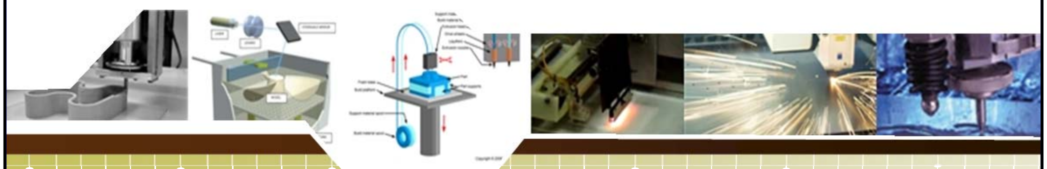
CAD/CAM Methods in Achieving Fully Dense Parts in Additive Manufacturing (AM)



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Ingram School of Engineering

TEXAS STATE UNIVERSITY SAN MARCOS
The rising STAR of Texas

Research Outline

1. An Overview of AM Processes
2. FDFF process
3. Problem statement & project objectives
4. Research methodology
5. Adaptive-slicing system development
6. Curved-form adaptive slicing
7. System implementation
8. DOE for FDFF process improvement
9. Conclusion & future works

1- Definitions of AM

AM is "A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."

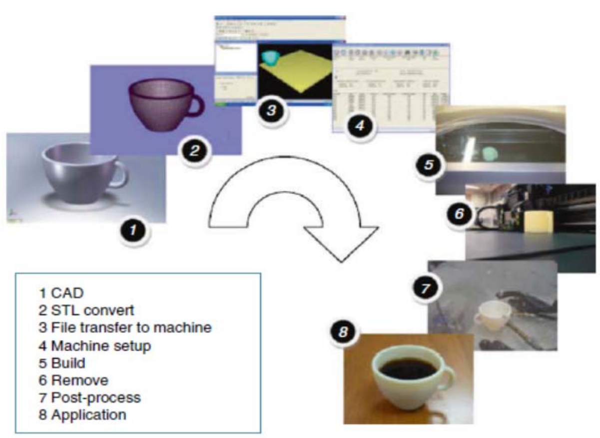
Video

In AM each layer is a thin cross-section of the part derived from the original CAD data. Obviously in the physical world, each layer must have a finite thickness to it and so the resulting part will be an approximation of the original data.

CAD Model **Different layer thicknesses**

2- Key Elements of AM (CAD to Part)

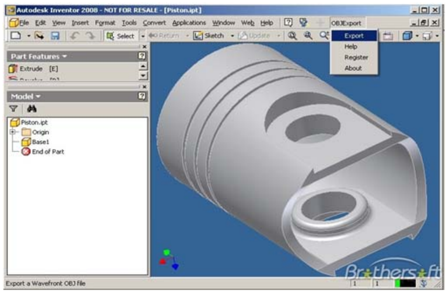
AM involves a number of steps that move from the virtual CAD description to the physical resultant part.



2- Key Elements of AM
Step 1: CAD

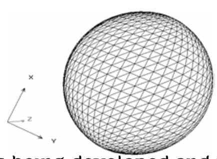
All AM parts must start from a software model that fully describes the external geometry. This can involve the use of almost any professional CAD solid modeling software.

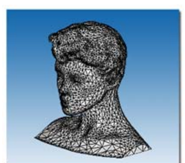
Reverse engineering equipment (e.g., laser scanning) can also be used to create this representation. (although technologies and software in this approach are not mature enough to capture everything and convert flawlessly yet)



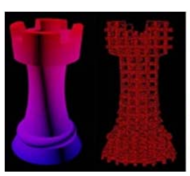
2- Key Elements of AM
Step 2: STL Convert

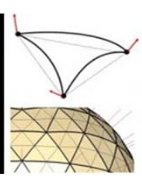
Nearly every AM machine accepts the STL file format (triangulated surface), which has become a de facto standard, and nearly every CAD system can output such a file format. This file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.





Additive Manufacturing File Format (AMF) is being developed and promoted to replace STL. Unlike its predecessor STL format, AMF supports features such as color and materials.

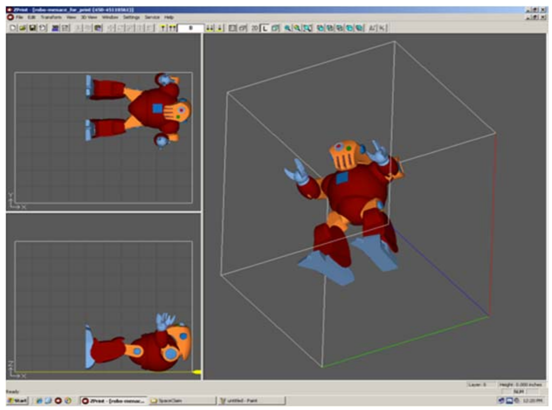




2- Key Elements of AM

Step 3: Transfer to AM Machine and STL File Manipulation

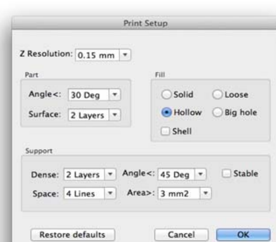
- The STL file describing the part must be transferred to the AM machine. Here, there may be some general manipulation of the file so that it is the correct size, position, and orientation for building.



2- Key Elements of AM

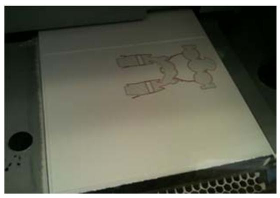
Step 4: Machine Setup

The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc.



2- Key Elements of AM
Step 5: Build

Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.



