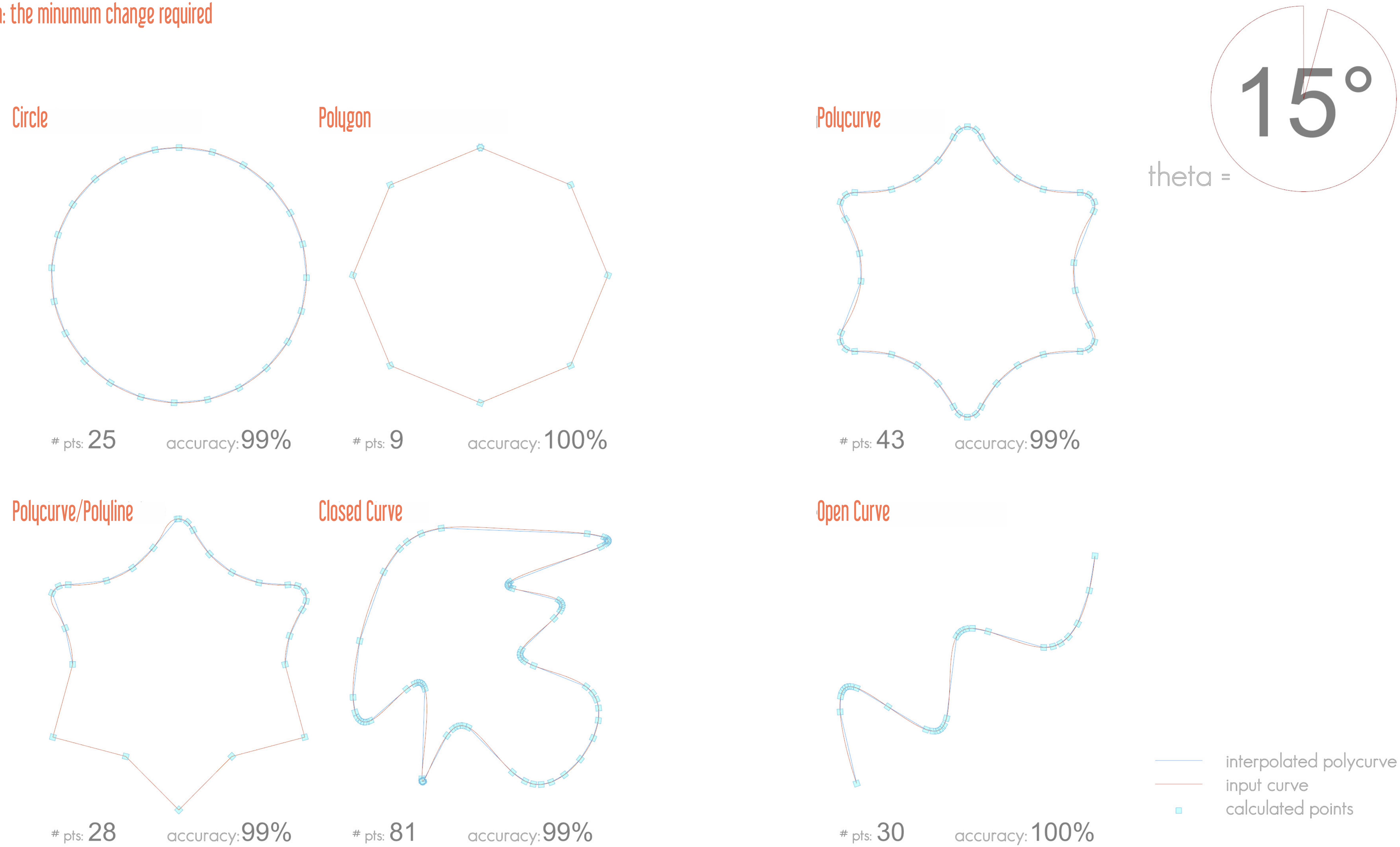


pts: 62 accuracy: 100%



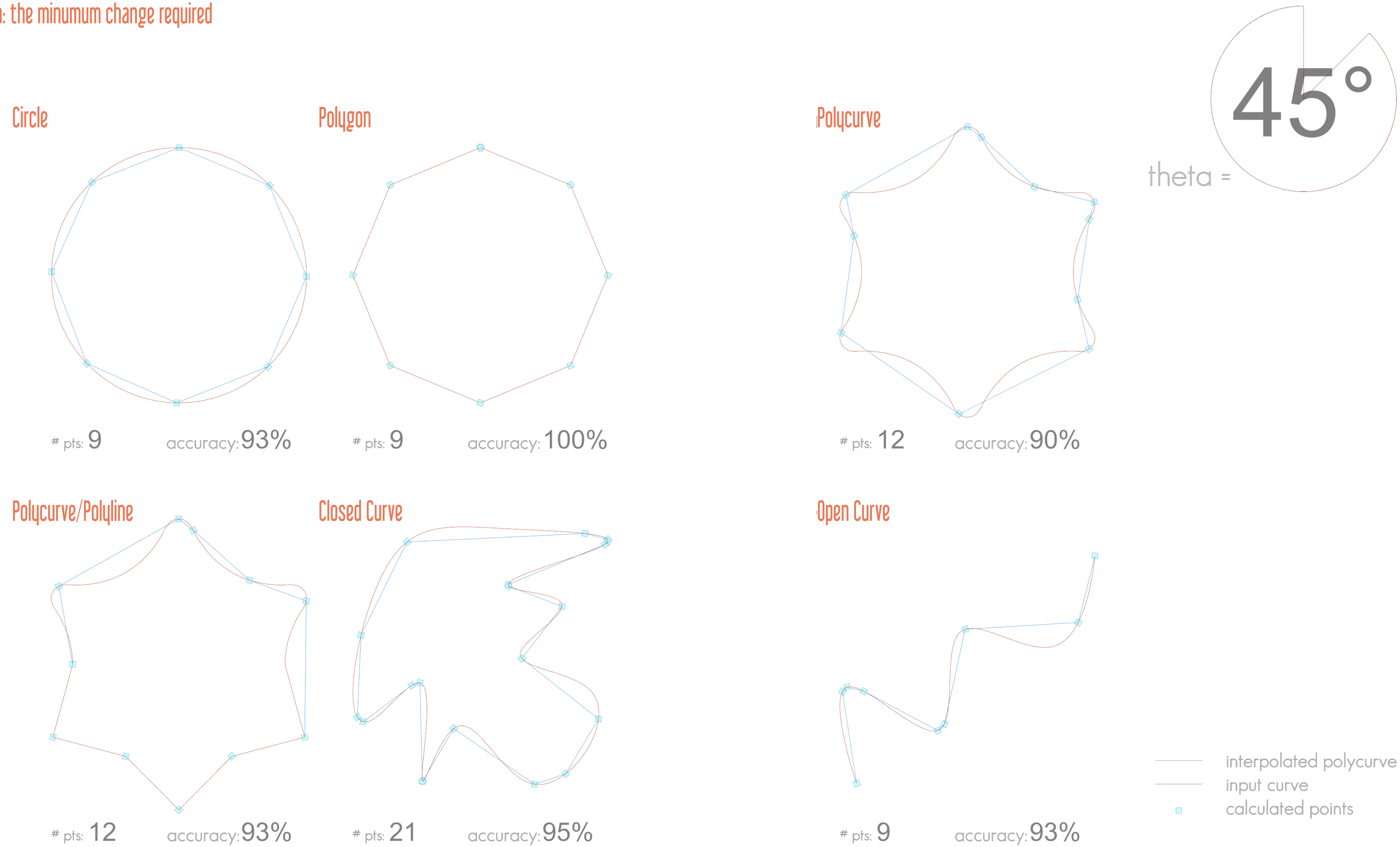
Divide by Change in Tangent Vector - Demonstration

Theta: the minumum change required



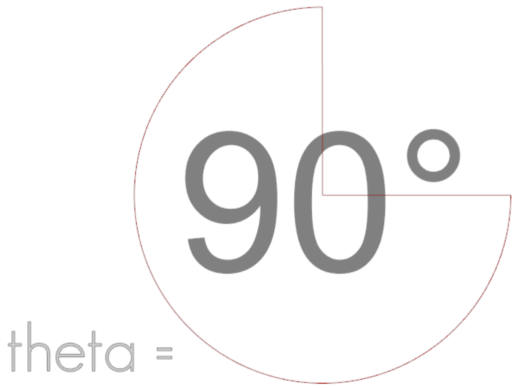
Divide by Change in Tangent Vector - Demonstration

Theta: the minumum change required

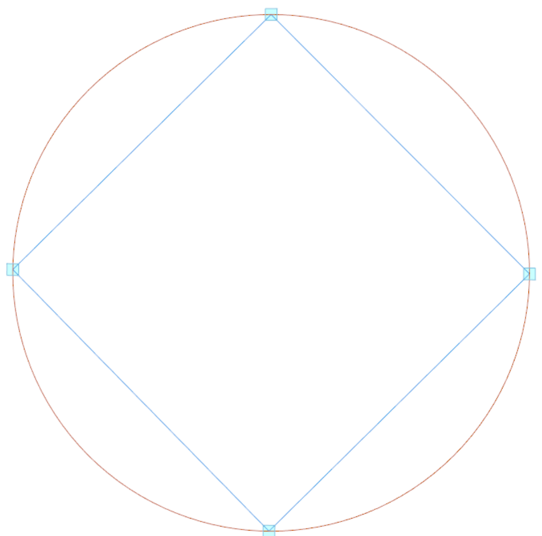


Divide by Change in Tangent Vector - Demonstration

Theta: the minumum change required

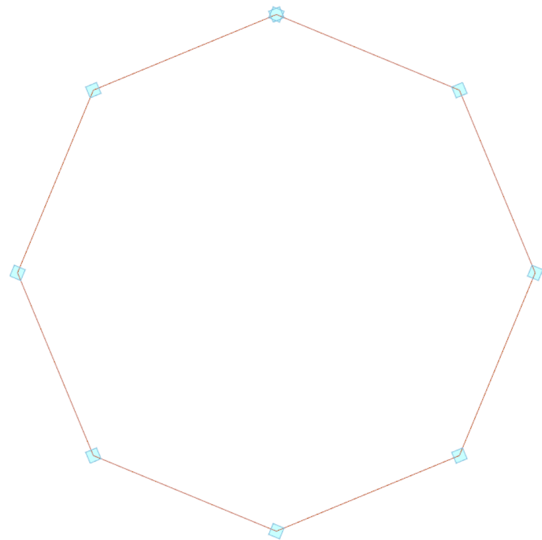


Circle



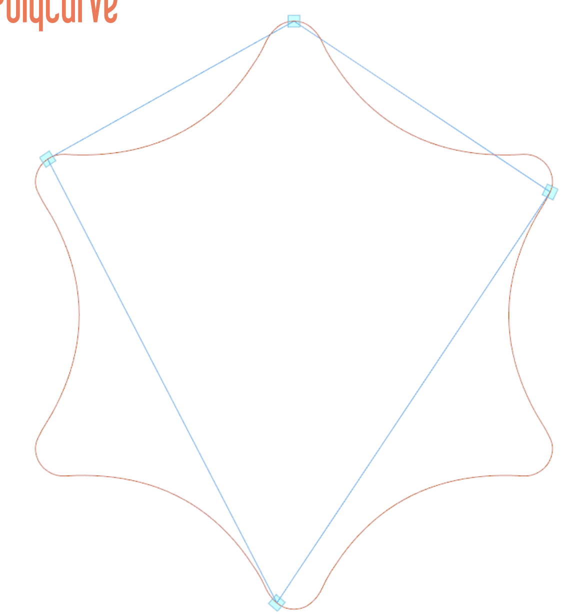
pts: 5 accuracy: 74%

Polygon



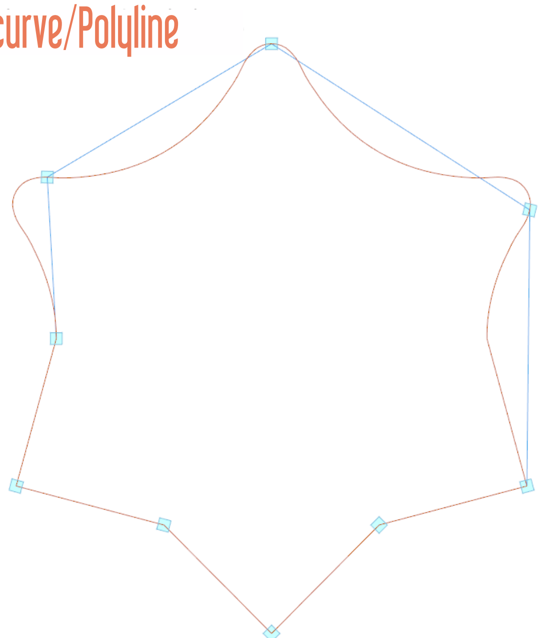
pts: 9 accuracy: 100%

Polycurve



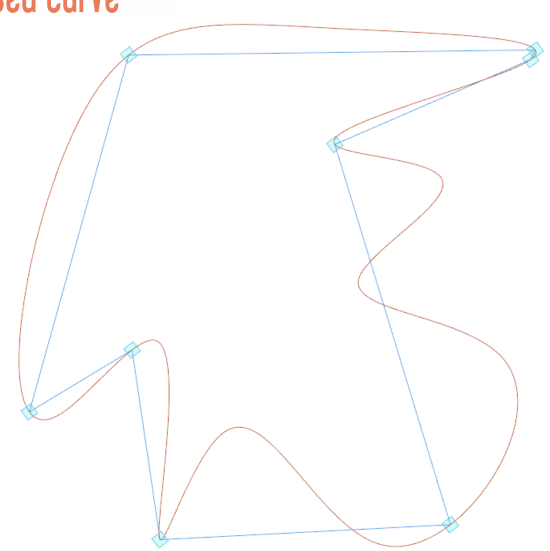
pts: 5 accuracy: 74%

Polycurve/Polyline



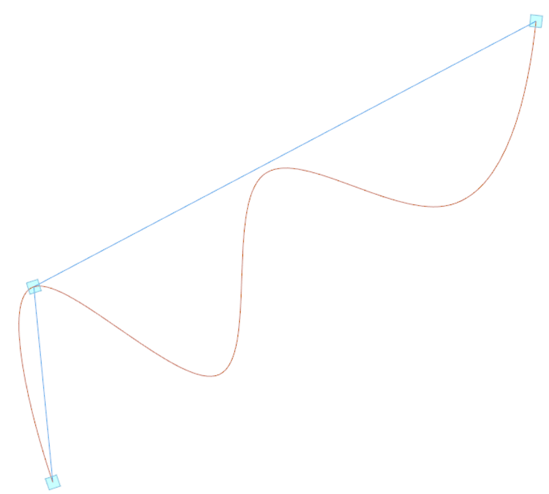
pts: 10 accuracy: 90%

Closed Curve



pts: 9 accuracy: 71%

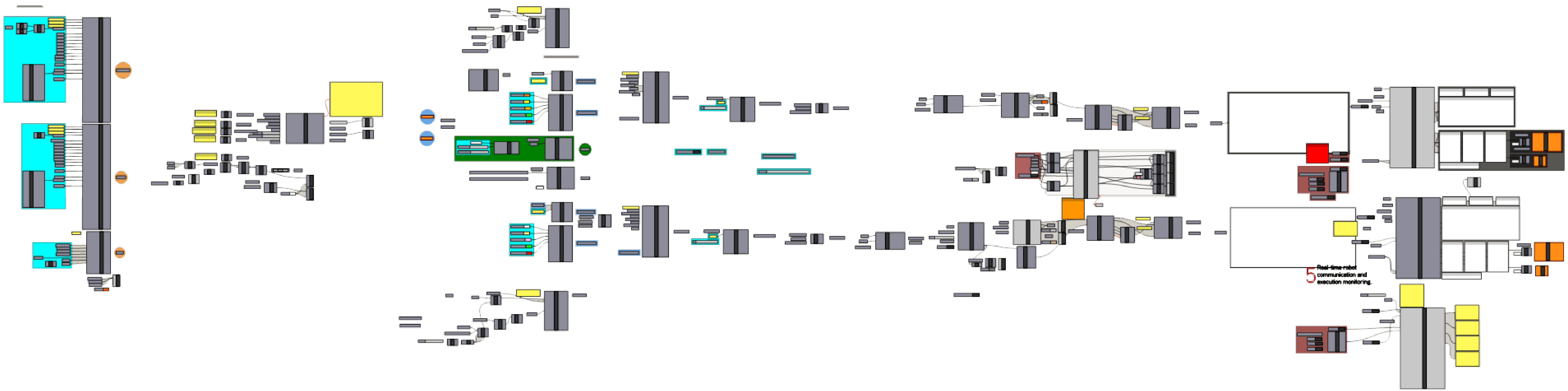
Open Curve



pts: 3 accuracy: 69%

interpolated polycurve
input curve
calculated points

Grasshopper Script



Declare Robots | Create Robot Targets | Declare Tools and Target Parameters | Simulate | Generate RAPID Code | Upload to Controller

Roboforming Target Creation Component

sheetThickness : double
Initial thickness of the sheet metal.

formingToolDiam : double
Diameter of the forming tool's tip.

supportToolDiam : double
Diameter of the support tool's tip.

stepdown : double
Interval used to contour the geometry.

former : int
0: 6640, 1: 4400

4400 Tool : int
0: Disk, 1: Ball-End

6640 Tool : int
0: Disk, 1: Ball-End

supportType : int
0: None, 1: Local, 2: Peripheral

formingToolAngle : double
The angle of the forming tool relative to the surface normal.

supportToolAngle : double
The angle of the support tool relative to the surface normal.

divisionAngle : int
The minimum change in angle between two targets.

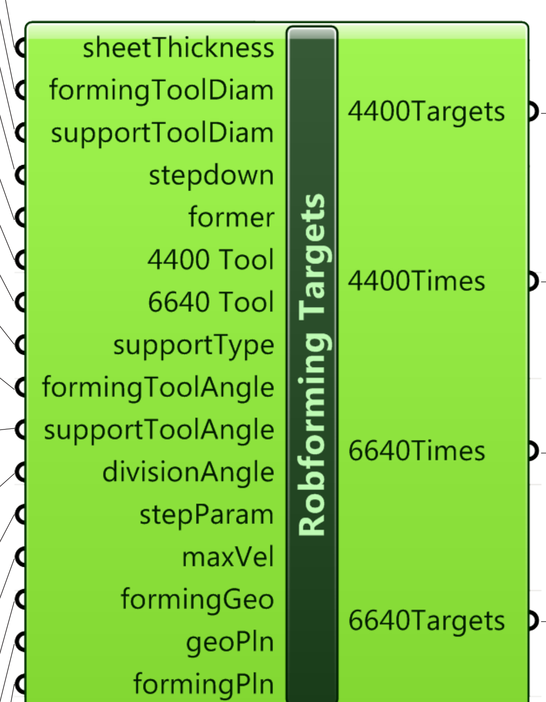
stepParam : double
The parameter along the curve of the stepdown.

maxVel : int
The maximum velocity of the robots.

formingGeo : Brep
The geometry to be formed.

geoPln : Plane
The plane of the formingGeo with the normal in the direction of the forming.

formingPln : Plane
The plane of the sheet metal in the frame with the normal in the direction of the forming.



formingTargets : Plane
The targets for the 4400 robot to follow in order.

formingTimes : double
Times for each forming target.

supportTargets : Plane
The targets for the 6640 robot to follow in order.

supportTimes : double
Times for each support target.

The Roboforming Targets component calculates the tool-path targets for the two robots. The goal of this compoenent is for it to be a safe, error-handling script that anyone with a basic knowledge of grasshopper can use without worrying about whether they are going to break the robots. An additional goal is to open source it and make it available to other students and fabricators to add additional functions. In order to realize this goal it is important that the code be clean and easy for even a novice programmer to understand and modify. To this end, this component is actually a cluster of sub-components, eahch with a specific function.

```
private void RunScript(double sheetThickness, double formingToolDiameter, doub
{
  //Declare variables
  int NO_SUPPORT = 0;
  int LOCAL_SUPPORT = 1;
  int PERIPHERAL_SUPPORT = 2;
  Surface formingSurface = formingGeometry.Faces[0];
  double[] times = new double[0];
  LinkedList < Plane > supportTargs = null;
  //Contour forming geometry based on stepdown
  //include formingToolDiameter so the tool does not project past the surface
  Curve[] contours = contourGeo(formingGeometry, stepdown, startPt,
    formingToolDiameter / 4);
  //Calculate planes where the tool will make contact with the geometry
  LinkedList<Plane> contactPlns = divideCrvsByDeltaTan(contours, minDeltaTan);
  //Create forming targets by offsetting the contact planes by the forming
  //tool diameter
  LinkedList<Plane> formingTargs = offsetPlnsFromNormal(contactPlns,
    formingSurface, formingToolDiameter / 2);

  if(type == NO_SUPPORT)
  {
    //Do not calculate support targets
    //To avoid outputting null to the support targets, give it the home target
    Plane[] pln = {new Plane(J6EndPt, new Vector3d(-1, 0, 0))};
    supportTargs = new LinkedList<Plane>(pln);
    times = calcTimes(formingTargs, velocity);
    formingTimes = times;
  }
  else if(type == LOCAL SUPPORT)
  {
    //Create support targets based on the contact planes
    //Offset the contact planes by the forming tool diameter and sheet
    //thickness.
    supportTargs = offsetPlnsFromNormal(contactPlns, formingSurface,
      -((formingToolDiameter / 2) + sheetThickness));
    supportTargs = flipNormal(supportTargs);
    //Calculate the times based on the support targets since they span
    //greater distances than the forming targets
    times = calcTimes(supportTargs, velocity);
    //Both the forming and supports times have the same number of points
    //so set their times are equal.
    formingTimes = times;
    supportTimes = times;
  }
  else if(type == PERIPHERAL_SUPPORT)
  {
    //Calculate center of forming geometry based on last contour
    Point3d center = getCentroid(contours[contours.Length - 1]);
    //The boundary curve will be the first element in contours
    Curve peripheralCrv = contours[0];
    supportTargs = calcPeripheralPlns(formingTargs, peripheralCrv, center,
      supportToolDiameter / 2);
    times = calcTimes(supportTargs, velocity);
    //Both the forming and supports times have the same number of points
    //so set their times are equal.
    formingTimes = times;
    supportTimes = times;
  }
  formingTargets = formingTargs;
  supportTargets = supportTargs;
}
```

Orientation Planes Component

```
/*
contourGeo : Brep * double * Point3d * double -> Curve[]
REQUIRES: geo is oriented s.t. the inner surface is facing in the same
direction as the x axis.
sD > 0.
ENSURES: contourGeo(geometry, stepdown) returns an array of curves s.t. each
curve is the result of an intersection between the geometry and a yz plane
with the plane's origin at the furthest point in the x axis + a displacement
vector in the negative x axis of stepDown*curveNumber.
*/
private Curve[] contourGeo(Brep geo, double stepDown, Point3d startPt,
  double r)
{
  double tolerance = 0.0000001;
  //Get depth of forming geometry
  BoundingBox bbox = geo.GetBoundingBox(true);
  Point3d p1 = bbox.Corner(false, true, true);
  Point3d p2 = bbox.Corner(true, true, true);
  p2.Transform(Transform.Translation(new Vector3d(r, 0, 0)));
  double depth = p1.X - p2.X;
  //Get number of contours based on depth and stepdown
  int numContours = (int) (depth / stepDown);
  //Set up final plane
  //This requires nudging the intersection plane
  Vector3d xAxis = new Vector3d(1, 0, 0);
  Point3d finalPt = p2;
  Vector3d vec = new Vector3d(tolerance, 0, 0);
  Transform nudgeX = Transform.Translation(vec);
  finalPt.Transform(nudgeX);
  Plane finalPlane = new Plane(finalPt, xAxis);
  //Set up parameters for contouring
  Plane[] planes = new Plane[numContours];
  vec = new Vector3d(-stepDown, 0, 0);
  Transform movex = Transform.Translation(vec);
  Point3d pt = p1;
  double seamParam;

  //Add one to the number of contours to account for the final intersection
  Curve[] contours = new Curve[numContours + 1];

  //Contour Brep
  for(int i = 0; i < numContours; i++)
  {
    planes[i] = new Plane(pt, xAxis);
    contours[i] = Brep.CreateContourCurves(geo, planes[i])[0];
    contours[i].ClosestPoint(startPt, out seamParam);
    contours[i].ChangeClosedCurveSeam(seamParam);
    //Increment
    pt.Transform(movex);
  }

  //Add in final curve to account for gaps in stepdown
  contours[numContours] = Brep.CreateContourCurves(geo, finalPlane)[0];
  contours[numContours].ClosestPoint(startPt, out seamParam);
  contours[numContours].ChangeClosedCurveSeam(seamParam);

  return contours;
}
```

```
/*
deg : double -> double
REQUIRES: true
ENSURES: deg(radian) converts radians to degrees
*/
private double deg(double rad)
{
  return rad * (180 / Math.PI);
}

/*
divideCrvsByDeltaTan : Curve[] * double -> LinkedList<Plane>
REQUIRES: theta > 0
ENSURES: divideCrvsByDeltaTan(crvs, theta) returns a linked list of planes
         along the curves s.t. there is a plane at every point along
         the curve where the change in the tangent vector between
         two points is greater than theta.
*/
private LinkedList<Plane> divideCrvsByDeltaTan(Curve[] crvs, double theta)
{
  //initialize parameters
  int n = crvs.Length;
  double stepSize = 0.5;
  Vector3d xAxis = new Vector3d(1, 0, 0);
  double rover; //steps along the curve by stepSize
  double oldRover; //stores the previous rover for comparison
  double discontinuity;
  Vector3d prevTan;
  Vector3d currTan;
  Curve crv;
  Interval dom;

  //initialize list
  Plane[] plns = {};
  LinkedList < Plane > targets = new LinkedList<Plane>(plns);
  Plane target;

  Rhino.Geometry.Continuity c = Rhino.Geometry.Continuity.C1_continuous;

  for(int i = 0; i < n; i++)
  {
    crv = crvs[i];

    //initialize data
    dom = crv.Domain;
    rover = dom.Min;

    //Add plane at start point of curve to list
    target = new Plane(crv.PointAt(rover), xAxis);
    targets.AddLast(target);

    //Increment
    prevTan = crv.TangentAt(rover);
    oldRover = rover;
    rover += stepSize;
```

Orientation Planes Component

```
      while(rover < dom.Max)
      {
        currTan = crv.TangentAt(rover);

        //If there is a discontinuity between the oldRover and rover
        //then place a point at the discontinuity and update prevTan.
        bool isDisc = crv.GetNextDiscontinuity(c, oldRover, rover,
          out discontinuity);
        if(isDisc)
        {
          target = new Plane(crv.PointAt(discontinuity), xAxis);
          targets.AddLast(target);
          prevTan = crv.TangentAt(discontinuity);
        }

        //If the change in tangent vector is greater than theta,
        //then drop a target at the rover and update prevTan.
        double delta = deg(Math.Abs(Vector3d.VectorAngle(prevTan, currTan)));
        if(delta > theta)
        {
          target = new Plane(crv.PointAt(rover), xAxis);
          targets.AddLast(target);
          prevTan = currTan;
        }
        //Increment
        oldRover = rover;
        rover += stepSize;
      }

      //Add target at end point of curve
      target = new Plane(crv.PointAt(dom.Max), xAxis);
      targets.AddLast(target);
    }
    return targets;
  }

  /*
  movePlane : Plane * Vector3d -> Plane
  REQUIRES: true
  ENSURES: movePt(pt, vec) returns the pt translated by the vec
  */
  private Plane movePlane(Plane pl, Vector3d vec)
  {
    var movex = Transform.Translation(vec);
    pl.Transform(movex);
    return pl;
  }
```

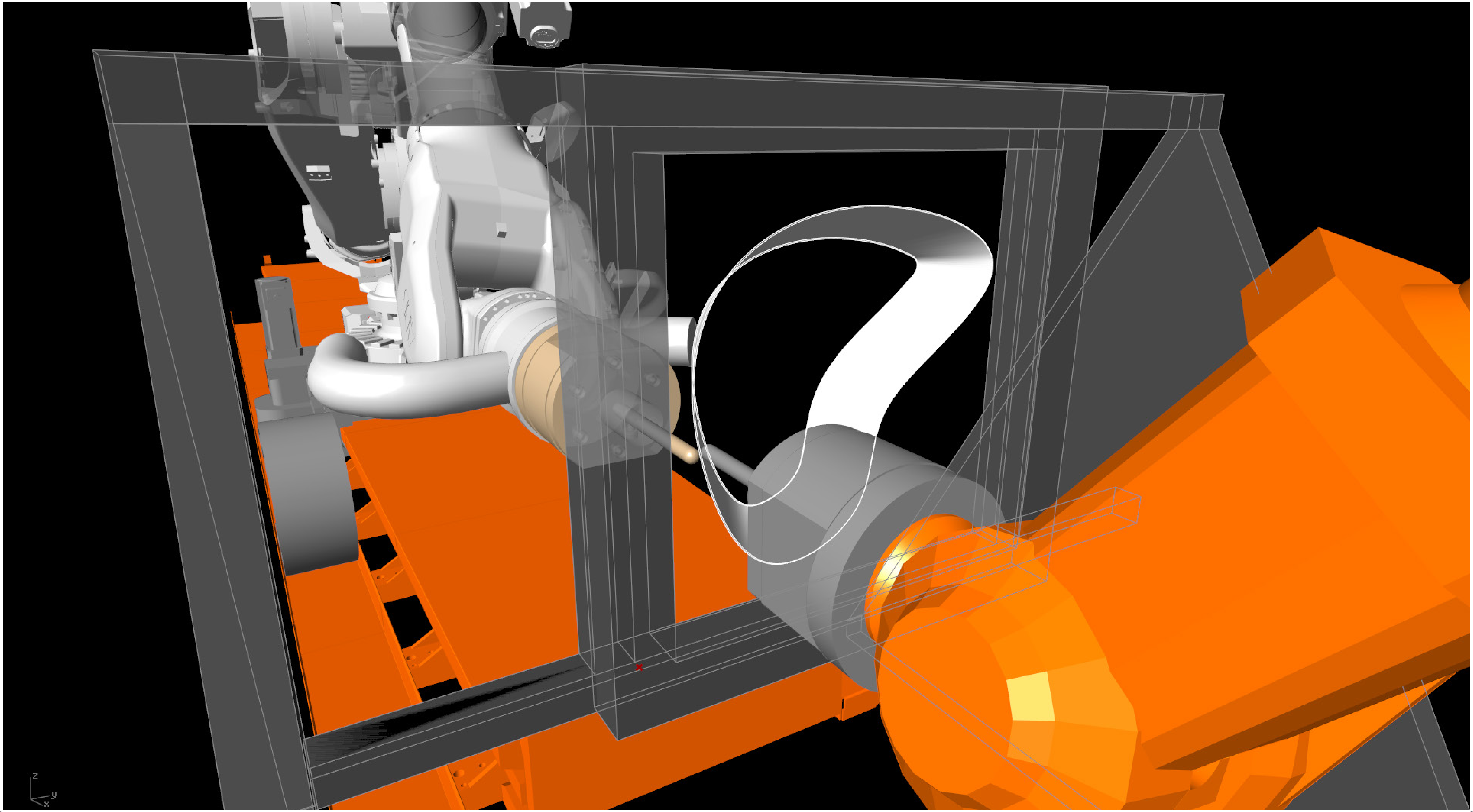
```
  /*
  offsetPlnsFromNormal : LinkedList<Plane> * Surface * double ->
    LinkedList<Plane>
  REQUIRES: true
  ENSURES: offsetPlnsFromNormal(pts, srf, mag) returns the pts translated by the
           normal vector at the closest point to the srf with a magnitude of mag
  */
  private LinkedList<Plane> offsetPlnsFromNormal(LinkedList<Plane> plns,
    Surface srf, double mag)
  {
    //Initialize variables
    Plane[] planes = {};
    LinkedList < Plane > offsetPlns = new LinkedList<Plane>(planes);
    double u,v;

    //Create a node to traverse the list
    LinkedListNode<Plane> p = plns.First;

    //Traverse the list and add the offset plane to the linked list
    while(p != plns.Last.Next)
    {
      srf.ClosestPoint(p.Value.Origin, out u, out v);
      offsetPlns.AddLast(movePlane(p.Value, srf.NormalAt(u, v) * mag));
      p = p.Next;
    }
    return offsetPlns;
  }

  /*
  flipNormal : LinkedList<Plane> -> LinkedList<Plane>
  REQUIRES: true
  ENSURES: flipNormal(plns) returns plns with the normal direction flipped
  */
  private LinkedList<Plane> flipNormal(LinkedList<Plane> plns)
  {
    //Initialize variables
    Plane[] planes = {};
    LinkedList < Plane > flippedPlns = new LinkedList<Plane>(planes);
    Plane pln;

    //Create a node to traverse the list
    LinkedListNode<Plane> p = plns.First;

    //Traverse the list and add the flipped plane to the linked list
    while(p != plns.Last.Next)
    {
      pln = p.Value;
      pln.Flip();
      flippedPlns.AddLast(pln);
      p = p.Next;
    }
    return flippedPlns;
  }
```

