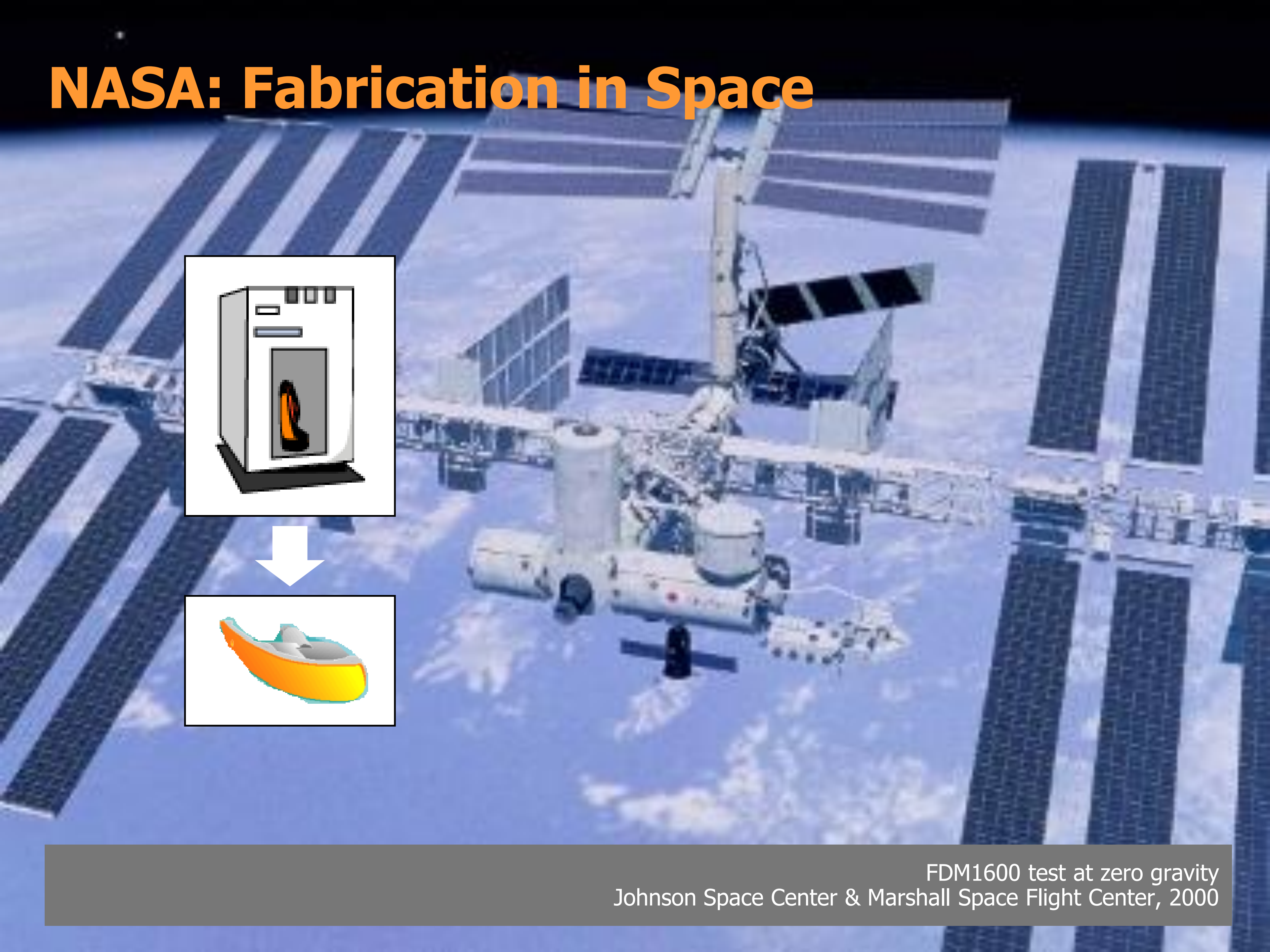
RP (Rapid Prototyping)

November 12, 2008

Sung-Hoon Ahn

School of Mechanical and Aerospace Engineering
Seoul National University

NASA: Fabrication in Space



FDM1600 test at zero gravity
Johnson Space Center & Marshall Space Flight Center, 2000

Requirements in Product Development

- Functional or aesthetic assessment
- Communication aids, visualization
- Assemblability checking
- 25 or 30% of product development budget are spent on physical prototypes and testing
- Rapid Prototyping fabricates a part of arbitrary shape directly from CAD model by forming thin layers of the part layer by layer

Introduction to RP

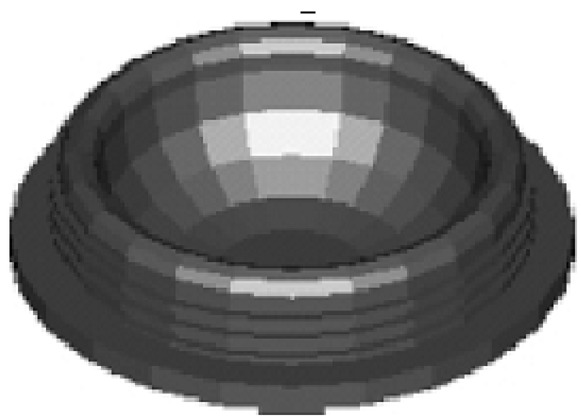
- Other name of RP
  - Layered Manufacturing
  - Rapid Prototyping and Manufacturing
  - Solid Freeform Fabrication (SFF)

- Group of related technologies that are used to fabricate physical objects directly from CAD data

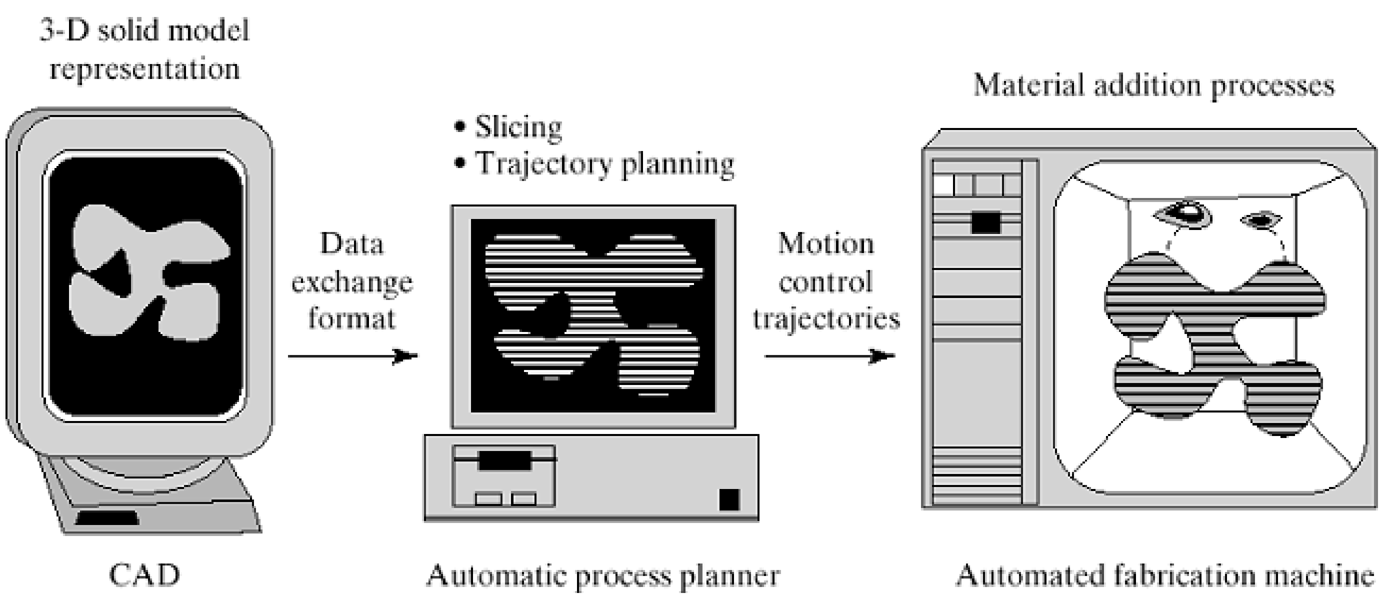
- Add and bond materials in layers to form objects

- Offer advantages compared to classical subtractive fabrication methods

Basic Idea



(a)

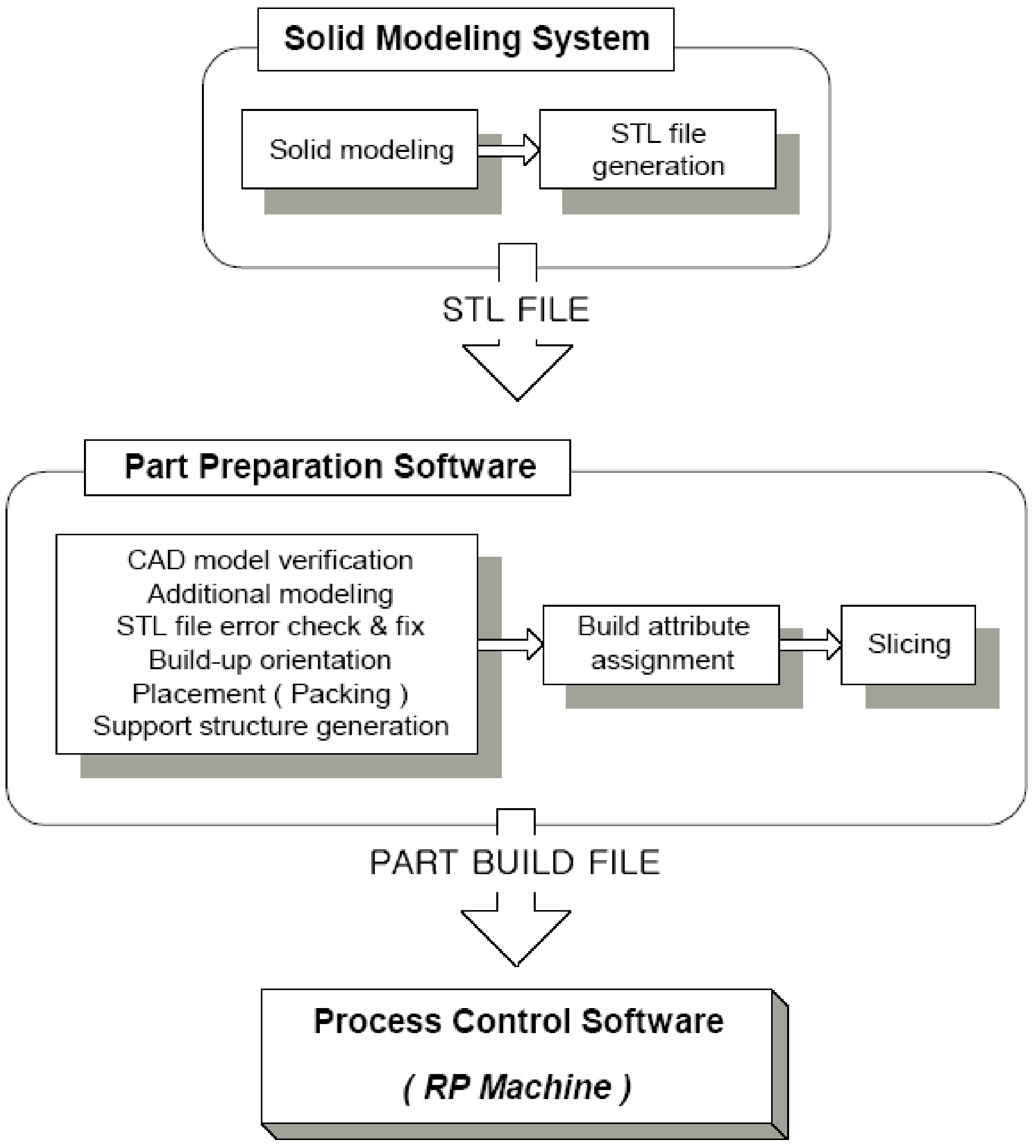


(b)

Advantages of RP

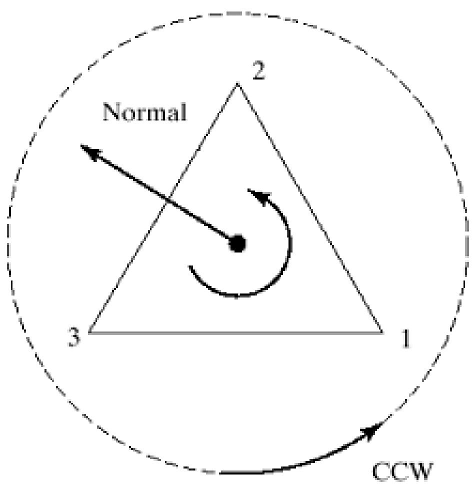
- No need to define a blank geometry
- No need to define set-ups and material handling
- No need to consider jigs, fixtures, and clamping
- No need to design mold and die

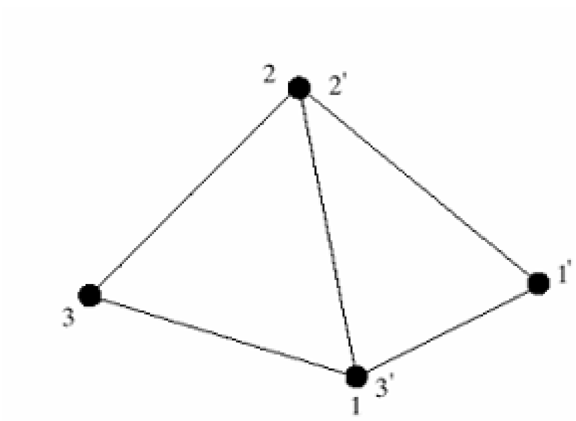
General System Configuration of RP



Stereo Lithography Process

- Geometry Input : STL file format
  - Developed for STereo Lithography
  - *De facto* standard for RP data
  - Most CAD systems support STL format





Stereo Lithography Process (cont.)

- STL file formats

```
solid example
    facet normal 6.89114779E-02 -9.96219337E-01 -5.28978631E-02
    outer loop
        vertex 2.73239994E+01 1.08957005E+01 4.57905006E+01
        vertex 2.81019993E+01 1.09582005E+01 4.56250000E+01
        vertex 2.75955009E+01 1.09116001E+01 4.58456993E+01
    endloop
    endfacet
        :
        :
endsolid example
```

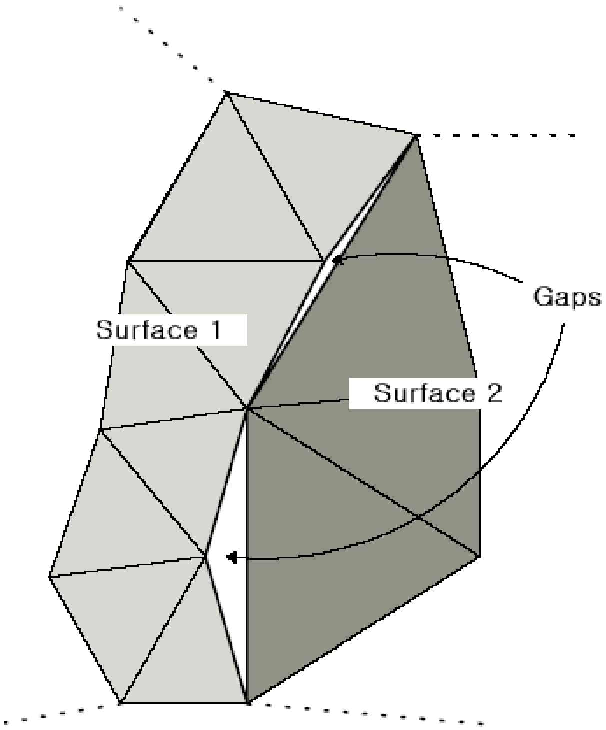
(a) ASCII

Byte	Type	Description
80	String	Head information such as the CAD system used
4	Unsigned long integer	Number of facets
First Triangle Definition		
4	Float	Normal x
4	Float	Normal y
4	Float	Normal z
4	Float	Vertex1 x
4	Float	Vertex1 y
4	Float	Vertex1 z
4	Float	Vertex2 x
4	Float	Vertex2 y
4	Float	Vertex2 z
4	Float	Vertex3 x
4	Float	Vertex3 y
4	Float	Vertex3 z
2	Unsigned long integer	Number of attributes bytes should be set to zero
Second Triangle Definition		
.. ..		