Printing in Zcorp 3D printing process

Laser sintering in SLS process

2- Key Elements of AM
Step 6: Removal

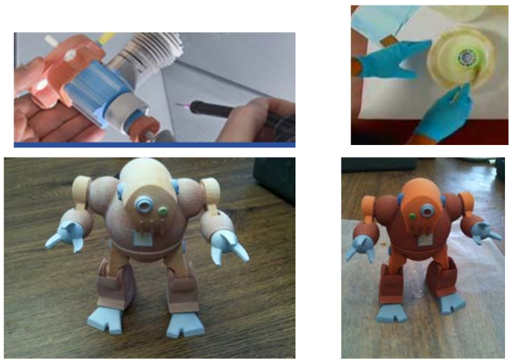
Once the AM machine has completed the build, the parts must be removed. This may require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts.

Zcorp 3D printing process

SLS process

2- Key Elements of AM
Step 7: Postprocessing

Once removed from the machine, parts may require an amount of additional cleaning up before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation.



Zcorp model cleaning and gluing

Bead blasting of the SLS part

2- Key Elements of AM
Step 8: Application

Parts may require priming and painting to give an acceptable surface texture and finish before use. They may also be required to be assembled together with other mechanical or electronic components to form a final model or product.

U.S. FDA has approved the 3D printed implant

An electromechanical system with combination of parts made in AM and non AM processes

NASA is hoping that astronauts will be able to 3D print their own tools in space

3- Uses of AM Parts
3 Fs: Form, Fit, and Function

The initial models were used to help fully appreciate the shape and general purpose of a design (Form).

Improved accuracy in the process meant that components were capable of being built to the tolerances required for assembly purposes (Fit).

Improved material properties meant that parts could be properly handled so that they could be assessed according to how they would eventually work (Function).

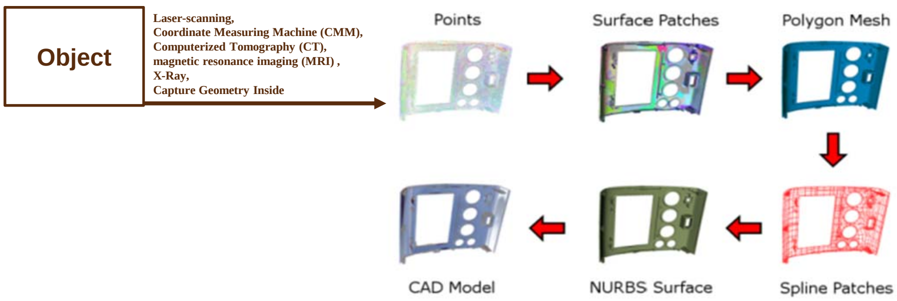
3- Uses of AM Parts
3 Fs: Form, Fit, and Function

- Exercise: From the web, find different examples of applications of AM that illustrate their use for “Form,” “Fit,” and “Function.”

4- CAD Tools

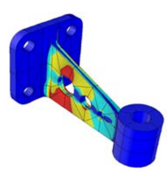
Variety of software might be used in the AM. All *3D CAD* systems can generate STL files. STL files can also be generated by Reverse Engineering (RE).

1. *Reverse Engineering* Technology, A physical part geometric data is captured and intermediate software convert them into STL file.

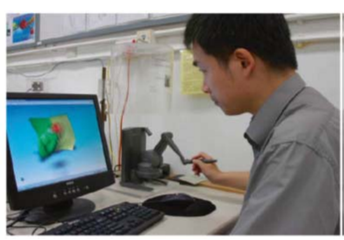


4- CAD Tools

2. *Computer-Aided Engineering* (CAE) software can calculate the mechanical properties of a design, such as forces, dynamics, stresses, flow, and other properties finite element method(FEM). These calculations backed up with AM-based experimental analysis, may be a useful solution.

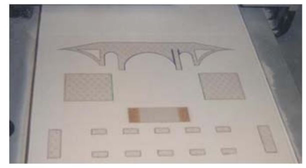


3. *Haptic-Based CAD* software use a robotic haptic feedback device called the Phantom provide force feedback relating to the virtual modeling environment. It provide more organic and freeform surfaces and can be used widely by nonengineer designers, sculptors, other artists.

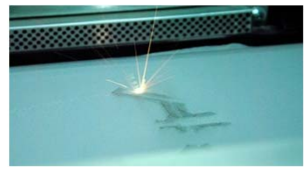


5- Current Technologies that Support Each Process

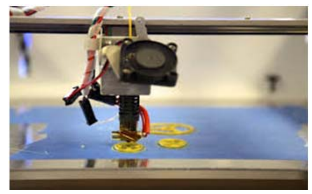
- **binder jetting,** an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.



- **directed energy deposition,** an additive manufacturing process in which focused thermal energy (e.g., laser, electron beam, or plasma arc) is used to fuse materials by melting as they are being deposited.



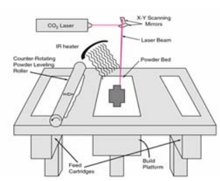
- **material extrusion,** an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.



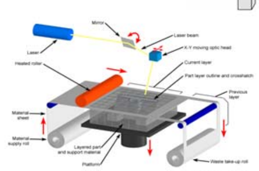
5- Current Technologies that Support Each Process

- **material jetting,** an additive manufacturing process in which droplets of build material (photopolymer and wax) are selectively deposited.

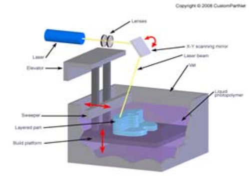
- **powder bed fusion,** an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.



- **sheet lamination,** an additive manufacturing process in which sheets of material are bonded to form an object.



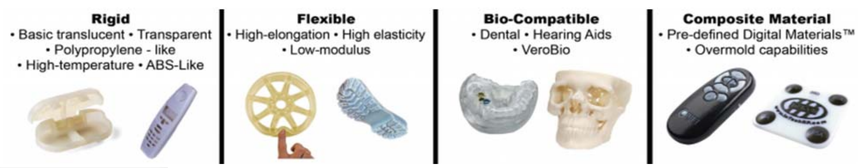
- **vat photopolymerization,** an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.