Orientation Planes Component

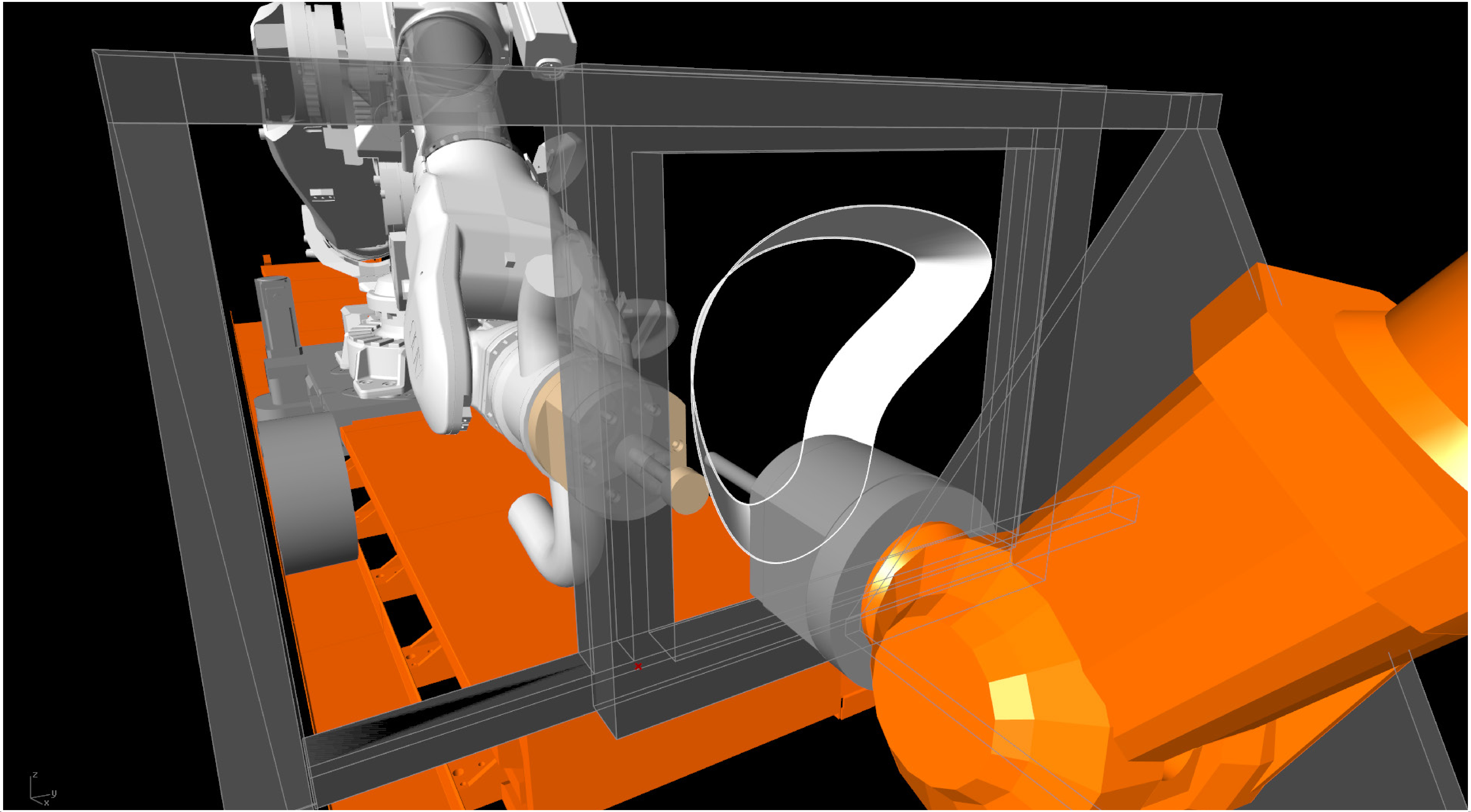
```
/*
calcTimes : Plane * Plane * double -> double
REQUIRES: vel > 0
ENSURES: calcTime(targ1, targ2, vel) determines the time necesary to ensure
the velocity between any two points = maxVel.
*/
private double calcTime(Plane targ1, Plane targ2, double vel)
{
  double distance = targ1.Origin.DistanceTo(targ2.Origin);
  return distance / vel;
}

/*
calcTimes : Plane[] * double -> double[]
REQUIRES: maxVel > 0
ENSURES: calcTimes(targs, maxVel) determines the time necesary to ensure the
         velocity between any two points = maxVel
*/
private double[] calcTimes(LinkedList<Plane> plns, double vel)
{
  //Initialize variables
  int numTargs = plns.Count;
  double[] times = new double[numTargs];
  //Set first targets's time to 30 secs to avoid the robot zooming to targ1
  times[0] = 30;
  LinkedListNode<Plane> p = plns.First.Next;
  int i = 1;

  //Traverse the list and calculate the time based on the distance/vel
  while(p != plns.Last.Next)
  {
    times[i] = calcTime(p.Previous.Value, p.Value, vel);
    //Increment
    p = p.Next;
    i++;
  }
  return times;
}

/*
getCentroid : Curve -> Point3d
REQUIRES: true
ENSURES: getCentroid(crv) returns the centroid of crv.
*/
private Point3d getCentroid(Curve crv)
{
  AreaMassProperties p = AreaMassProperties.Compute(crv);
  return p.Centroid;
}
```

```
/*
calcPeripheralPlns : LinkedList<Plane> * Curve * Point3d * double
  -> LinkedList<Plane>
REQUIRES: true
ENSURES: getCentroid(crv) returns the centroid of crv.
*/
private LinkedList<Plane> calcPeripheralPlns(LinkedList<Plane> formingPlns,
  Curve crv, Point3d center, double r)
{
  //Initialize Variables
  double tol = 0.000001;
  Point3d offsetPt = new Point3d(1000, 0, 0);
  Vector3d xAxis = new Vector3d(1, 0, 0);
  Line line;
  Plane pln;
  Point3d pt;
  Curve intCrv;
  Vector3d negXaxis = new Vector3d(-1, 0, 0);
  Plane[] planes = {};
  LinkedList < Plane > peripheralPlns = new LinkedList<Plane>(planes);

  //Offset crv by radius of support tool
  crv = crv.Offset(offsetPt, xAxis, r, tol, CurveOffsetCornerStyle.Round)[0];

  //Project center to plane of border curve
  center.X = crv.PointAtEnd.X;

  //Create node to traverse linked list
  LinkedListNode<Plane> p = formingPlns.First;

  //Traverse list of planes and determine intersection point on border curve
  while(p != formingPlns.Last.Next)
  {
    pt = p.Value.Origin;
    pt.X = crv.PointAtEnd.X;
    //Draw a Line from the center to the forming point
    line = new Line(center, pt);
    //Extend the Line to ensure that it intersects with the border curve
    line.Extend(0, 1000);
    //Convert the Line to a Curve so the CurveCurve intersect works
    intCrv = line.ToNurbsCurve();
    Rhino.Geometry.Intersect.CurveIntersections pts =
      Rhino.Geometry.Intersect.Intersection.CurveCurve(crv, intCrv, tol, tol);

    //Create a new plane and add it to the list of peripheral targets
    pln = new Plane(pts[0].PointA, negXaxis);
    peripheralPlns.AddLast(pln);
    //Increment
    p = p.Next;
  }
  return peripheralPlns;
}
/**/

}
```

Robot Simulation - Local Support

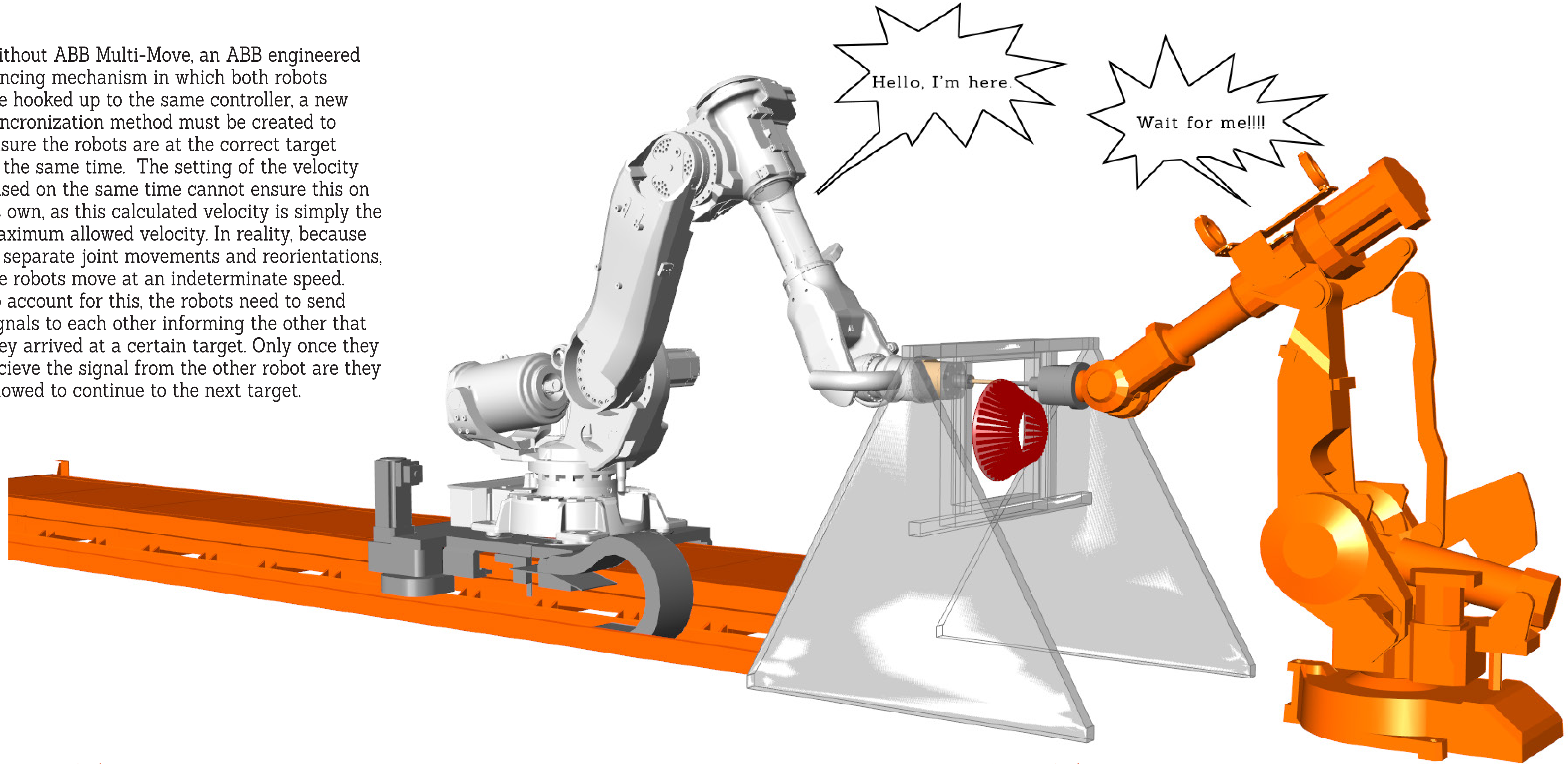


Robot Simulation - Peripheral Support



Syncing

Without ABB Multi-Move, an ABB engineered syncing mechanism in which both robots are hooked up to the same controller, a new syncronization method must be created to ensure the robots are at the correct target at the same time. The setting of the velocity based on the same time cannot ensure this on its own, as this calculated velocity is simply the maximum allowed velocity. In reality, because of separate joint movements and reorientations, the robots move at an indeterminate speed. To account for this, the robots need to send signals to each other informing the other that they arrived at a certain target. Only once they recieve the signal from the other robot are they allowed to continue to the next target.



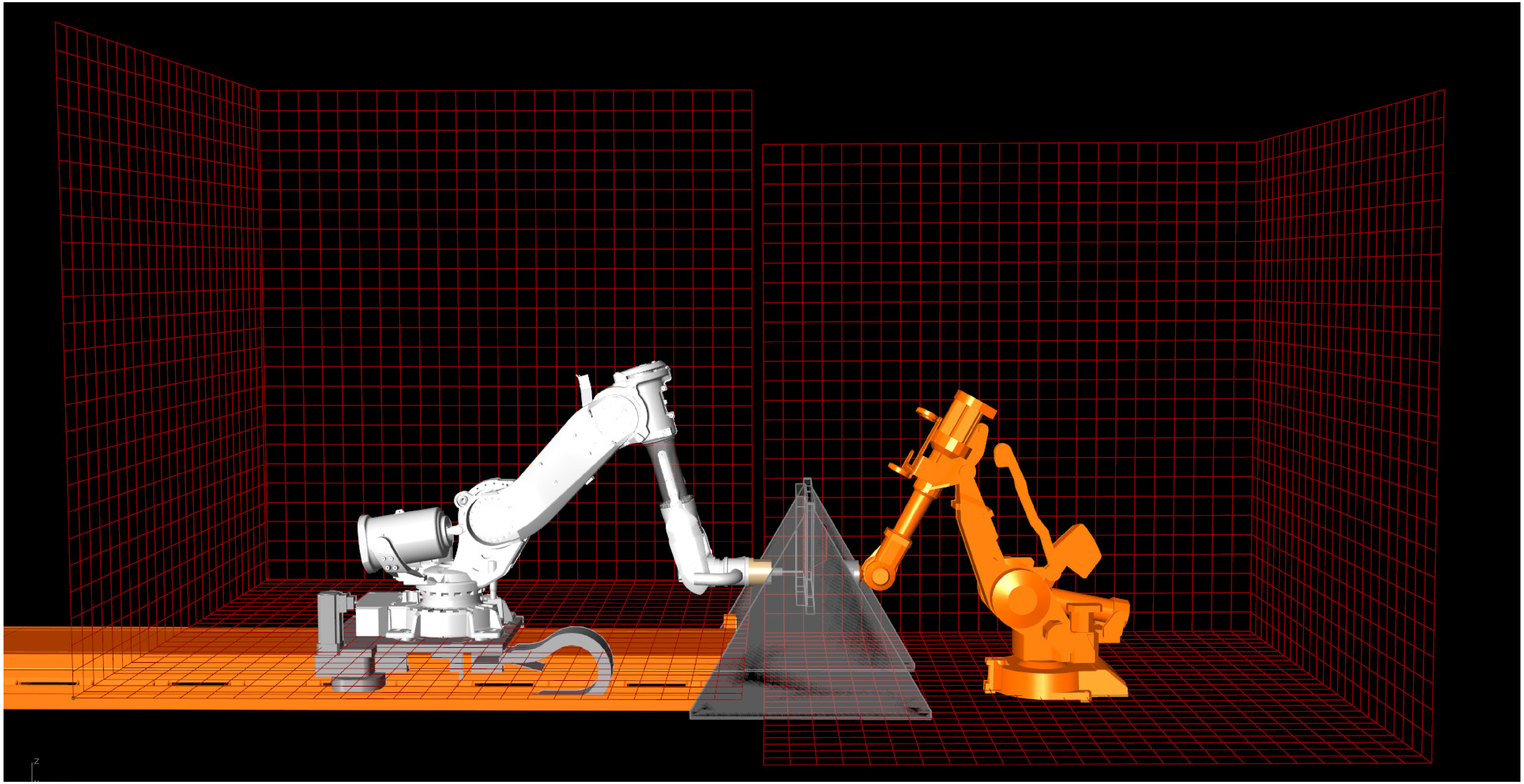
6640 RAPID Code

```
Reset DO_IRB4400; ! Reset the Digital Out value of the 4400 Robot to 0
MoveAbsJ SixtySixTarg0,Slow\T:=10,FINE,formingTool\WObj:=WObj0;  ! Move to targ0
Set DO_IRB4400; ! Set the Digital Out value of the 4400 Robot to 1
WaitDI DI_IRB4400,1; ! Wait until you recieve a Digital In value 1 from the 6640.
MoveL SixtySixTarg1,Slow\T:=0.72,FINE,formingTool\WObj:=WObj0; ! Move to targ1
Reset DO_IRB4400; ! Reset the Digital Out value of the 4400 Robot to 0
WaitDI DI_IRB4400,0; ! Wait until you recieve a Digital In value 0 from the 4400
MoveL SixtySixTarg2,Slow\T:=0.72,FINE,formingTool\WObj:=WObj0; ! Move to targ2
Set DO_IRB4400; ! Set the Digital Out value of the 4400 Robot to 1
```

4400 RAPID Code

```
Reset DO_IRB6640; ! Reset the Digital Out value of the 6640 Robot to 0
MoveAbsJ FortyFourTarg0,Slow\T:=10,FINE,formingTool\WObj:=wobj0;  ! Move to targ0
Set DO_IRB6640; ! Set the Digital Out value of the 6640 Robot to 1
WaitDI DI_IRB6640,1; ! Wait until you recieve a Digital In value 1 from the 6640.
MoveL FortyFourTarg1,Slow\T:=0.72,FINE,formingTool\WObj:=wobj0; ! Move to targ1
Reset DO_IRB6640; ! Reset the Digital Out value of the 6640 Robot to 0
WaitDI DI_IRB6640,0; ! Wait until you recieve a Digital In value 0 from the 6640
MoveL FortyFourTarg2,Slow\T:=0.72,FINE,formingTool\WObj:=wobj0; ! Move to targ2
Set DO_IRB6640; ! Set the Digital Out value of the 6640 Robot to 1
```

Aligning Worlds



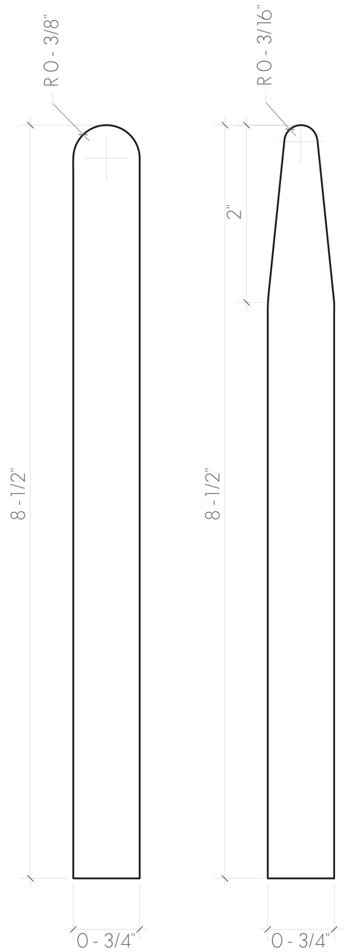
Ensuring that the robots are thinking in the same space was a challenge of its own. Since the robots were installed at different times and on different pours of the concrete floor, no matter how hard the installers tried, the robots would never be perfectly aligned in their x, y, and z axes.

In order to find the base plane of one robot relative to the other, the same three points describing a plane on the frame were probed by each robot. Then these points were offset from the current inaccurate base plane by the probed values. Then a genetic algorithm was run to find the best fit model base plane of the second robot, minimizing the distance between each of the relative points.

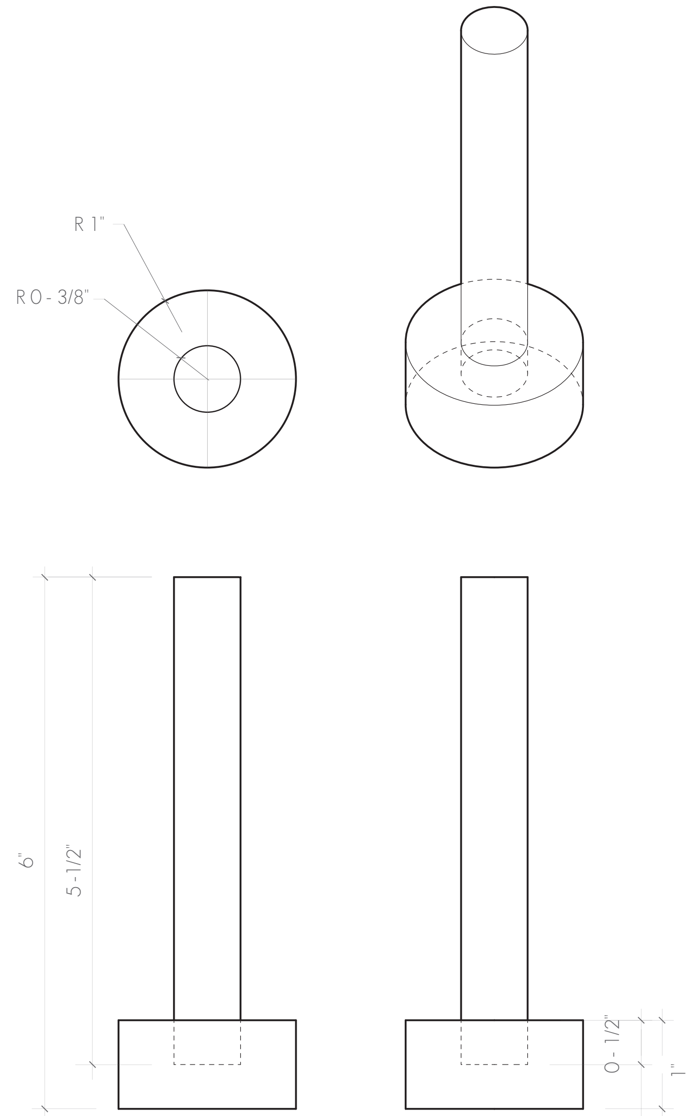
Tools

Forming Tools

Design



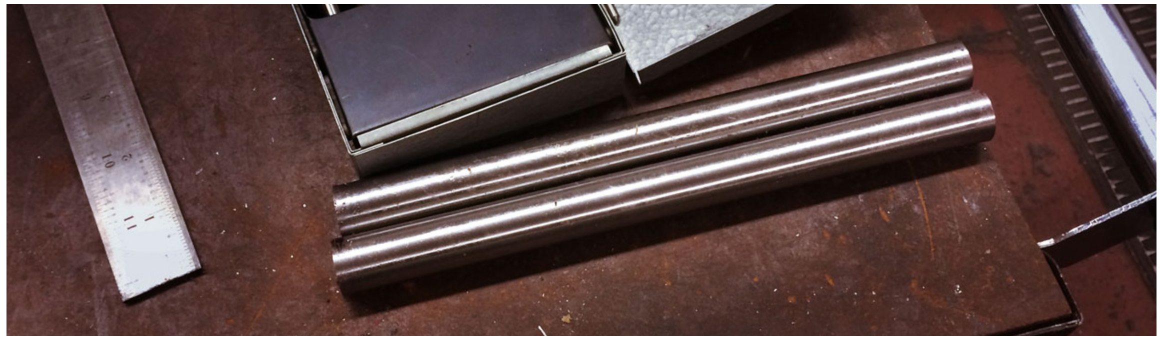
Forming Tools



Support Tool

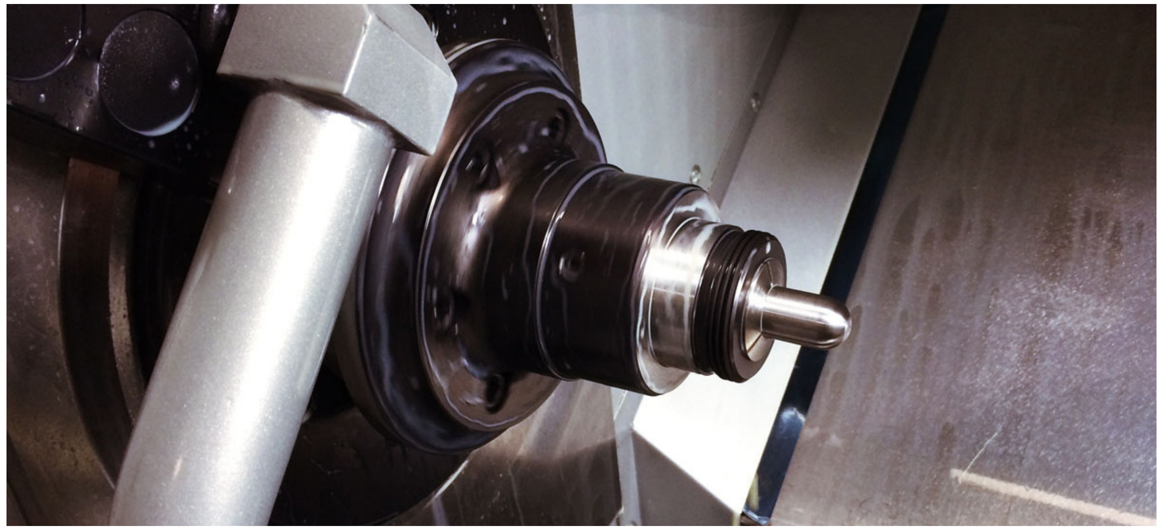
Two forming tools were made from A2 Tool Steel. A diameter of 3/4" was chosen as a healthy medium between the thickness needed to prevent the tool from bending while still within a reasonable cost range. The support tool is also made from the 3/4" rod in order to standardize the connection to the robot. Ideally the tools would be as long as possible to reduce the chance of the robot joint colliding with the forming geometry. However the longer the tool, the more likely it is to break. The tools were made on a metal lathe and heat-treated to increase their strength.

Machining Process



A2 Tool Steel 3/4" Rods

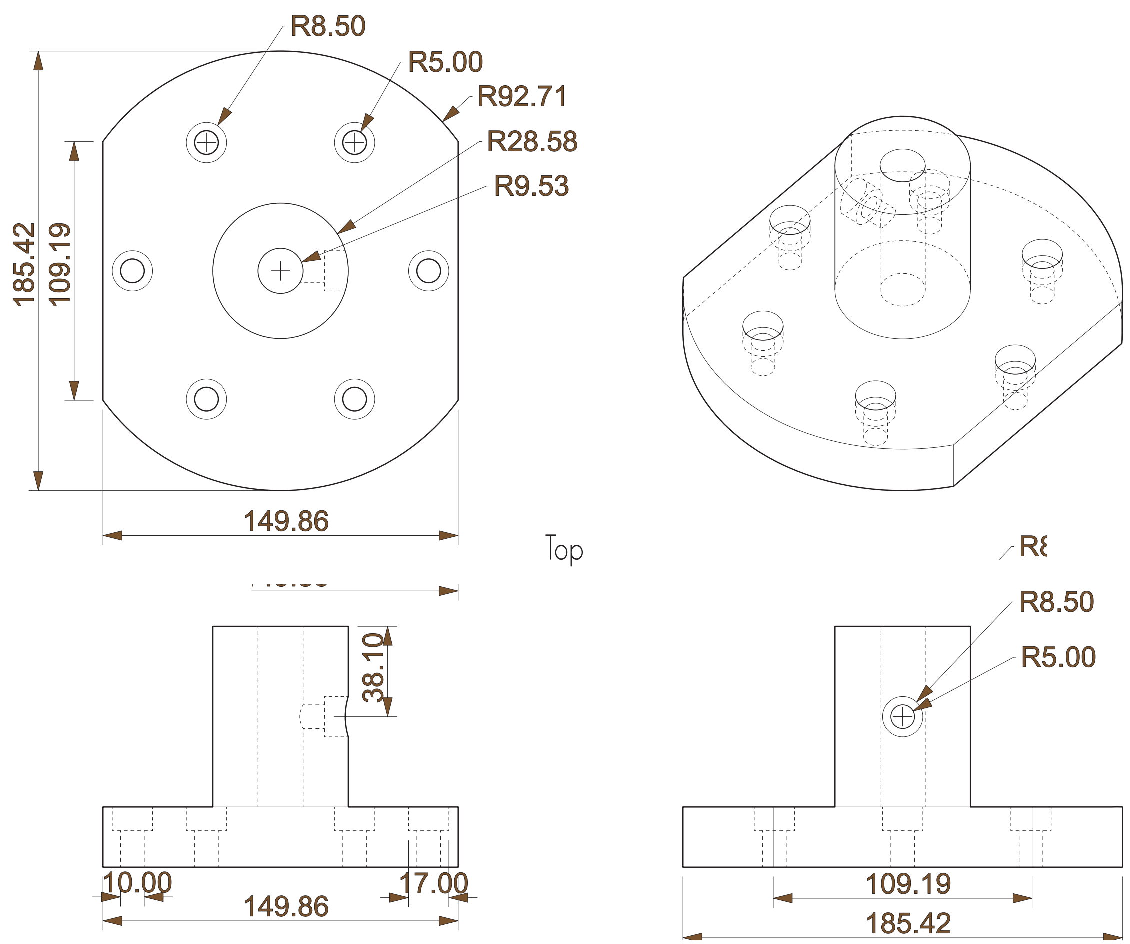
Lathe Turning



Result

Tool Holder

Design



Top

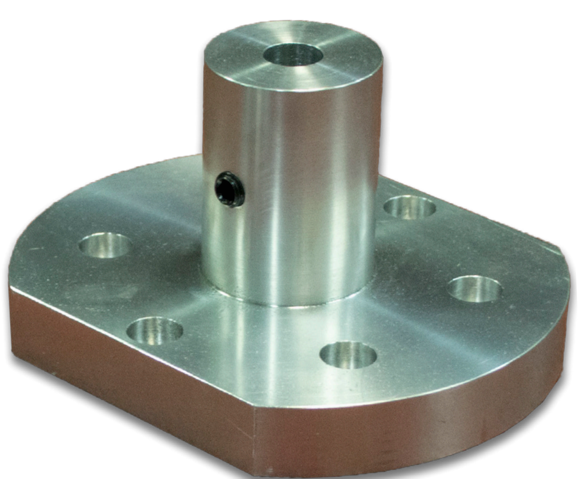
Axo

Front

Right

units: millimeters

Tool Holder - Drawings



Tool Holder

The mechanism for holding the forming and support tools is straighforward. A 3" shaft with a set-screw secures the tool to the holder. The holder is bolted to the ATI AC-110 Tool Changer attached to joint 6 of both robots via 6 holes in the base of the tool holder. The manufacturing process involved turing a 7-1/2"x6" block of Multipirpose 6061 Aluminum on a lathe, then milling the holes for the bolts.