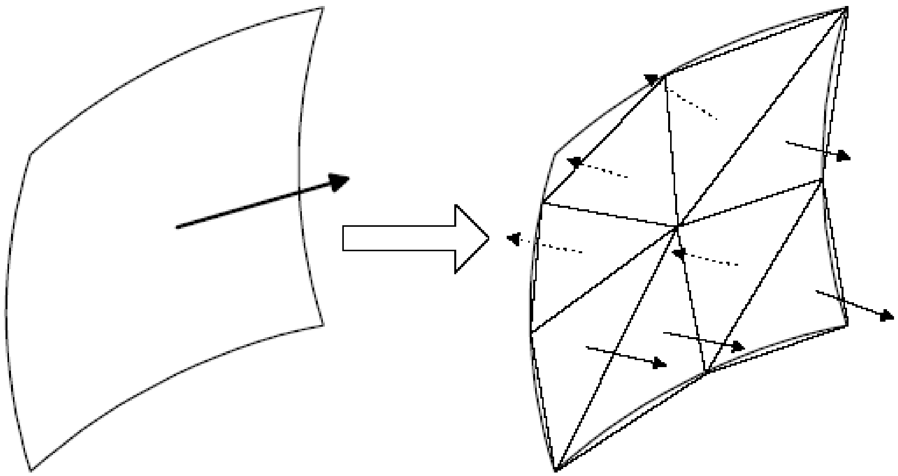
(b) Binary

Typical Errors in STL file

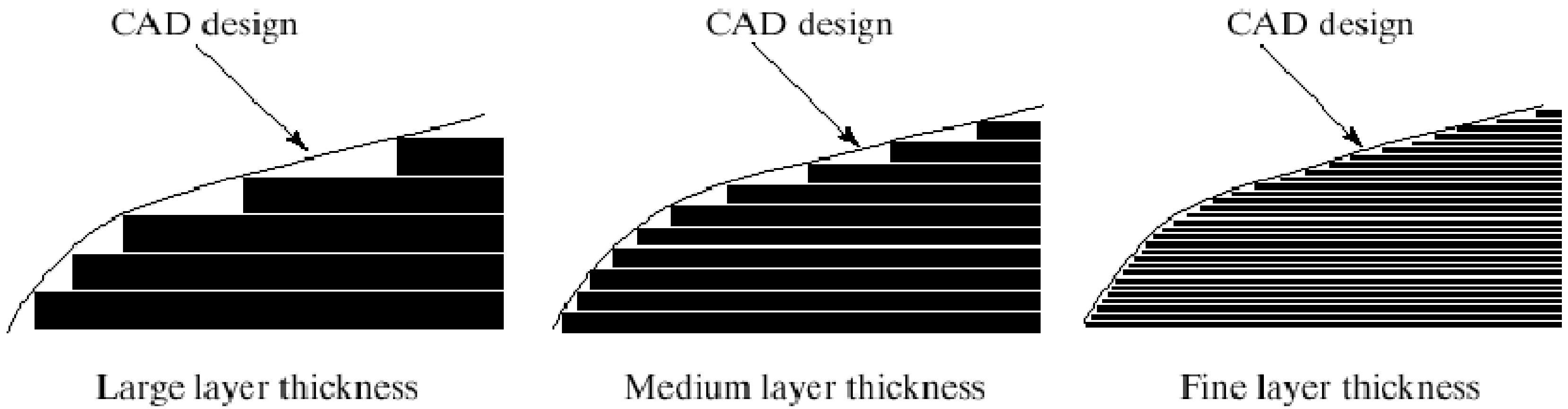
Gaps in STL file



Flipped normals in a facet

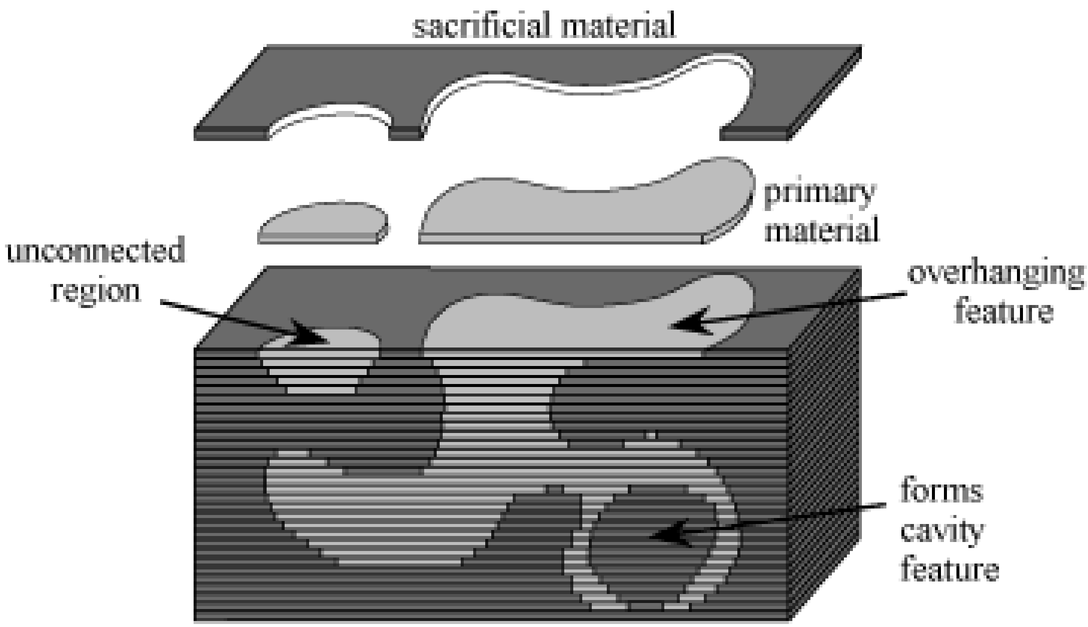


Stair-Step Effect

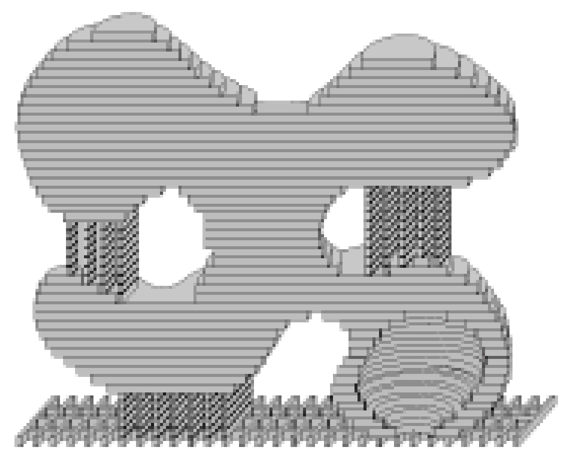


Surface roughness vs. build time

Support Structures



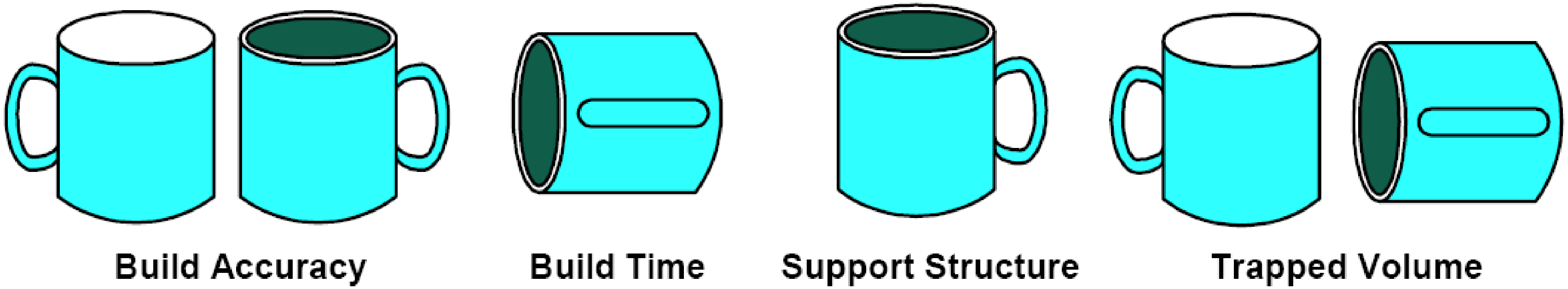
a. Complementary support.



b. Explicit support.

Determination of Build-up Direction

- Accuracy
- Build-up speed
- Trapped volume
- Necessity of support structure



Issues in RP

- Accuracy and Surface Finish

- Material
  - Stereo Lithography Resins
  - Metals
  - Ceramics and Paper

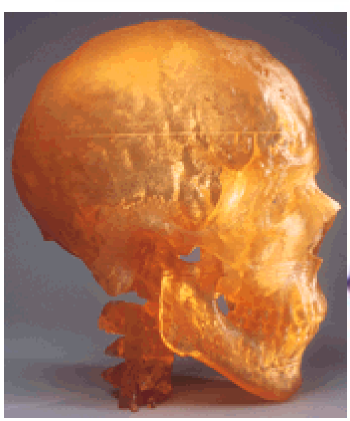
- Cost
  - Equipment
  - Maintenance

- Time

1. Stereo Lithography Apparatus (SLA)

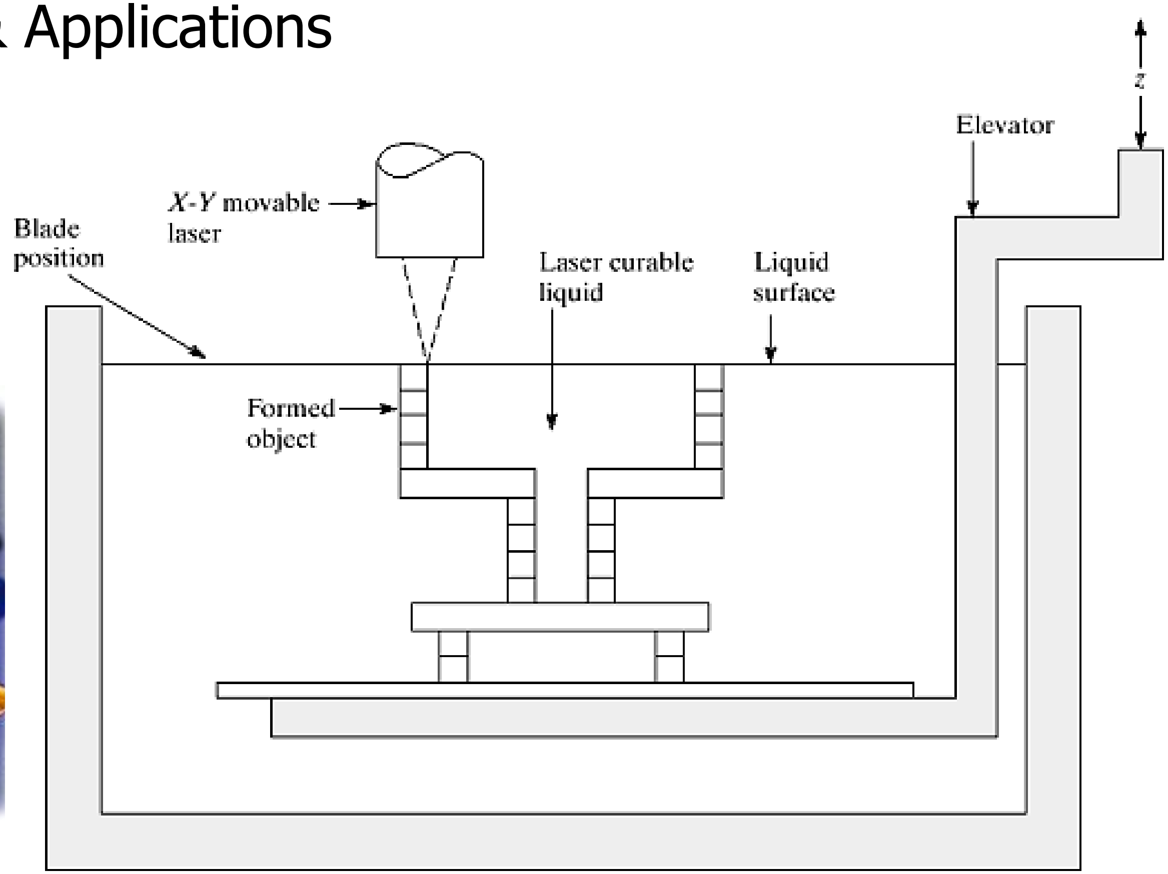
- Developed by 3D Systems, Inc
- Laser beam will scan the surface following the contours of the slice
- Commercial machines & Applications

SLA-3500



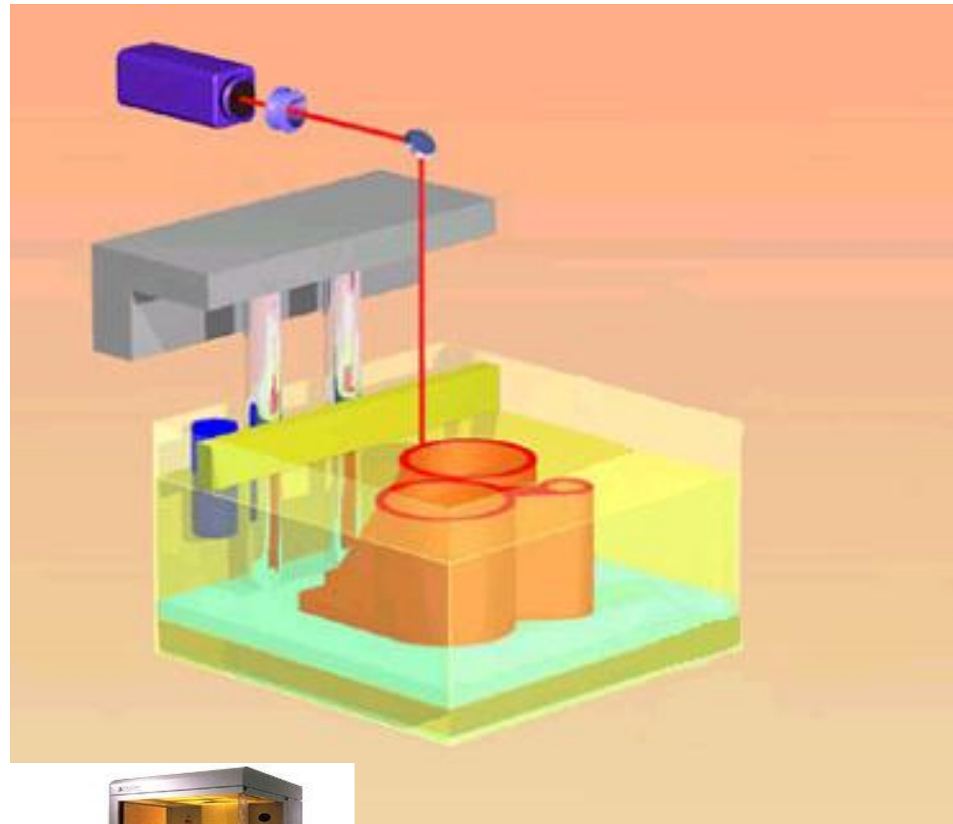
Skull

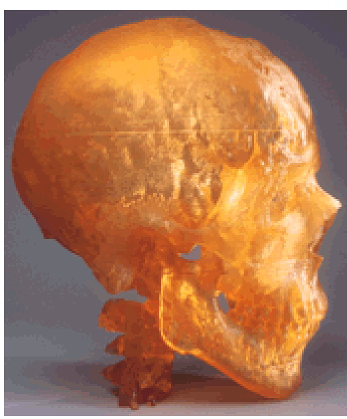
Manifold

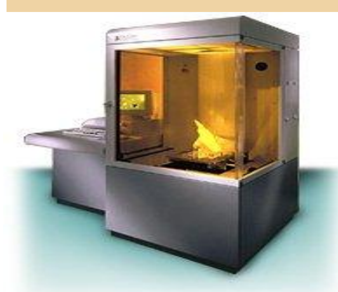


1. Stereo Lithography Apparatus (SLA)

- Developed by 3D Systems, Inc.
- Laser beam will scan the surface following the contours of the slice