6- AM Materials

AM technology was originally developed around polymeric materials, waxes and paper laminates. Subsequently, there has been introduction of composites, metals, and ceramics. Common materials used by different AM processes are:

Engineered plastics	Photopolymer	Metals	Plaster	Sand	Ceramic
Paper	Concrete	Bio-materials	Wax	Thermo-plastic	Other



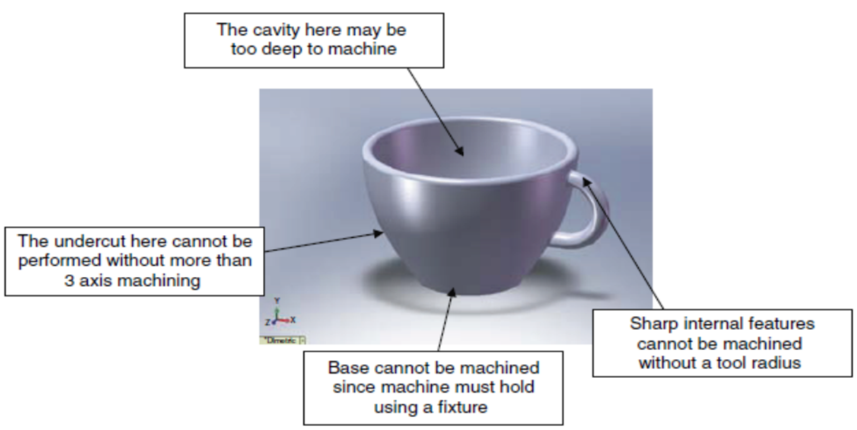
7- AM Advantages Over Traditional Manufacturing

- Fast: Since 3D CAD is being used as the starting point and the transfer to AM is relatively seamless, there is much less concern over data conversion or interpretation of the design intent. There is no need for multiple processes and tools.
  - Example: To fabricate a complex part, a craftsman must employ a variety of construction methods, ranging from hand carving (tedious, difficult, and prone to error), through molding and forming techniques (messy and obviously requires the building of one or more molds), to CNC machining (requires careful planning and a sequential approach). AM can simplify many of these multi-stage processes.
- Geometry complexity: Because they build parts layer-by-layer, AM processes are not constrained. Undercuts and internal features can be easily built without specific process planning.

8- AM versus CNC comparison

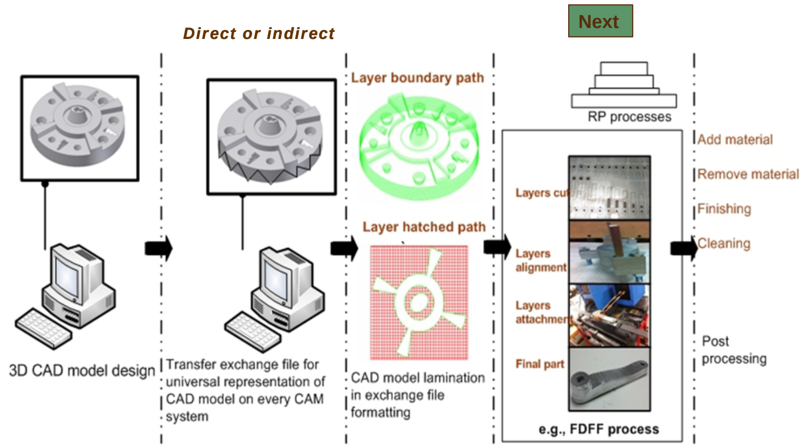
	CNC	AM
Material	Uses soft material (machineable foams and waxes) for multistage process (casting), uses hard materials (steel) in final product. Well defined materials.	Parts may have voids or anisotropy (direction) that are a function of part orientation.
Speed	CNC cuts faster than AM adds materials but it requires considerable setup and process planning, particularly as parts become more complex in their geometry. Speed must therefore be considered in terms of the whole process rather than just the physical interaction of the part material.	Overall, AM is faster.
Complexity	Since a machining tool must be carried in a spindle, there may be certain accessibility constraints or clashes preventing the tool from being located on the machining surface of a part.	The higher the geometric complexity, the greater the advantage AM has over CNC.
Accuracy	The accuracy of CNC machines is mainly determined by a similar positioning resolution along all three orthogonal axes and by the diameter of the rotary cutting tools.	AM machines generally operate with a resolution of a few tens of microns. Typically, the vertical build z axis corresponds to layer thickness and this would be of a lower resolution compared with the two axes in the build plane.
Geometry	Even with 5 axis CNC it is almost impossible to built Undercuts, enclosures, sharp internal corners	AM breaks up a 3D problem into a series of simple 2D cross-sections, therefore complex parts can be manufactured.
Programming	CNC program needs tool selection, machine speed settings, approach position, and angle, etc. Incorrect programming results in severe damage and safety risk.	Very limited choices to change. In the worst case, the part will not be built very well.