Machining Process

Lathe

Mill

The Frame

Modularity of the Frame

Precedents

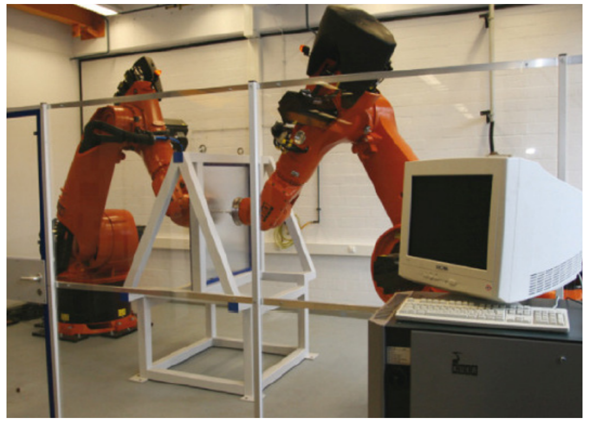


Image credit: (Meier et al., Roboforming, 601)

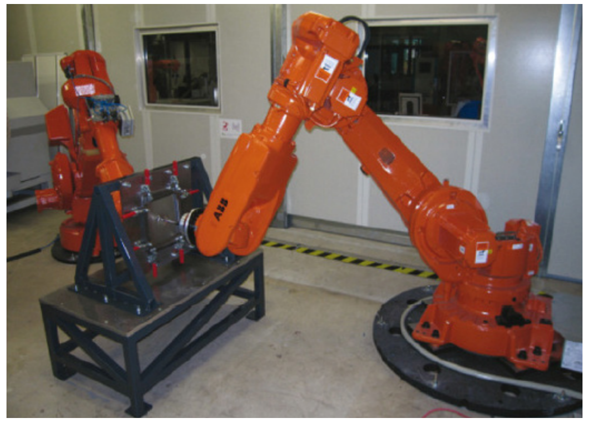


Image credit: (Meier et al., Roboforming, 601)

Image credit: (Meier et al., Roboforming, 601)

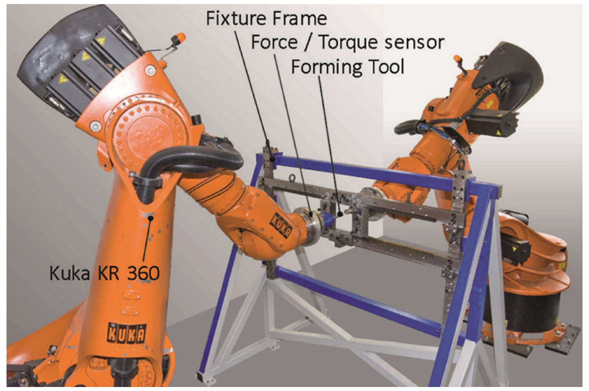
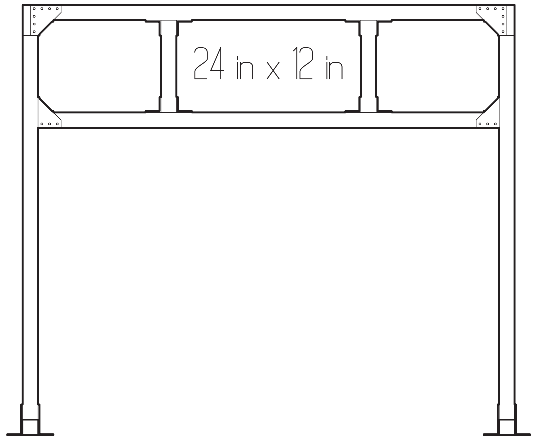
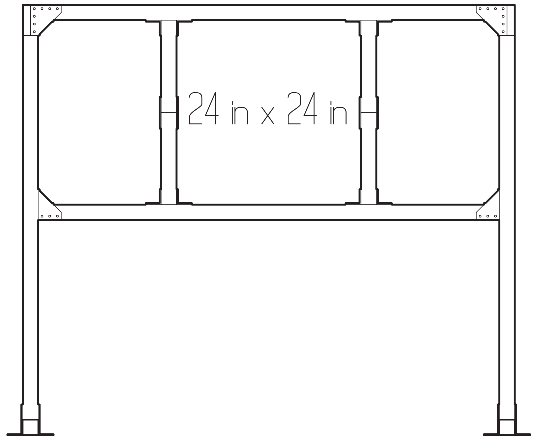


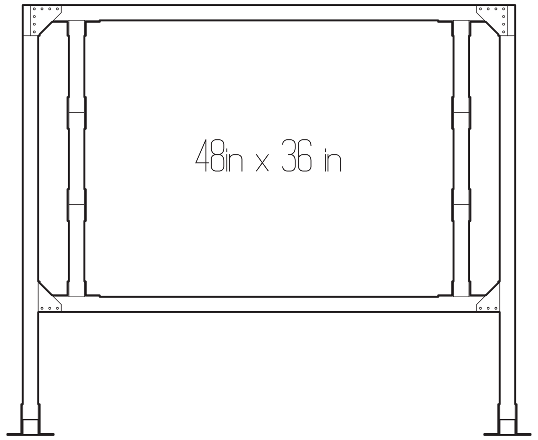
Image credit: (Kreimeier, CAM, 890)

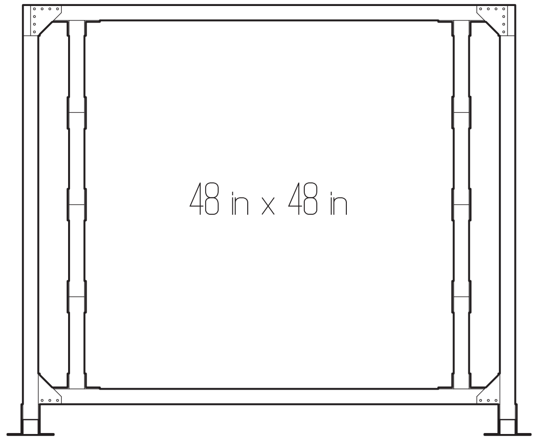
Image credit: (University of Michigan)

Modular Design







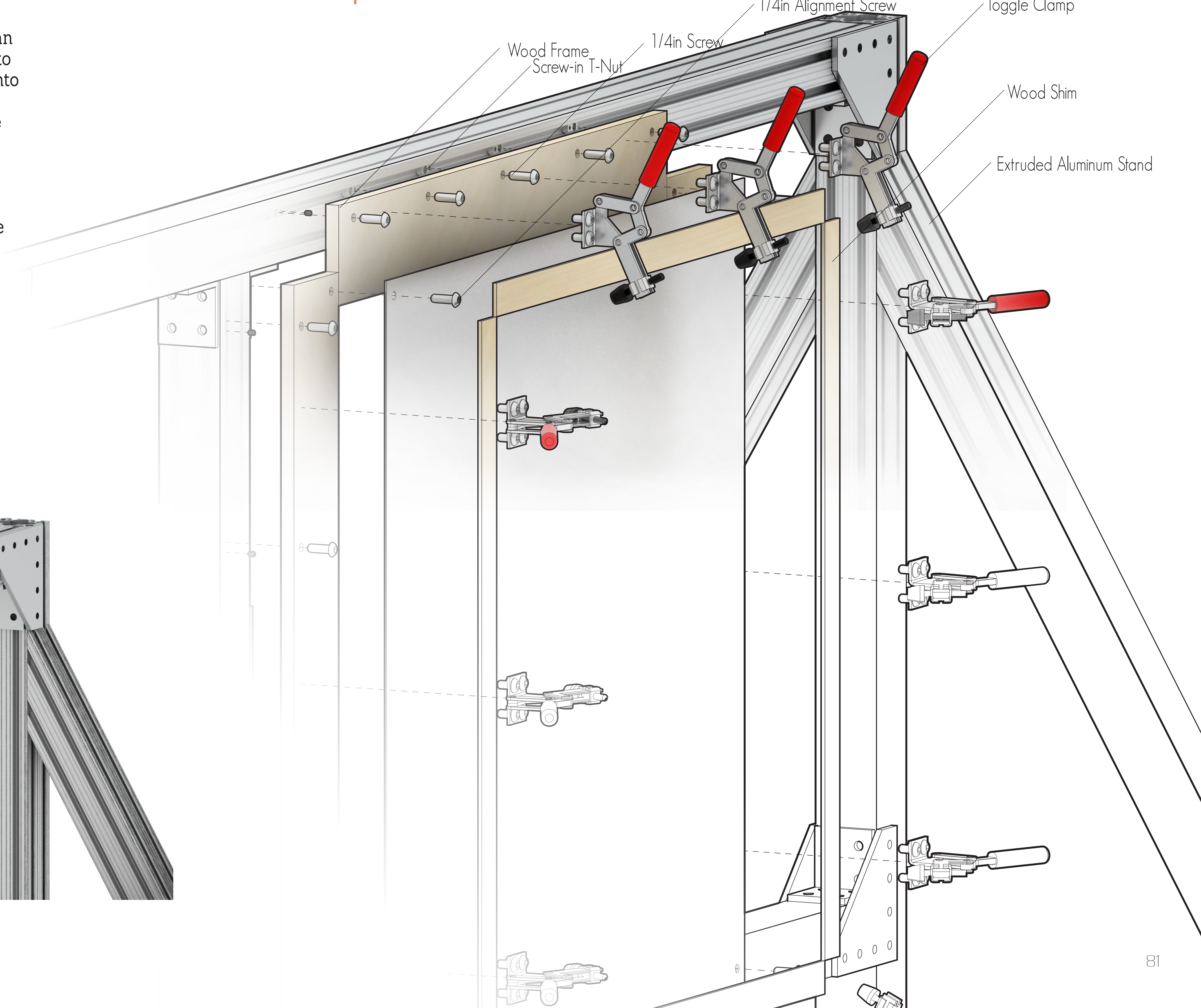


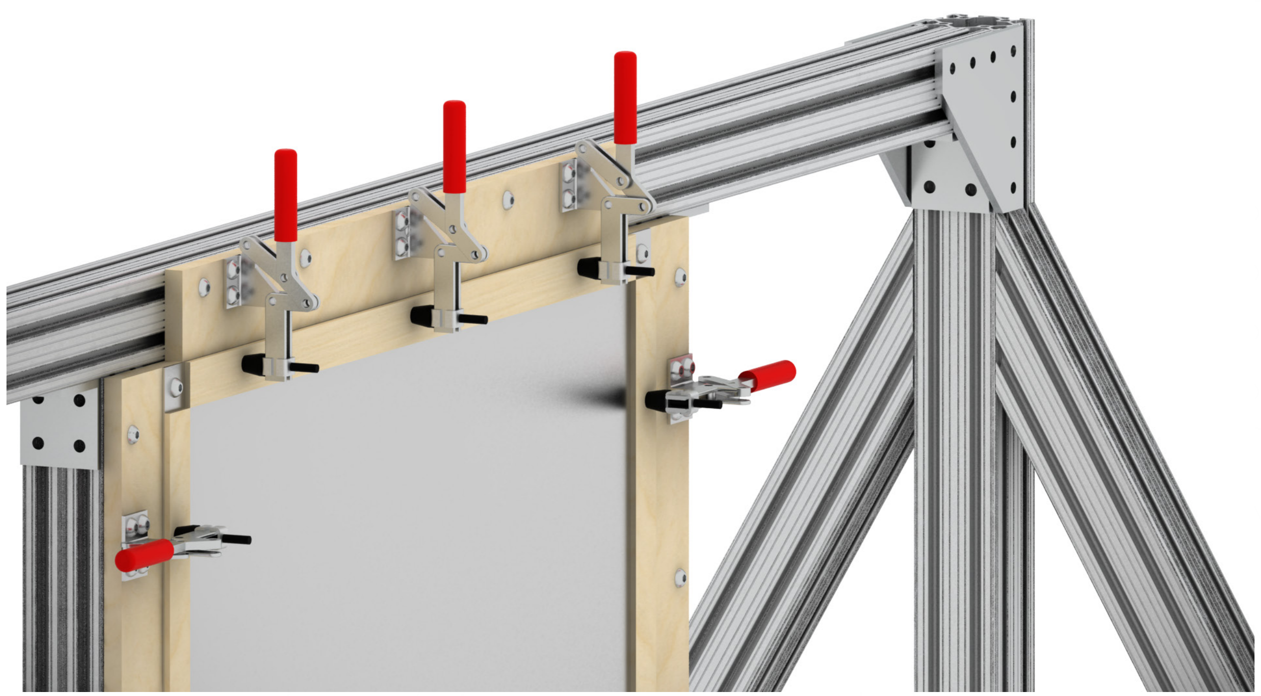
The frame I will be constructing needs to be modular for it to be capable of holding sheets of material of various dimensions. This is one of the reasons t-slotted extruded aluminum was chosen as the frame material. The t-slotted components allow for changes to be made to the positioning of the horizontal and vertical bars that define the sheet boundaries. The vertial bars are in turn made up of 1 foot segments of the extruded aluminum, joined together by a metal plate. This allows for varied sized sheets in the y dimension, in 1 foot increments. The largest dimension possible is 48in x 48in, chosen to reduce waste, since sheet materials come in 4ft x 8ft standard sizes. The larger dimensions, such as 48in x 36in and 48in x 48in are most likely too large for accurate forming given the thickness of the sheet metal. However, wood and other materials could be attached to the frame for other students to use in their projects. This is a multi purpose frame for any project needing to use two robots simultaneously acting on a sheet material.

Sheet Attachment Detail

Having worked with sheet forming before, and being aware of the challenges with attachment, I have come up with what I believe to be an ideal solution. I reduced the number of holes that need to be drilled into the metal sheet down to 4 due to the energy and time needed to drill into metal.
4 **alignment holes** are mostly used to ensure the sheet is secured in the same place each time.
Toggle clamps which have a clamping force of 500 lbs. do the real holding work These are ideal as they are inexpensive and have a low profile, so the robot does not collide with the clamps.
These clamps are screwed into a 1/5 inch **wood frame** that matches the dimensions of the blank. Wood was chosen as the frame material as it is easy and relatively inexpensive to mill custom dimensioned parts as needed. The wooden backplate also provides additional leverage since the extruded aluminum stand has rounded edges.
The toggle clamps act upon a thin **wooden shim** that serves merely to disperse the force across the length of the sheet.
Screw-in t-nuts are slide into place and recieve 1/4 inch screws which hold the wood frame to the **extruded aluminum stand**.

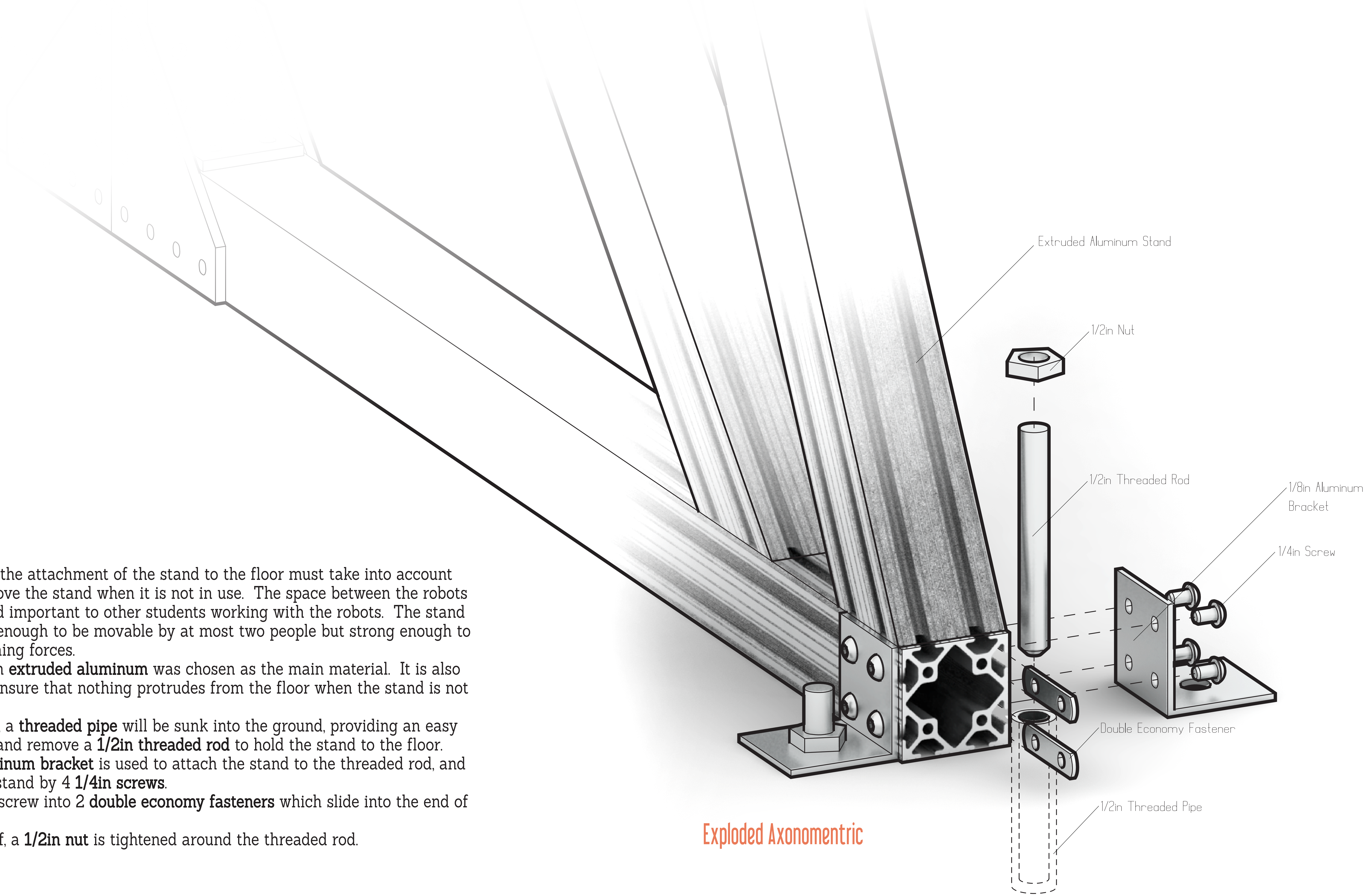
Exploded Axonomentric





Secured Sheet

Floor Attachment Detail



Exploded Axonomentric

The design of the attachment of the stand to the floor must take into account the need to move the stand when it is not in use. The space between the robots is valuable and important to other students working with the robots. The stand must be light enough to be movable by at most two people but strong enough to resist the forming forces.

For this reason **extruded aluminum** was chosen as the main material. It is also important to ensure that nothing protrudes from the floor when the stand is not in place.

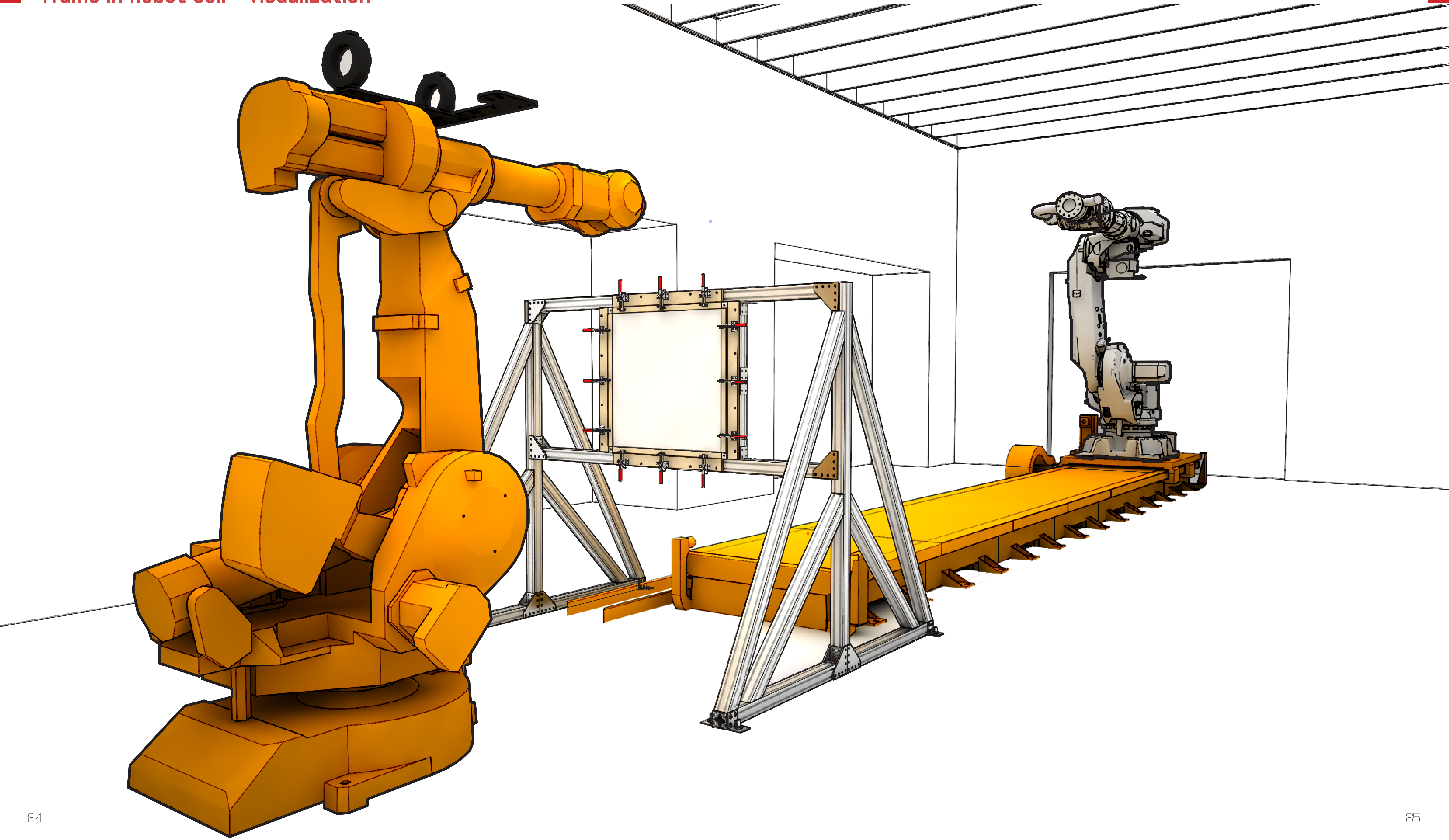
To ensure this, a **threaded pipe** will be sunk into the ground, providing an easy way to insert and remove a **1/2in threaded rod** to hold the stand to the floor.

An **1/8in aluminum bracket** is used to attach the stand to the threaded rod, and is held to the stand by 4 **1/4in screws**.

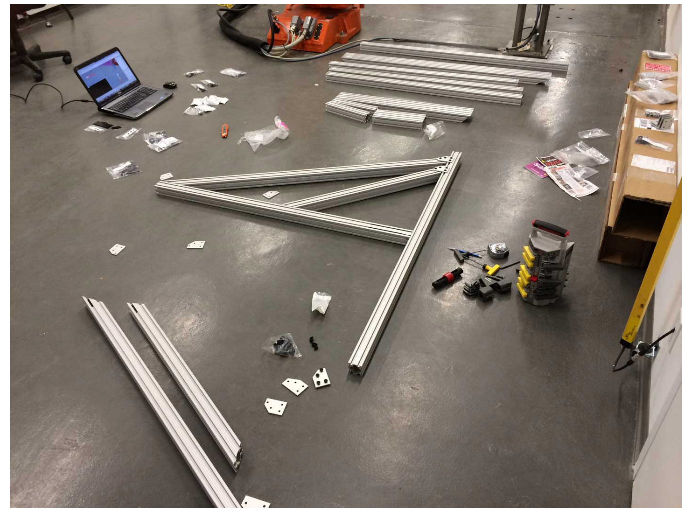
These screws screw into 2 **double economy fasteners** which slide into the end of the stand.

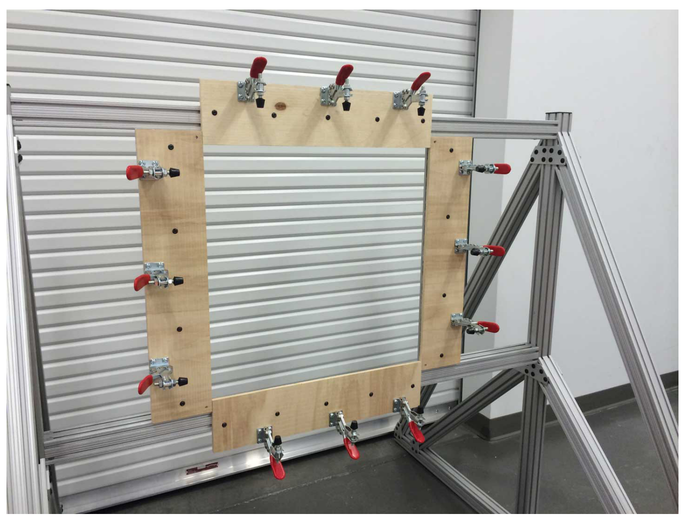
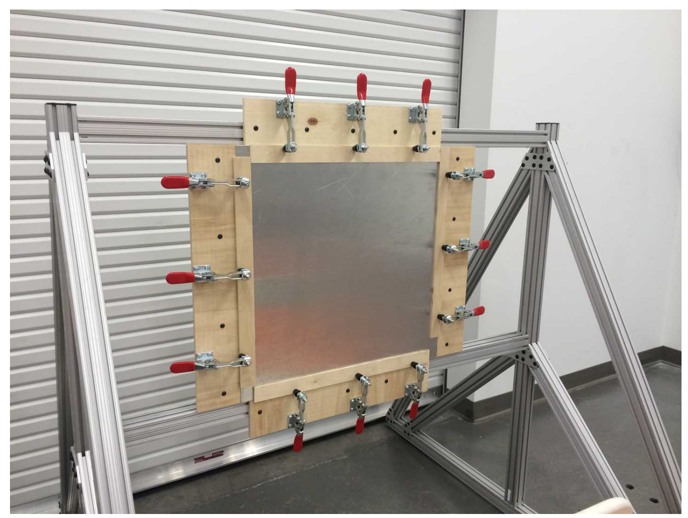
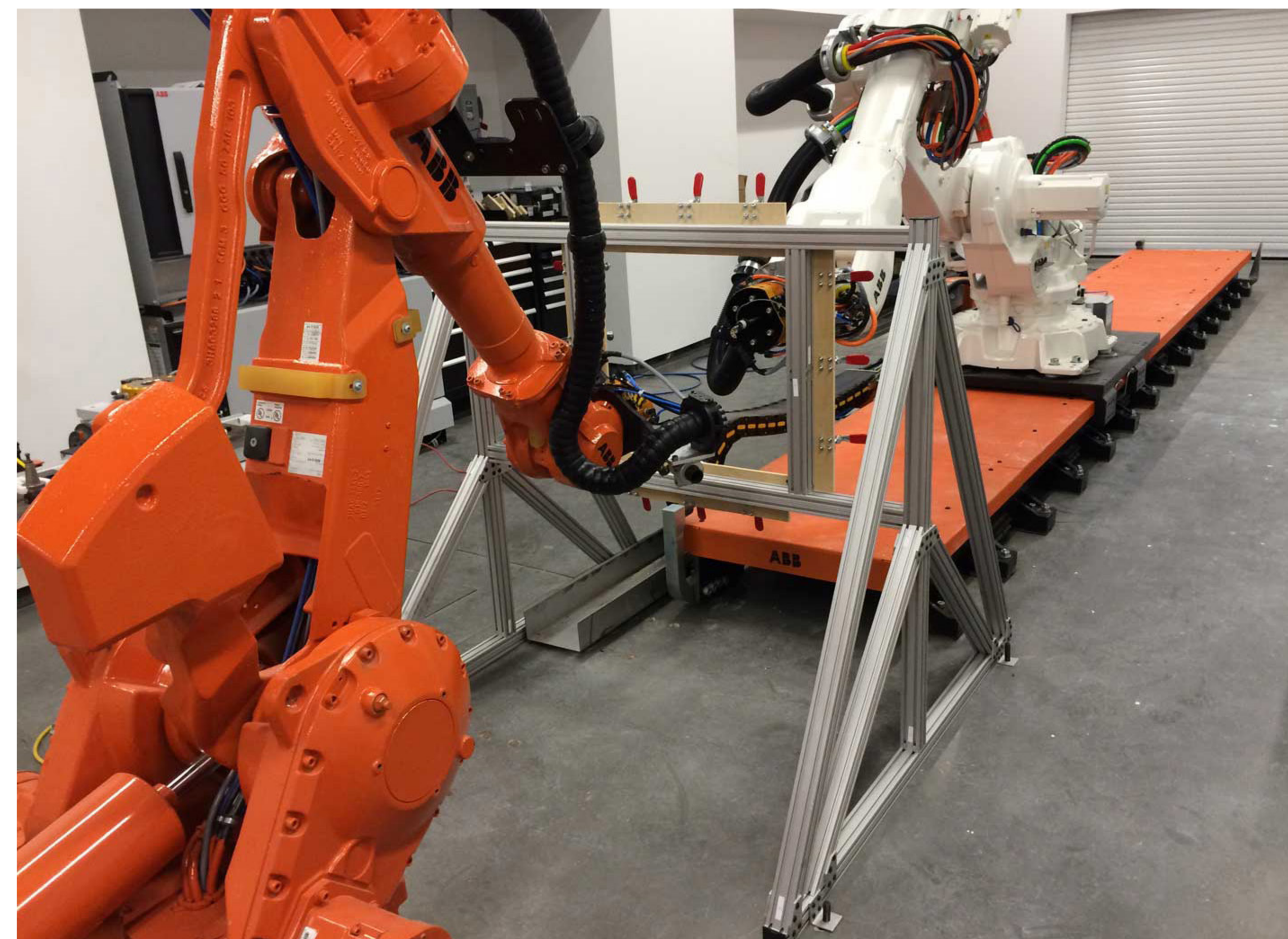
To top it all off, a **1/2in nut** is tightened around the threaded rod.