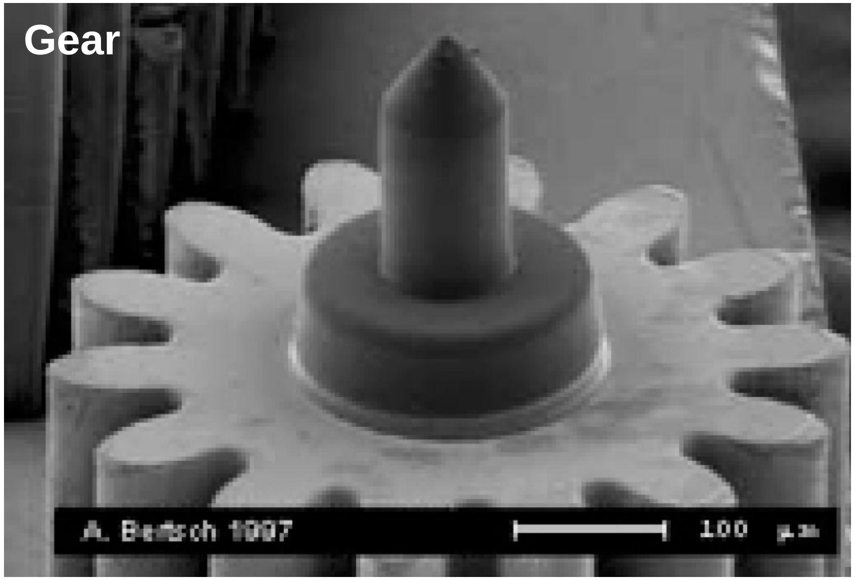


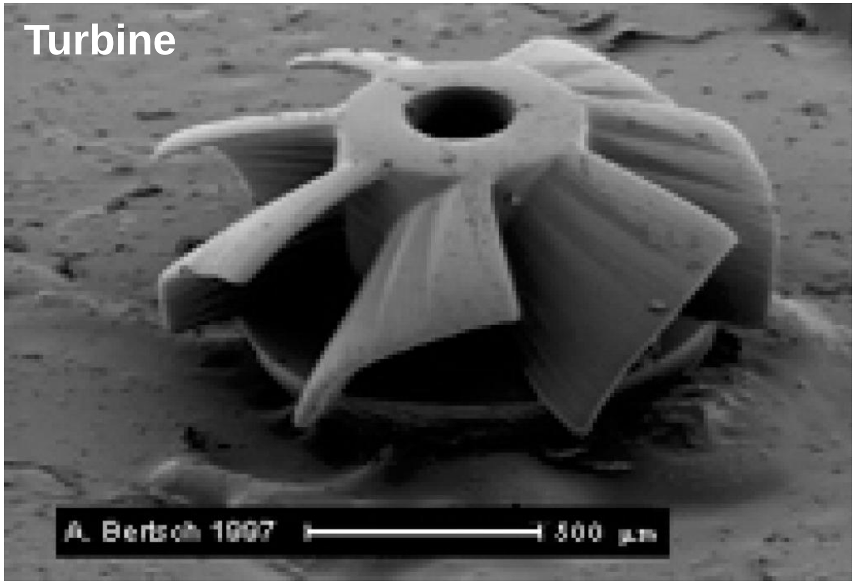


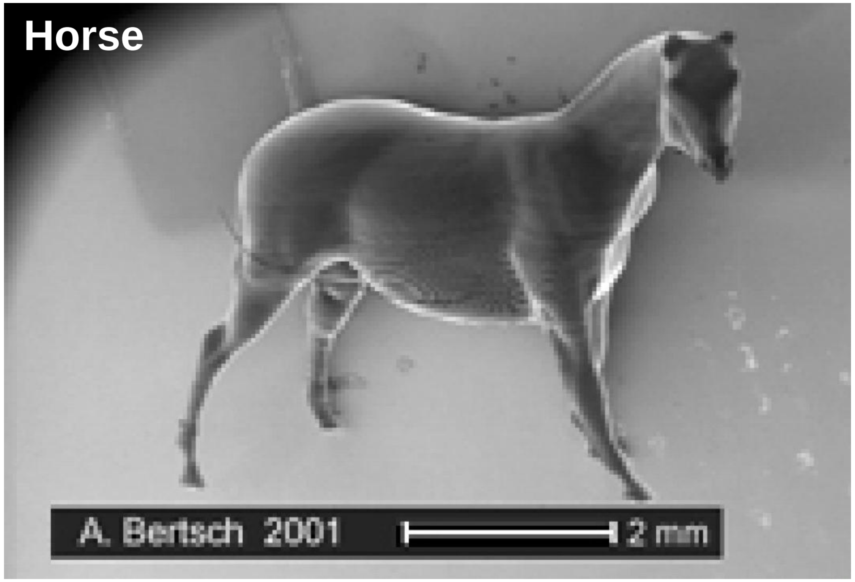


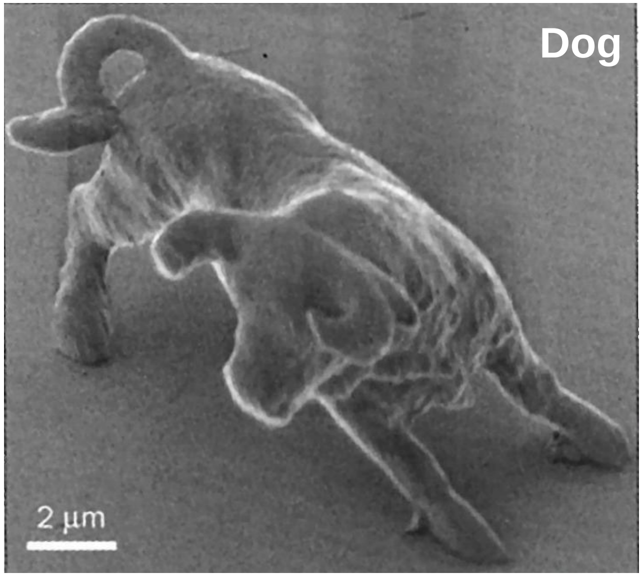
SLA-3500

Micro SLA Part



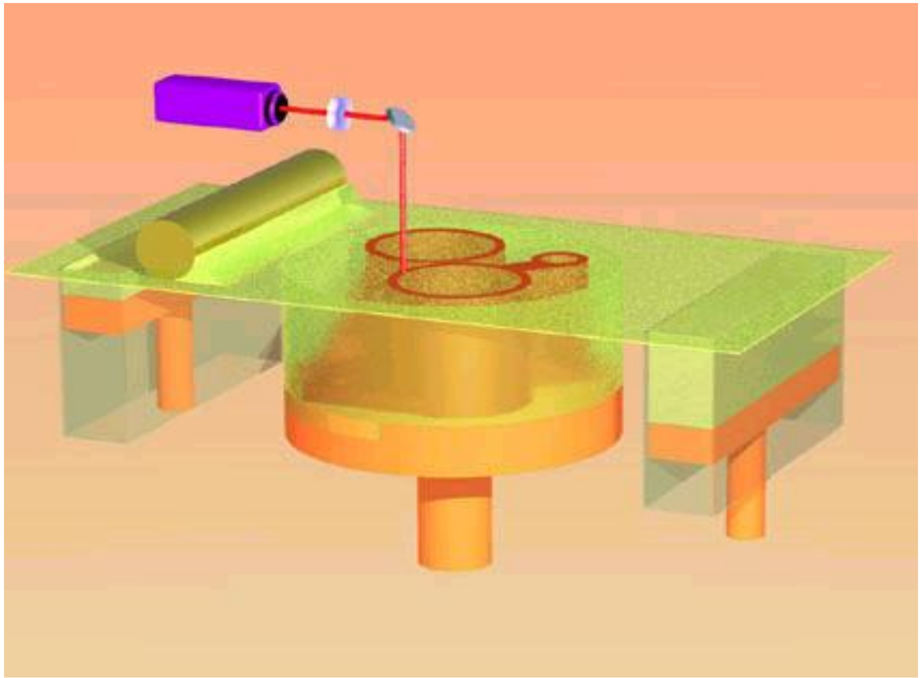






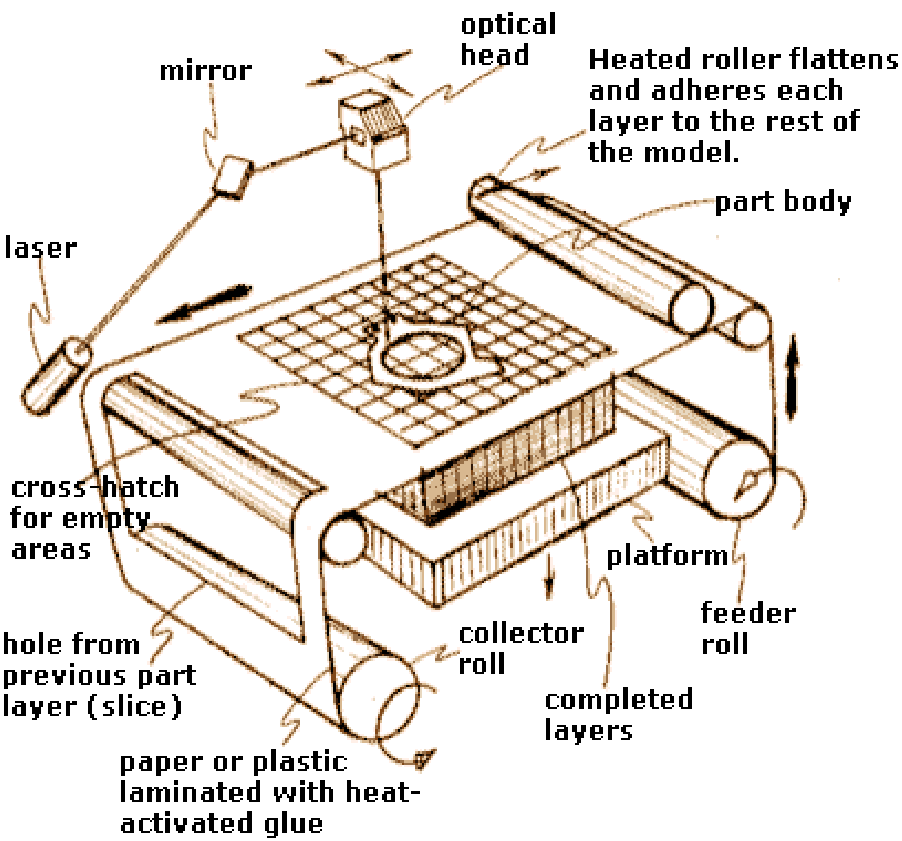
2. Selective Laser Sintering (SLS)

- Developed by The University of Texas at Austin
- Powders are spread over a platform by a roller
- A laser sinters selected areas causing the particles to melt and then solidify



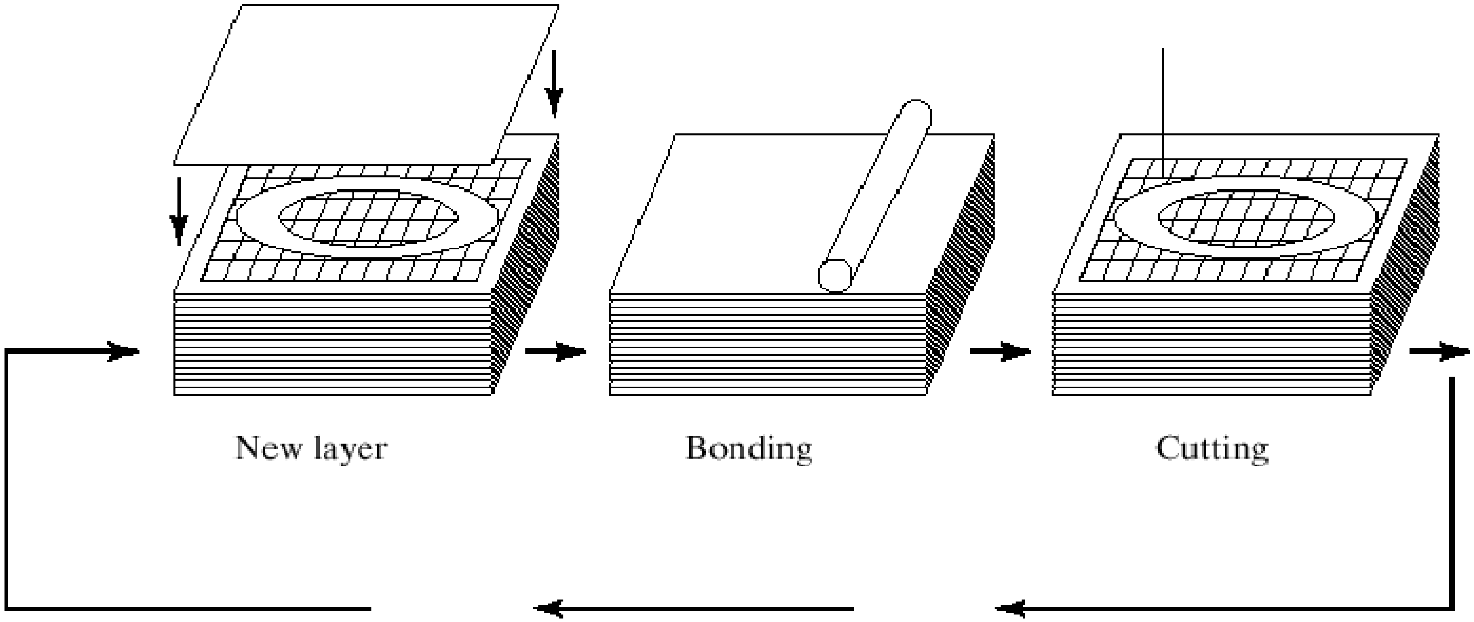
3. Laminated Object Modeling (LOM)

- Developed by Helysis
- The undersurface of the foil has a binder that when pressed and heated by the roller causes it to glue to the previous foil.
- The foil is cut by a laser following the contour of the slice

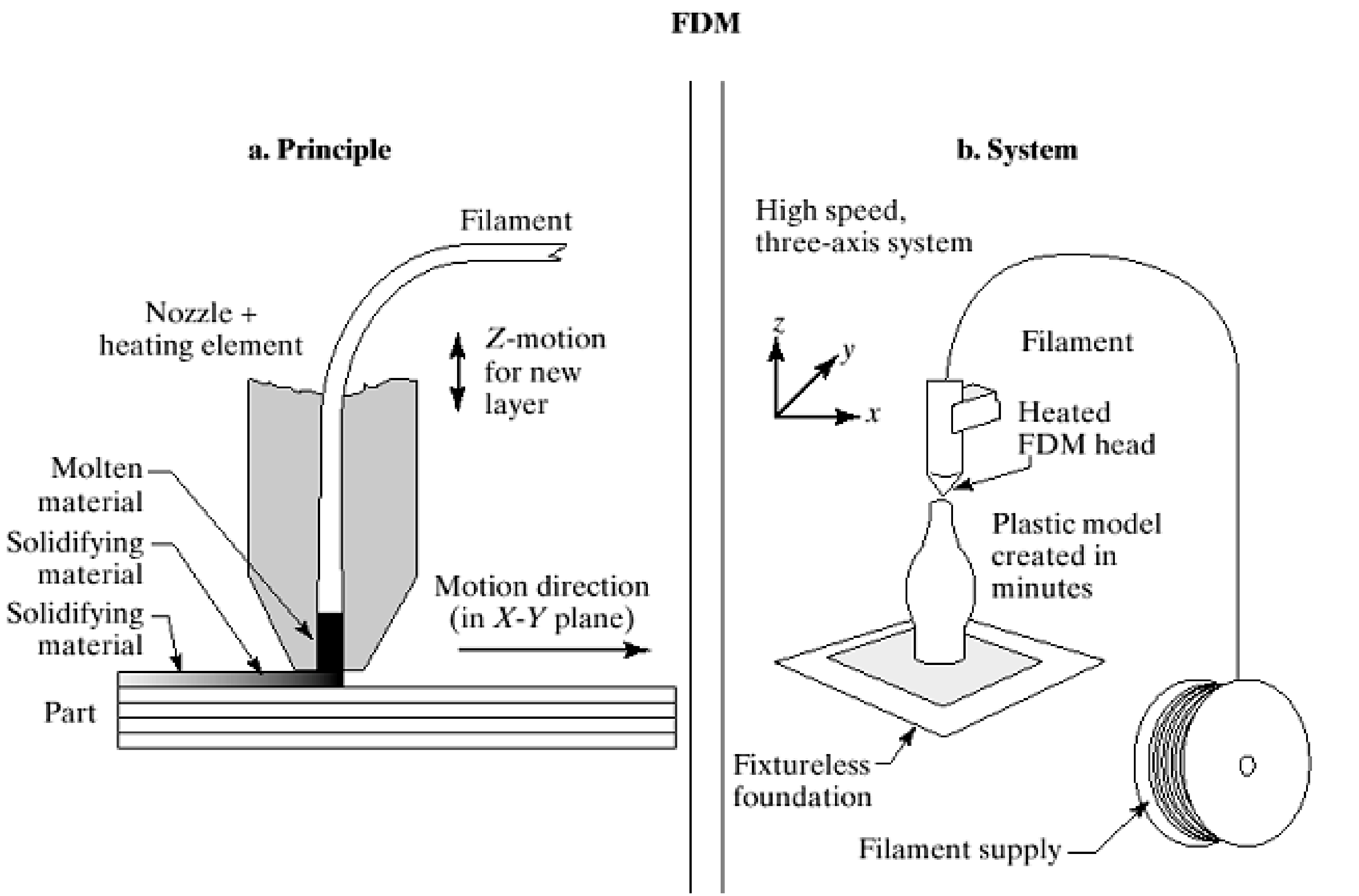


Helisys 2030E LOM machine Part envelope size 32"x22"x20"

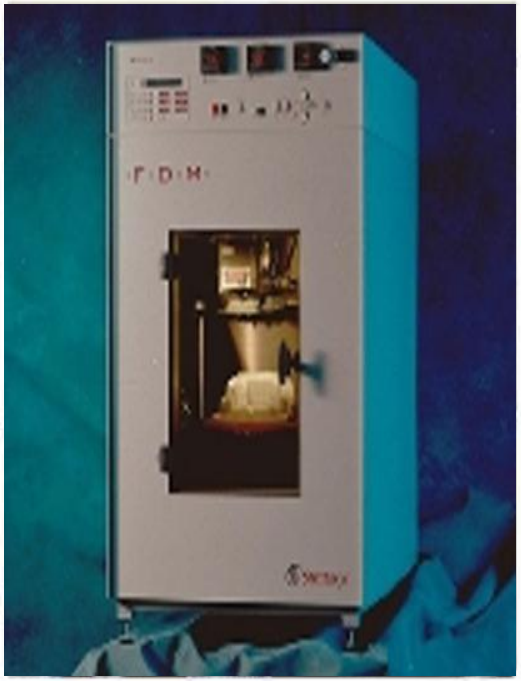
LOM Process

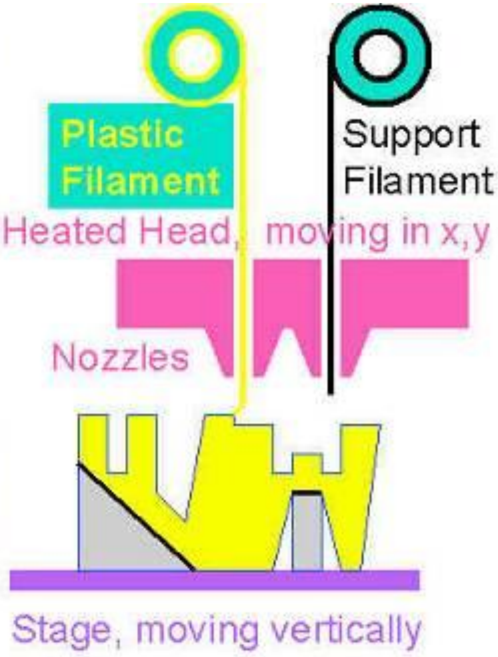


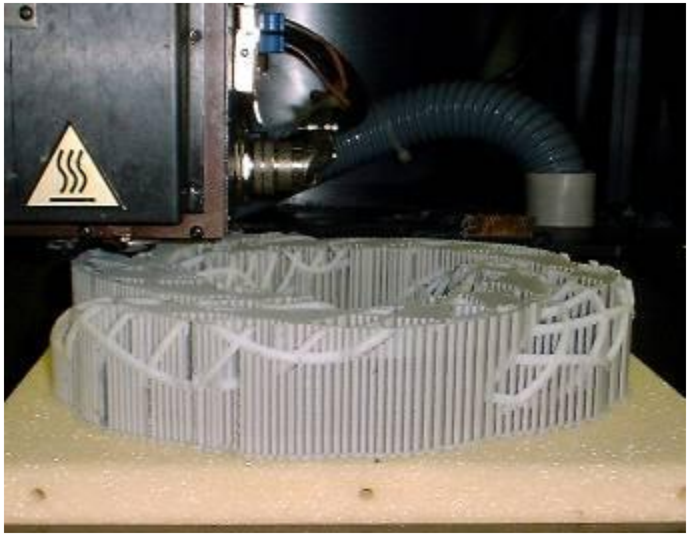
4. Fused Deposition Modeling (FDM)



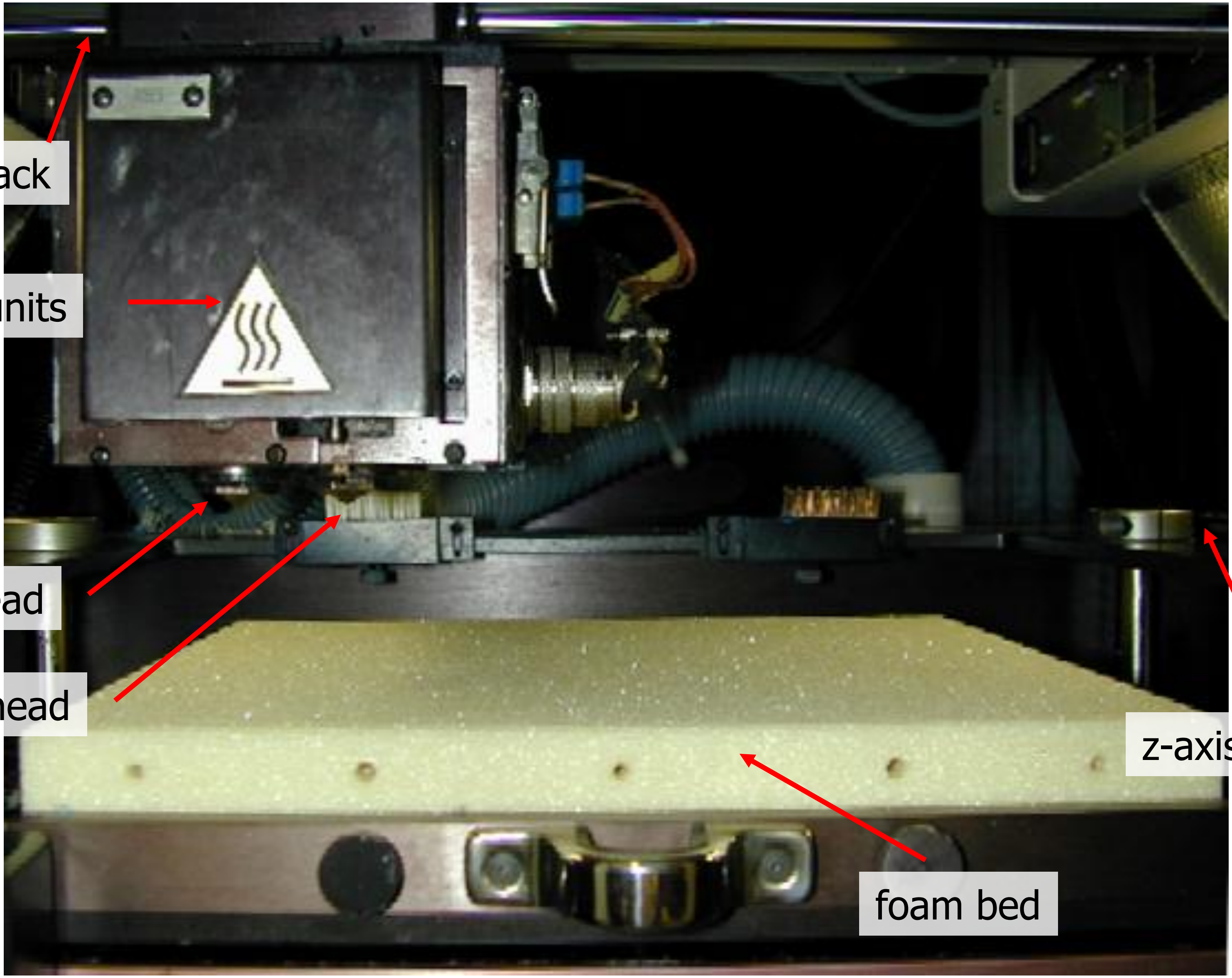
Fused Deposition Modeling (FDM)