8- AM versus CNC comparison



An overview of Fully Dense Freeform Fabrication (FDFF) process

Next



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RP processes

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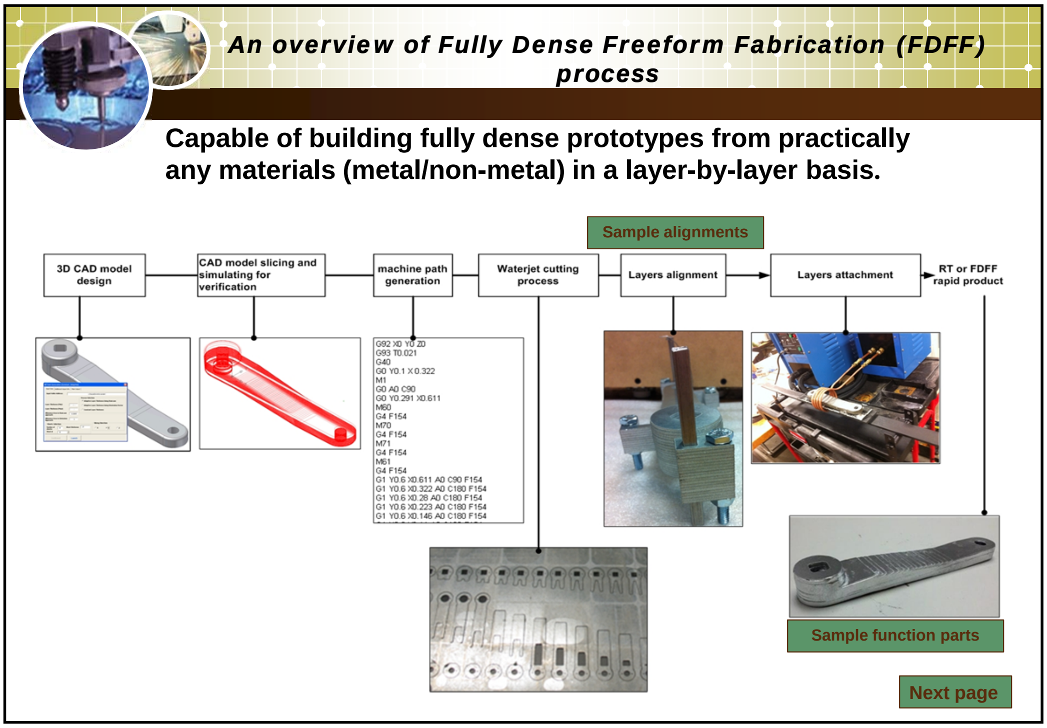
To name few widely used RP systems

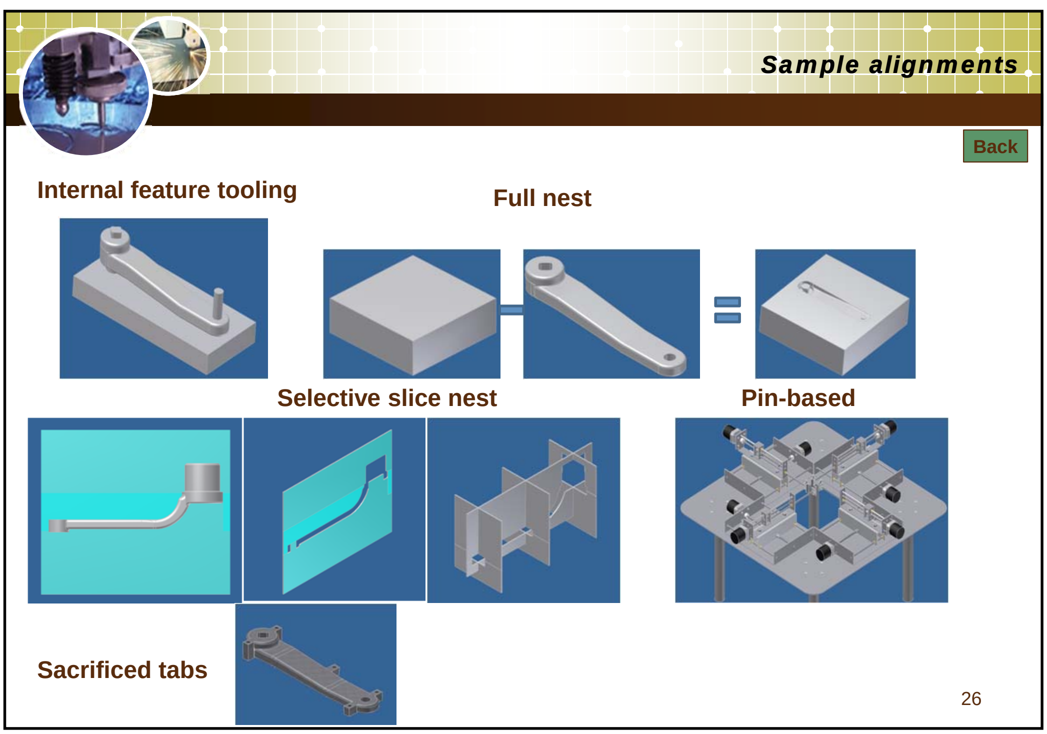
- •Direct metal laser sintering (DMLS)
- •Fused deposition modeling (FDM)
- •Selective laser sintering (SLS)
Stereolithography apparatus (SLA)
- •3D printing

Part prototyping approach

•layer-based processes: layer is built at once by applying binder or heat to the base material

•point by point-based processes: the machine's head is moved point-by-point to extrude, glue, fuse, or cut the material.


An overview of Fully Dense Freeform Fabrication (FDFF) process
Capable of building fully dense prototypes from practically any materials (metal/non-metal) in a layer-by-layer basis.
Sample alignments
3D CAD model design
CAD model slicing and simulating for verification
machine path generation
Waterjet cutting process
Layers alignment
Layers attachment
RT or FDFF rapid product
G92 X0 Y0 Z0
G93 T0.021
G40
G0 Y0.1 X 0.322
M1
G0 A0 C90
G0 Y0.291 X0.611
M60
G4 F154
M70
G4 F154
M71
G4 F154
M61
G4 F154
G1 Y0.6 X0.611 A0 C90 F154
G1 Y0.6 X0.322 A0 C180 F154
G1 Y0.6 X0.28 A0 C180 F154
G1 Y0.6 X0.223 A0 C180 F154
G1 Y0.6 X0.146 A0 C180 F154
Sample function parts
Next page