Frame in Robot Cell - Visualization



Assembly Process

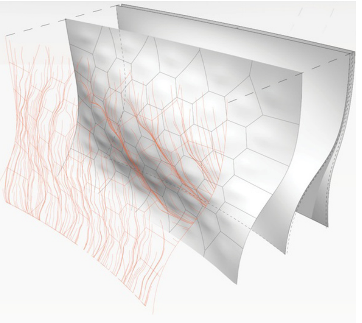





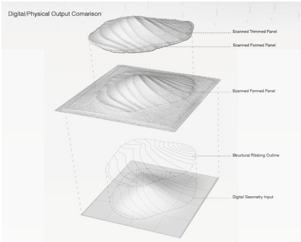
Frame in Robot Cell

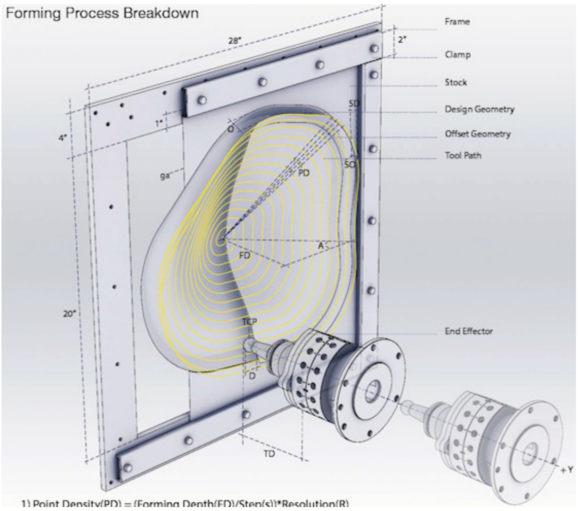
Precedents

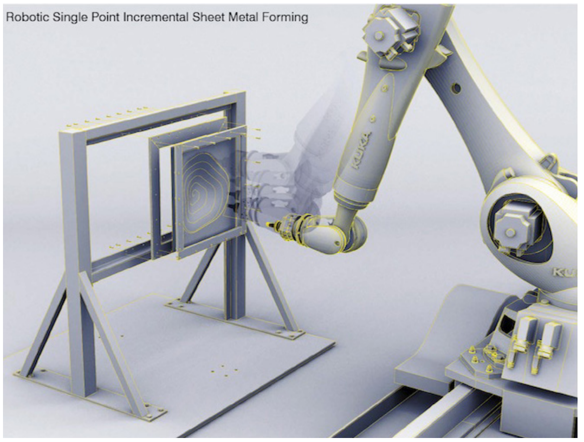
per-Forming - Incremental Sheet Formed Cladding

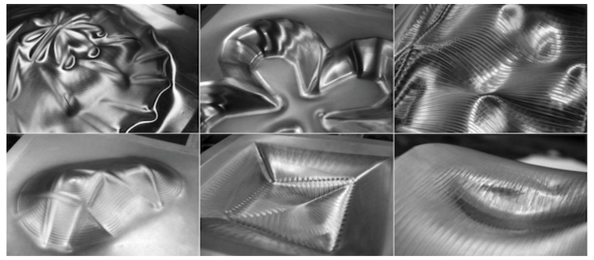
by Jake Newsume at the University of Michigan, 2013











Submission for Tex-Fab's Skin Competition

Image credit: (Newsumme)

No Ribbing

Diagonal Ribbing

Edge to Center Ribbing

Global Linear Ribbing

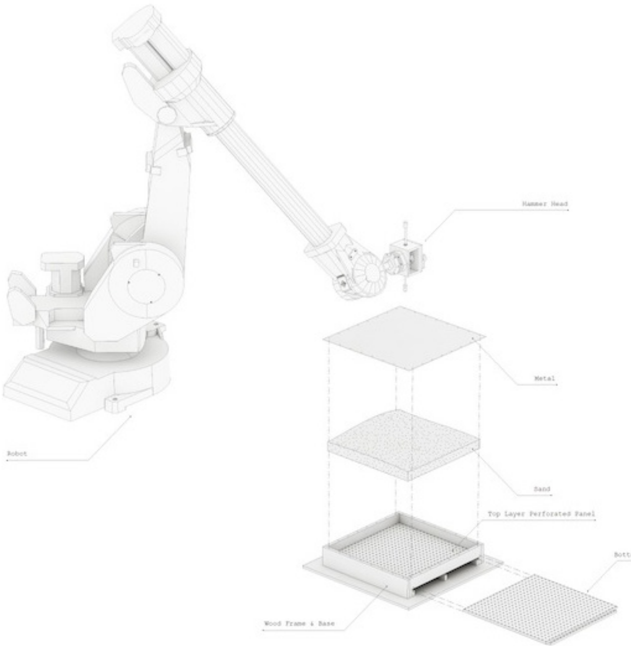
Ribbing Typologies

Image credit: (Newsumme)

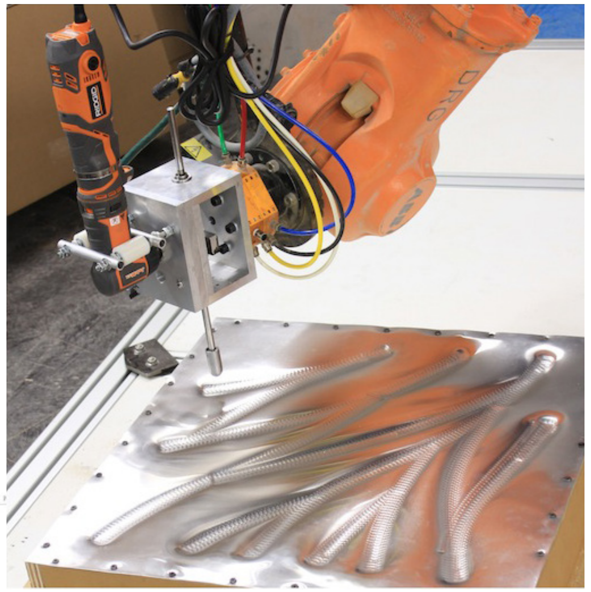
"Throughout the development of the physical and digital tools for this process, feedback has constantly been taken and given between design and fabrication. These parameters are being used in the design to influence the metal skin's global curvatures, local subdivision, and surface articulations to increase forming accuracy. The metal formed panels have been analyzed using 3D scanning technologies to understand where the structural ribs are needed for stabilization. The formed ribs are used as dynamic corrugations across the aggregation which makes a structured skin that identifies panel location." (Newsumme)

Robot Assisted Sheet Metal Shaping - Hammer-Formed Cladding

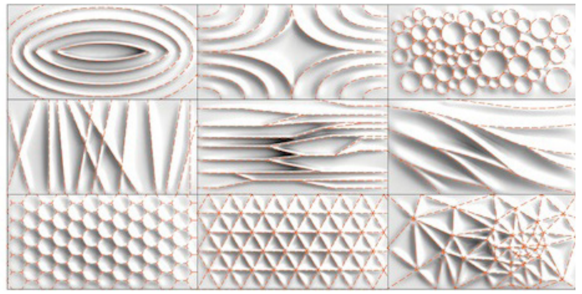
by Lik Hang Gu at the Harvard GSD, 2013



Robot working senario



Scotch York Mechanism for the Hammer



Patterns

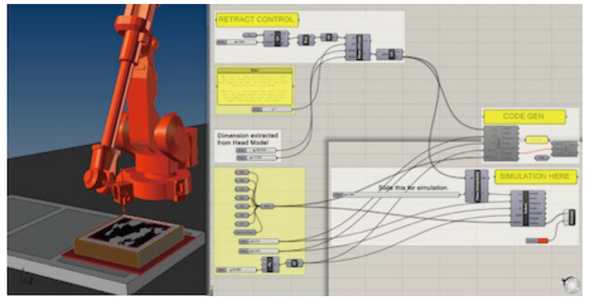
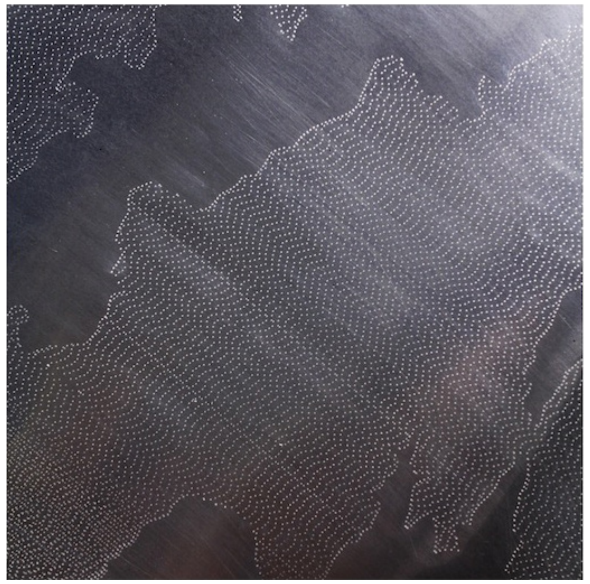


Image credit: (Gu)

Submission for Tex-Fab's Skin Competition

Pattern 1

Pattern 2



Pattern 3

Pattern 4

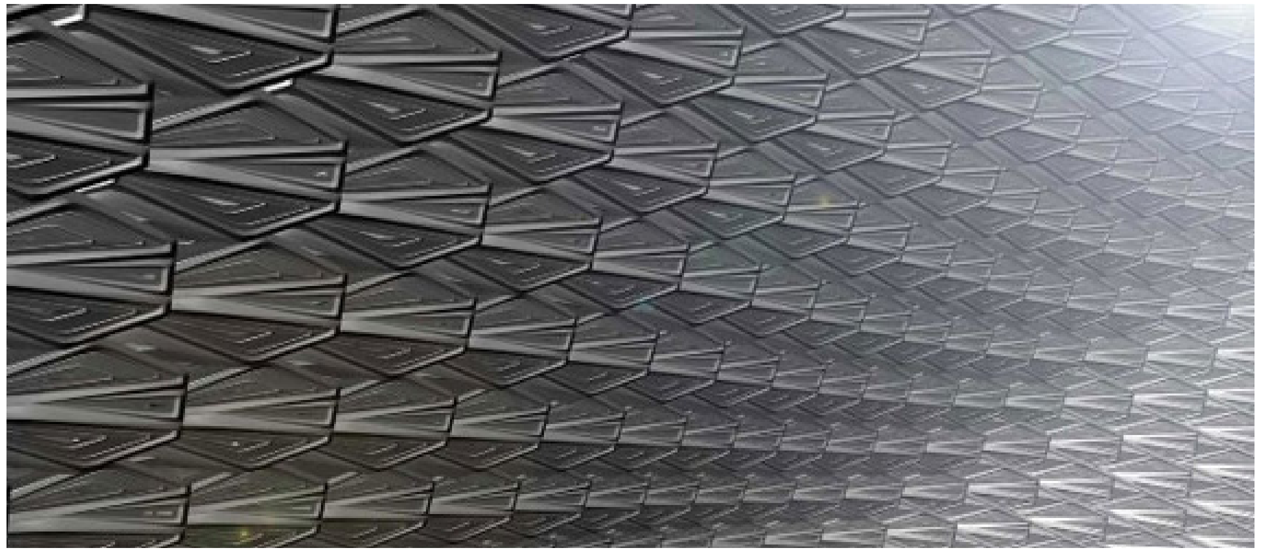
Image credit: (Gu)

Patterning Typologies

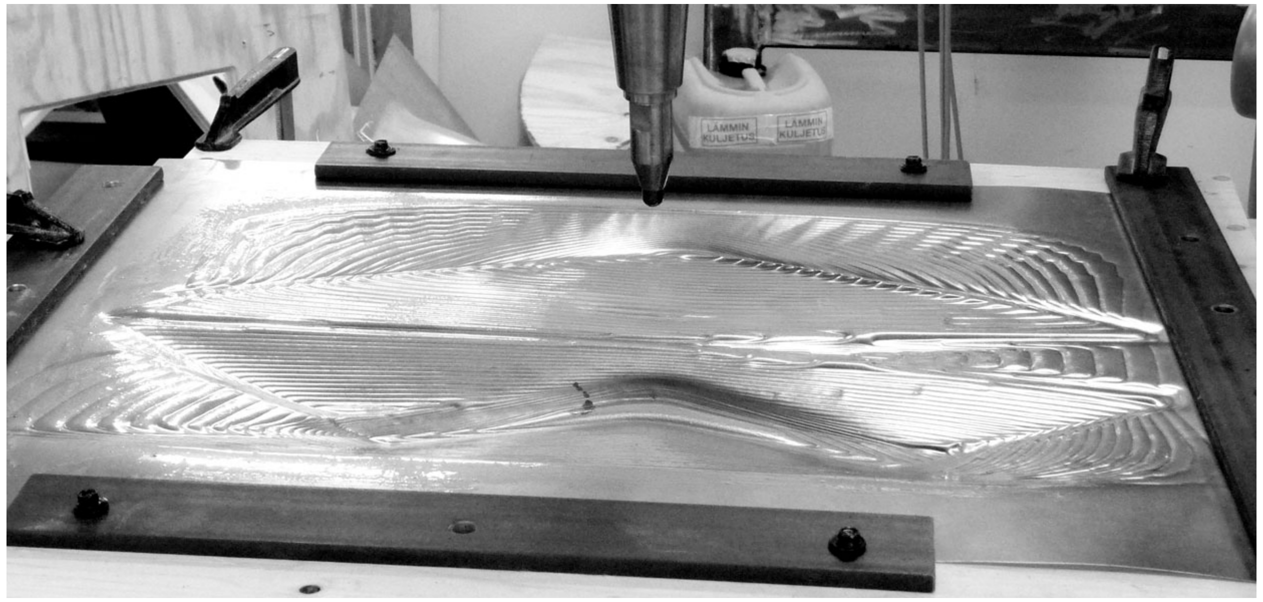
The hammering of sheet metal is much the the process of pointilism in drawing. One by one a robotic hammer punches the sheet at inputed points. There are many variations of this method which lead to decidedly different tacticle qualities. The result looks like a stiched cusion and the tool-path creates an ornamental aspect to each piece. "The sand base is designed to be able to adjust the hollow space under the sheet metal in order to allow further punching after sands are fully packed. Pattern followed by the curves generated in modeling software and translated into RAPID code for ABB robotic arm." (Gu)

Responsive Skin - Incremental Sheet Formed Molds

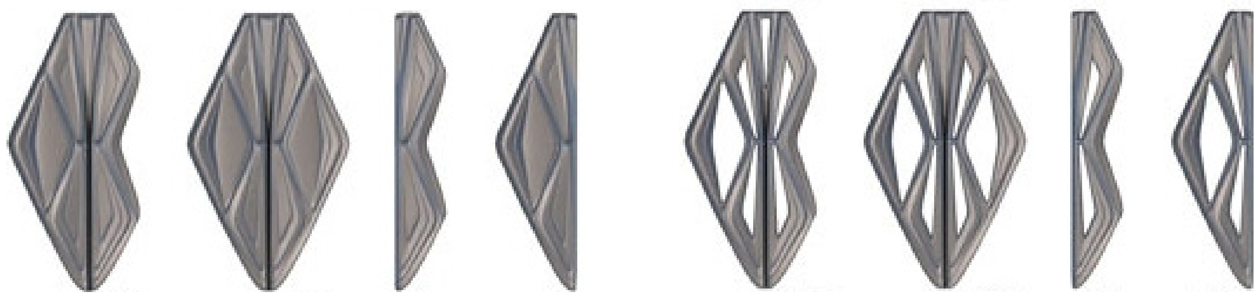
by Brian Cadiz, Gabriel Huerta, and Joseph Mathias at UCLA and Aalto University



Visualization



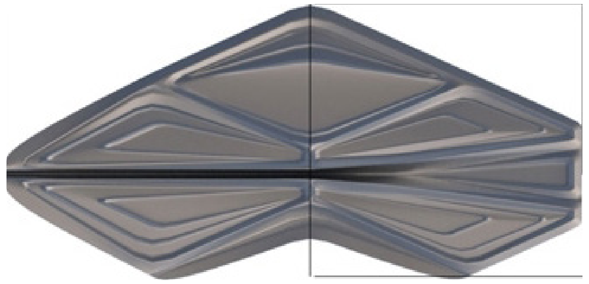
Fabrication



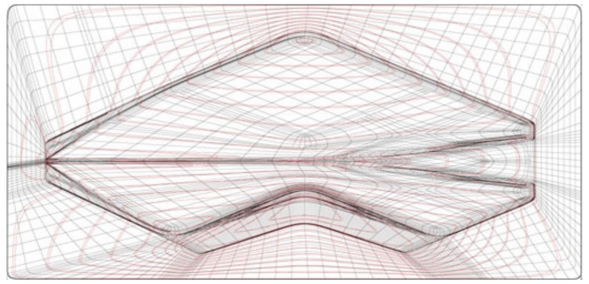
Shingle Typologies

Shingles

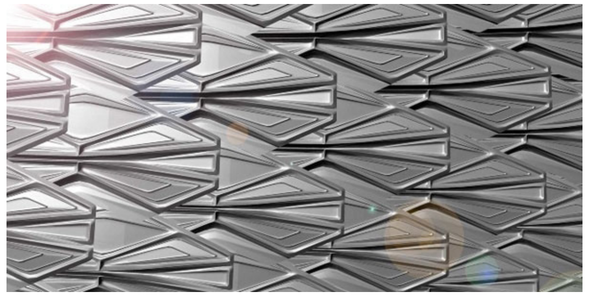
Image credit: (Cadiz et al)



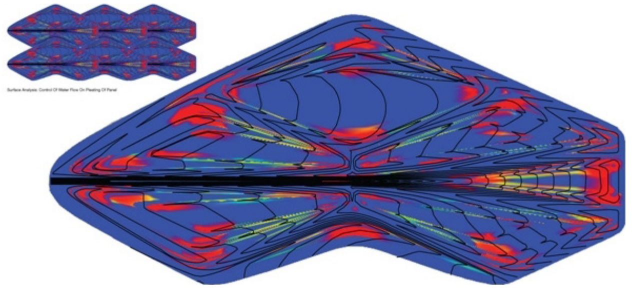
Shingle



Tool-path



Overlapping Shingles



Pleating based on stiffness and environment

Shingles Parameters

Image credit: (Cadiz et al)

"The lack of cost-efficient manufacturing techniques has been an obstacle for avant-garde architecture. Digital design and production is changing that, and increasing the potential to realize more avant-garde architectural designs for today's needs. The project looks at the digital fabrication process of incremental sheet forming and its potential architectural application in the development of responsive building skins. The process, developed by the Aalto University Department of Material Technology, utilizes an industrial robot to form a sheet of metal against a computer guided piston-field as a means to create a low-cost reusable mould. The prototype shingle unit is designed within the constraints of the fabrication process and the maximization of the material properties of the recycled paper composite, UPM Profi, that it is to be injected molded from. Pleating on the shingle panel provides performative ornament that allows for both material stiffness and environmental performance. The ornamental patterning of the pleats, inspired by ancient armor, is contoured to control the flow of water from panel to panel. The variable thickness of the pleating further allows for a reduction in the overall panel thickness and weight by concentrating material in critical zones. Versatility is embedded into the form of the unit through the shaped grooves that allow for the seamless interconnection between shingles in the panelization of a rainscreen. Through the development of a series of scripts, the panelization of the unit was biased to be responsive to the environment and the minimization of unique pieces. Porosity and surface coverage of the building skin was optimized with data inputs from solar analysis and surface curvature." (Cadiz et al)

Folded Plate Structures - Two Point Incremental Formed Panels

by Univ.-Prof. Dr.-Ing Martin Trautz, Dipl.-Ing. Ralf Herkrath at RWTH Aachen University, 2009

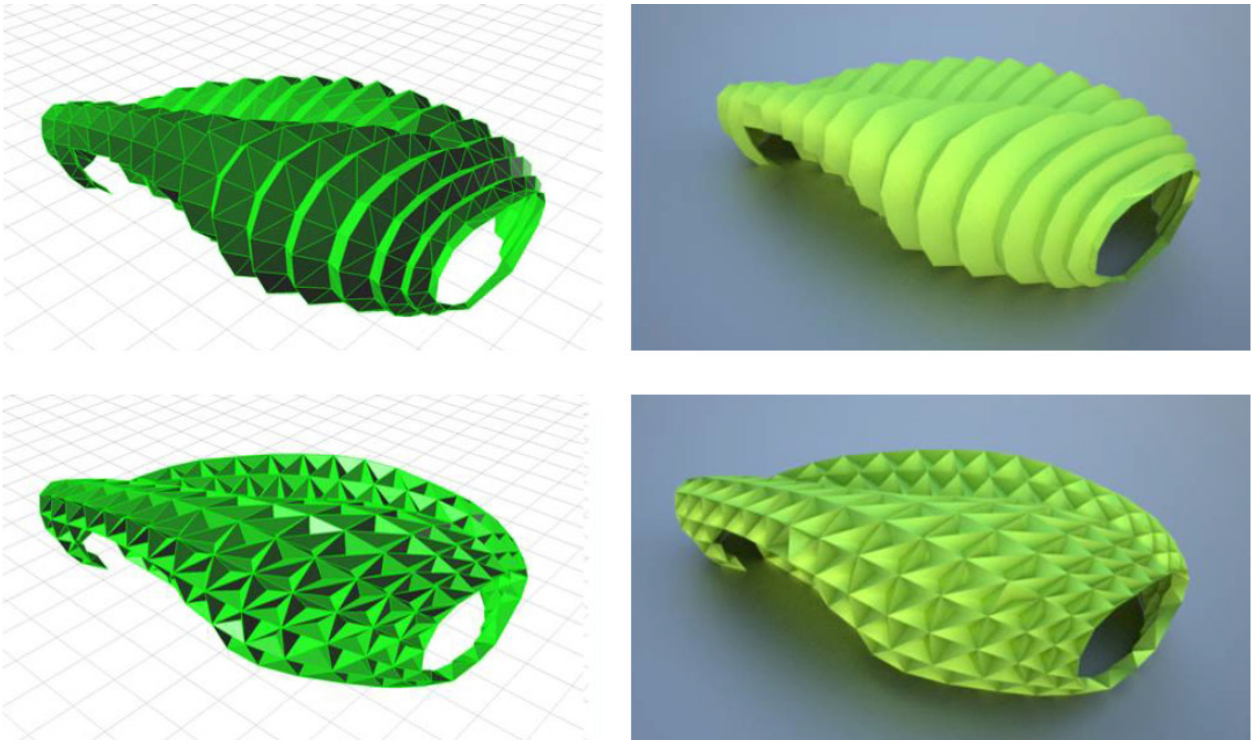
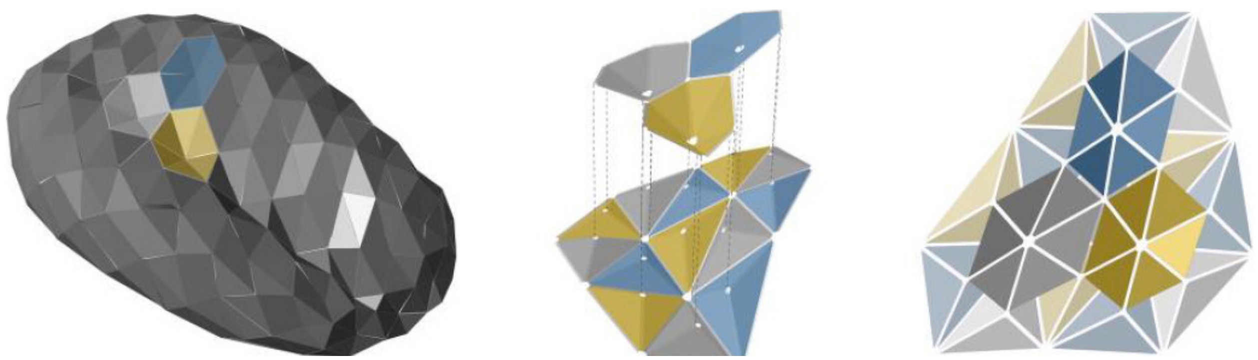


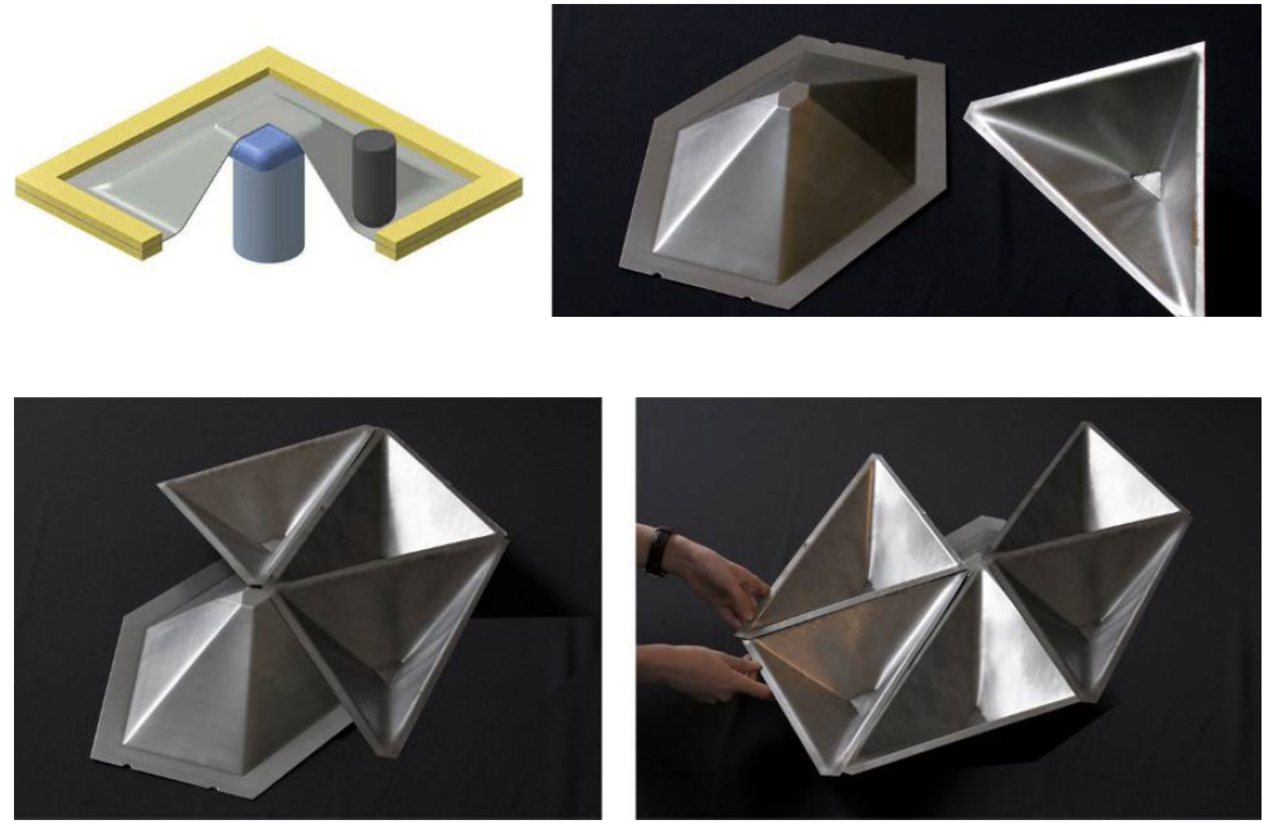
Image crecit: (Trautz and Herkath, 10)



Double-Layered Facet-Like Folding Structure

Image crecit: (Trautz and Herkath, 10)

The pre-elementing happens according to the chosen folding structure (longitudinal or facet-like). Metal pyramids with a hexagonal base area on the outer and a triangular base area on the inner site evolve from a double-layered facet-like folding. The softwaretool processes the individual metal pyramids for the CNC controlled sheet metal forming with the help of software that translates the geometry of the free-form into the data to control the CAM production (computer aided manufacturing). All different parts are labeled to assure a correct typological erection." (Trautz and Herkath, 10)



Assembly Process

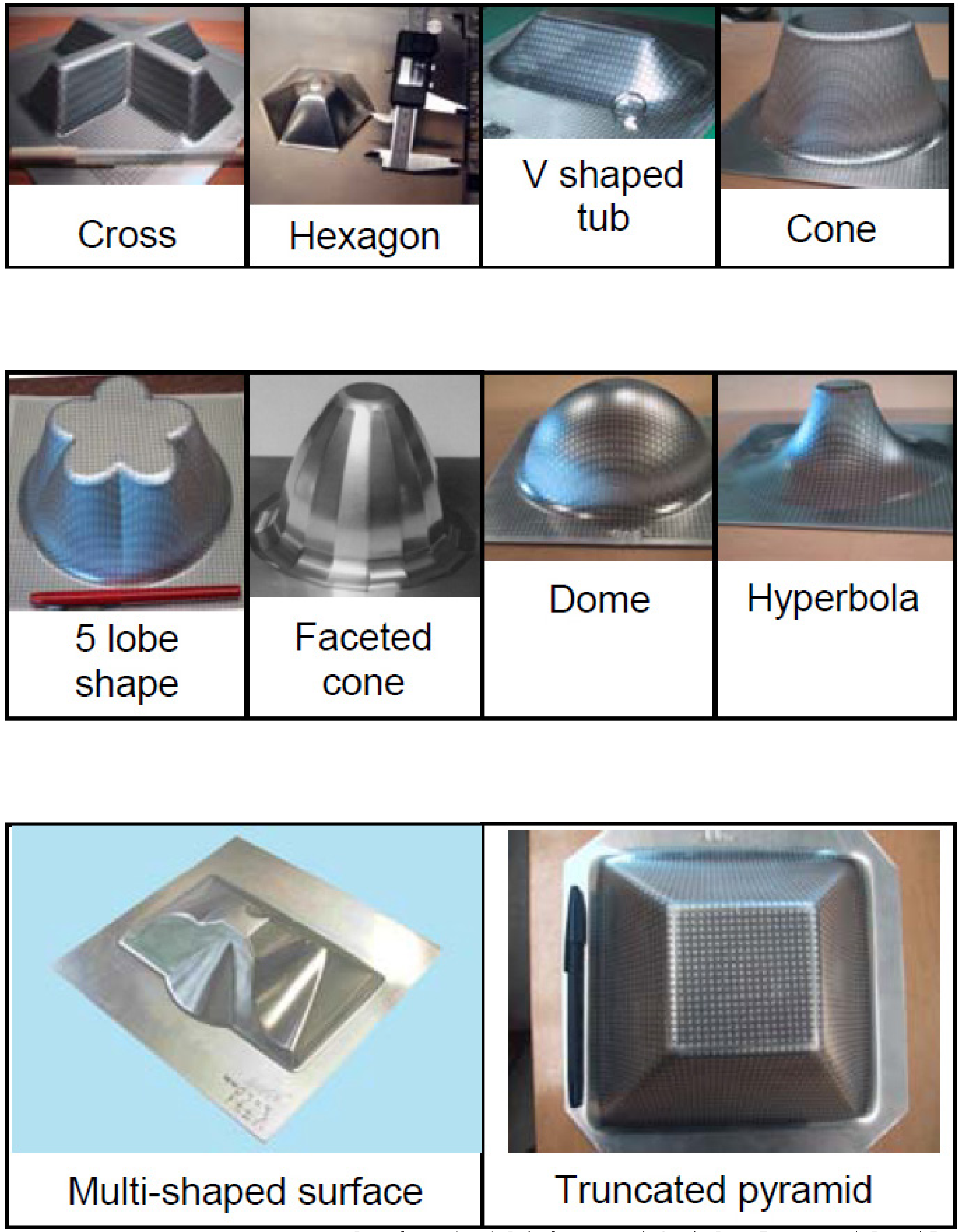
Image crecit: (Trautz and Herkath, 12)