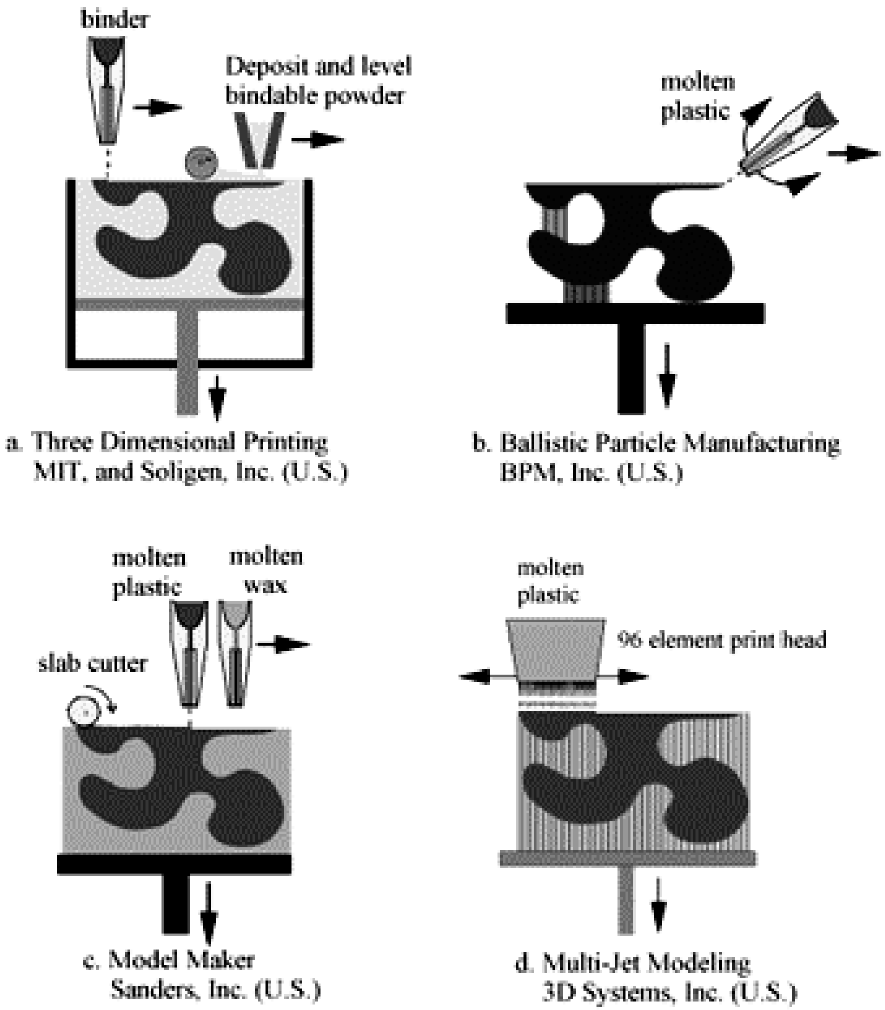
FDM Head



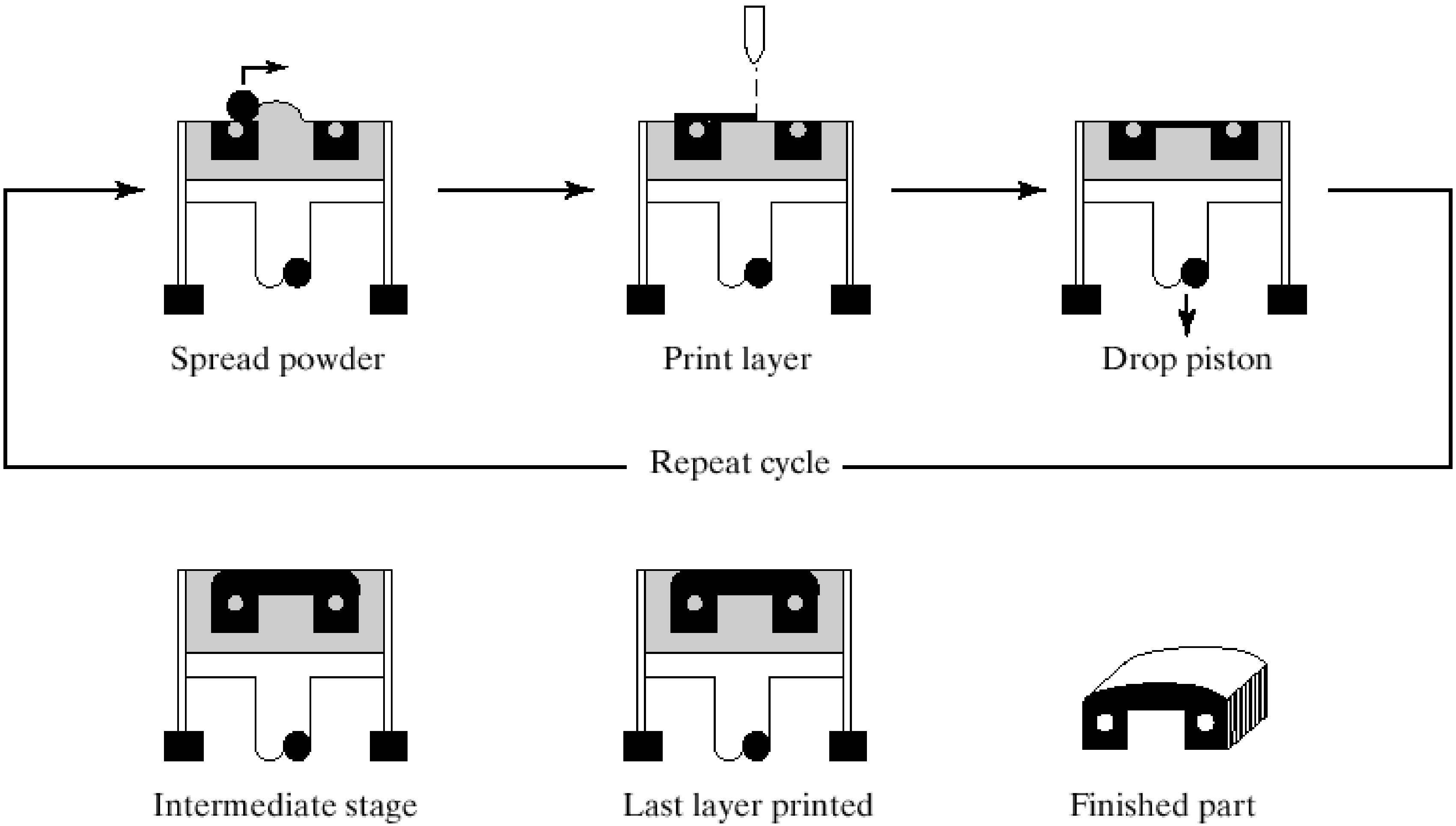
x-axis track
heating units
model head
support head
z-axis track
foam bed

5. 3D Printers

- Developed at MIT
- Parts are built upon a platform situated in a bin full of powder material.



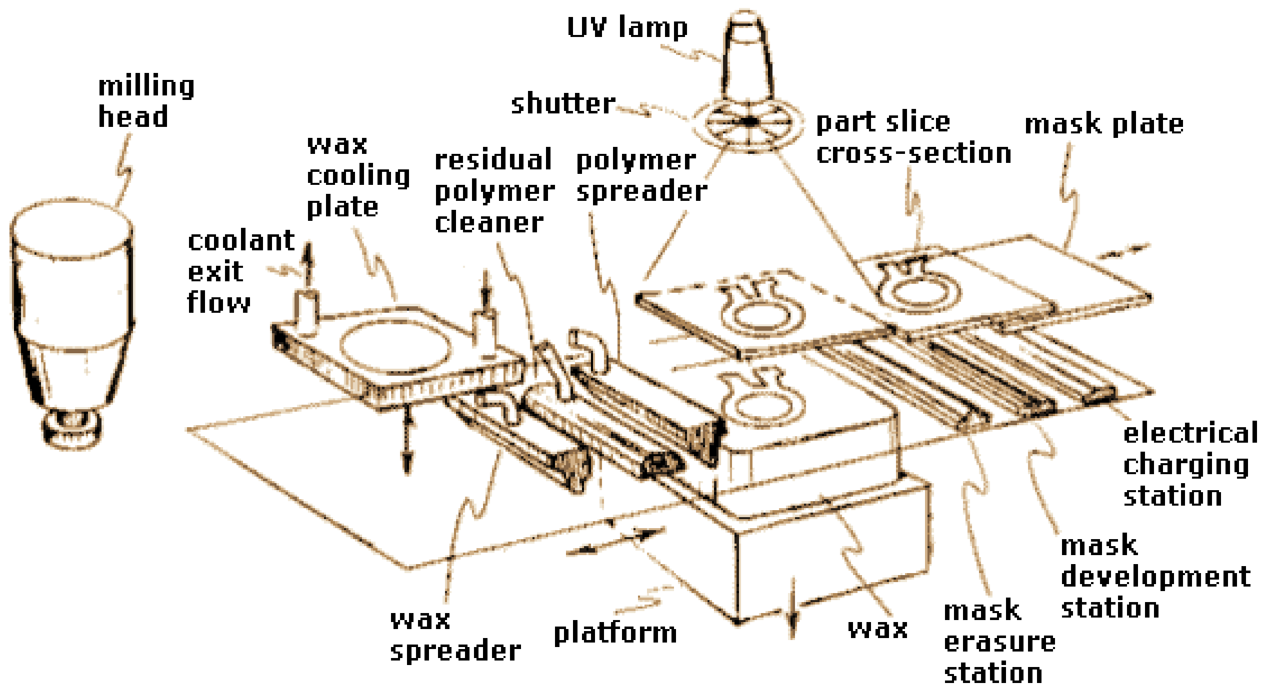
3D Printing Process



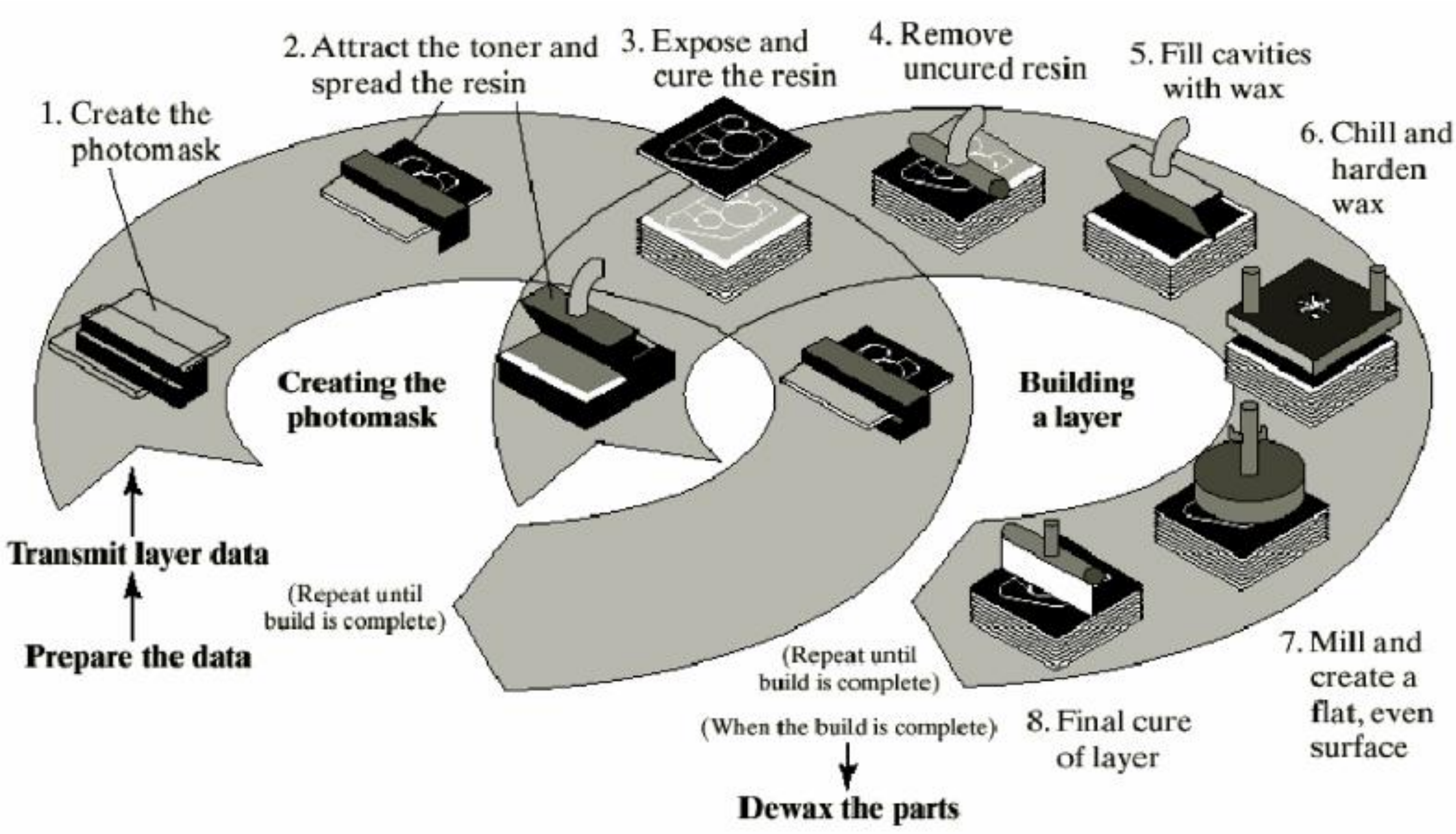
3-D printing method developed by Sachs and colleagues (2000)

6. Solid Ground Curing (SGC)

- Developed and commercialized by Cubital Ltd. (Israel)
- Uses a Photopolymer, sensitive to UV-light
- The vat moves horizontally as well as vertically
- The horizontal movements take the workspace to different stations in the machine



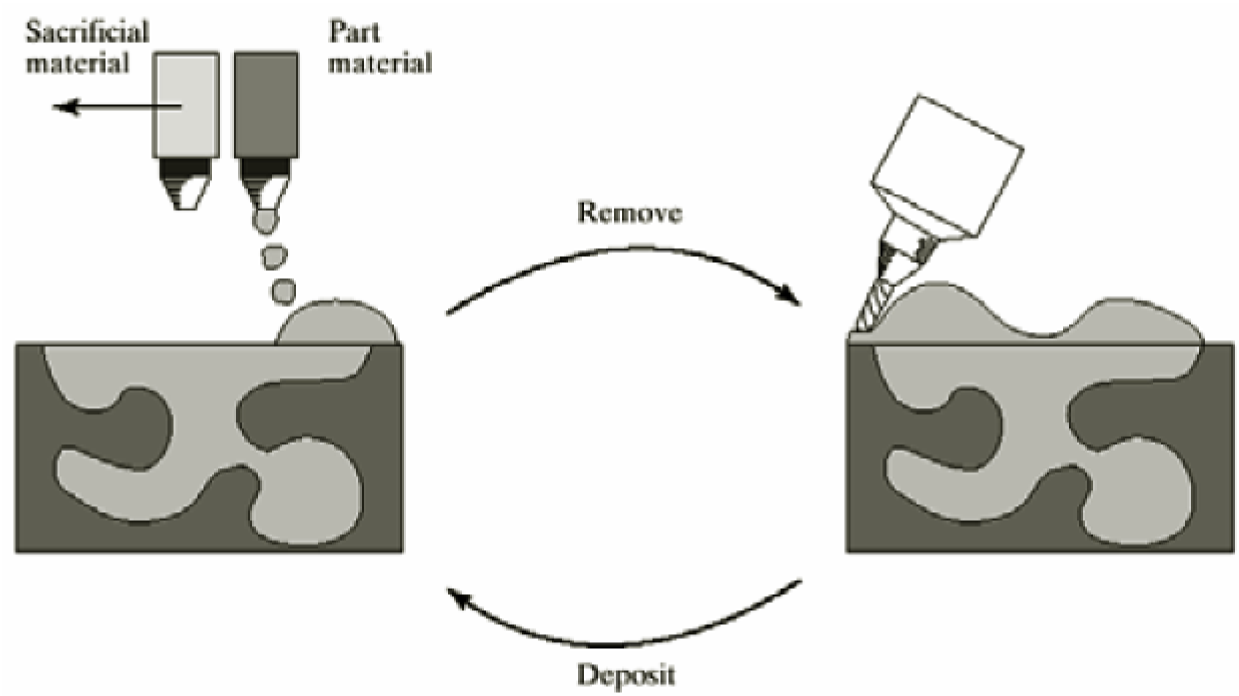
SGC Process



1. Create the photomask
2. Attract the toner and spread the resin
3. Expose and cure the resin
4. Remove uncured resin
5. Fill cavities with wax
6. Chill and harden wax
7. Mill and create a flat, even surface
8. Final cure of layer
Creating the photomask
Building a layer
Transmit layer data
Prepare the data
(Repeat until build is complete)
(Repeat until build is complete)
(When the build is complete)
Dewax the parts

7. Shape Deposition Manufacturing (SDM)

- Developed by Stanford University/CMU
- Uses deposition and milling
- Provides good surface finish



Issues in RP Materials

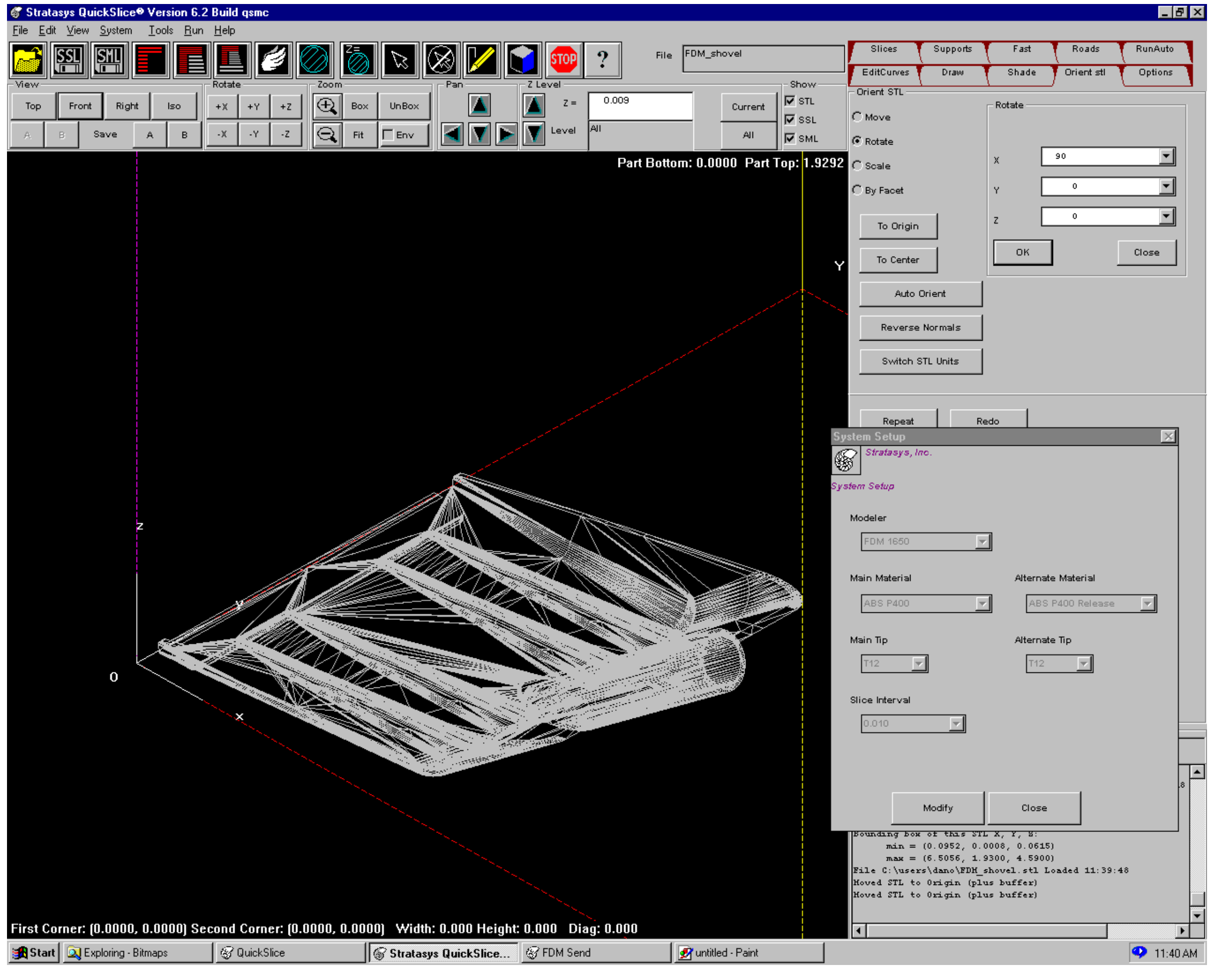
- Rapid Fabrication of functional parts
  - Structural
  - Optical
  - Surface Roughness
  - Electrical
  - Thermal
  - Color
  - … … …