Sample alignments
Back
Internal feature tooling
Full nest
Selective slice nest
Pin-based
Sacrificed tabs
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Sample function parts

Back

Demolition hammer head

Bike crank

Crank-slider assembly

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Problem statement & project objectives

Problems

- **Staircase effect error**
- **Long build time**
- **Bad bonding for metallic parts**

Project objectives

- **Reduce the build time**
- **Improve the quality of parts fabricated by FDFF**

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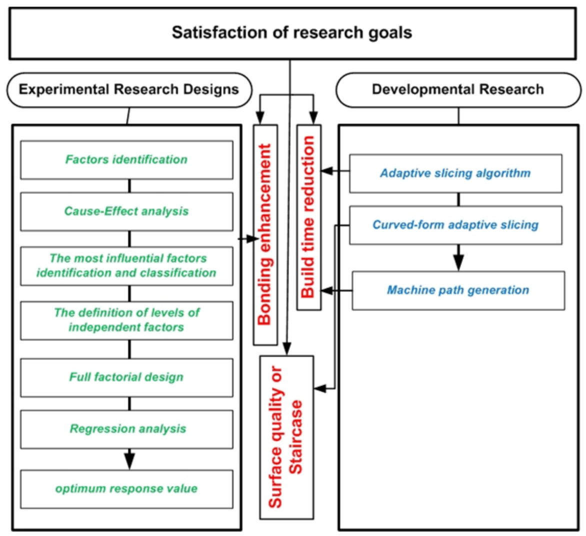
Research methodology



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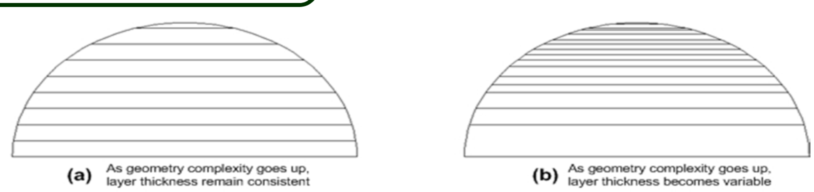
Types of 3D CAD model slicing

Uniform slicing

3D model is sliced into layers at uniform available thickness

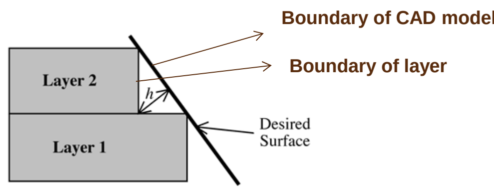
Adaptive slicing

3D model is sliced into layers at variable predetermined thicknesses



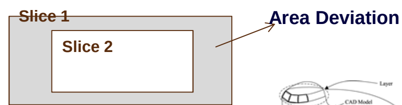
Geometry distortion error

1st well-known geometry distortion error : cusp height

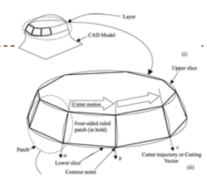


2nd geometry distortion error : Surface Roughness, Ra.