"The different metal pyramids are assembled to buildings elements which are to be erected on site. The assembling of the elements is guaranteed by overlapping of the different metal sheets." (Trautz and Herkath, 11)

"The principle of folding structures is an established principle of construction in nature whose potential has rarely been used in architecture. Based on folding structures, high-stressed and wide-spanning light weight structures can be realised. More than the complex requirements for their constructive detailing, the limited possibilities to describe them geometrically with mathematical geometrical functions have constraint their realisation. Numerical digital methods annul this limitation by making the tessellation and triangulation of arbitrary shapes possible. Due to this method, almost any folding structure can be constructed (Trautz [7]).
After the development of the software tool and after the first successful shaping, the research has now the aim to approach the application of folding structures in context of the sustainable use of material and to gain new impulses for this principle of structural shaping. Additionally, new ideas of the building process for free-forms should be generated which could also serve as helpful suggestions for other engineering disciplines." (Trautz and Herkath, 12)

Examples - Single Point Incremental Formed Parts

With Partial Die



Parts formed with Roboforming with Single Point Forming with Partial Die

Image crecit: (Jeswiet, SPIF, 20)

Comparison of SPIF vs Roboforming with Local Support

Part formed with Single Point Incremental Forming

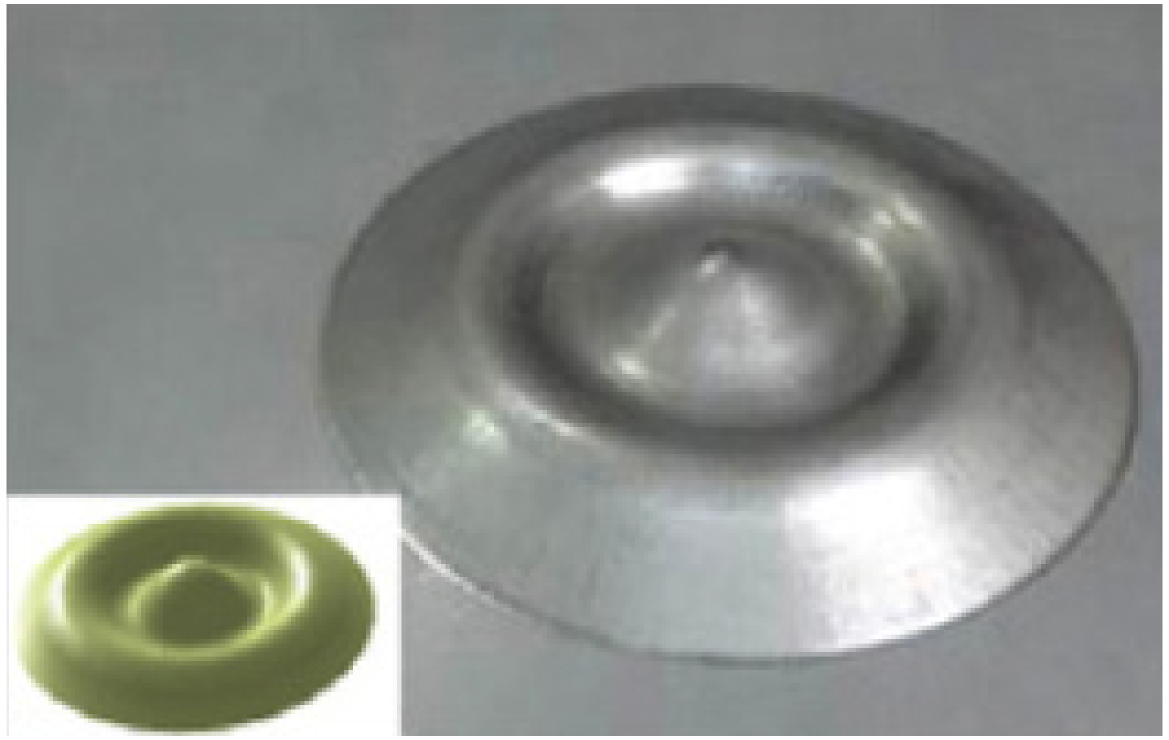
Part formed with Roboforming with Local Support

Image crecit: (Buff et al., Accuracy, 153)

Examples - Roboformed Parts - Local Support

Concave and Convex

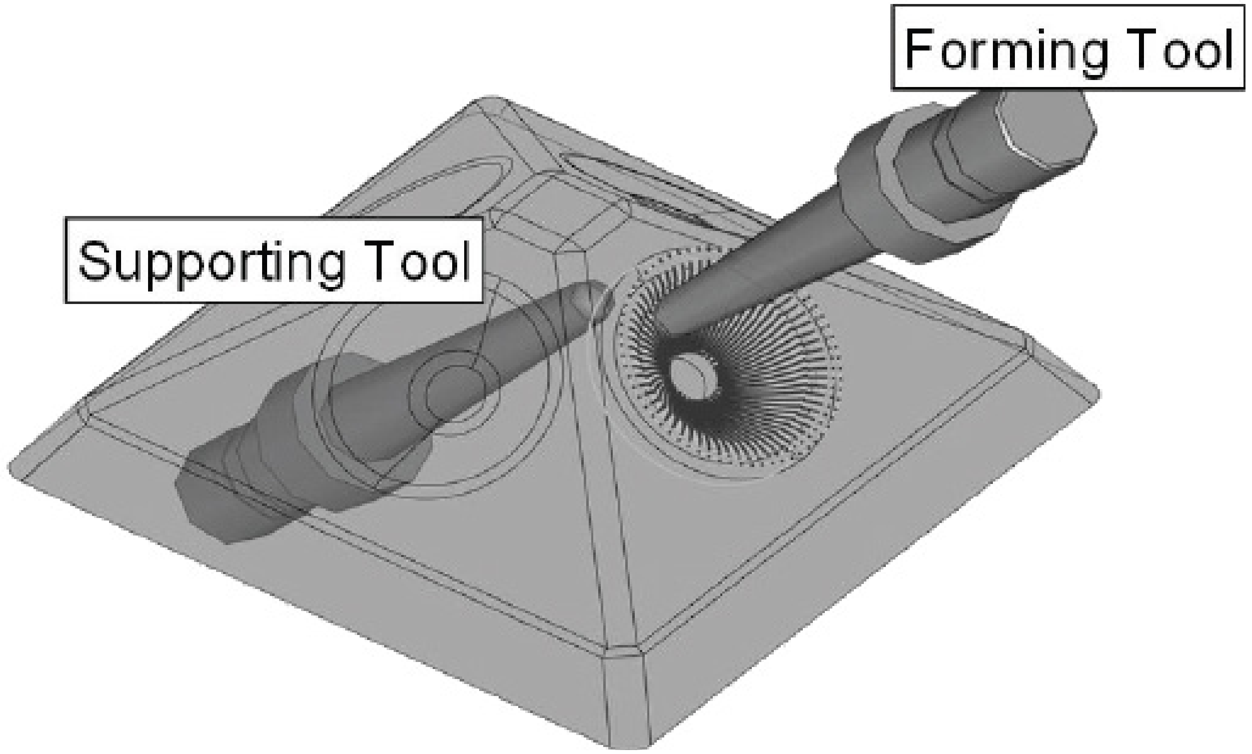
Parallel Forming



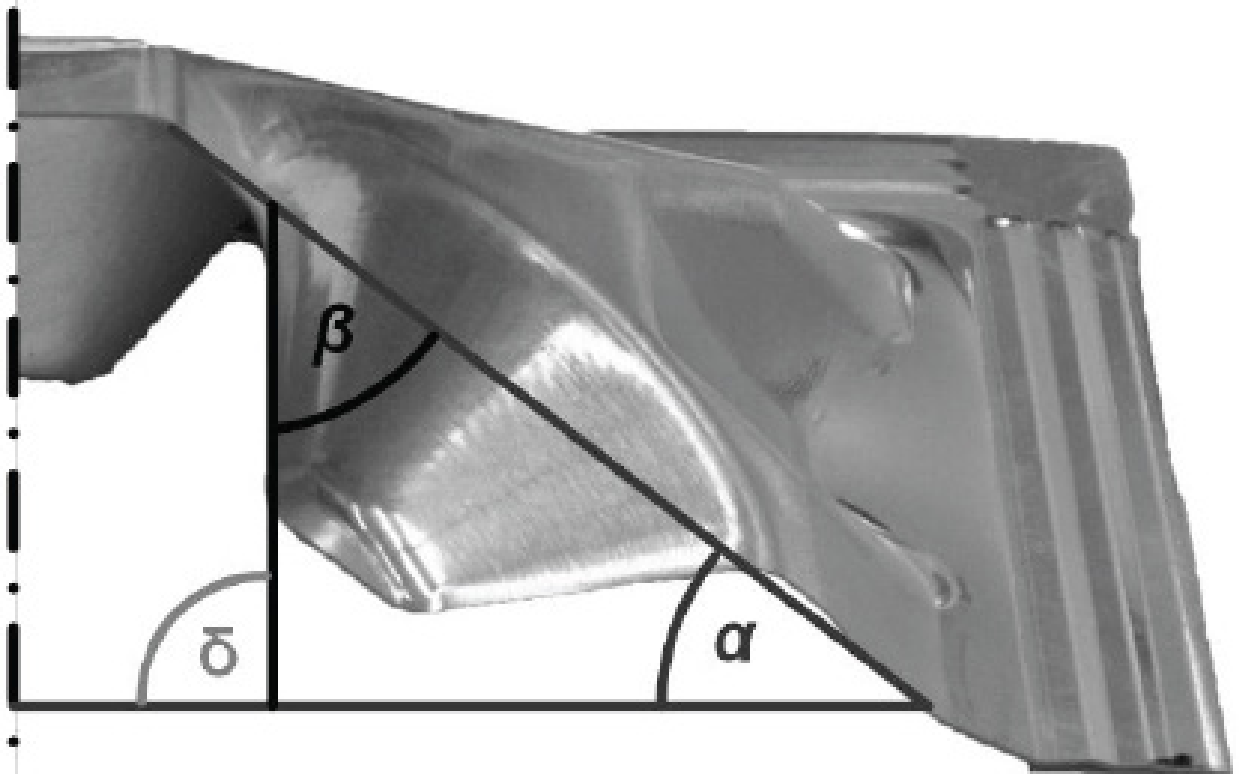
Sequential Forming

Image crecit: (Malhotra , Accumulative-DSIF, 253)

Subsequent Forming



Support Tool acts as Peripheral Support



Maximum Draw Angle for Subsequent Forming

Image crecit: (Buff et al., Accuracy, 154)

Examples - Roboformed Parts - Peripheral Support

Peripheral Support Pieces

Wierd Bean Thing

Twisted Hexigon

Image crecit: (Meier et al., Tool Path, 149)

Comparison of Formability - Peripheral Support vs Local Support

Point of Failure with Peripheral Support

Point of Failure with Local Support

Image crecit: (Meier et al., DPIF, 330)

Examples - Roboformed Parts - Multiple Forming

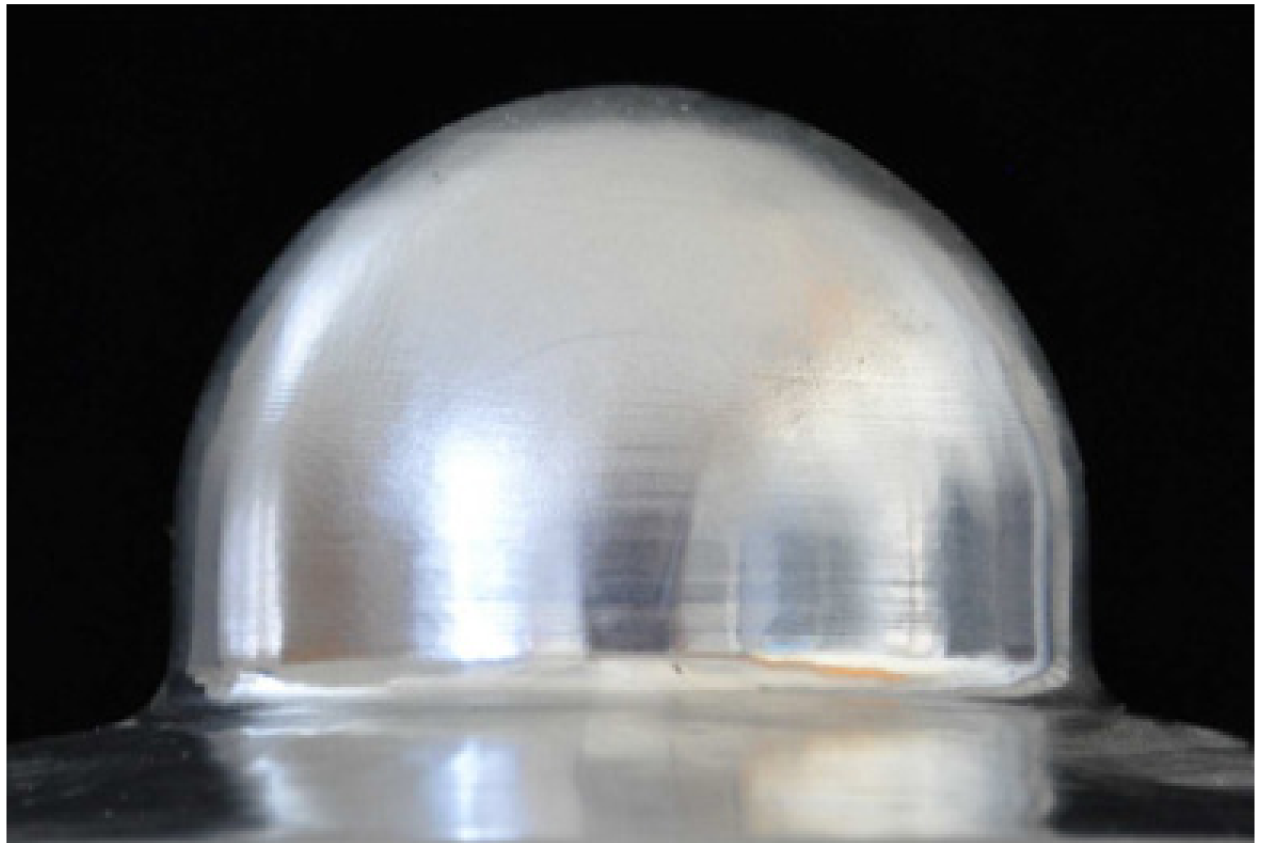
Multi-Pass Forming

Complex Automotive Part

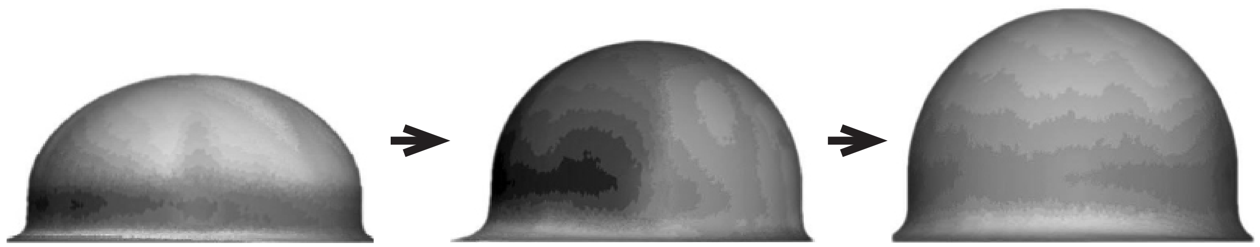
Cylinder with Undercut (97°)

Image crecit: (Meier et al., DPIF, 328)

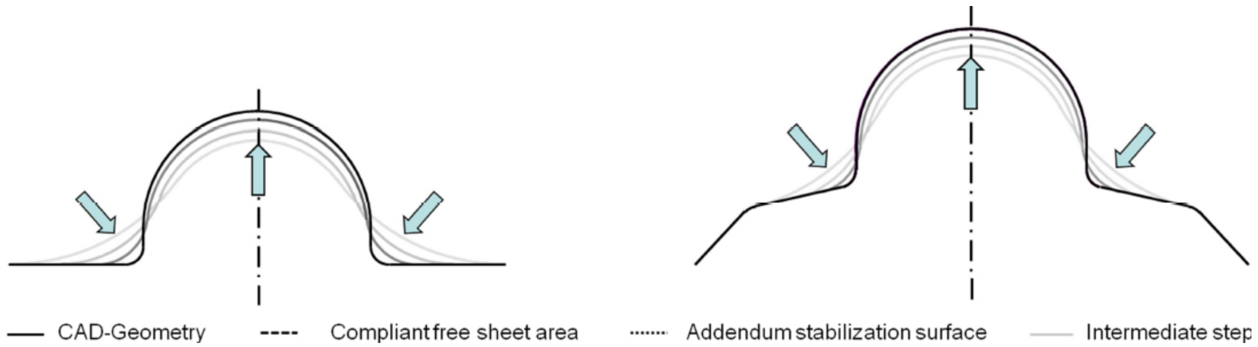
Multiple Forming with Stabilization Surface



Hemisphere



3 Step Forming Process

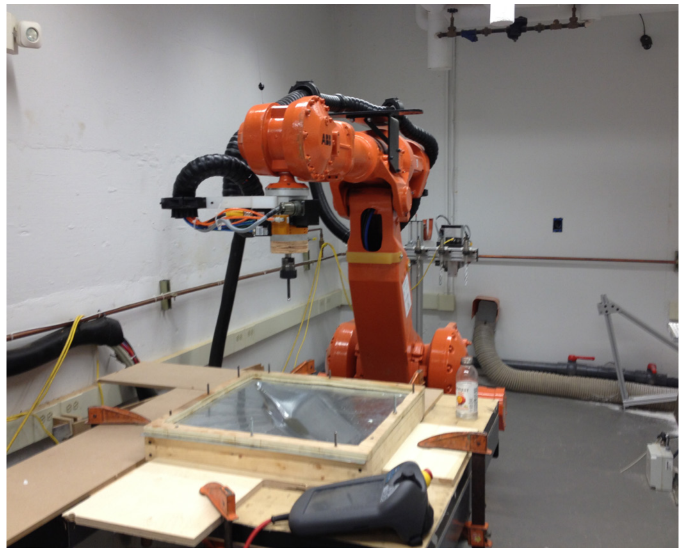


Stabilization Surface

Image crecit: (Kreimeier, Accuracy, 859)

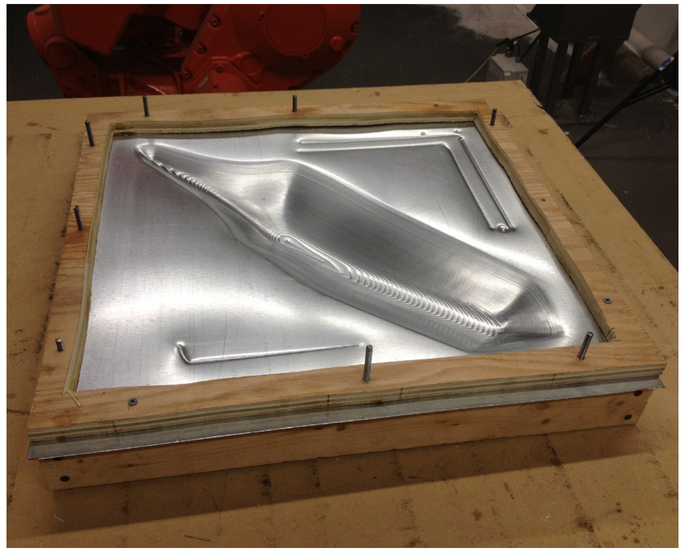
Incremental Sheet Formed Prototype - Process

By Alex Fischer and Matt Adler at Carnegie Mellon University, 2013



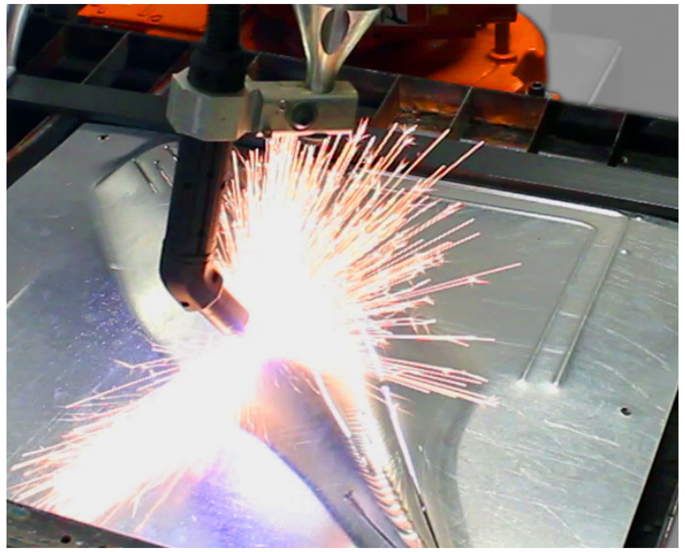
Incremental Sheet Forming

Step 1



Incremental Sheet Forming - Result

Step 2

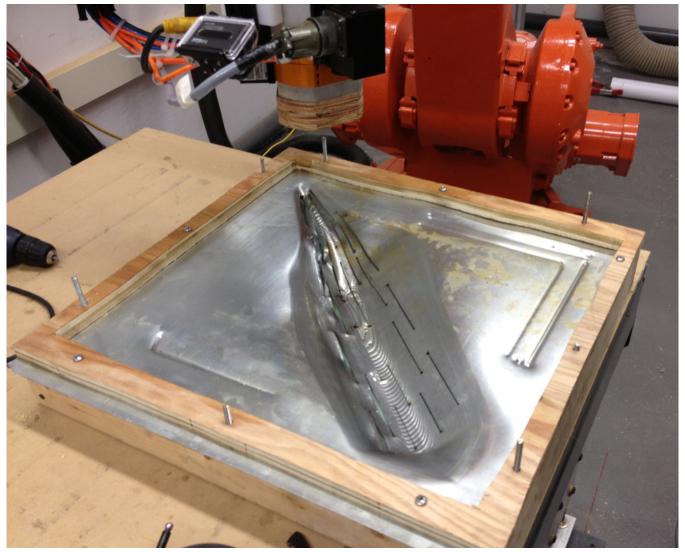


3D Plasma Cutting

Step 3

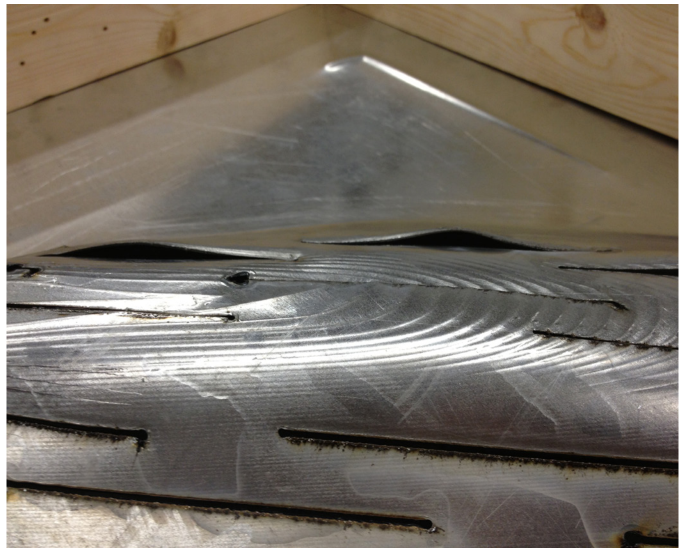
3D Plasma Cutting - Result

Step 4



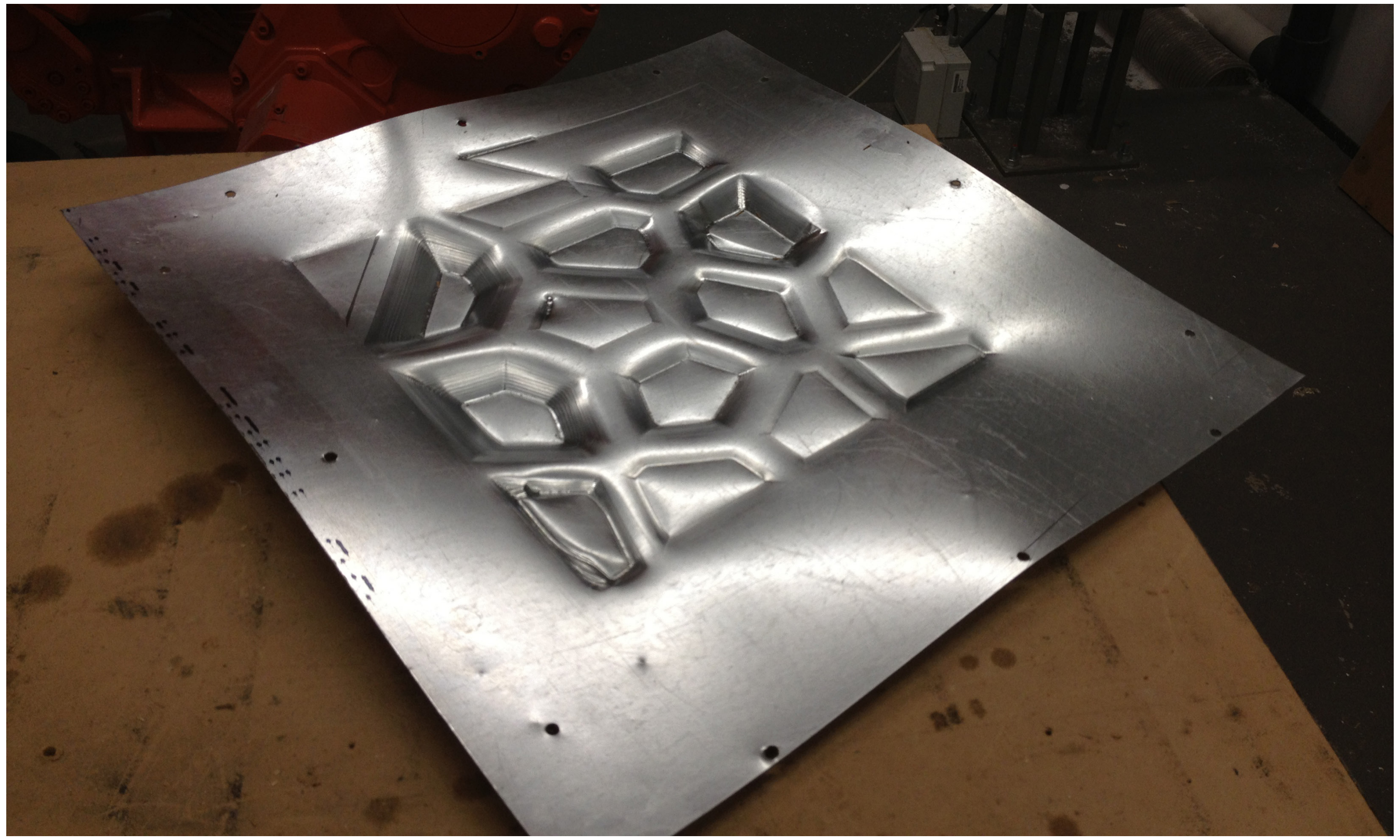
2nd Incremental Sheet Forming

Step 5



2nd Incremental Sheet Forming - Result

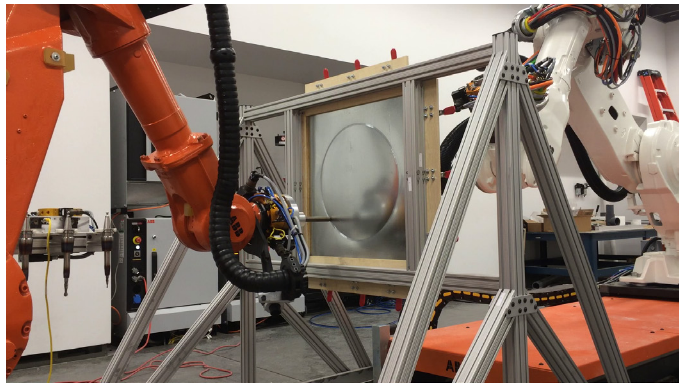
Step 6

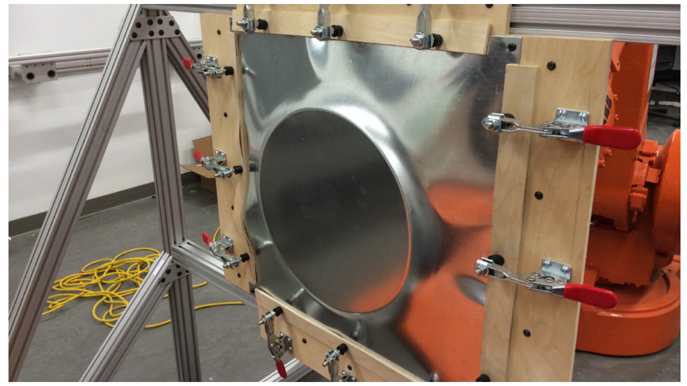


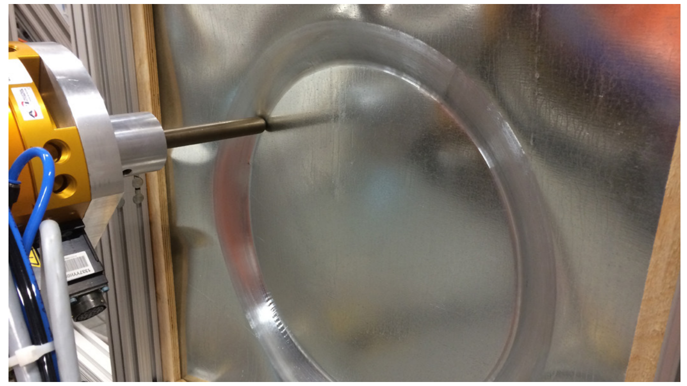
Local Deformations made without backing plate

Experiments

Incremental Forming - ABB 4400 Robot







Parameters

Forming Type: ISF
Former: 4400
Supporter: None
Forming Tool: 3/4" Ball-End
Support Tool: None
Material: Galvanized Steel
Sheet Thickness: 1mm
Sheet Size: 24" × 24"
Feed Rate: 100m/s
Stepdown: 1mm
Max Wall Angle: 60°
Diameter: 18"
Lubricant: Silicone

Results

Achieved Depth: 7/8"
Forming Duration: 9min
Cause of Stop: Forming Forces

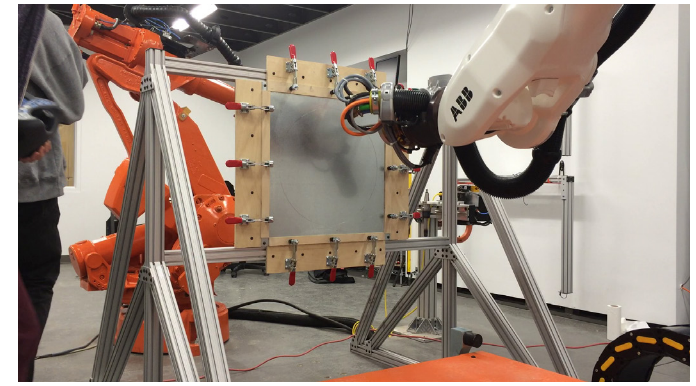
Conclusions

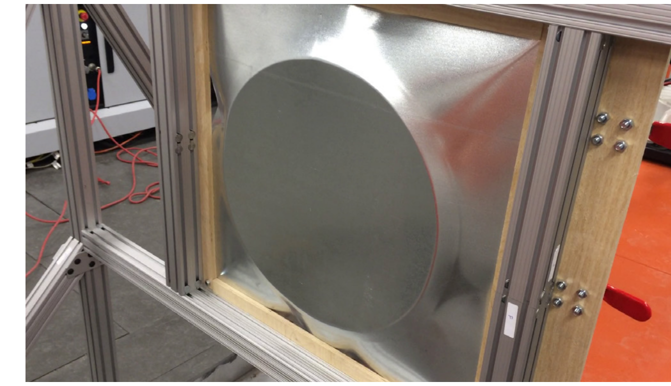
The wood shims clamped to the backside of the sheet to keep the sheet in place were not sufficient. The ply layers split apart and buckled under the forces. This allows the sheet to buckle from the edges, drastically reducing the accuracy of the formed part.