FDM Software – Three Levels

- **STL file** – Tessellated Stereolithography file – export from solid modeling package
- **SSL file** – Sliced Layer File, Support Calculation – Proper part orientation can drastically affect build time, support requirements, and part strength
- **SML file** – Raster, Build Parameters, time estimation

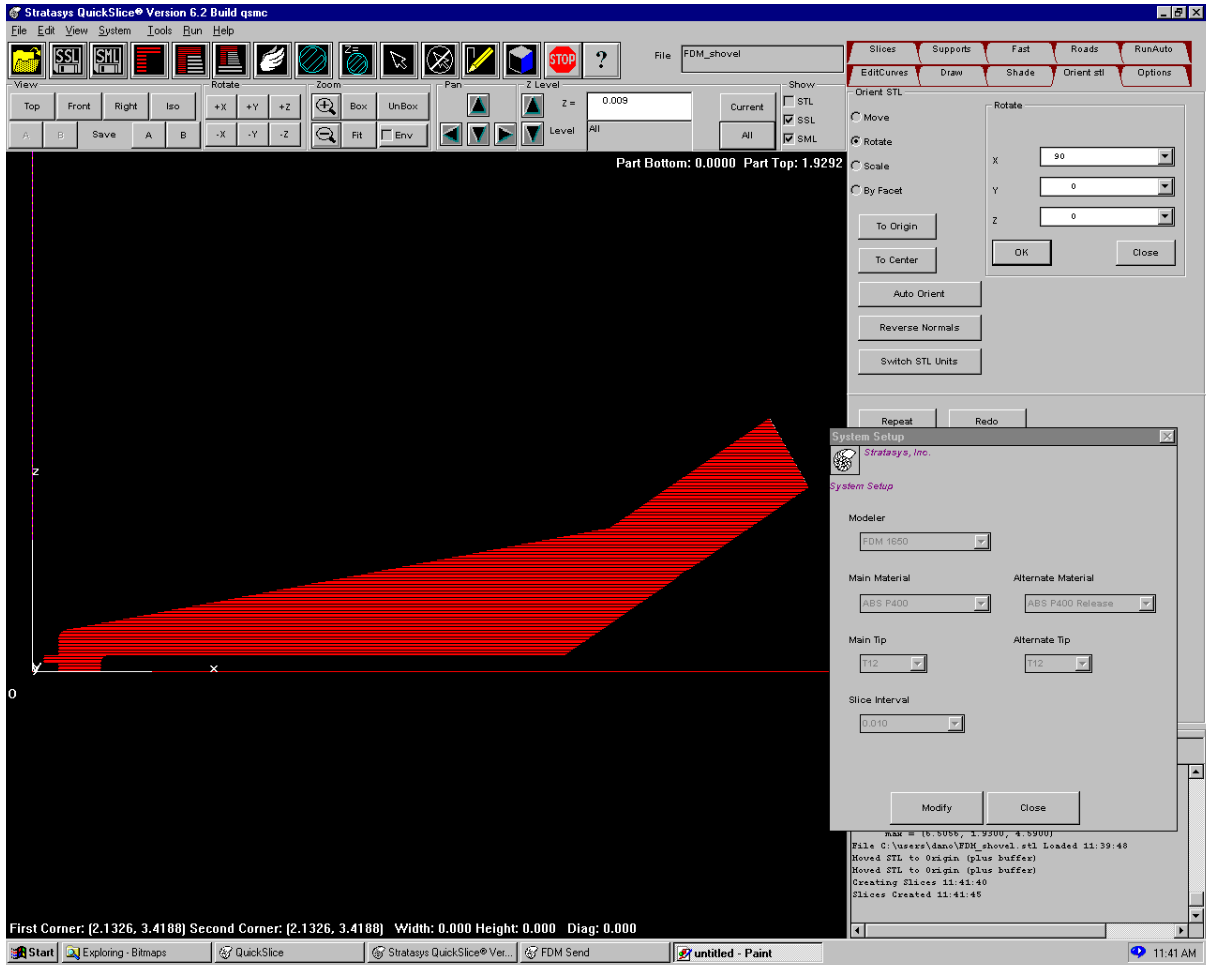
STL File – Collapsible Shovel Head

- Tessellated (Triangulated) format
- Standardized Export Type
- Quickslice Layout



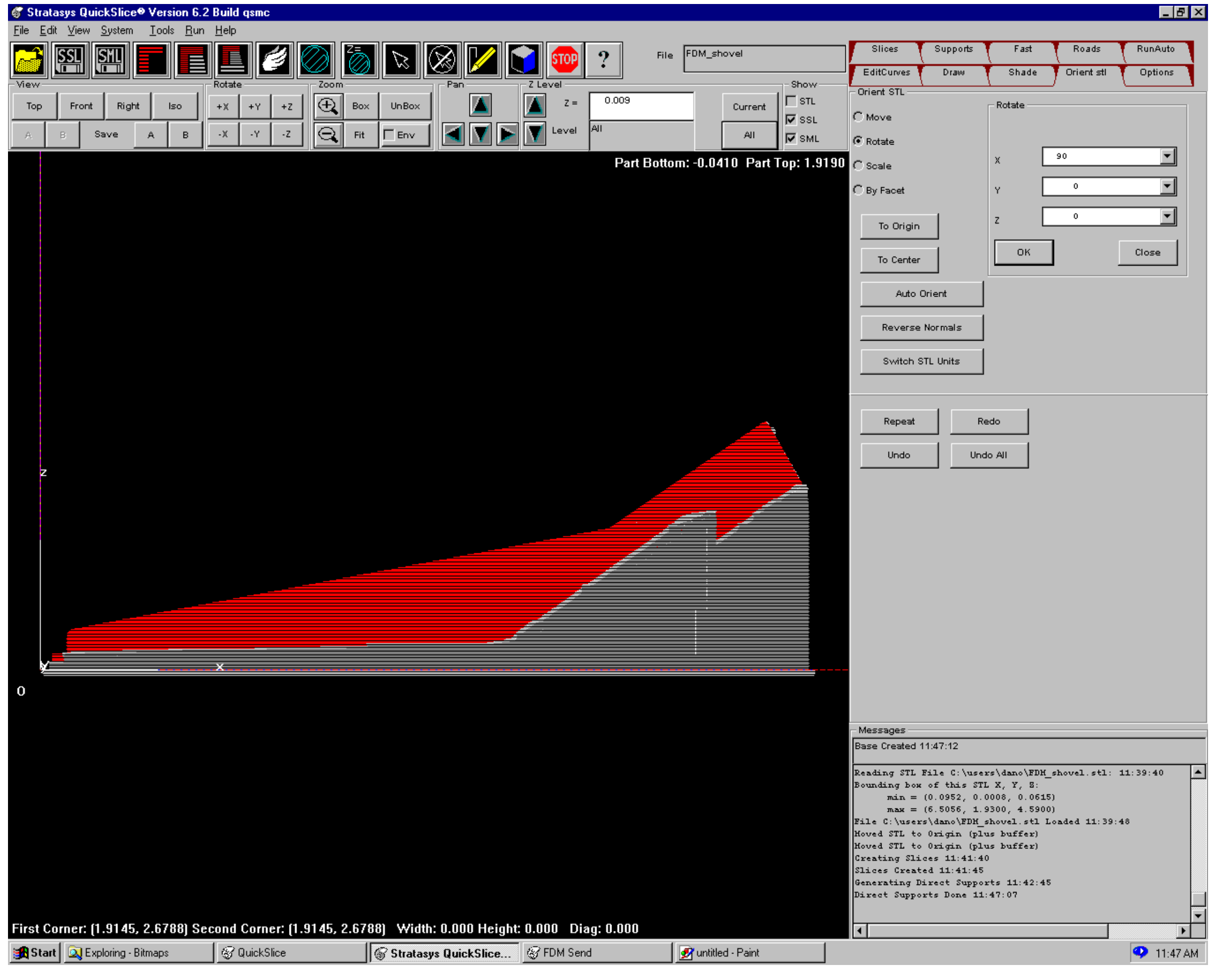
SSL File – Unsupported, Front View

- Vertically Sliced File
- Orientation Important!
- Unsupported Material will fall



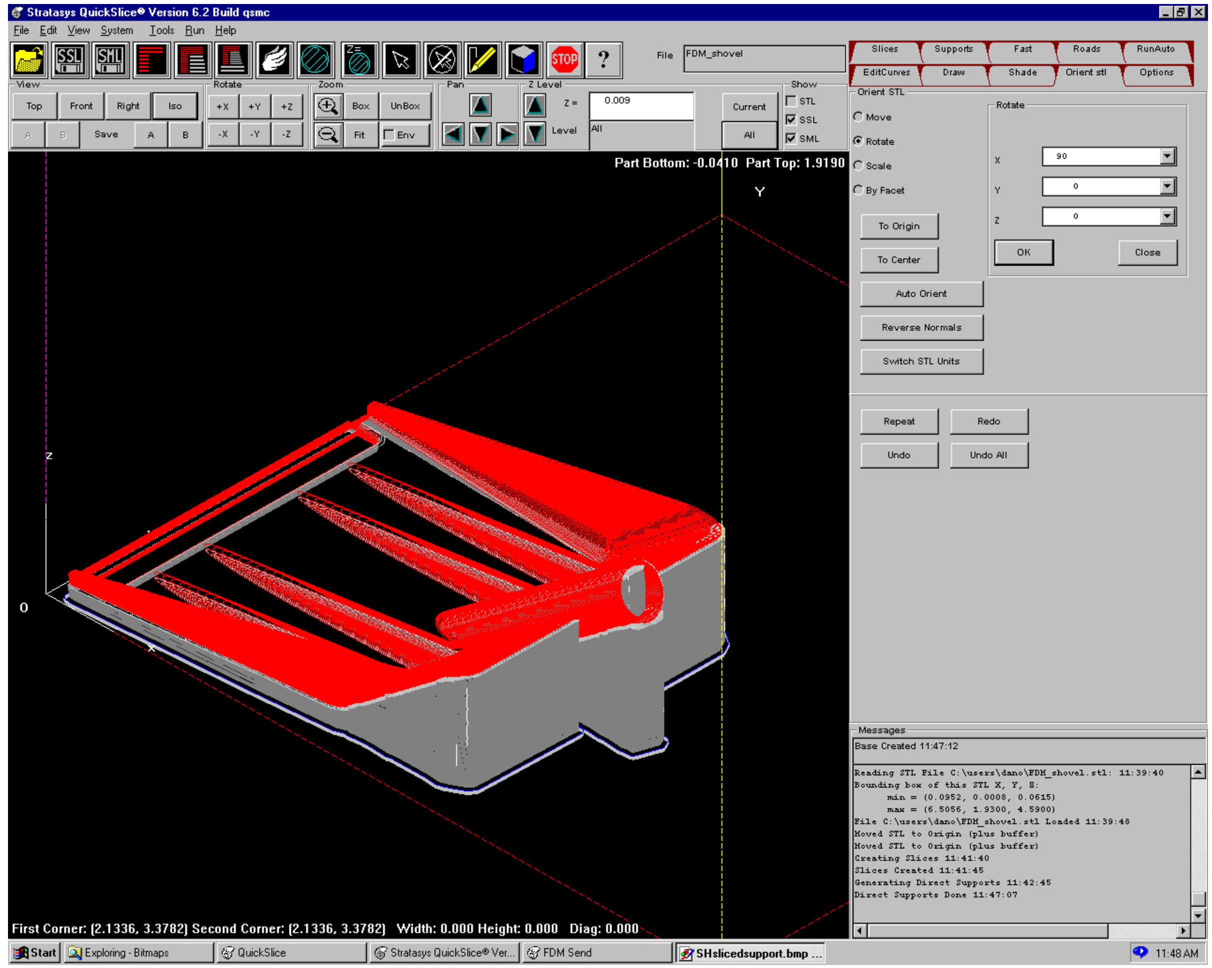
SSL File – Supported, Front View

- Support Calculation
- 45° Support rule
- Foam Substrate
- Foam Irregularities



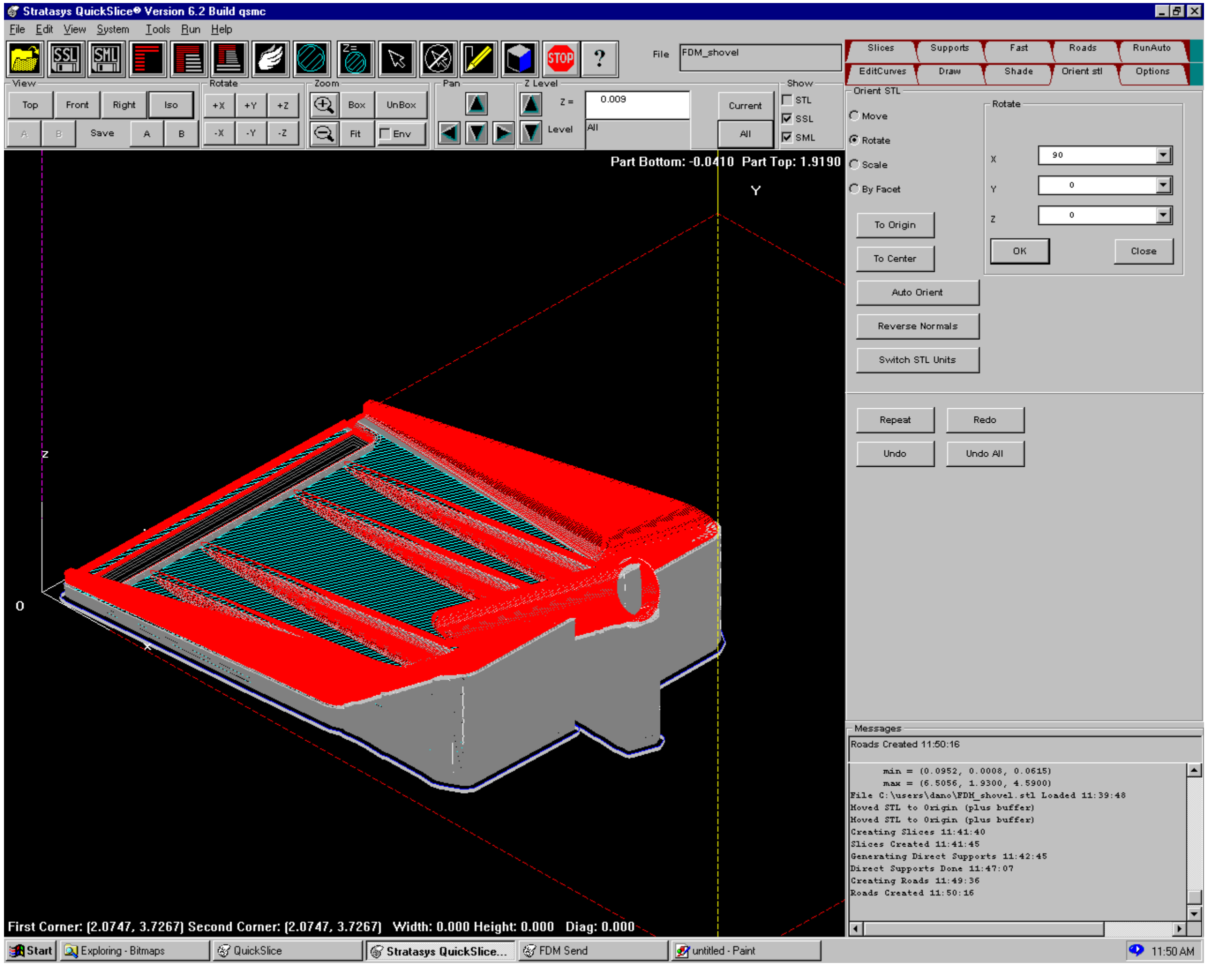
SSL File – Supported, Isometric View

- Support Base (Blue)
- Removing Support Material
- Calculation and Removal can be time intensive



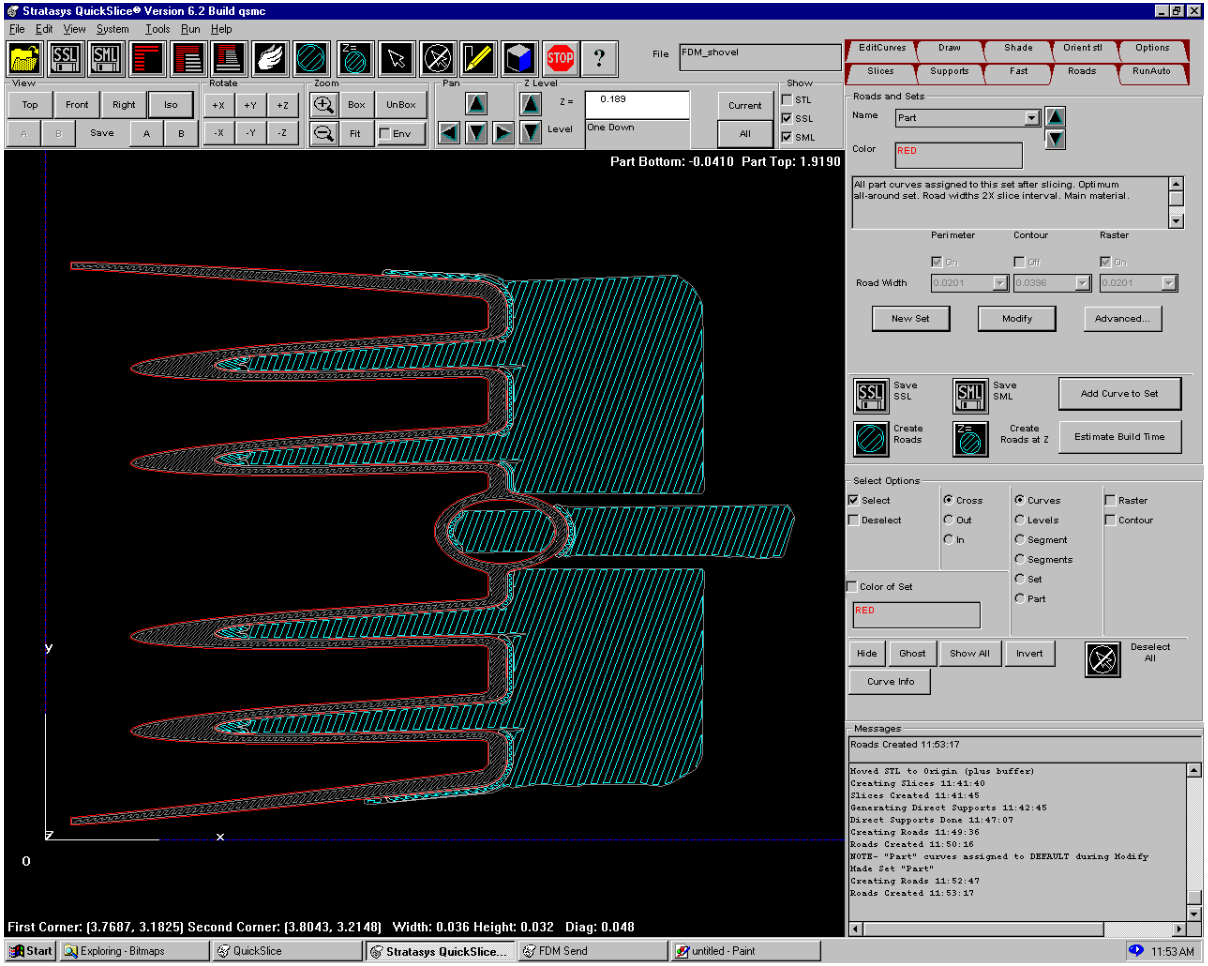
SML File – Supported, Isometric View

- Road Generation
- Colored Layer of SSL file determines road orientation
- Road type and orientation strongly affects build time and part strength