3rd geometry distortion error : Area deviation

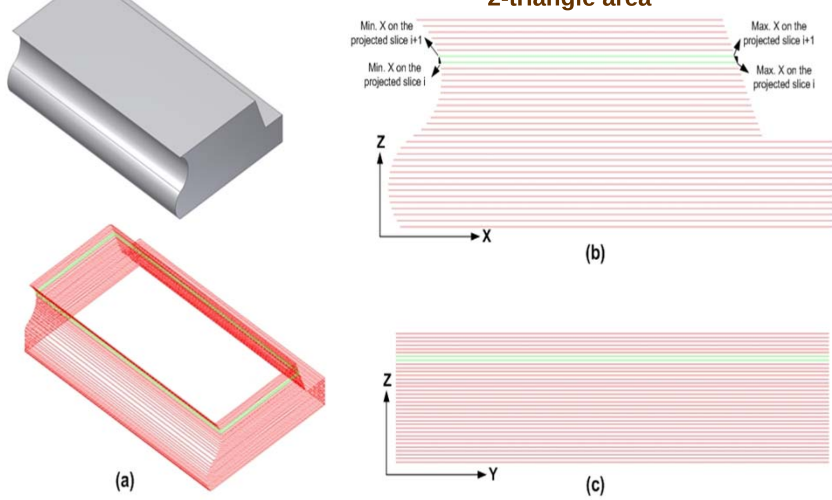


4th geometry distortion error : Volume deviation



New adaptive slicing approach

1-Area deviation
2-triangle area



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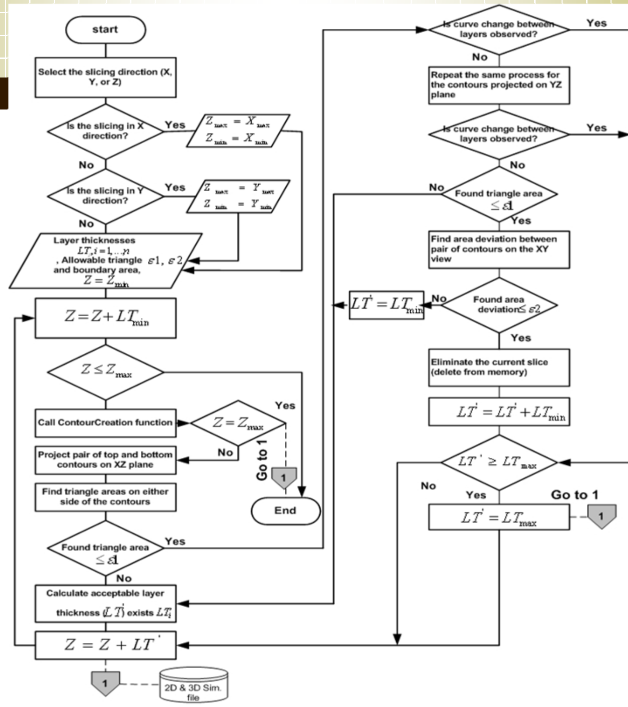
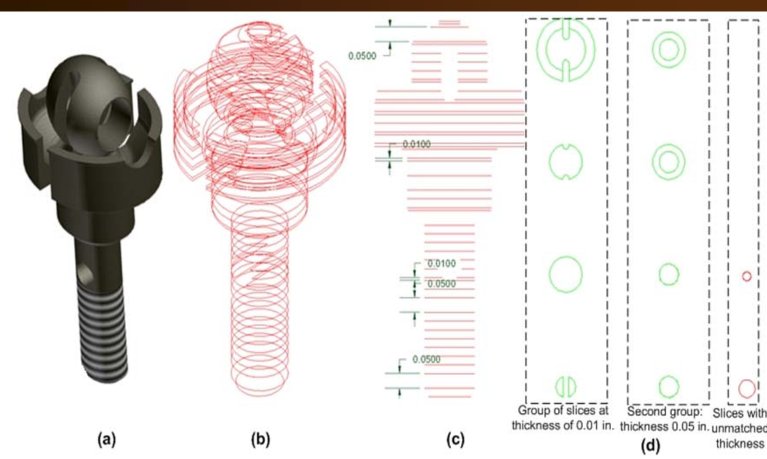
Algorithm flow chart



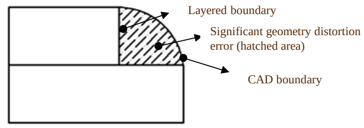
Results and software output



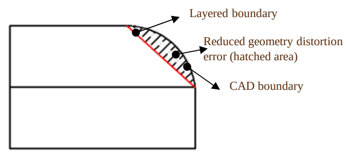
Visualization of the original Inventor CAD model (a), adaptive 3D slices (b), front view of the sliced CAD model (c), the illustration of few layers grouped based on their similar thickness and spread on 2D plane (d).

Comparison between adaptive and adaptive sloped-edge slicing

Staircase effect error for adaptive slicing

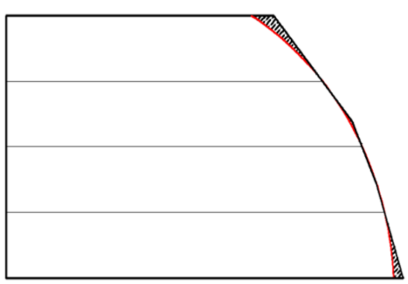


Staircase effect error for adaptive slicing for sloping surfaces

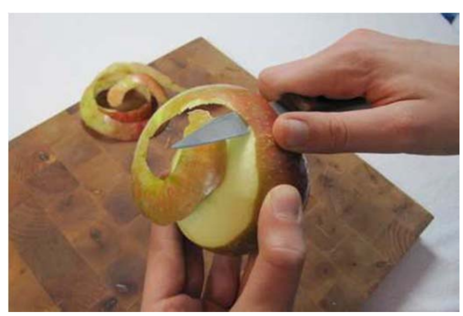


An Ideal curved-form adaptive slicing

Thin layers that form thick adaptive layer

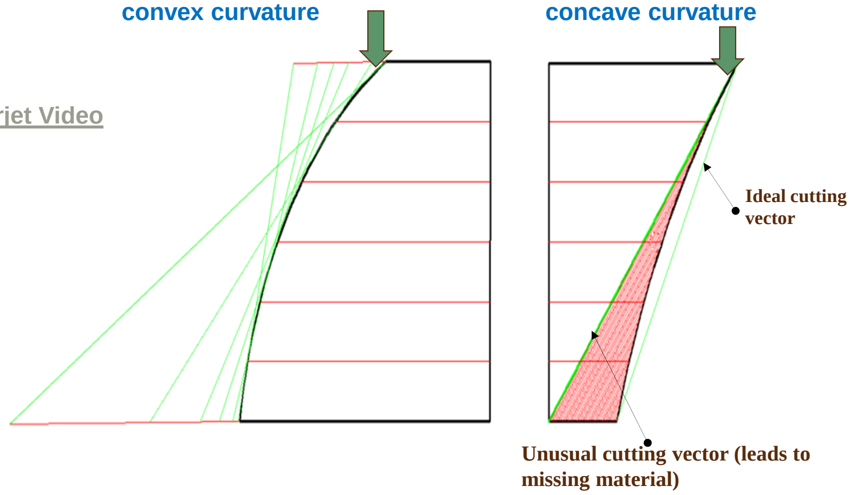


Hand peeling of an apple in which a knife's orientation and movement is continuously changed and adjusted to cut with minimum waste in each slice