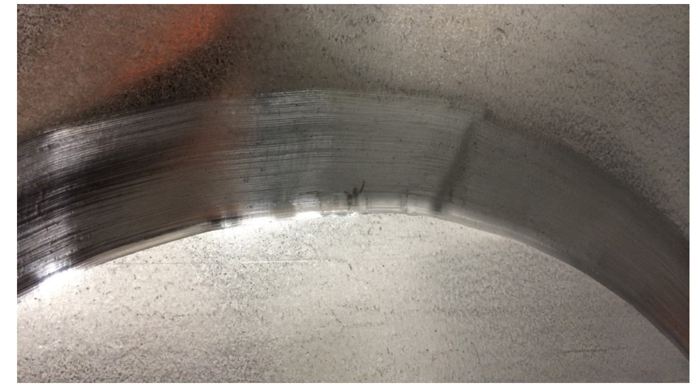
The silicone lubricant dried up too fast and was most likely a factor in the robot throwing a collision error.

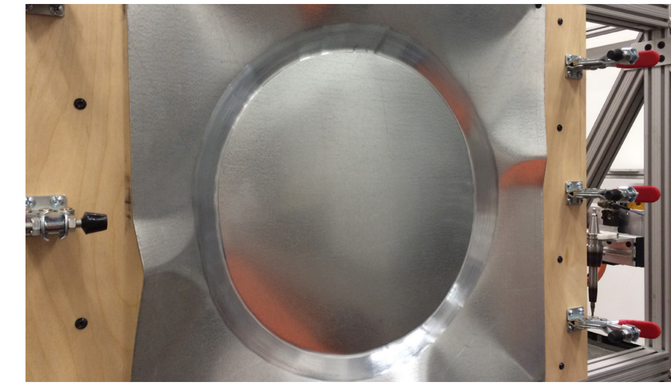
Without the second robot providing leverage, the sheet buckled a lot, making the case for the supporting robot.

Incremental Forming - ABB 6640 Robot









Parameters

Forming Type: ISF
Former: 6640
Supporter: None
Forming Tool: 3/4" Ball-End
Support Tool: None
Material: Galvanized Steel
Sheet Thickness: 0.8mm
Sheet Size: 24" × 24"
Feed Rate: 100m/s
Stepdown: 1mm
Max Wall Angle: 60°
Diameter: 16"
Lubricant: Silicone

Results

Achieved Depth: 1"
Forming Duration: 11min
Cause of Stop: Forming Forces

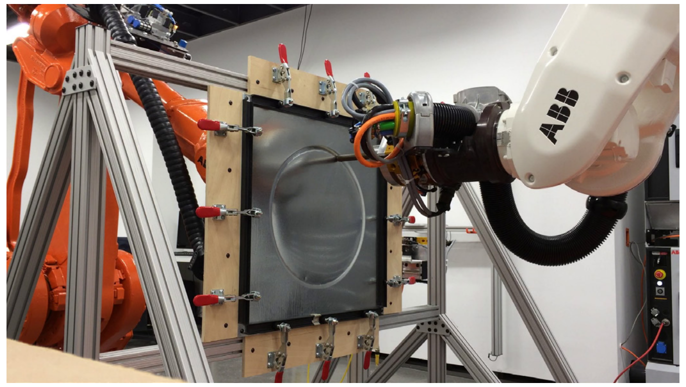
Conclusions

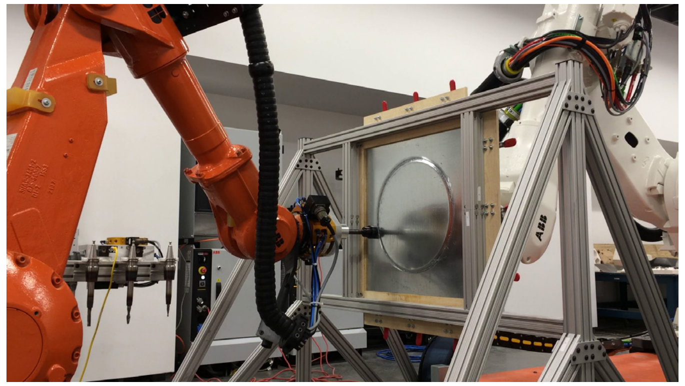
The wood shims clamped to the backside of the sheet to keep the sheet in place were not sufficient. The ply layers split apart and buckled under the forces. This allows the sheet to buckle from the edges, drastically reducing the accuracy of the formed part.

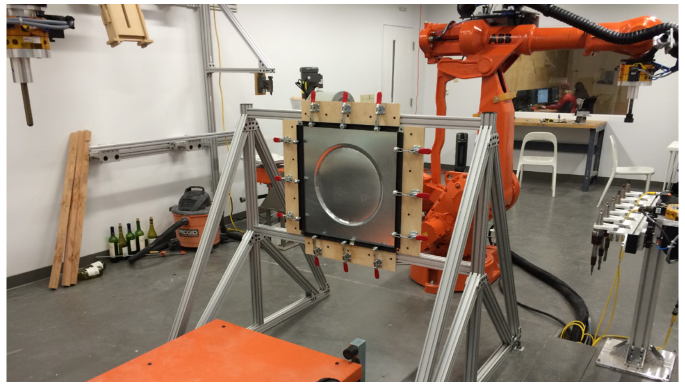
The silicone lubricant dried up too fast and was most likely a factor in the robot throwing a collision error. You can also see the result of the poor lube: scratches on the formed surface.

Without the second robot providing leverage, the sheet buckled a lot, making the case for the supporting robot.

Peripheral Support - Forming Tool × Support Tool







Parameters

Forming Type: DPIF-P
Former: 6640
Supporter: 4400
Forming Tool: 3/4" Ball-End
Support Tool: 2" Disk
Material: Galvanized Steel
Sheet Thickness: 1mm
Sheet Size: 24" × 24"
Feed Rate: 25m/s
Stepdown: 1mm
Max Wall Angle: 60°
Diameter: 16"
Lubricant: Silicone

Results

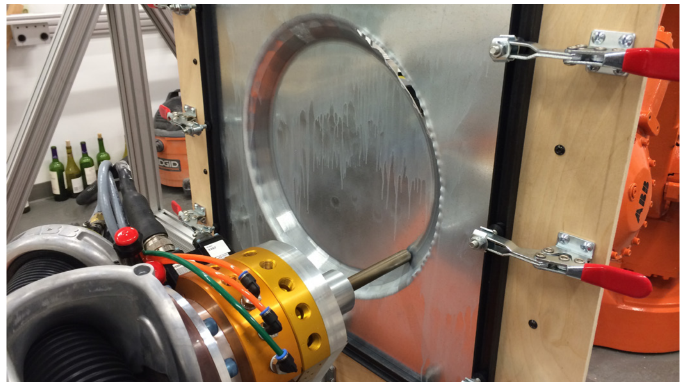
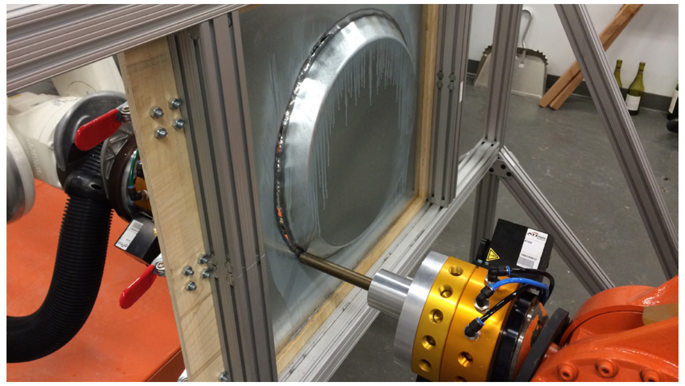
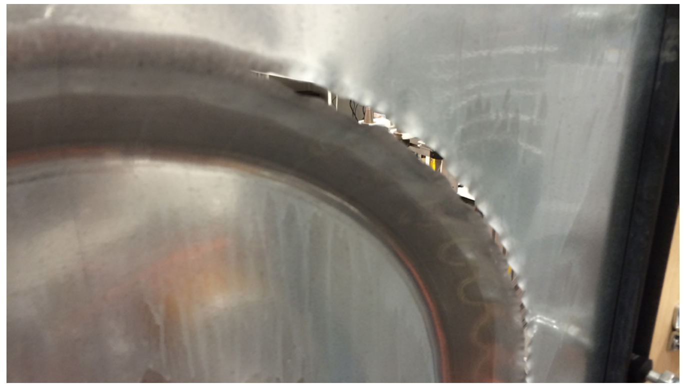
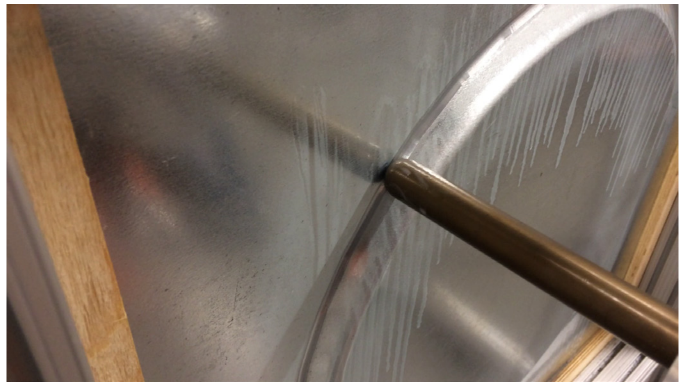
Achieved Depth: 5/8"
Forming Duration: 12min
Cause of Stop: Forming Forces

Conclusions

The thickness of the sheet combined with the material lead to very high forming forces, resulting in a collision error being thrown by the supporting 4400 robot. A 1mm sheet of galvanized steel is not appropriate for these robots.

In addition, the support disk tool shaved some of the material off of the backside, which could have lead to a tear along the periphery.

Peripheral Support - Forming Tool × Forming Tool

Parameters

Forming Type: DPIF-P
Former: 6640
Supporter: 4400
Forming Tool: 3/4" Ball-End
Support Tool: 3/4" Ball-End
Material: Galvanized Steel
Sheet Thickness: 0.5mm
Sheet Size: 24" × 24"
Feed Rate: 25m/s
Stepdown: 1mm
Max Wall Angle: 60°
Diameter: 16"
Lubricant: Silicone

Results

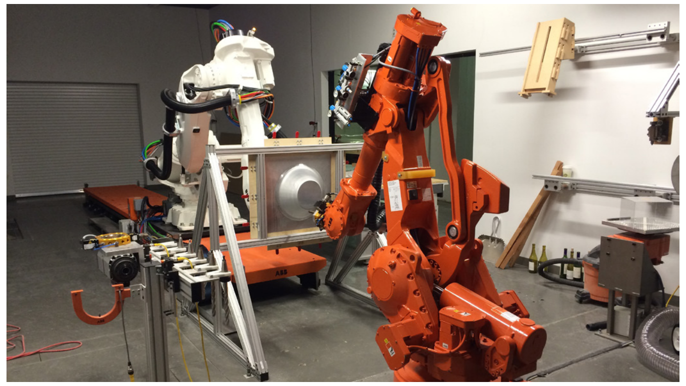
Achieved Depth: 1-1/4"
Forming Duration: 28min
Cause of Stop: Peripheral Tear

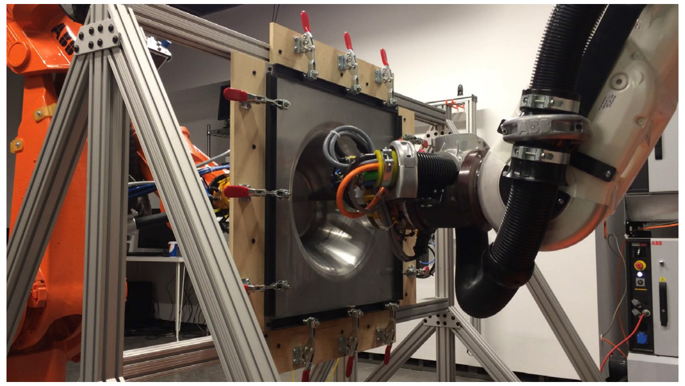
Conclusions

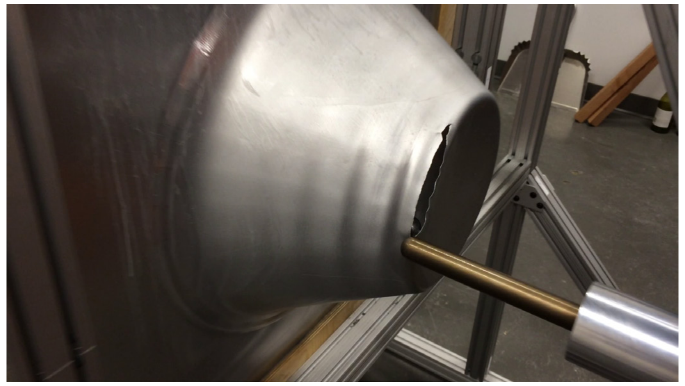
The difference between having the disk support tool versus the ball-end acting as a support tool is that the ball-end creates a direct point of leverage along the periphery. This results in the material being stretched mostly along the periphery. The final outcome is a tear at the peripheral edge, where the sheet became too thin to stretch any more. In addition, the backside's edge surface quality was different. The ball-end created a darker filleted edge as opposed to the scratched flat surface caused by the disk tool.

The 0.5mm sheet seemed to be very formable, and the peripheral support prevents the thin sheet from buckling too much.

Local Support







Parameters

Forming Type: DPIF-L
Former: 6640
Supporter: 4400
Forming Tool: 3/4" Ball-End
Support Tool: 3/4" Ball-End
Material: Aluminum
Sheet Thickness: 1.5mm
Sheet Size: 24" × 24"
Feed Rate: 25m/s
Stepdown: 1mm
Max Wall Angle: 60°
Diameter: 16"
Lubricant: White Lithium Grease

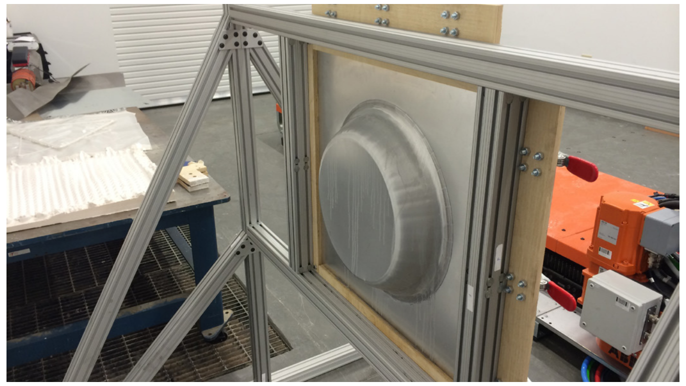
Results

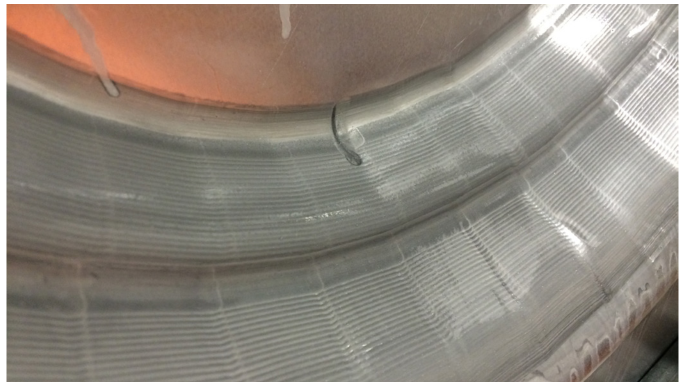
Achieved Depth: 6-1/2"
Forming Duration: 134min
Cause of Stop: Local Tear

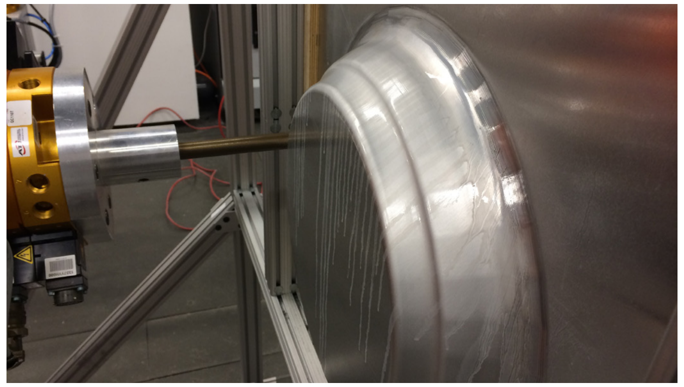
Conclusions

This was the first test that did not end because of high forming forces causing the robot to throw a collision error. I attribute this sucess to three factors.
1. Material choice: this was the first test of aluminum sheet forming. Aluminum is more maleable than Steel and therefore the forming forces were reduced.
2. Lubricant: The White Lithium Grease was all around a much better lubricant for this purpose than Silicone lube. The grease was specially made for metal to metal contact, and also stuck to the sheet better than the silicone, which dried up or dripped off.
3. Sheet Thickness: The 1.5mm sheet of aluminum seemed to be optimal in that it is maleable but not too thin to result in tearing too early.

Multiple Forming - Local Support







Parameters

Forming Type: DPIF-L
Former: 6640
Supporter: 4400
Forming Tool: 3/4" Ball-End
Support Tool: 3/4" Ball-End
Material: Aluminum
Sheet Thickness: 0.75mm
Sheet Size: 24" × 24"
Feed Rate: 25m/s
Stepdown: 1mm
Max Wall Angle: 60°
Diameter: 16"
Lubricant: White Lithium Grease

Results

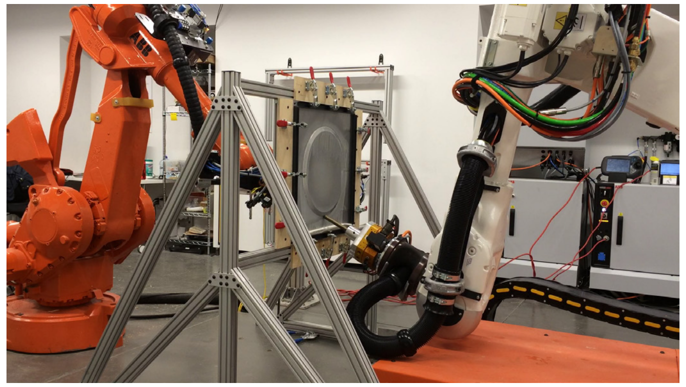
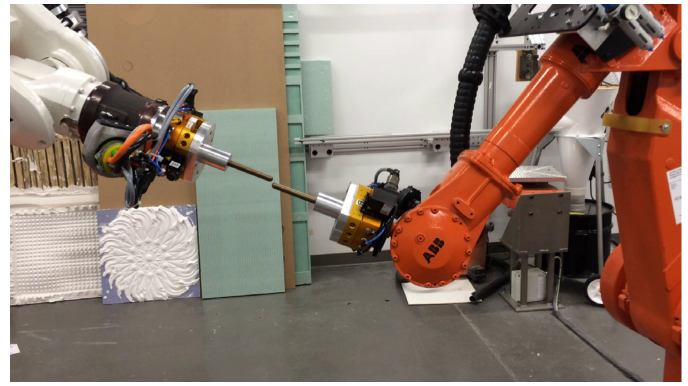
Achieved Depth: 3"
Forming Duration: 28min
Cause of Stop: Completed Procedure

Conclusions

After the three passes of the same procedure, the formed geometry was the closest to the desired geometry out of all the tests so far. In each pass the robots formed the sheet a little bit more, until the third pass when there was no visible change in the formed geometry.

However, the supporting robot stopped making contact with the formed geometry after a certain point in each pass. This means that the forming robot is not pushing the sheet to the depth that the supporting robot expects it to be. This will be hard to fix until the lab recieved a force torque sensor for both robots to ensure contact is made for the whole forming procedure.

Undercut Attempt 1 - 30° Angle Step

Parameters

Forming Type: DPIF-P
Former: 4400
Supporter: 6640
Forming Tool: 3/4" Ball-End
Support Tool: 3/4" Ball-End
Material: Aluminum
Sheet Thickness: 1.25mm
Sheet Size: 24" × 24"
Feed Rate: 25m/s
Stepdown: 1mm
Max Wall Angle: 75°
Diameter: 16"
Lubricant: White Lithium Grease

Results

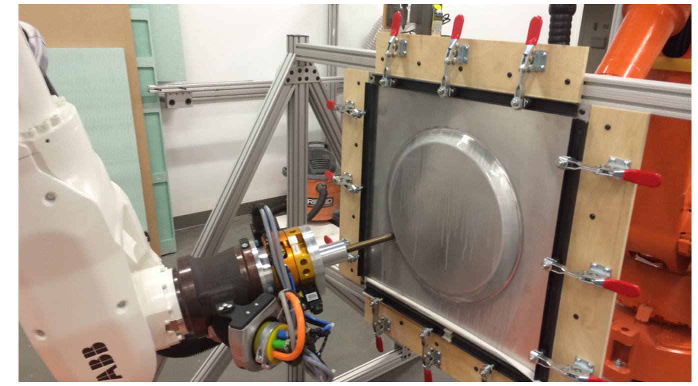
Achieved Depth: 1-1/2"
Forming Duration: 82min
Cause of Stop: Local Tear

Conclusions

The first pass formed a 60° trucated cone, the second pass formed a 90° cone, and the third pass was suppored to form a 97° cone, but the sheet tore during the 90° pass.

At a angle step size of 30°, the sheet was being stretched too much in each step, causing it to tear.

Undercut Attempt 2 - 15° Angle Step




Parameters

Forming Type: DPIF-P
Former: 4400
Supporter: 6640
Forming Tool: 3/4" Ball-End
Support Tool: 3/4" Ball-End
Material: Aluminum
Sheet Thickness: 1.5mm
Sheet Size: 24" × 24"
Feed Rate: 50m/s
Stepdown: 1mm
Max Wall Angle: 90°
Diameter: 16"
Lubricant: White Lithium Grease

Results

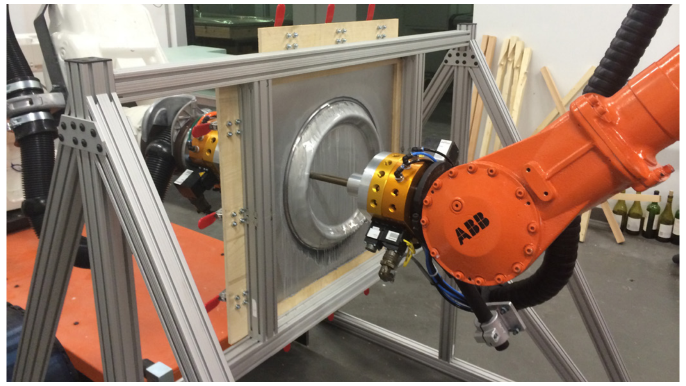
Achieved Depth: 1-1/2"
Forming Duration: 68min
Cause of Stop: Local Tear

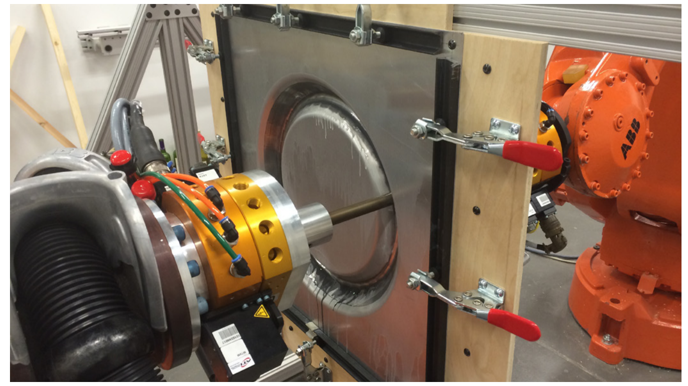
Conclusions

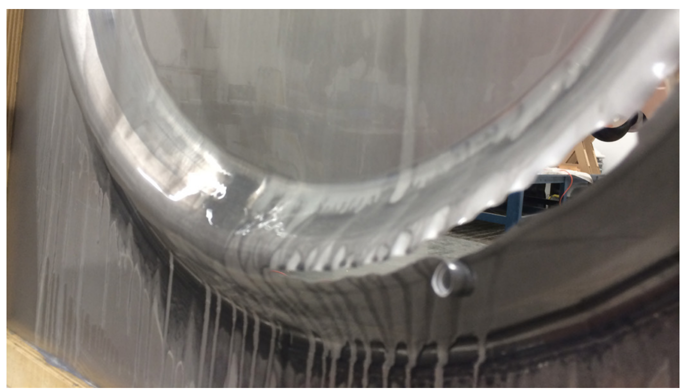
The smaller 15o angle step allowed the maximum wall angle to reach 90o after 4 passes. The first pass formed a 60o truncated cone, the second pass was meant to form a 75o wall angle but a third pass that was a repeat of the second pass was needed, just like multiple forming, so that the wall angle actually reached 75o. Then the fourth pass formed a 90o wall angle but tore the sheet a little bit.

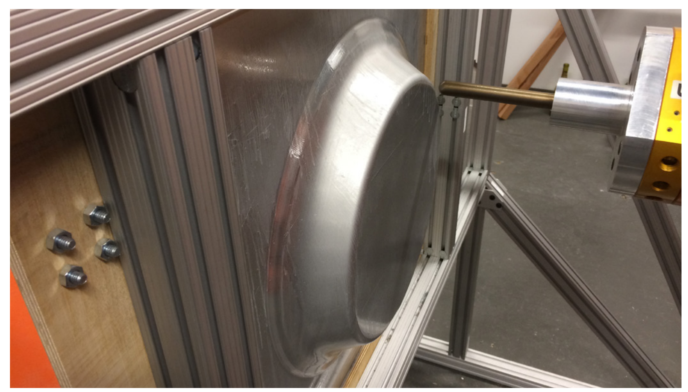
It seems as if the sheet will always tear when trying to form an undercut in multiple angle steps. The problem is that the circular face resulting from the first pass keeps being stretched from its center in the subsequent passes..

Subsequent Forming









Parameters

Forming Type: DPIF-P
Former: 6640 -> 4400
Supporter: 4400 -> 6640
Forming Tool: 3/4" Ball-End
Support Tool: 3/4" Ball-End
Material: Aluminum
Sheet Thickness: 1.5mm
Sheet Size: 24" × 24"
Feed Rate: 50m/s
Stepdown: 1mm
Max Wall Angle: 60°
Diameter: 16"
Lubricant: White Lithium Grease

Results

Achieved Depth: 1-1/2" -> 3/4"
Forming Duration: 55min
Cause of Stop: Peripheral Tear

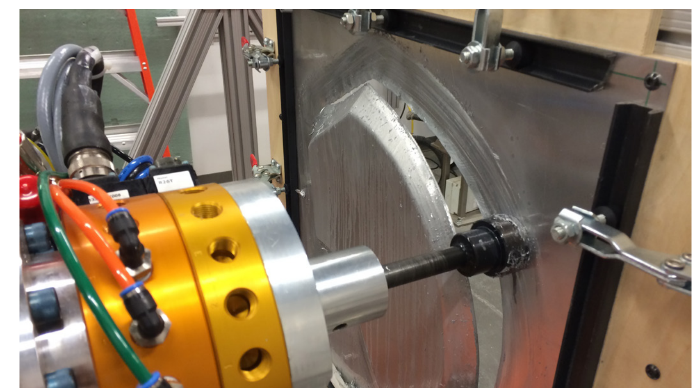
Conclusions

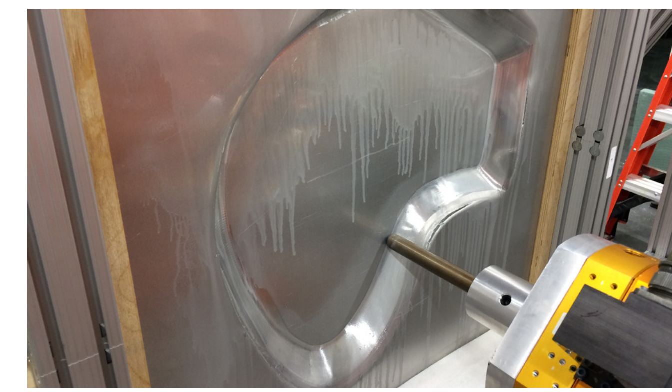
First the 6640 robot formed a 3" truncated cone while the 4400 robot supported it along the periphery. Then the 4400 switched into the forming role and formed in the opposite direction while the 6640 acted as peripheral support along the inside circle it just formed.