SML File – Supported, Top Layer

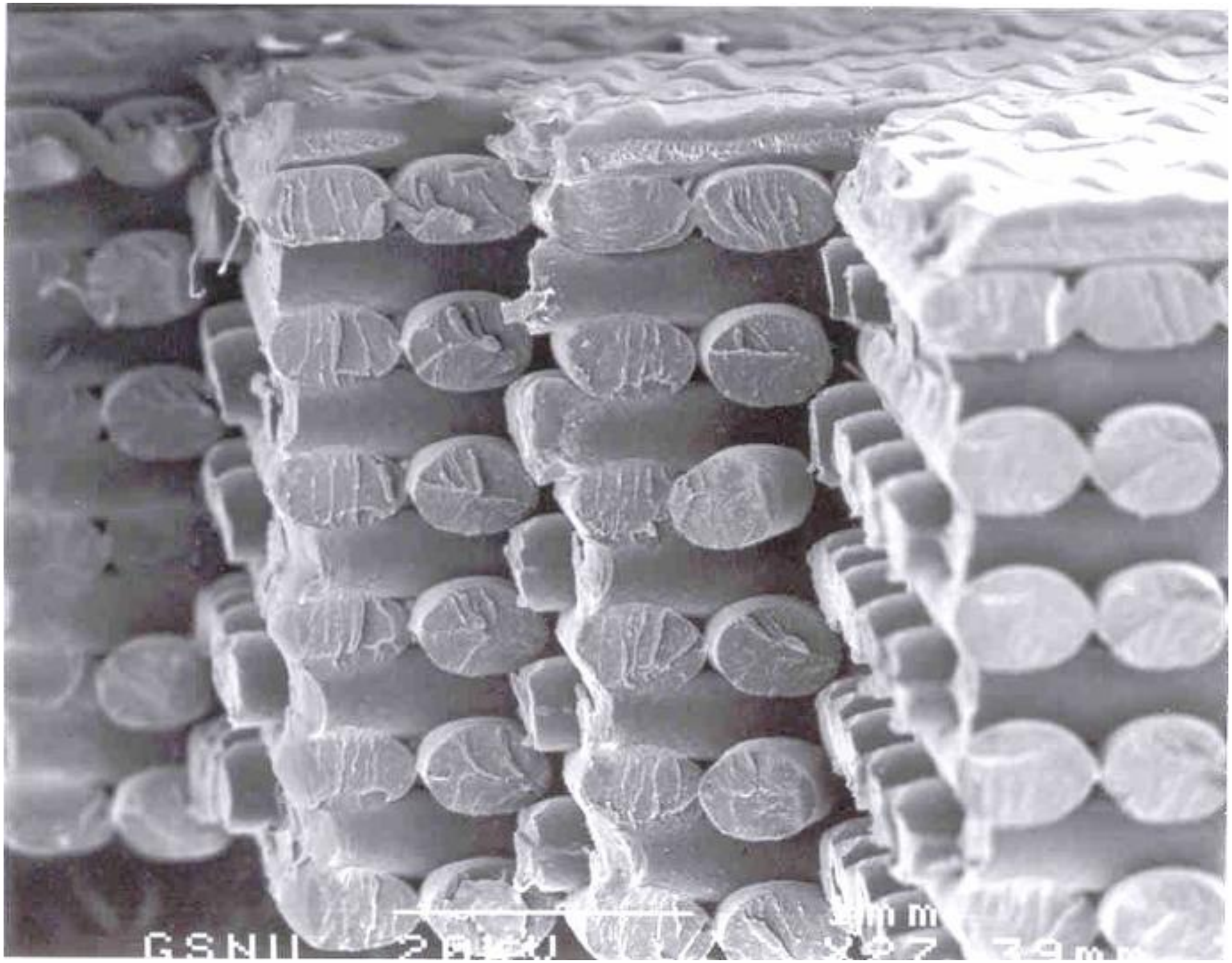
- Oriented raster at 45° angle (FDM material behaves like a composite)
- Note loose fill of support material – easier to break and quicker to build



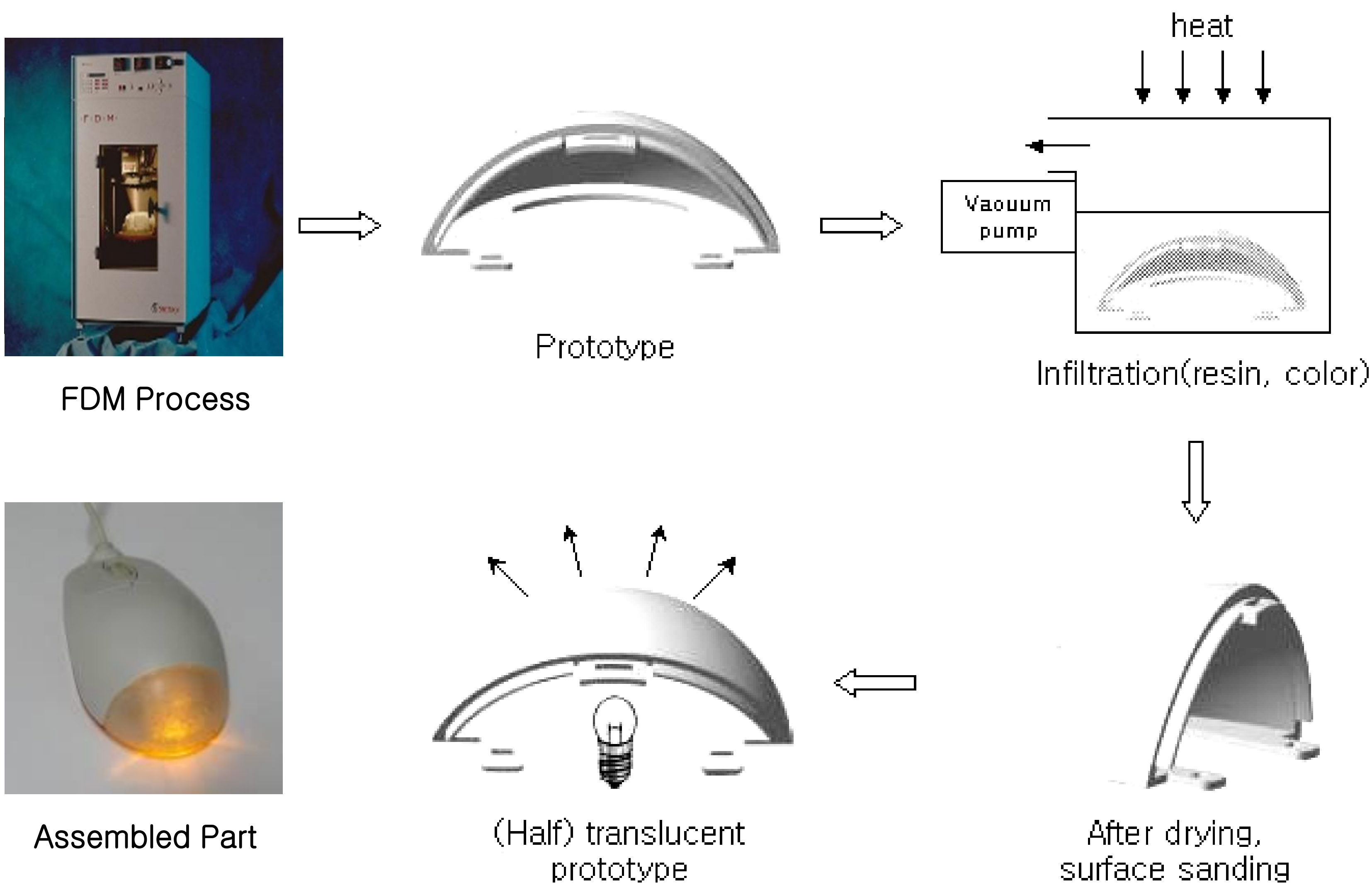
FDM Build Parameters - Software

- Perimeters, Contours, Raster (Road type)
  - Perimeter: Follows outer shape of current slice - ideal for cosmetic outer surface
  - Contour: Follows shape of perimeter on part interior - not commonly used as it leaves gaps
  - Raster: Standard back and forth part fill - adds strength to part, composite theory (raster angles)
- Road width - Dependant on nozzle size and feed rate - ranges from .012 to .0396 for T12 nozzle
- Air Gap - Gap between roads - allows for tightly fused, strong surface, or sparse, quick building fill

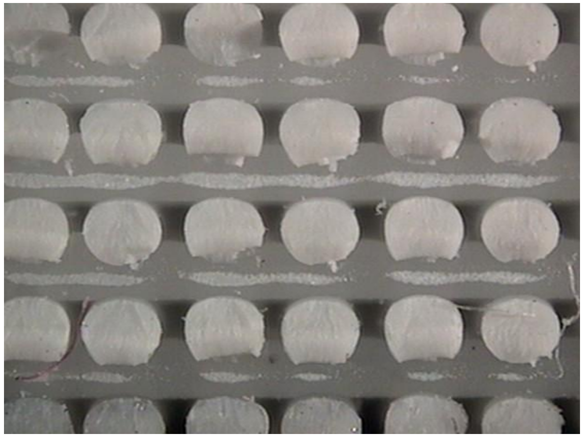
Micro Structure of FDM



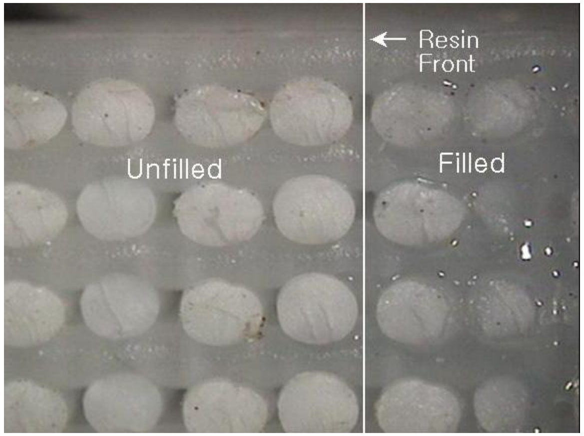
Part Post-process of FDM



Resin Infiltration

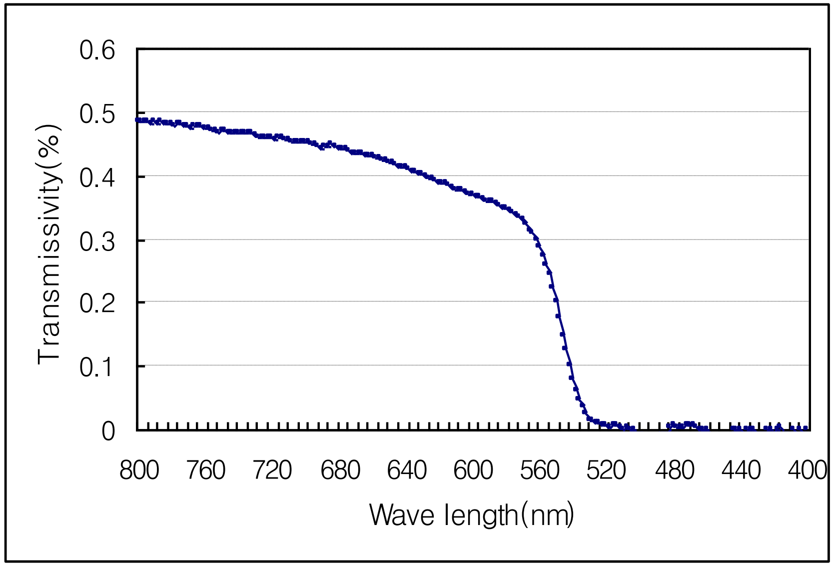


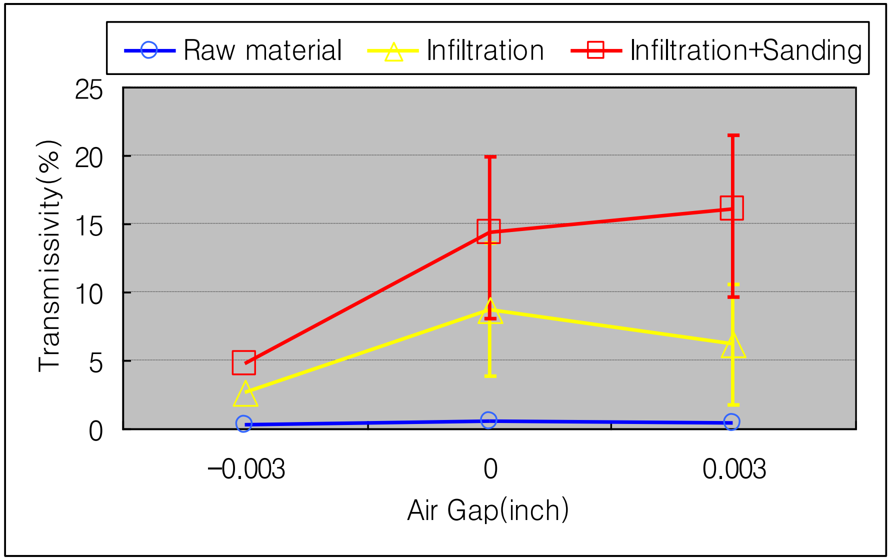
Raw FDM ABSi



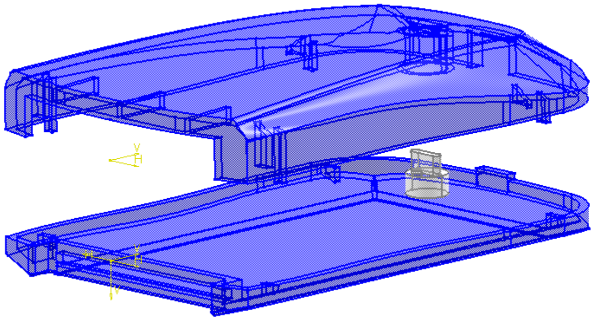
During Infiltration

After Infiltration





Flash Memory Reader



CATIA modeling:

5 hours

FDM process:

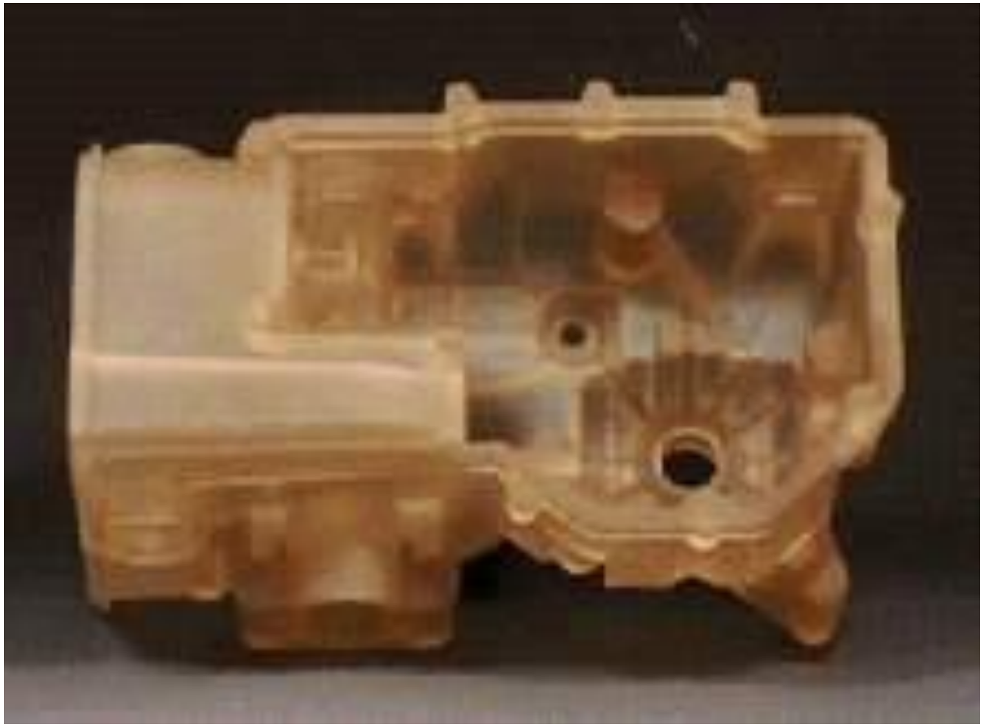
10 hours

Post-process : 24 hours

Total prototyping time : 39 hours

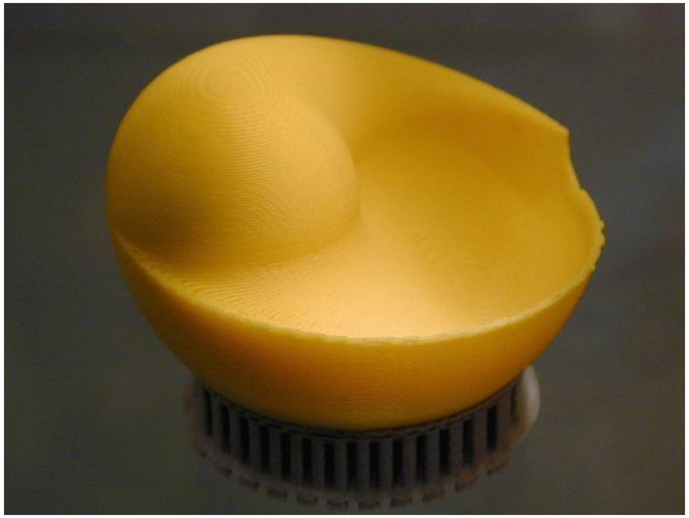
Gallery

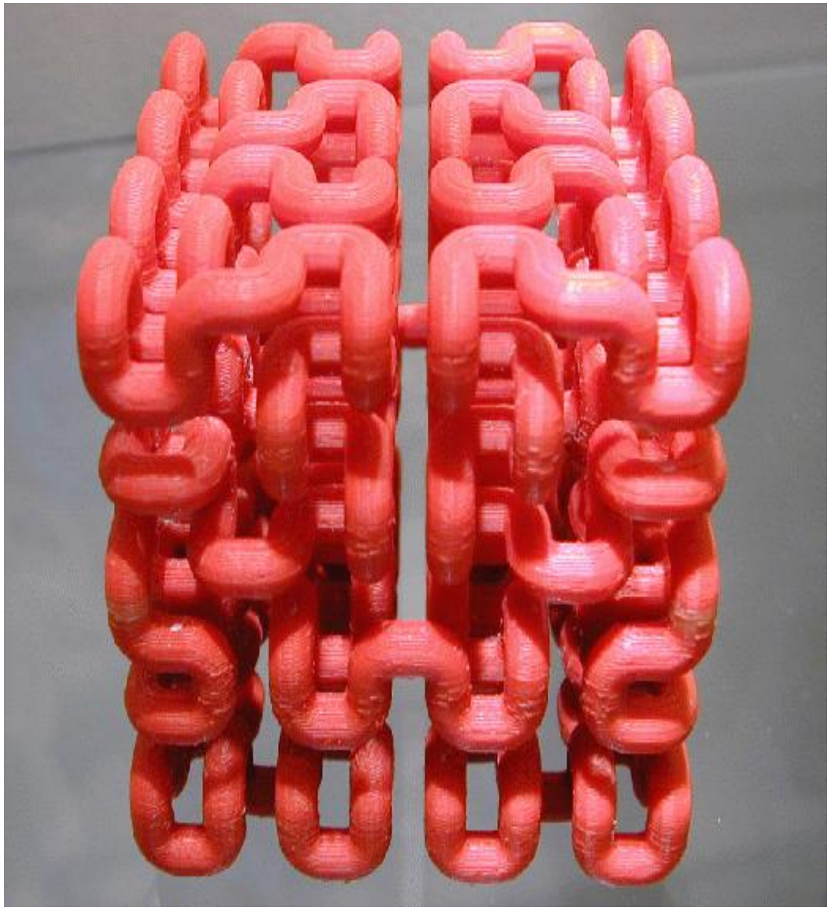
- SLA



Gallery (cont.)