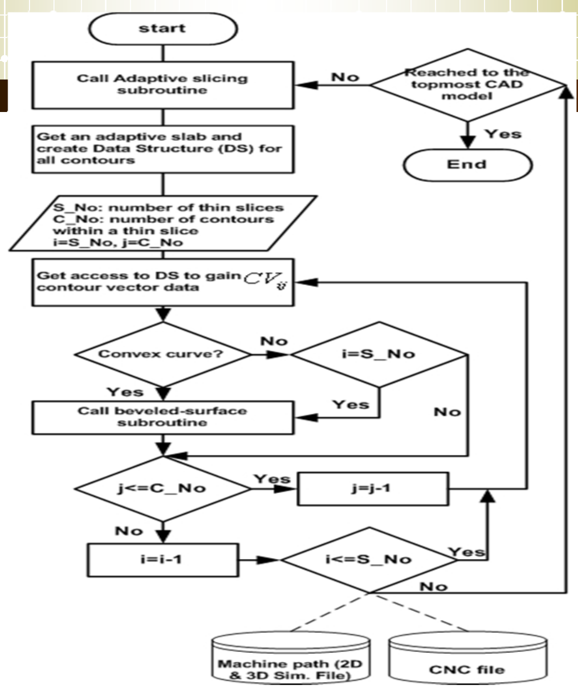


Curved-form adaptive slicing

5 Axis Waterjet Video

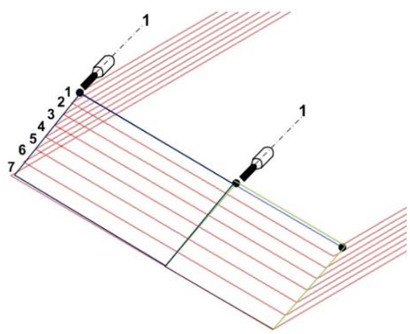


Algorithm flow chart

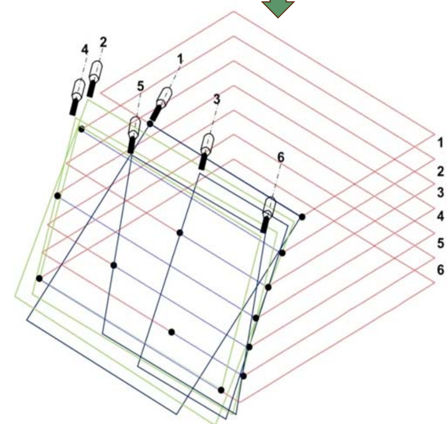


Cutting stream on 5-axis AWJ cutter machine

single cutting stream for concave



multiple cutting streams for convex edge



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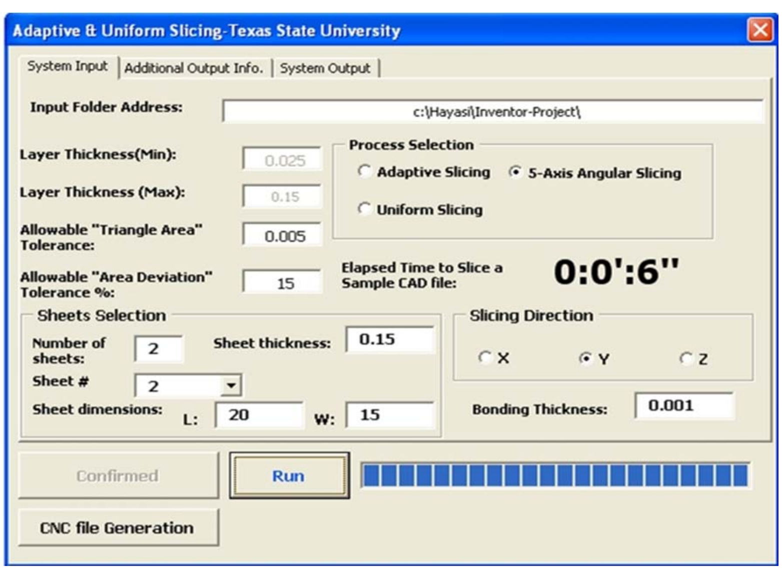
System implementation



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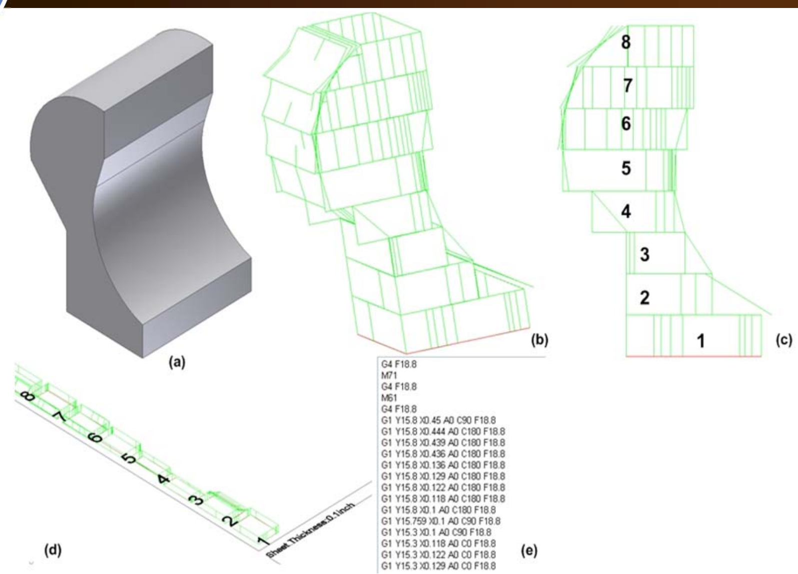
System results-example 1



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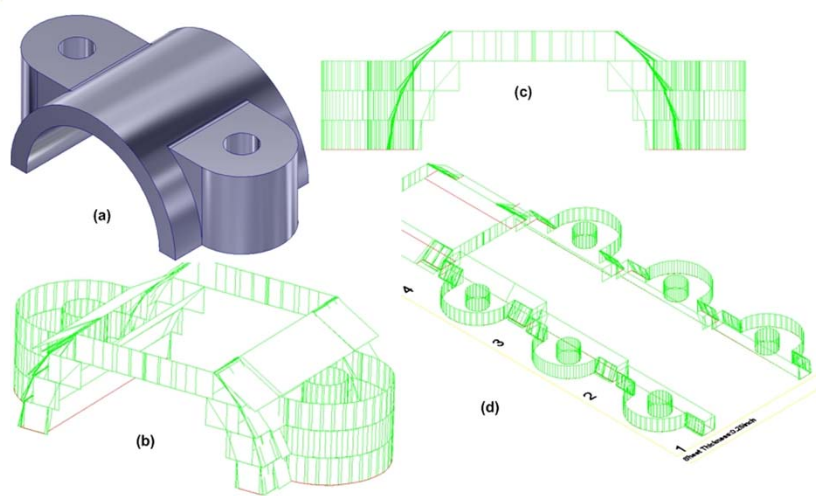
System results-example 2