As with the other local forming test, the supporting robot stopped making contact with the metal after a certain point.

The sheet was thinned after the first forming pass, so it tore after only 3/4" of forming in the opposite direction. Either the subsequent forming has to be very shallow, or a different toolpath technique is needed to ensure the sheet is not thin at that point.

Complex Polysurface





Parameters

Forming Type: DPIF-P
Former: 4400
Supporter: 6640
Forming Tool: 3/4" Ball-End
Support Tool: 2" Support Disk
Material: Aluminum
Sheet Thickness: 1.5mm
Sheet Size: 24" × 24"
Feed Rate: 50m/s
Stepdown: 1mm
Max Wall Angle: 47°
Diameter: 21"
Lubricant: White Lithium Grease

Results

Achieved Depth: 2"
Forming Duration: 21min
Cause of Stop: Peripheral Tear

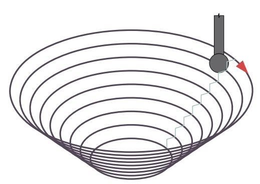
Conclusions

This was the most complex toolpath of all the tests. The polysurface raised many additional issues. For one, a determination for what the normal of a discontinuity between two surfaces should be needed to be made. Second, the peripheral toolpath had more points than the forming toolpath, so syncing was much more challenging to achieve.

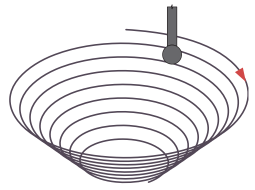
The support tool scraped material off of the periphery due to the flat surface beign dragged along the sheet. This caused the material to be thinned, eventually causing a tear. By continuing even once the sheet tore, the shape was almost completely separated from the sheet. This is an interesting side effect and could be leveraged in the future.

Recomendations For Further Research

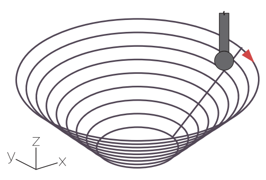
Tool-path Variation



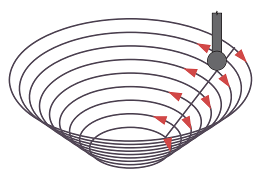
Stepped



Helical



Contoured



Alternating

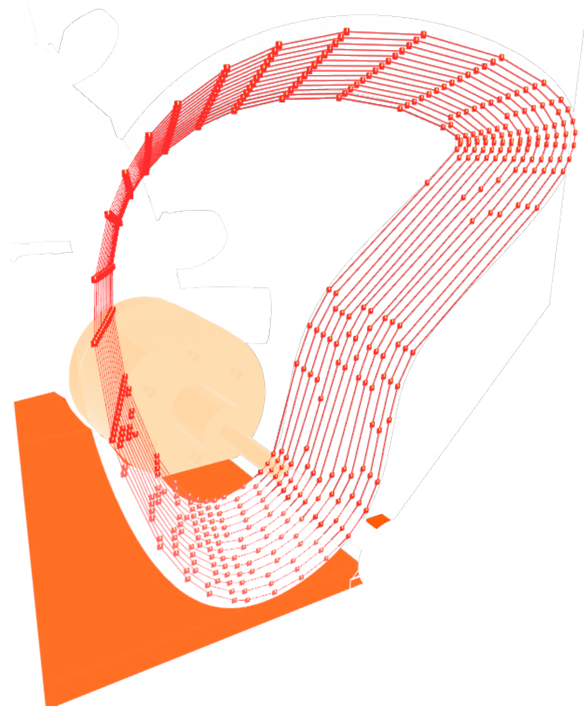
?

????????

?

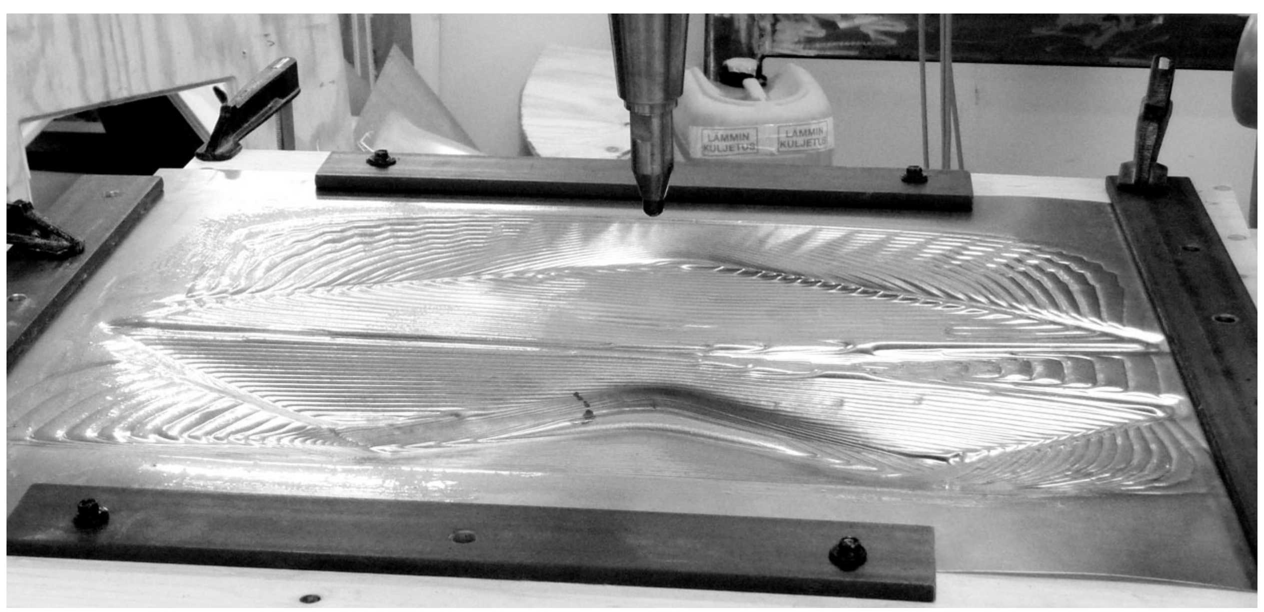
????????

Custom Toolpath Types



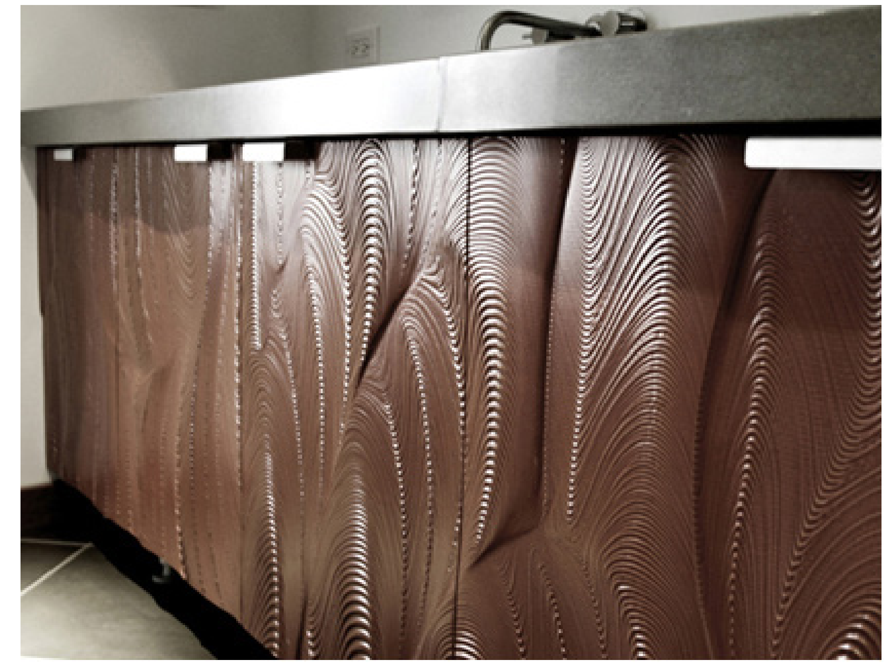
Toolpath resulting from divByDeltaTan

divByDeltaTan causes irregular spaced targets which influences the appearance of the formed part.



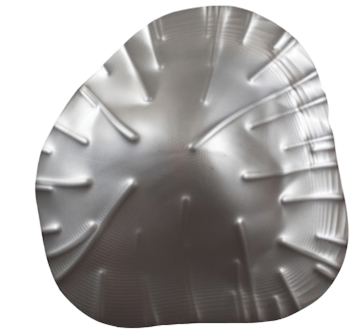
Fabrication

Image credit: (Cadiz et al)

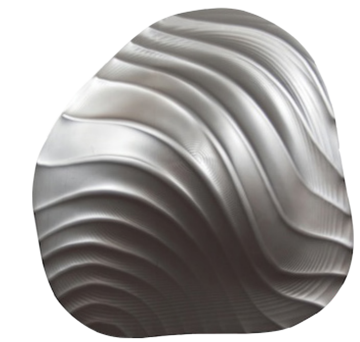


Path Responsive Surface Milling - Leaves Style

Image credit: (Skylar Tibbits)



Edge to Center Ribbing



Global Linear Ribbing

Image credit: (Newsumme)

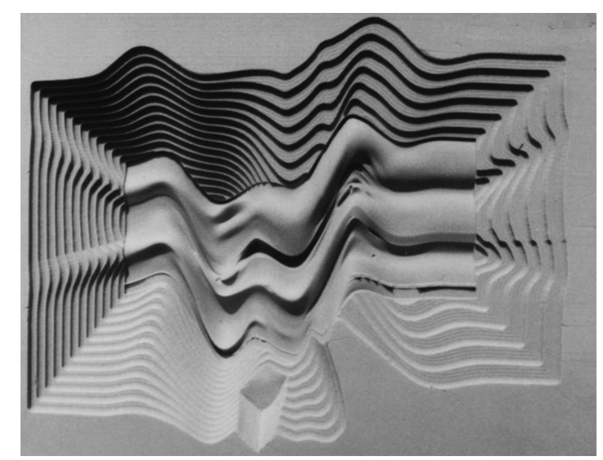


Figure Ground Mill File

Image credit: (subdv.com)

Ornamental Tracer Ribs

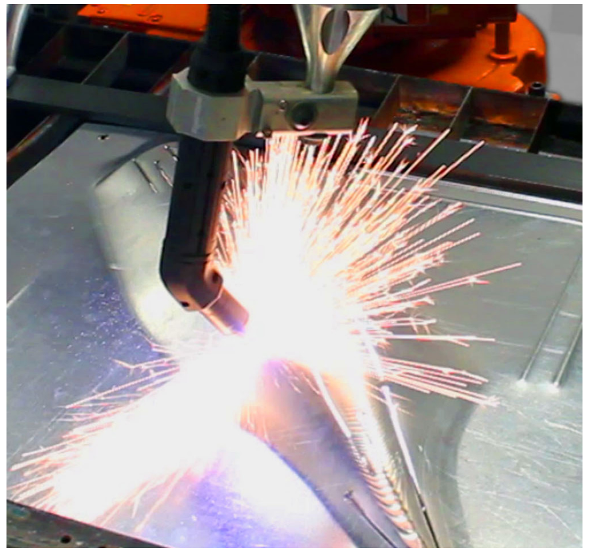
Image credit: (Newsumme)

Path Responsive Surface Milling - Cloth Style

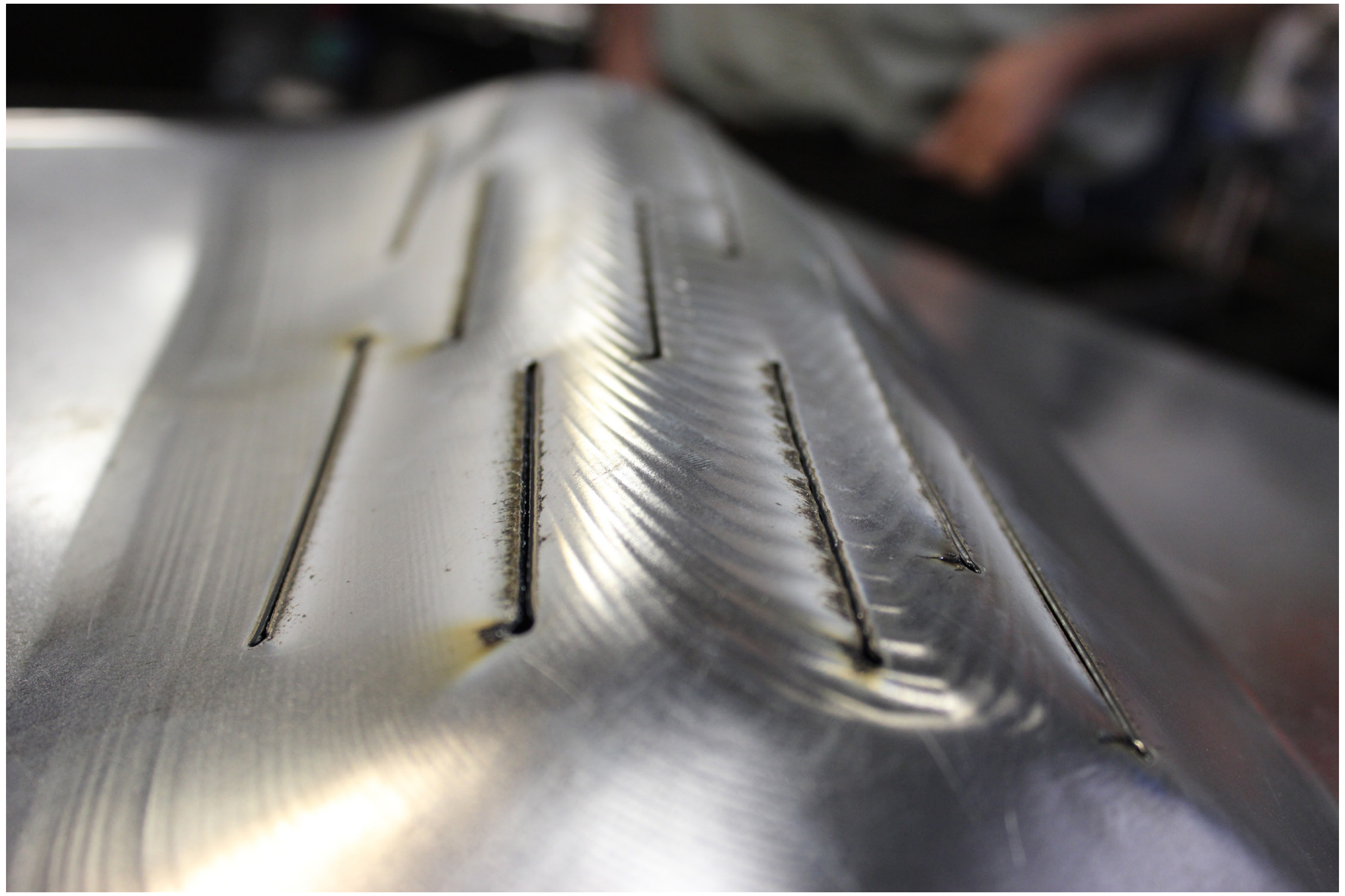
Image credit: (Skylar Tibbits)

3D Plasma Cutting of Formed Parts

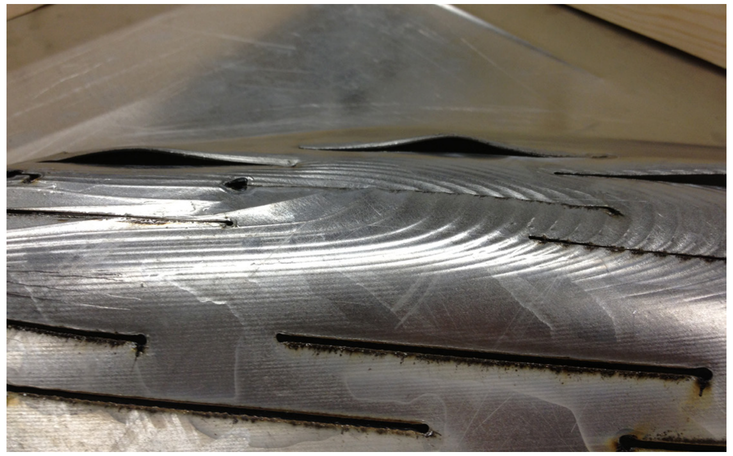
Prototype by Alex Fischer and Matt Adler, Carnegie Mellon University, 2013

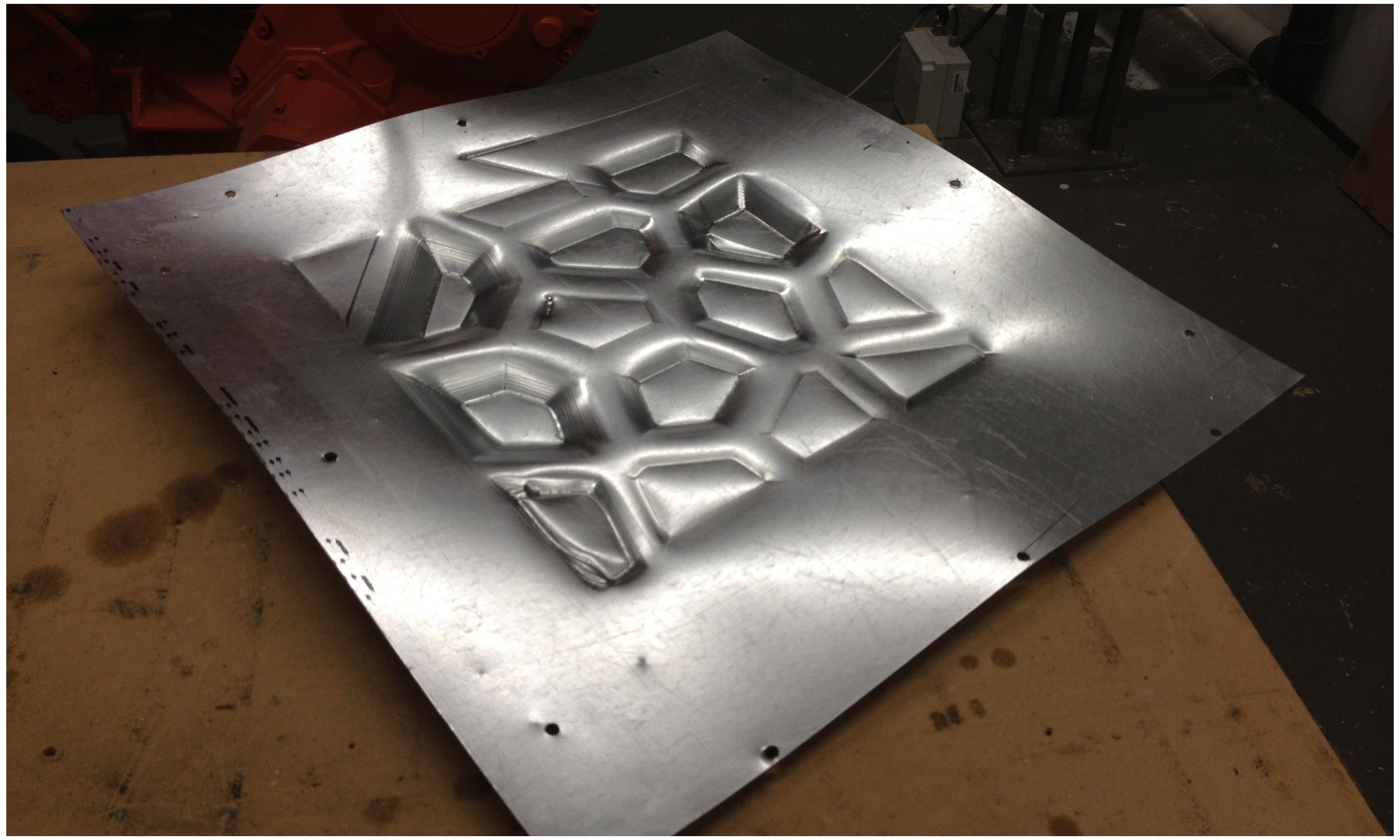

3D Plasma Cutting - Arc Firing


3D Plasma Cutting - Calibration


Plasma Cuts Closeup - Interaction with Toolpath


Incrementally Form -> 3D Plasma Cut -> Incrementally Form

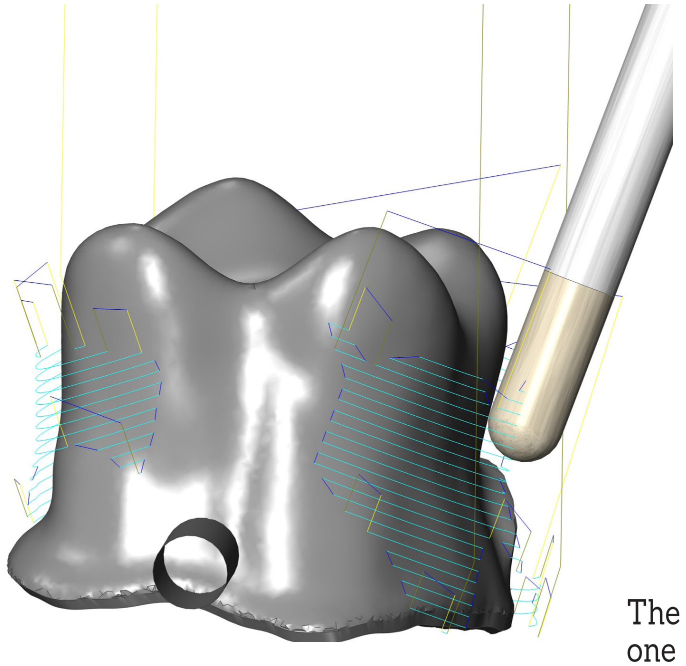

Roboformed Slit Apperatures


Local Deformations could be 3D Plasma Cut out to Ceate Apperatures

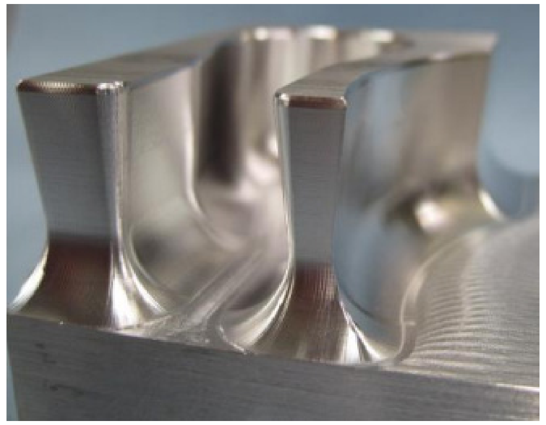
3D Plasma cutting of formed parts can be used to create appertures in panels. It would be interesting to see the result of multiple local deformations with their flat aread cut out. This could be used as a architectural cladding to control the passage of light across the facade

Undercuts via Multiple Forming

Cylinder with Undercut (97°)
Image crecit: (Meier et al., DPIF, 328)



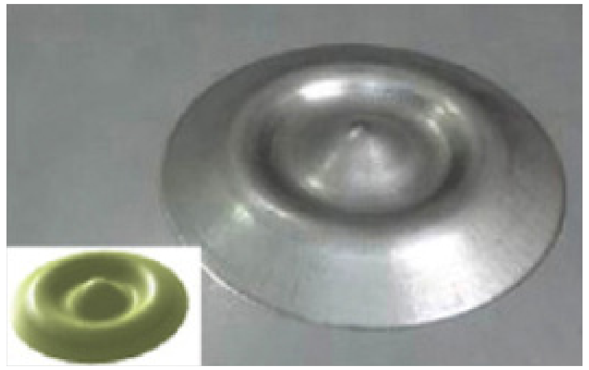
Custom Dental Crown with Undercuts
Image crecit: moduleworks.com



Undercuts made with a 5-axis Mill
Image crecit: onecnc.net/

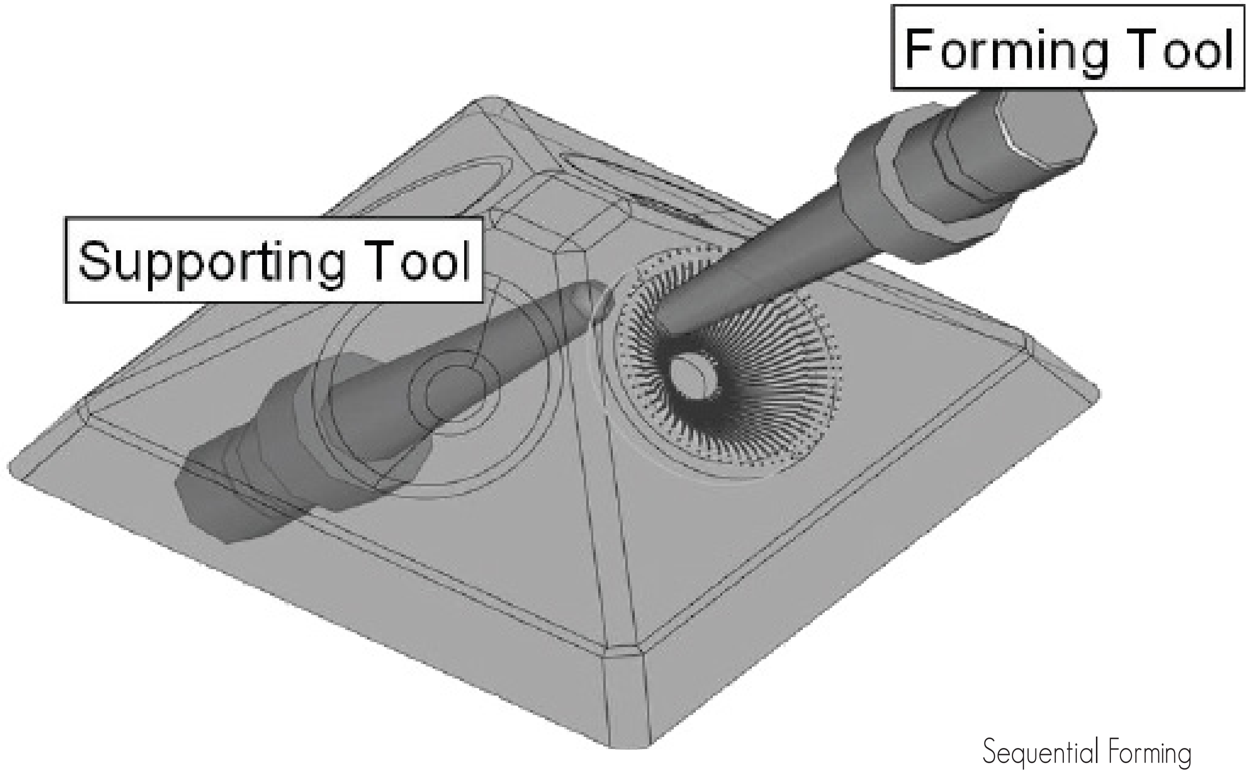
The abilty to create undercut geometry is one of the unique benefits of Roboforming. It would be natural to find some architectural use for undercut panels. Interestingly, one proposed application of Microforming, essentially (Roboforming at a small scale) was bespoke dental crowns which have complex forms with undercut areas. (Jeswiet, SPIF, 23)

Concave and Convex Forms via Sequential and Parallel Forming



Sequential Forming

Parallel Forming
Image crecit: (Malhotra , Accumulative-DSIF, 253)



Sequential Forming
Image crecit: (Buff et al., Accuracy, 154)

An essential advantage of Roboforming is the ability to form on both sides of the sheet. By setting the robots to trade the roles of former and supporter in the middle of a forming process, it is possible to create concave and convex forms in a single run. Another method is to form a geometry and then form the result in select areas. In this case the support tool is physically a forming tool but behaves like a peripheral support tool, except in locations local to the forming tool.

Speculation

Design Based on Competition Breif

TEX-FAB's SKIN Competition

BRIEF

The building envelope represents the most complex and fundamentally linguistic element of architecture today. Its formal development and performative capacity – what may be called the *activated envelope* – is foundational to its purpose and presents a dialogue the building has with itself and that of its context. We can understand this relationship in many ways, but ultimately it is one that mimics our own skin. Fundamental to this is an explicit or implicit *adaptability* found in its performance – how it functions and meets the needs of the building. In the preceding 100 years since the beginning of the 21st century the transformation from a static, heavy and obfuscating series of load bearing walls, to its current role of a communicative envelope, dynamical and exploratory, sets the stage for this competition and in what we believe is the most important area of research in architecture. It is within this framework that the international digital fabrication competition SKIN asks designers and researchers to speculate, or if they so choose – to present existing research - on the role of the building envelope by exploring new methods to enable the performative and aesthetic qualities of a façade.

Design submissions may develop any context they choose, real or virtual, at any scale and on any building type so as to present a complete thesis. Integrating structure, dynamical cladding or other system whether static or active may be submitted. We encourage the boldest visions and challenging technologies in the development of your proposal.
The competition will select four of the most robust and intriguing projects, that best rethink the building envelope, supporting those selections through prototypes developed to illustrate the potential of the competition submission.

CONTEXT

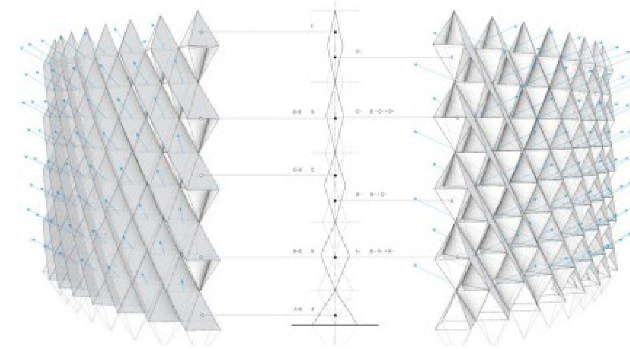
SKIN is a two-stage international design competition established to foster the deeper developments within the field of *computational fabrication*. We are soliciting design proposals that further existing research, by enabling prototyping at a larger scale or full scale, and proposals to jumpstart new research and design concepts into a first prototype. Choice of project location, contextual constraints, programmatic and functional requirements are open and should be freely interpreted to further the proposal's thesis.

MATERIALS AND FABRICATION

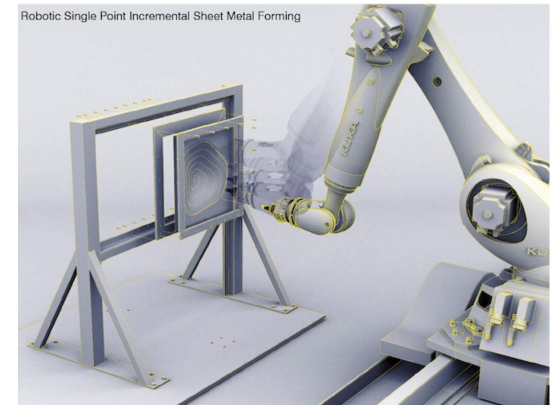
SKIN seeks proposals that specifically leverage the advancement of metal fabrication systems; however, we are open to hybridized material assemblies. As such it is not expected that metal is the only material system utilized in the design research, though we are seeking to collect and promote a concentrated body of work that can focus not only on metal application but also the methodology. Note, you must propose a specific fabrication method based on your research, thus the competition entry needs to specify techniques and materials.