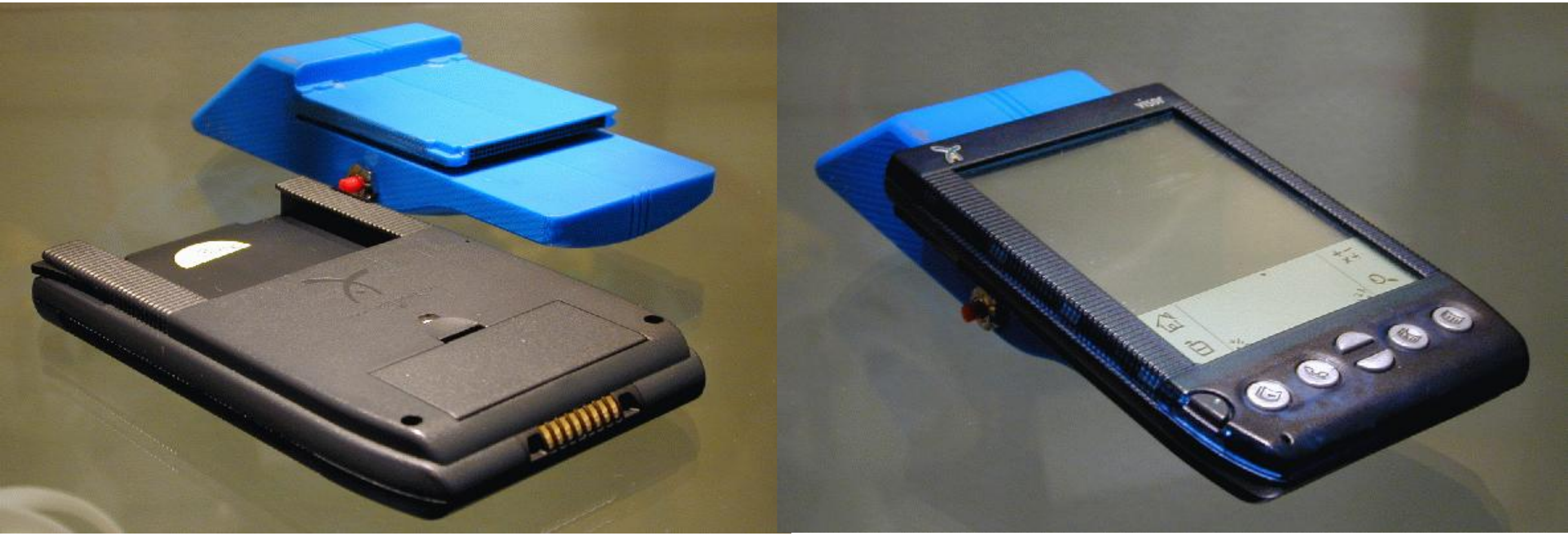
- FDM





Gallery (cont.)

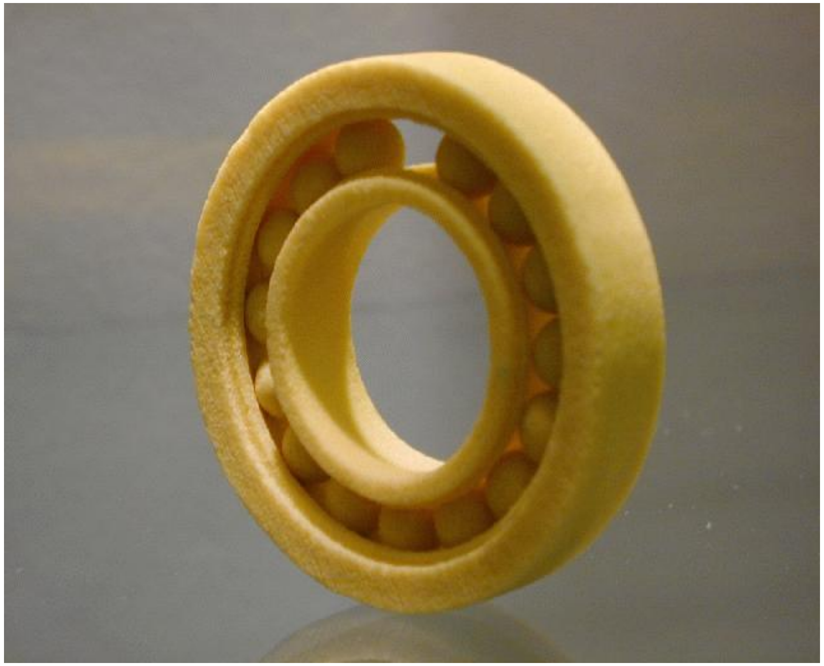
- FDM



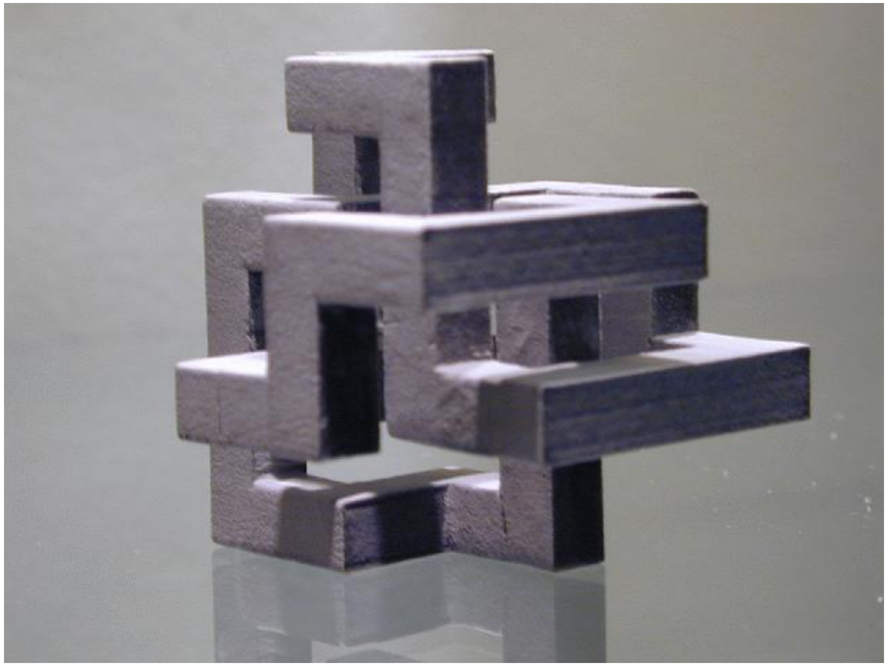
GPS module for PDA

Gallery (cont.)

- Z- corp (3D Printer)

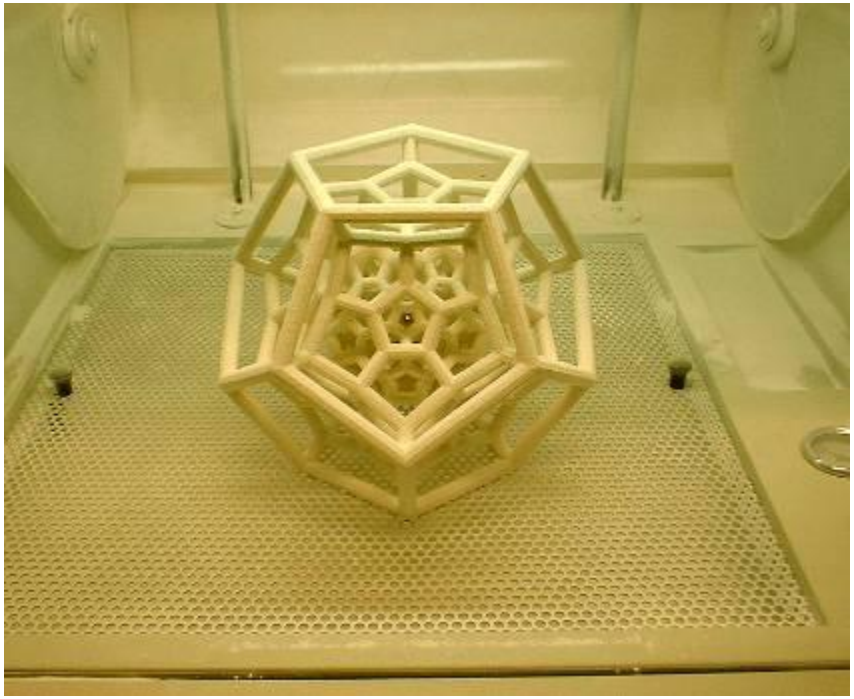


- SLS



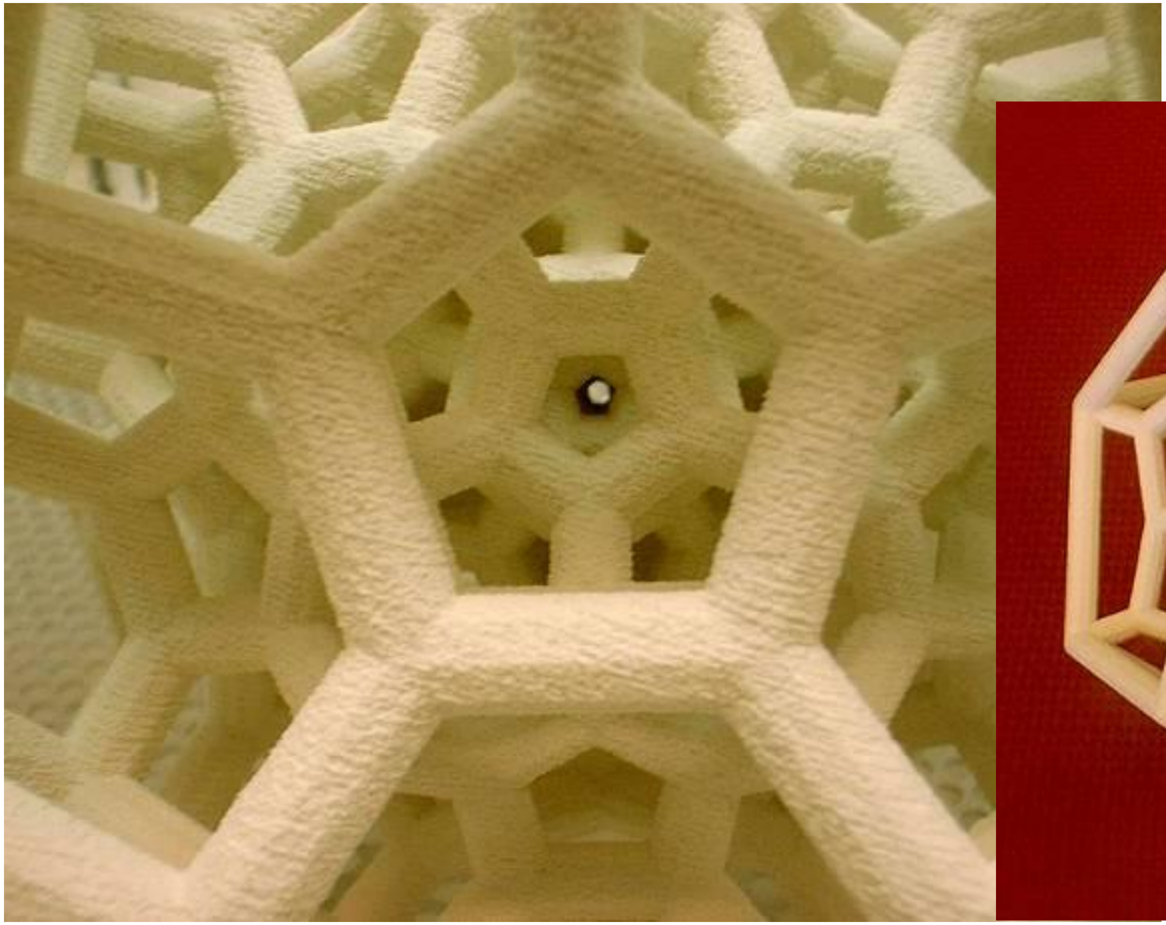
Gallery (cont.)

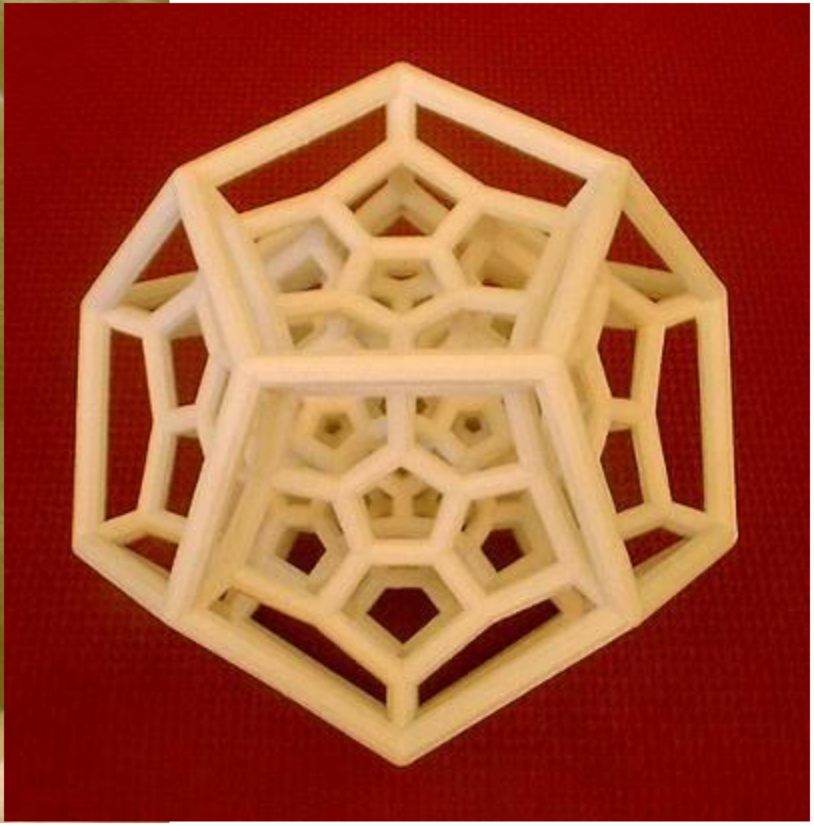
- Z- corp (3D Printer)



Gallery (cont.)

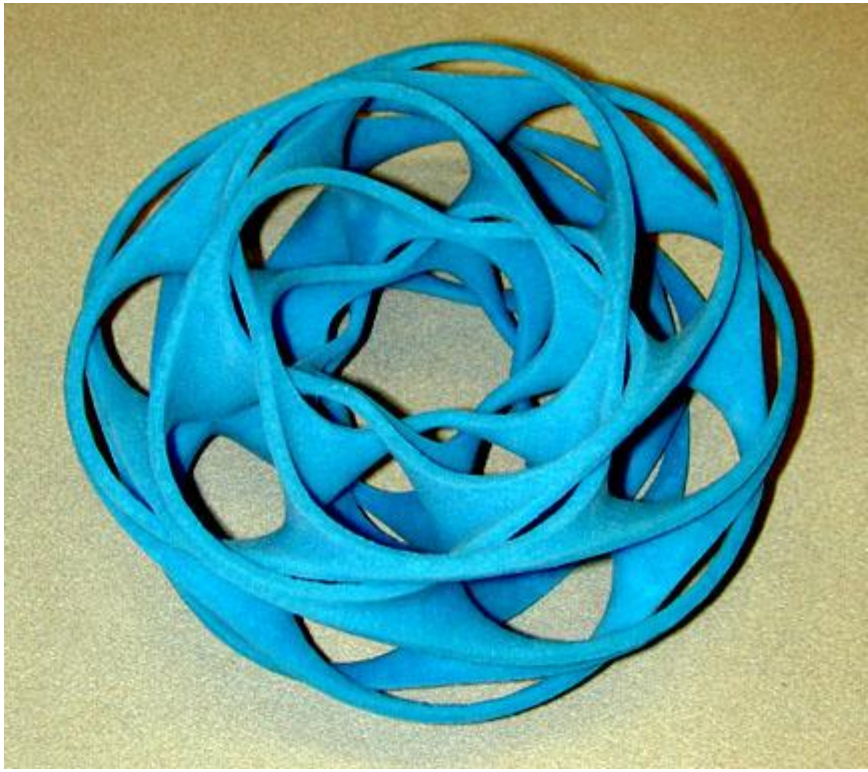
- Z- corp (3D Printer)





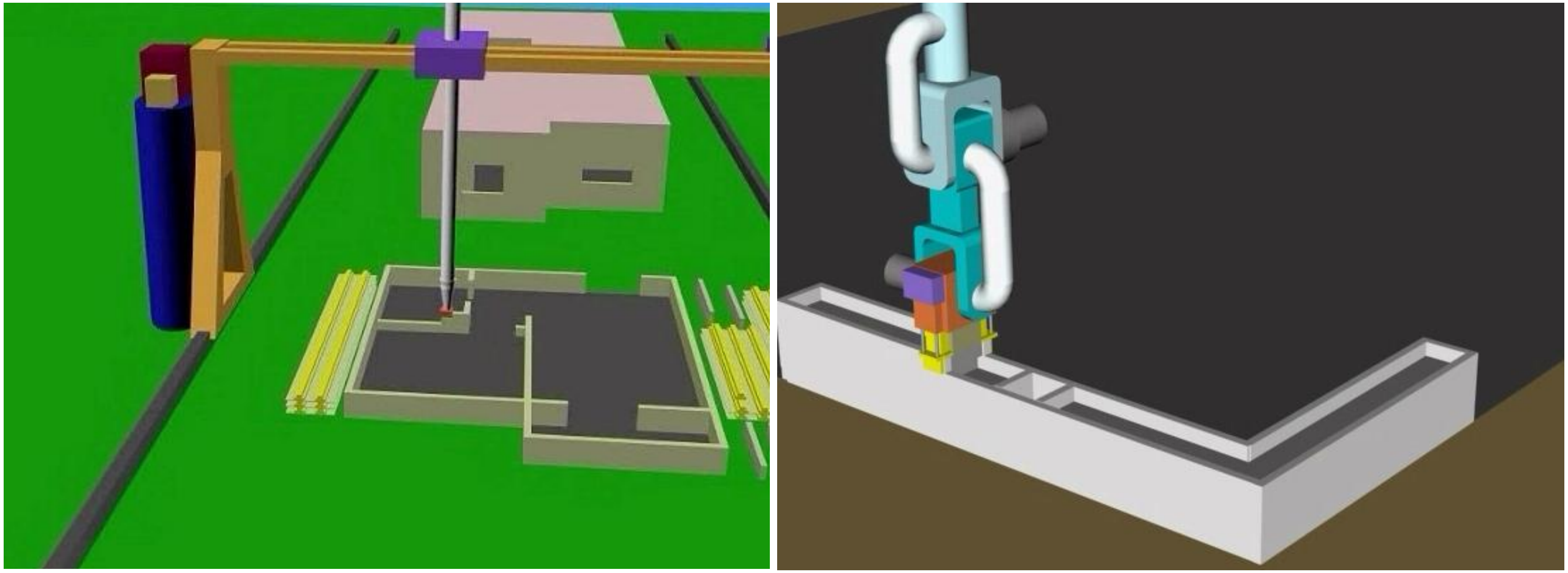
Gallery (cont.)