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Design of Experiment for the improvement of FDFF process

Improvement of the FDFF process are measured by the following quality characteristics

- ***Surface roughness*** → ***Accurate machine feed rate***
- ***Part accuracy*** → ***Good layers alignment***
- ***Part tensile strength*** → ***Good layers attachment***

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Heat sources for layers bonding

Layers are bonded using direct heat sources: Torch flame

Sheet Type	**Galvanized steel or stainless steel**
Filler Material	**Tin & Bismuth**
Flux	**Sure Flo flux**
Software	**FDFF Adaptive Slicing software**
Heating Method	**Direct torch flame**

Soldering process

Layers are bonded using indirect heat sources: Induction heating

Sheet Type	**Galvanized steel or medium carbon steel**
Filler Material	**Silver Alloy Braze 560**
Flux	**Sure Flo flux**
Software	**FDFF Adaptive Slicing software**
Heating Method	**Induction**
Induction Setting	**700 Amps (Max)**
Coil Type	**Water cooled 4 turn 4 cm diameter**

Brazing process

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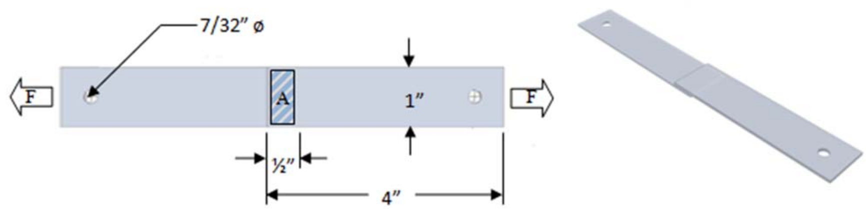
Strength measurement standard

ASTM Standard D 2294-96



Samples were pulled apart using a Tinius Olsen Electro Mechanical Tester, 600kN capacity

Affecting factors and DOE

Soldering process

Factors	Levels
%Tin & bismuth	%100-0
	%90-10
	%80-20
	%70-30
	%60-40
	%50-50
Filler Weight (grams)	0.1
	0.2
	0.3
Metal sheet type	Stainless steel
	Galvanized

DOE: Full factorial design

Number of runs: 6*3*2*2=72

Brazing process

Factors	Levels
Heating Time (second)	30
	35
	40
Filler Weight	Low
	High
Sheet thickness (inch)	0.065
	0.25

DOE: Full factorial design

Number of runs: 3*2*2*2=24

Results analysis

ANOVA analysis for soldering process

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	5	3604610	3604610	720922	11.08	0.000
B	2	266696	266696	133348	2.05	0.143
C	1	18191758	18191758	18191758	279.67	0.000
A*B	10	1115202	1115202	111520	1.71	0.115
A*C	5	2342676	2342676	468535	7.20	0.000
B*C	2	20556	20556	10278	0.16	0.854
A*B*C	10	1020887	1020887	102089	1.57	0.156
Error	36	2341721	2341721	65048		
Total	71	28904106				

S = 255.045 R-Sq = 91.90% R-Sq(adj) = 84.02%

A, B, and C denote tin percentage, filler material weight, and coded sheet, respectively.

A: %Tin & bismuth **B:** Filler Weight (grams) **C:** Metal sheet type

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Results analysis

ANOVA analysis for brazing process

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	7914974	7914974	3957487	26.08	0.000
B	1	2208873	2208873	2208873	14.56	0.002
C	1	3002630	3002630	3002630	19.79	0.001
A*B	2	23811337	23811337	11905668	78.47	0.000
A*C	2	12484105	12484105	6242053	41.14	0.000
B*C	1	466767	466767	466767	3.08	0.105
A*B*C	2	2038969	2038969	1019485	6.72	0.011
Error	12	1820703	1820703	151725		
Total	23	53748358				

S = 389.519 R-Sq = 96.61% R-Sq(adj) = 93.51%

A, B, and C denote heating time, sheet thickness, and filler weight, respectively.

A: Heating Time (second) **B:** Sheet thickness (inch) **C:** Filler Weight

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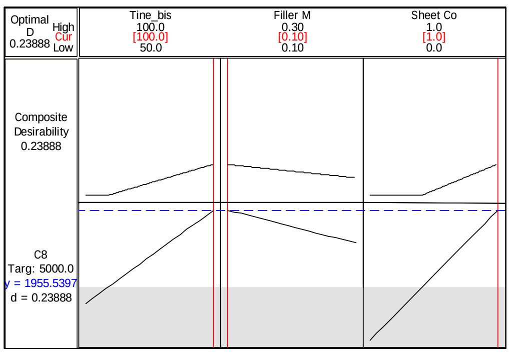
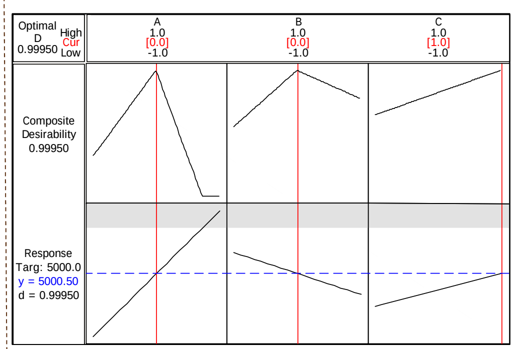
Optimum process selection

Target Value for both are 5000psi

Optimal tensile strength for soldering process



Optimal tensile strength for brazing process



Much higher tensile strength (5000.50psi) at the same target value

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Future Work

Future work

- Develop the system independent of Autodesk Inventor
- Automated layer alignment
- Develop study on the sheet and filler material types
- FDFF process system integrity

Thank You !