SKIN Competion - Ended October 25, 2013

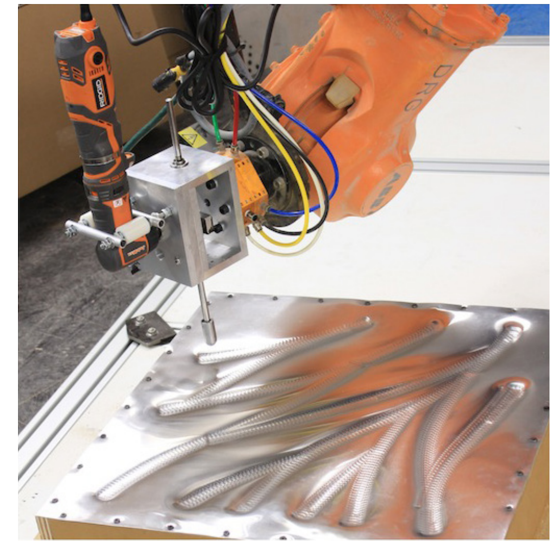
Entries

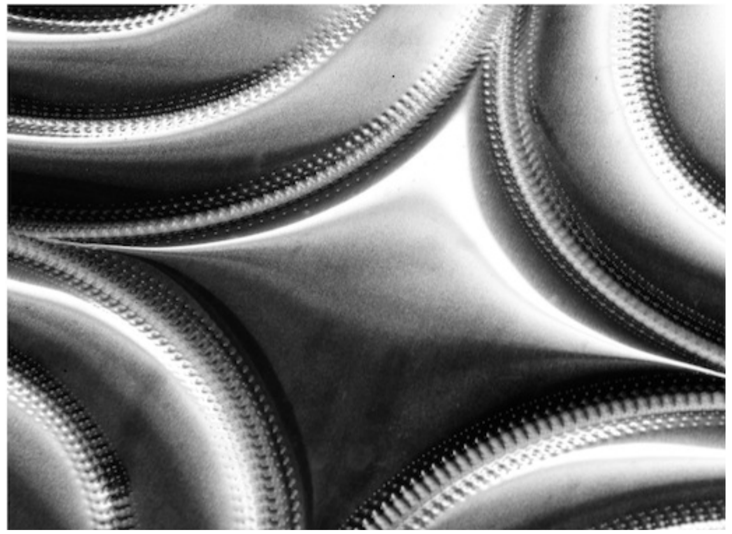


3xLP by Christopher Romano and Nicholas Bruscia



per-Forming by Jake Newsum

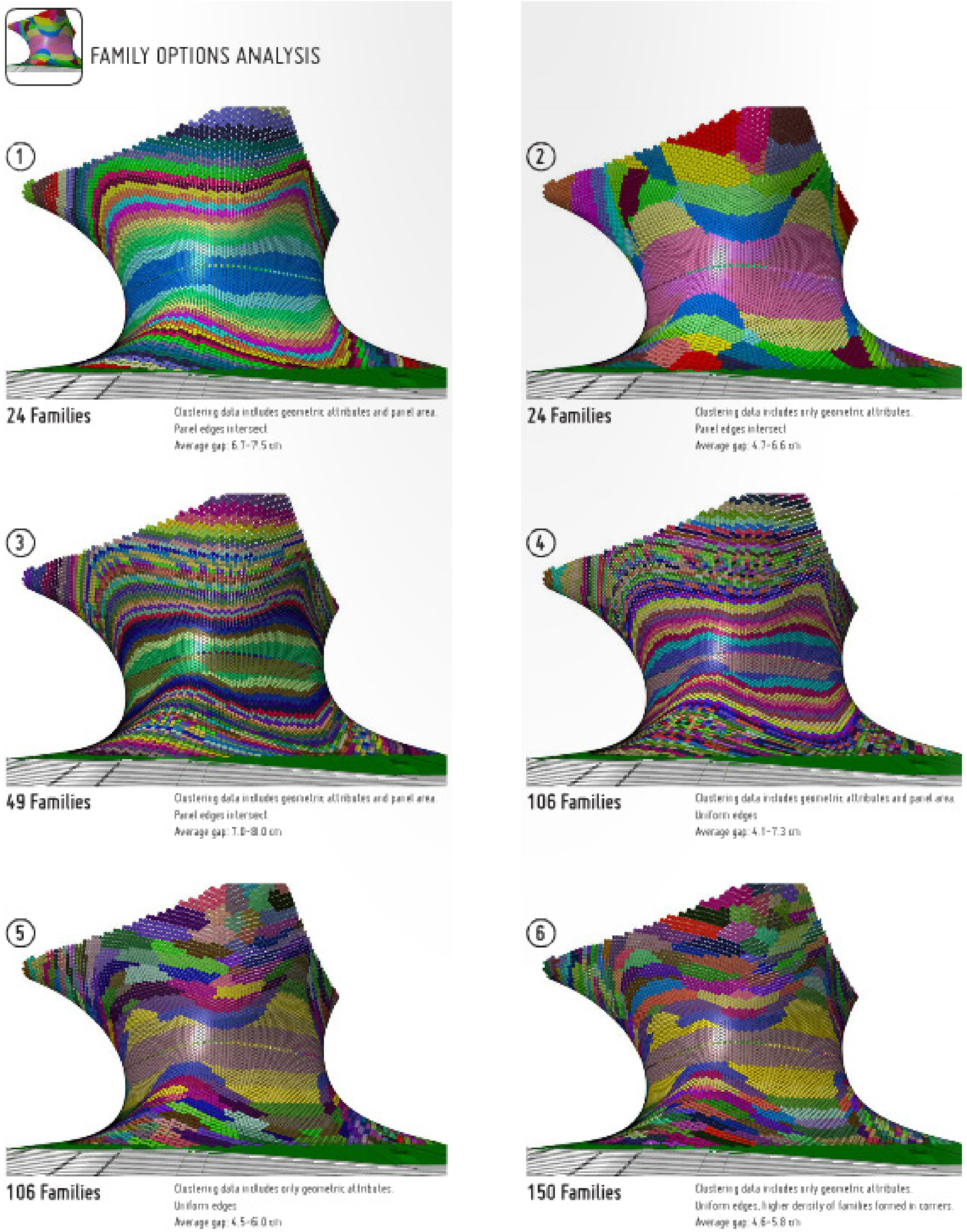




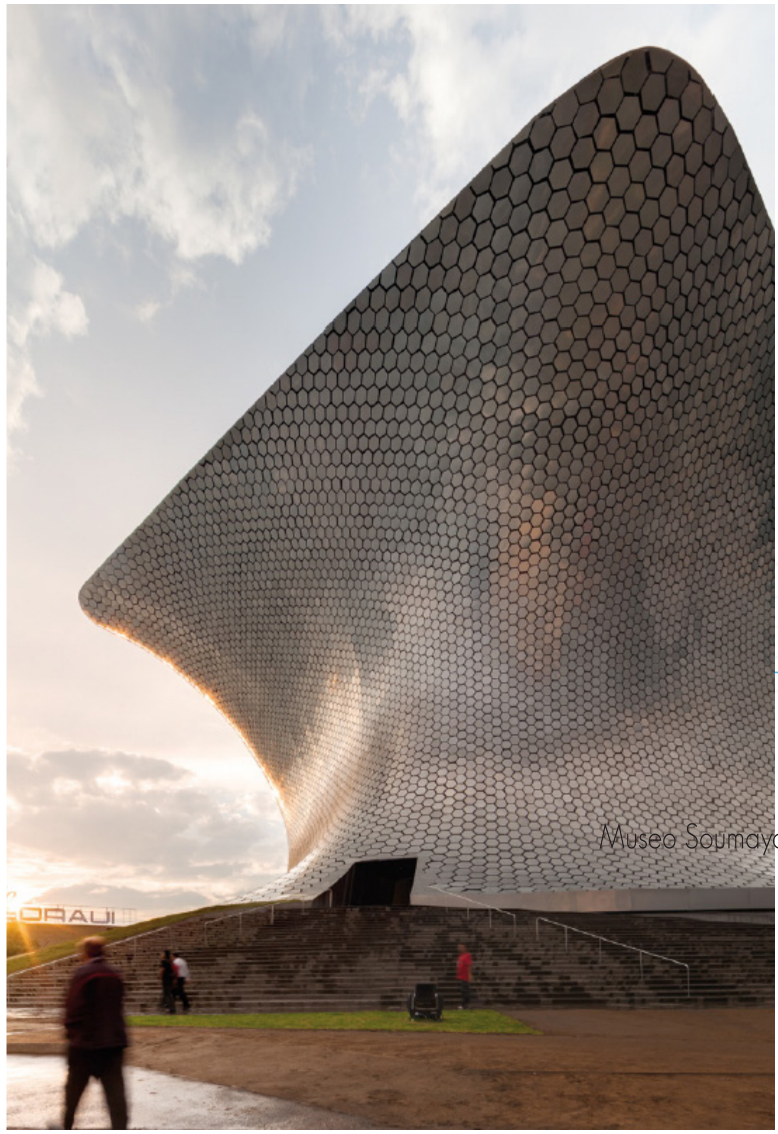
Hammer Forming by Lik Hang Gu

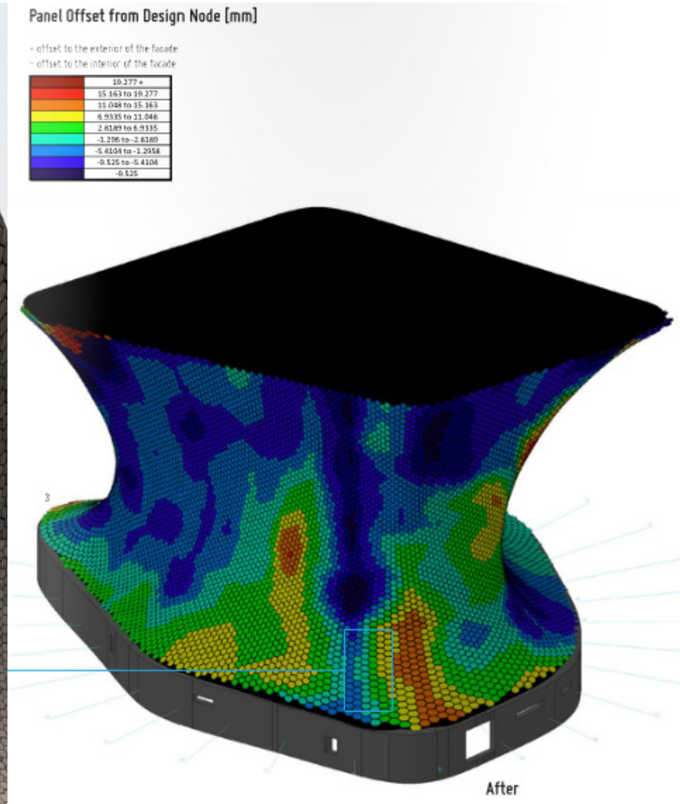
Design Based on Case Study of Existing Facade

Museo Soumaya by Free Architects

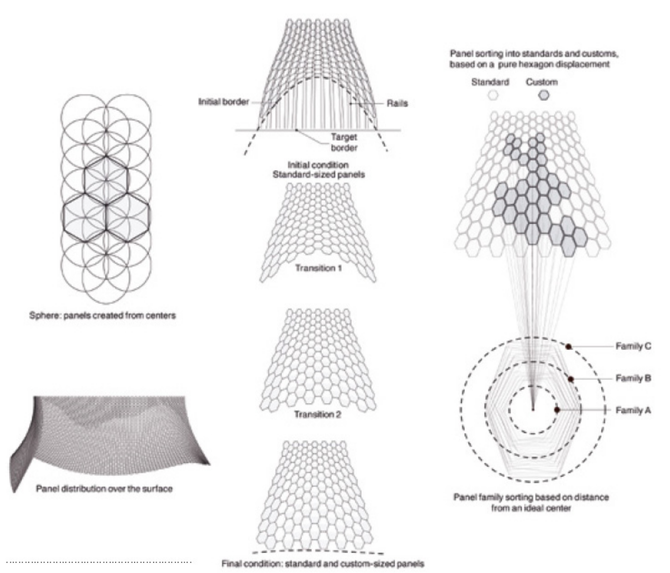


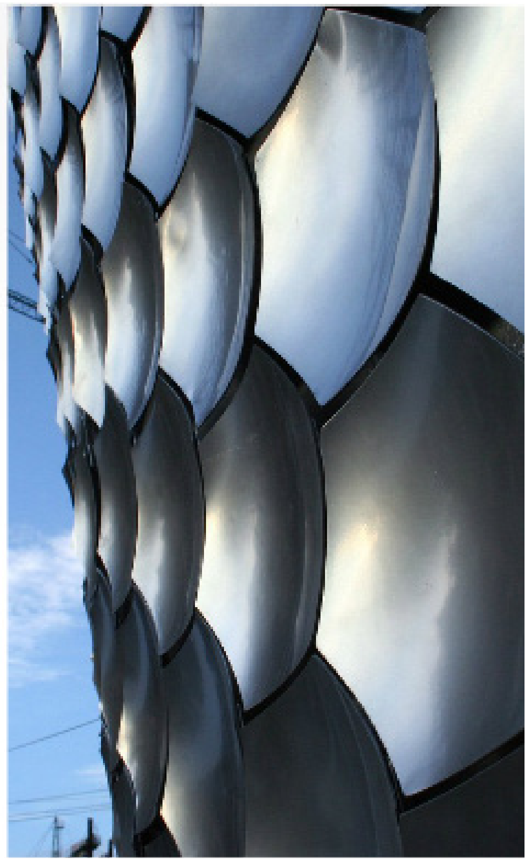
Museo Soumaya - Facade Design to Fabrication by Gehry Technologies, 69





Museo Soumaya - Facade Design to Fabrication by Gehry Technologies, 43





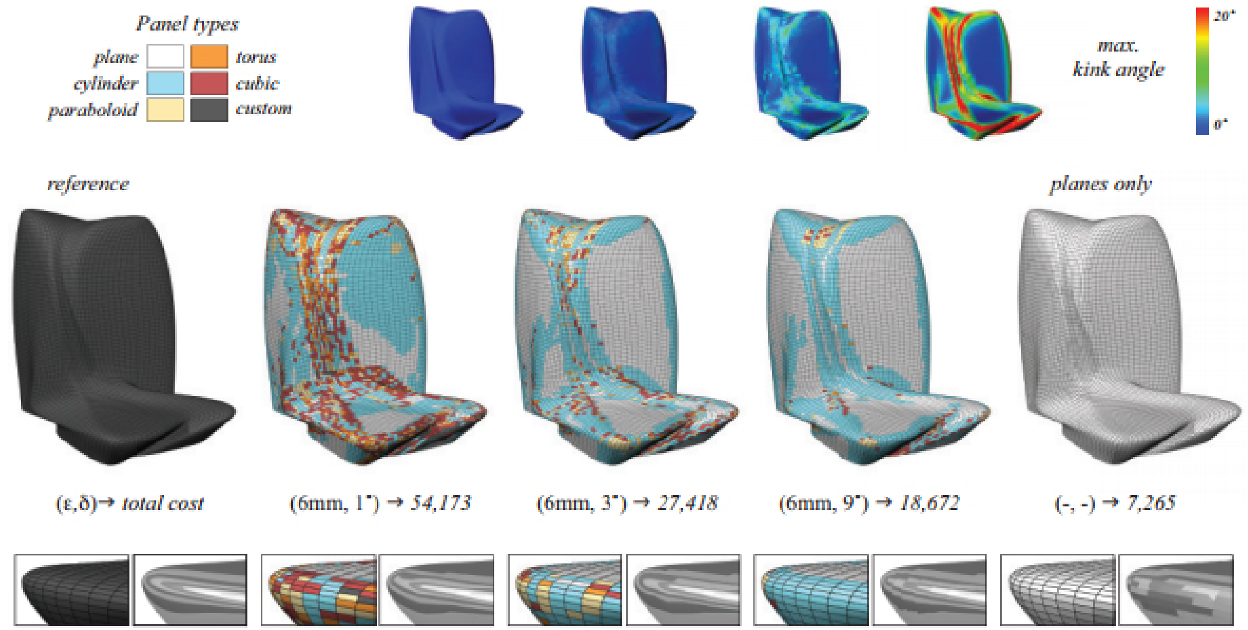
Museo Soumaya - Facade Design to Fabrication by Gehry Technologies, 103

Design Based on Case Study of Existing Facade

Dongdaemun Design Plaza and Park by Zaha Hadid Architects

Image courtesy: failedarchitecture.com

Image courtesy: arabianindustry.com



6mm, 1°						
molds	-	263	236	265	551	196
panels	1164	3680	603	526	1096	196

6mm, 3°						
molds	-	312	158	75	243	11
panels	2907	3389	395	142	421	11

6mm, 9°						
molds	-	354	95	18	104	3
panels	3178	3667	228	23	166	3

Figure 7: *Paneling results with varying kink angle thresholds δ and fixed divergence thresholds ε = 6mm for the design of the National Holding Headquarters. The images on the right show a solution using only planar panels of which 3,796 do not meet the prescribed divergence threshold. The zooms show reflection lines to illustrate inter-panel continuity which successively improves with lower kink angle thresholds.*

total cost: 98,232

molds	-	3793	2023	63	746	201
panels	1559	3793	2023	63	746	201

total cost: 51,397

molds	-	506	144	37	552	201
panels	1557	3794	1414	122	1297	201

total cost: 25,337

molds	-	253	128	64	150	5
panels	2964	4576	426	124	290	5

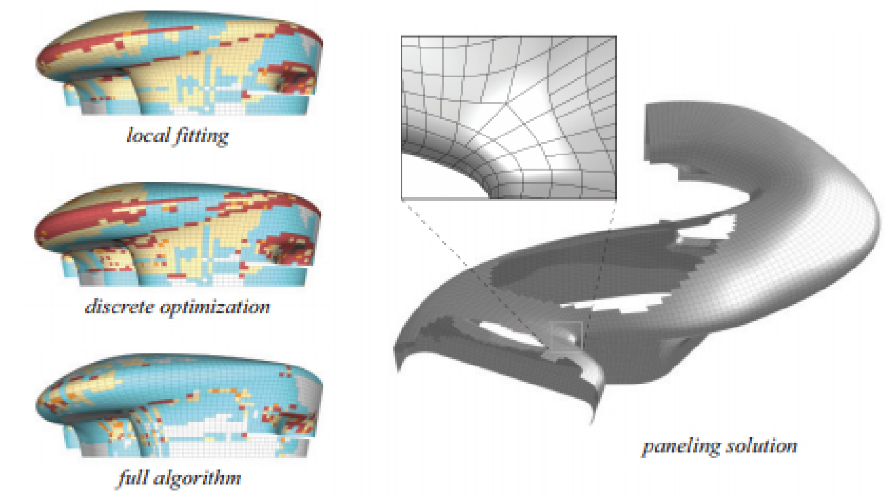
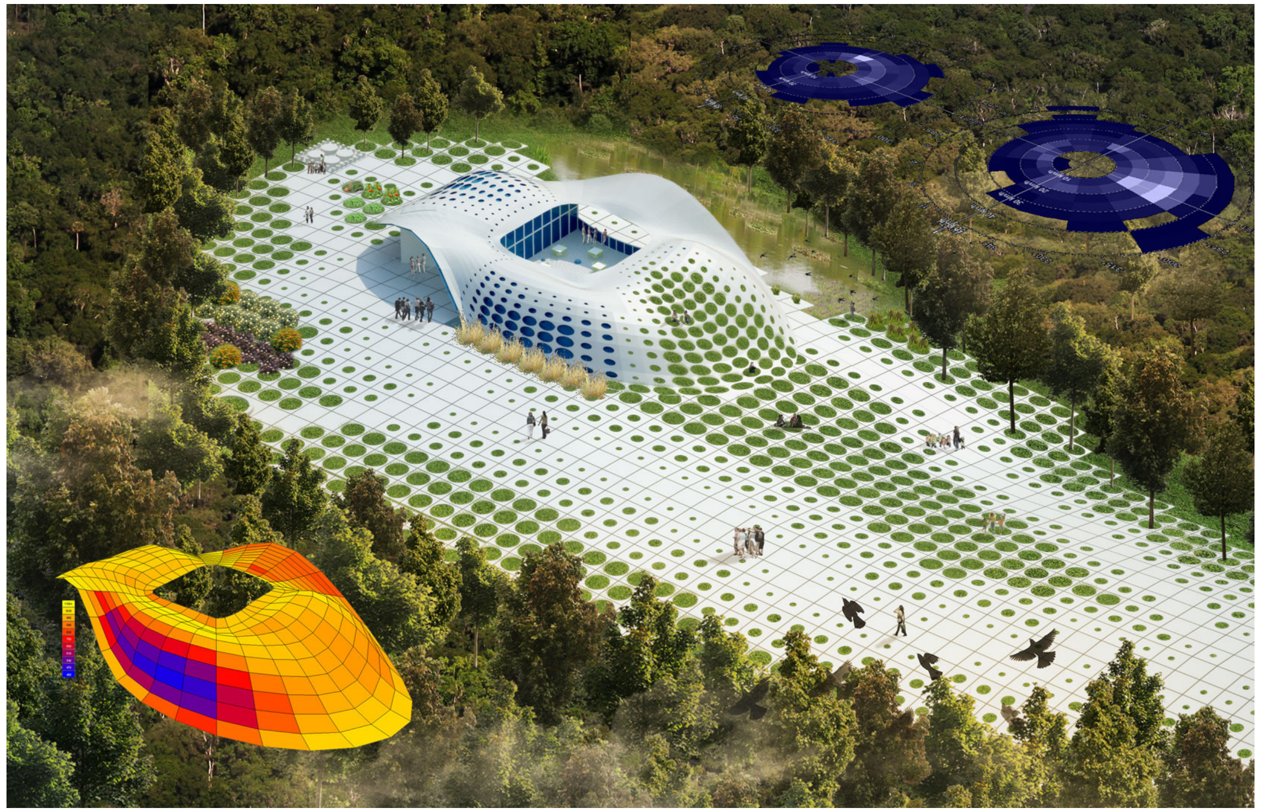


Figure 8: *Comparison of different methods for the same quality thresholds. State-of-the-art commercial tools only support a greedy panel assignment based on local fitting (top). Just one single application of our discrete optimization greatly reduces cost without loss in surface quality (middle). The full paneling algorithm interleaving discrete optimization with global continuous registration produces a high quality paneling (bottom). This solution contains 90% single curved panels and a very small number of custom molds, leading to a significantly reduced cost compared to greedy and local methods. The zoom on the right shows that our algorithm supports arbitrary curve network topology, including t-junctions. (Zaha Hadid Architects, Dongdaemun Design Plaza and Park, Seoul.)*

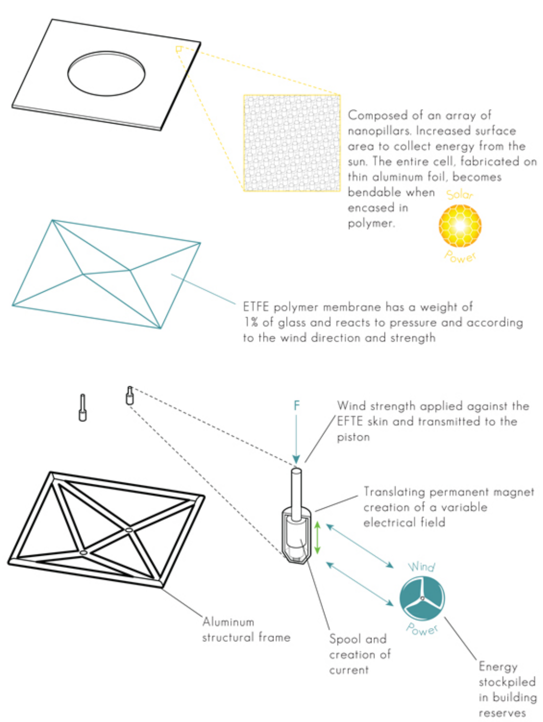
(Eigensatz, Paneling Freeform Surfaces, 1)

Design Based on Performative Quality

Environmental and Programattical Factors



Eco-Skin Environmental Center by Alex Fischer, 2011

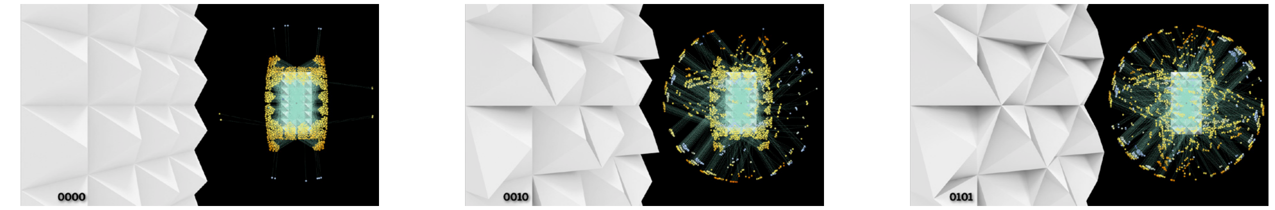


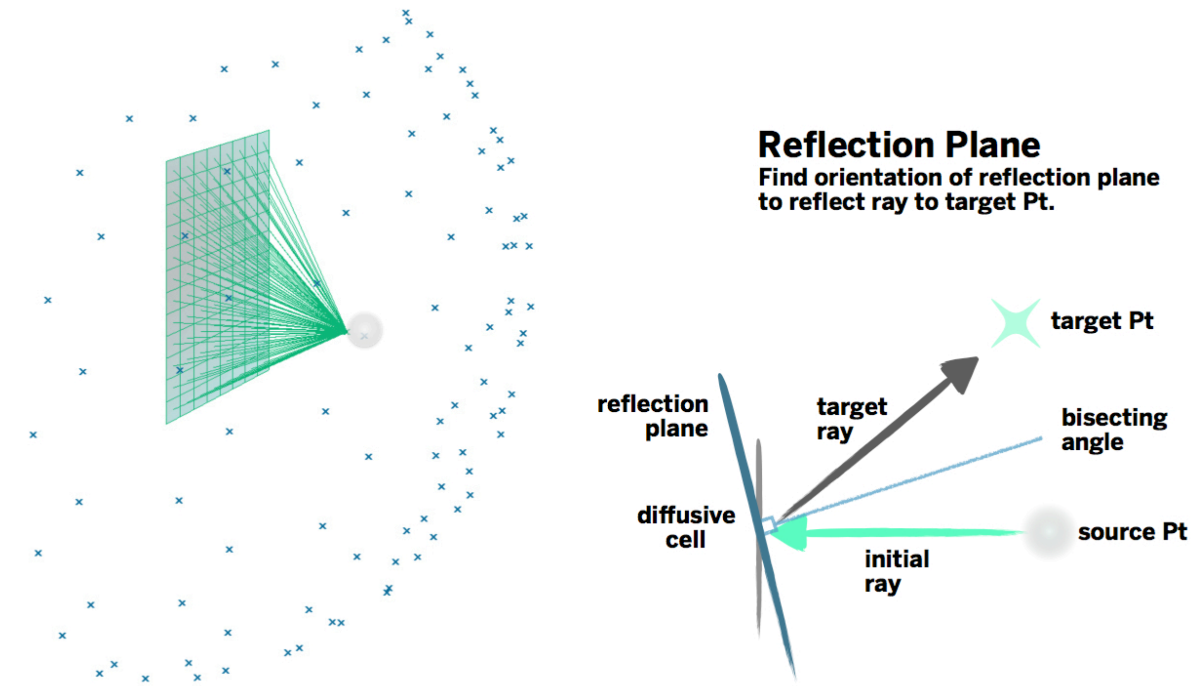
Double-Layer Solar and Wind Energy Harvesting Panel

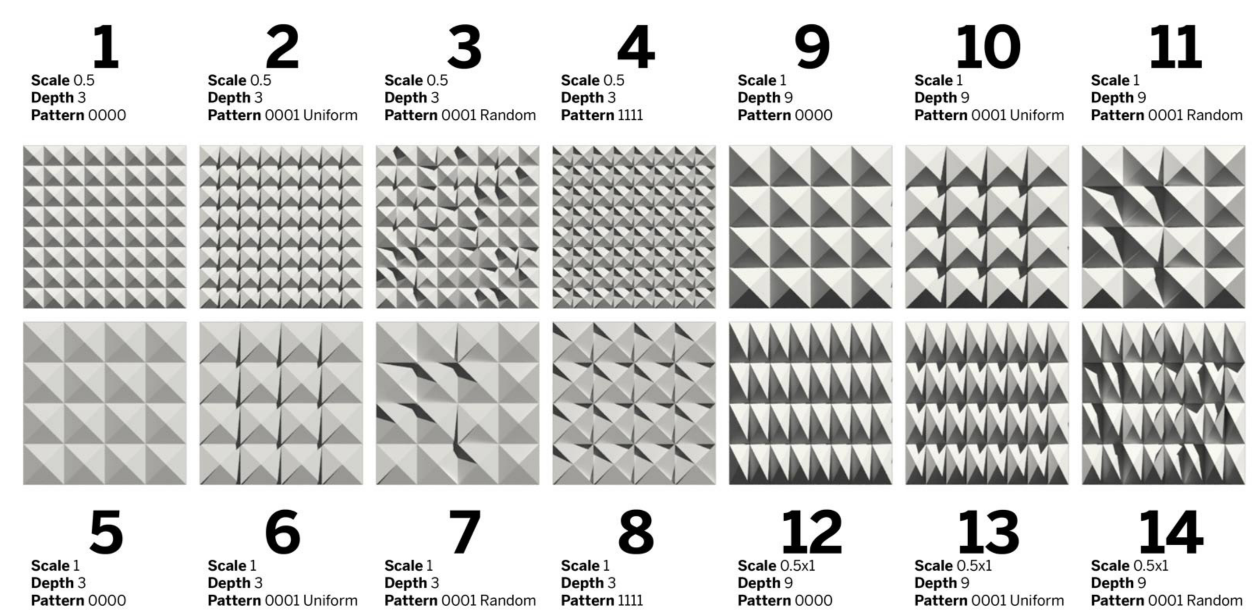
The panelization is based on enironmental factors such as sun exposure, wind direction and temperature. These enironmental parameters are then overridden in certain areas by programatic factors such as program type and occupancy.

The double-layer panel consists of a wind harvesting EFTE layer and a new nano-solar energy layer on top. In areas with high winds the aperture on the solar layer gets wider or smaller to allow more or less wind flow based on the season. Conversely, the areas that recieve the most sunlight have panels with no aperature to maximize solar gain.

Acoustic Panel







Project by and Images courtesy: LMNTS.lmnarchitects.com