- Z- corp (3D Printer)



Applications

- Architectures



A machine mounted on rails might be used to build multiple houses

Applications (cont.)

- Materialization of arts

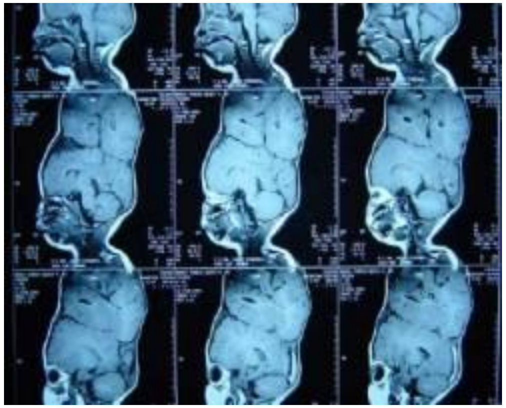
Lifting the kouros out of the Mammoth

The original Volomandra Kouros and the SLA replica

Applications (cont.)

- Medical Domain

Before surgery



CT Scan

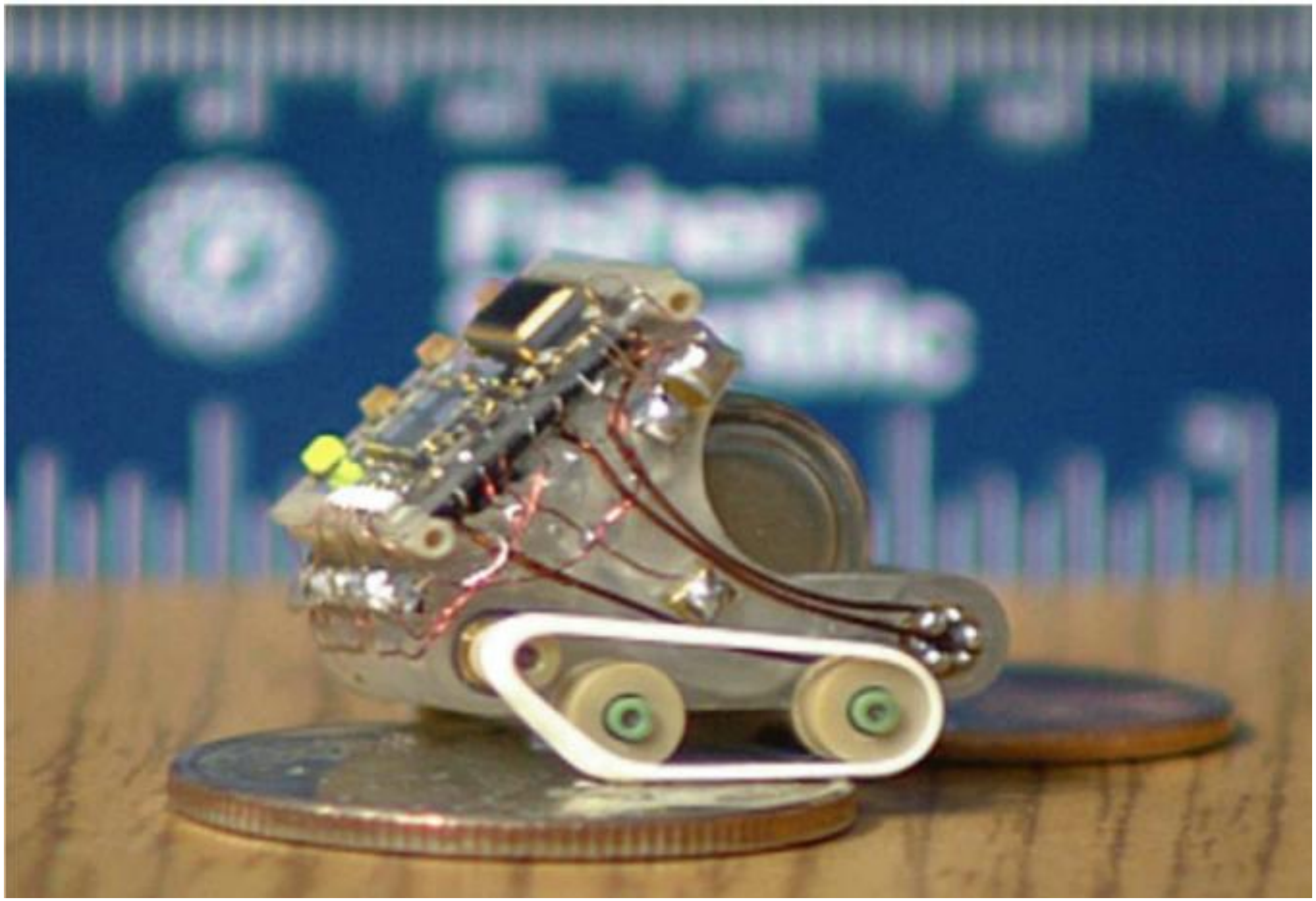
RP part

After surgery

Virtual surgery

Applications (cont.)

- Micro component



Micro robot by Sandia Lab

Applications (cont.)

- Rapid Tooling (RT)

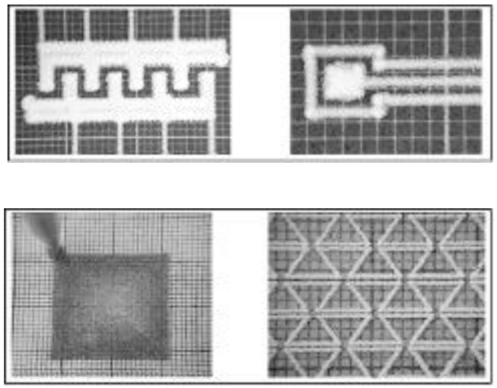
DTM's RapidTool™ process for rapid mold making

Core and cavity sets produced by RapidTool ™

Applications (cont.)

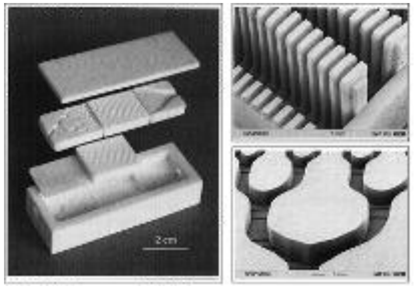
- Other Examples

Patterning with Ceramic



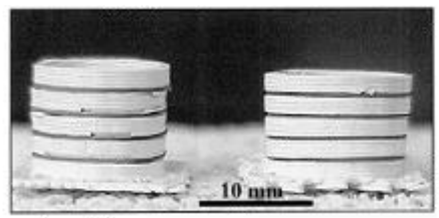
P. Kumar *at al,* Ann Arbor

Microreactor

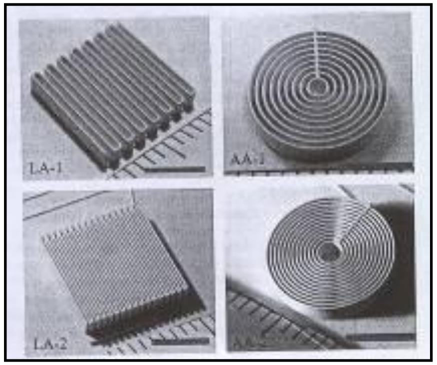


R. Knitter *at al.*
RP Journal

Sensor and Actuator



Electrode ; A. Safari *et al.* IEEE



PZT Sensor ; J. E. Smay *et al.* J. Am. Ceram. Soc.

Artificial Bone and Ear

Artificial bone

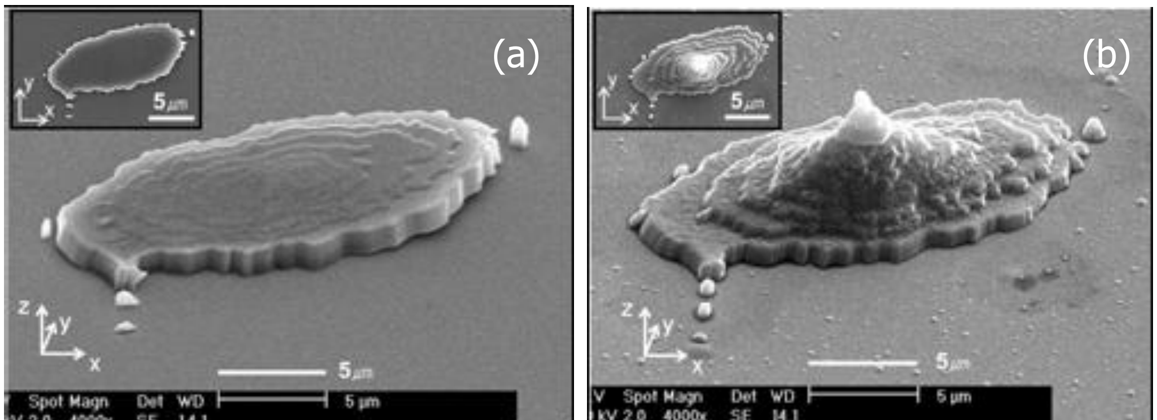
Y. Tan *et al.*
Am. Ceram. Soc.

Artificial ear

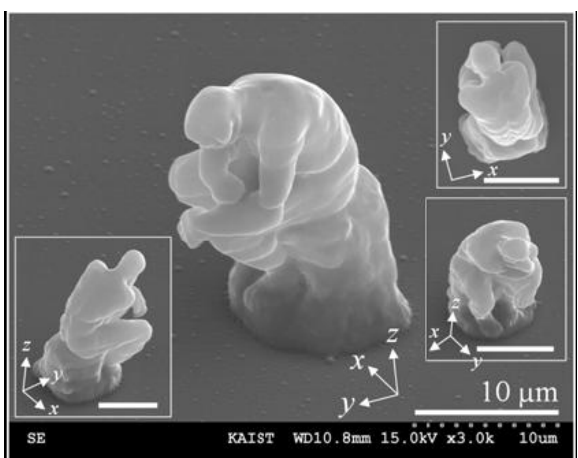
Bio-compatible Material

3D Nano/Micro Parts

- Two-photon Stereolithography

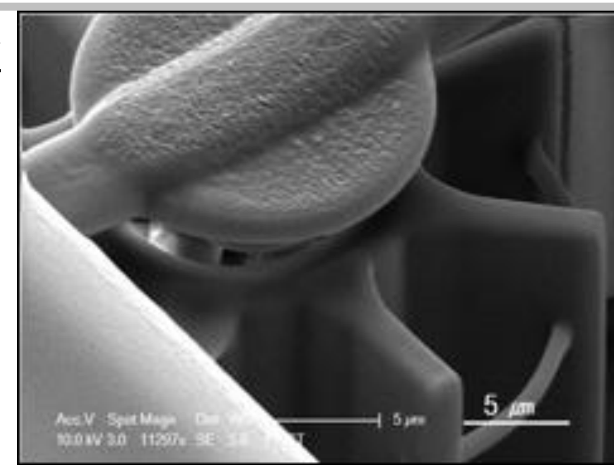


SEM images of fabricated islands with (a) actual and (b) exaggerated ratio of height vs. width by controlling both exposure time and laser power simultaneously. Inset is top view of the structure



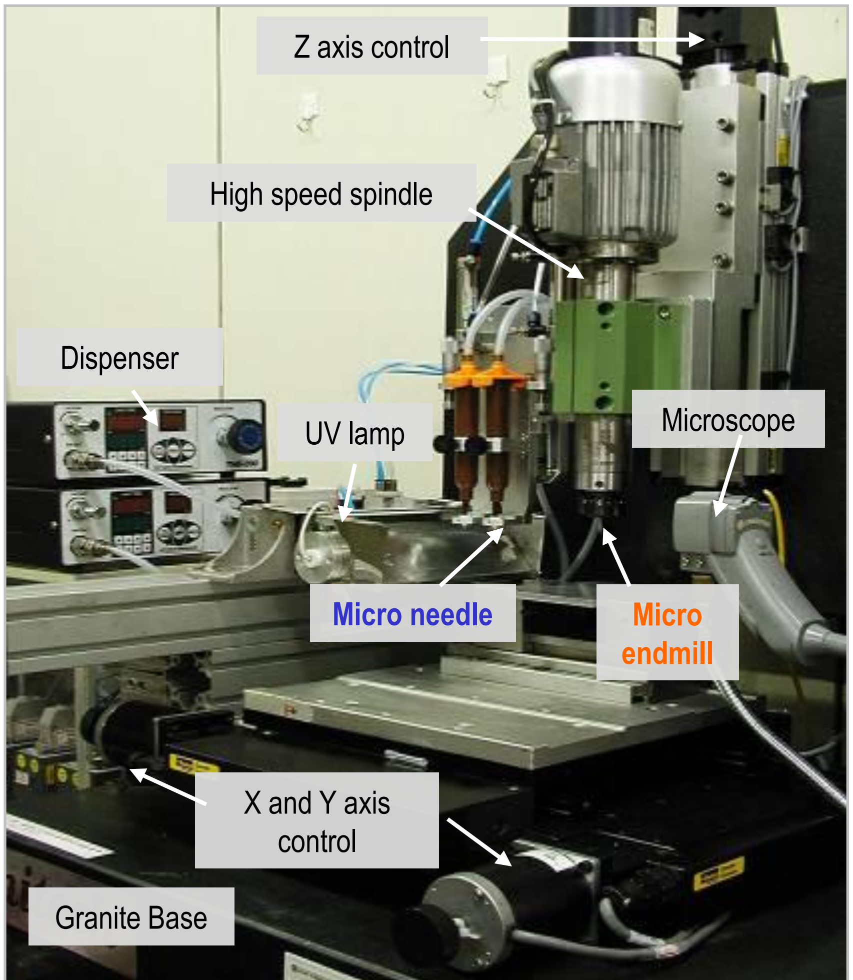
SEM images of fabricated micro-Thinker by double-scanning path. The insets are the same micro-Thinker with various view angles, and the scale bars are 10 ㎛

Fabricated micro-prototypes of a micro rotor



Hybrid RP System

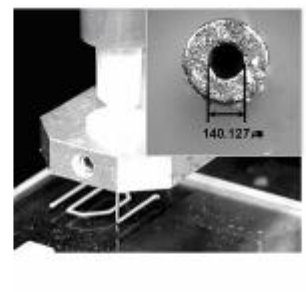
- Hardware



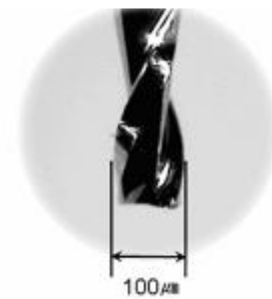
✓ ***Deposition; Rapid Prototyping***

✓ ***Cutting; Milling***

✓ ***Hybrid; Both***



Micro needle



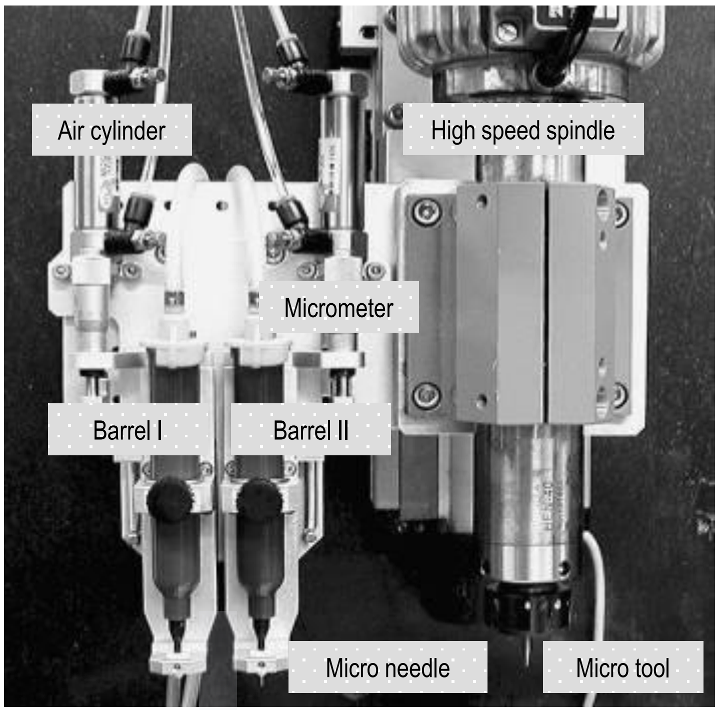
Micro endmill

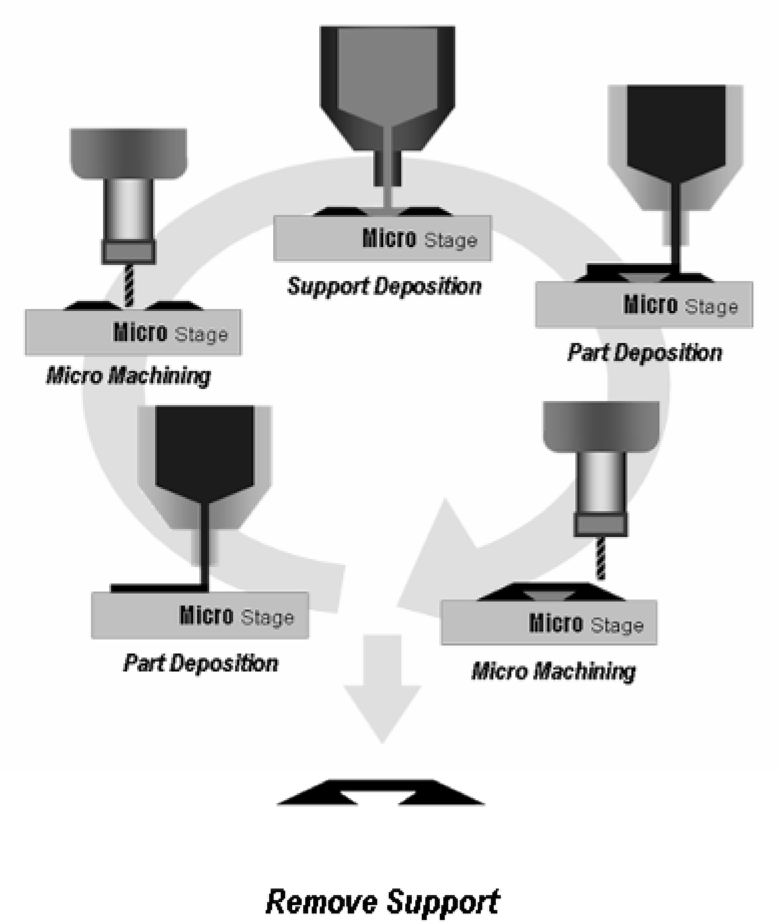
SPECIFICATIONS

3 Axes-stage	1㎛ resolution
Dispenser	15 ~ 700 kPa
Micro needle	ϕ 140 ㎛ ~ϕ 800 ㎛
Micro tool	ϕ 100 ㎛ ~ϕ 1000 ㎛
High speed spindle	Max. 46,000rpm
UV curing system	0 ~ 400 W, λ = 365 nm
Controller	PMAC (Multi-tasking board)

Hybrid RP System (cont.)

- Hybrid process: depositing + machining

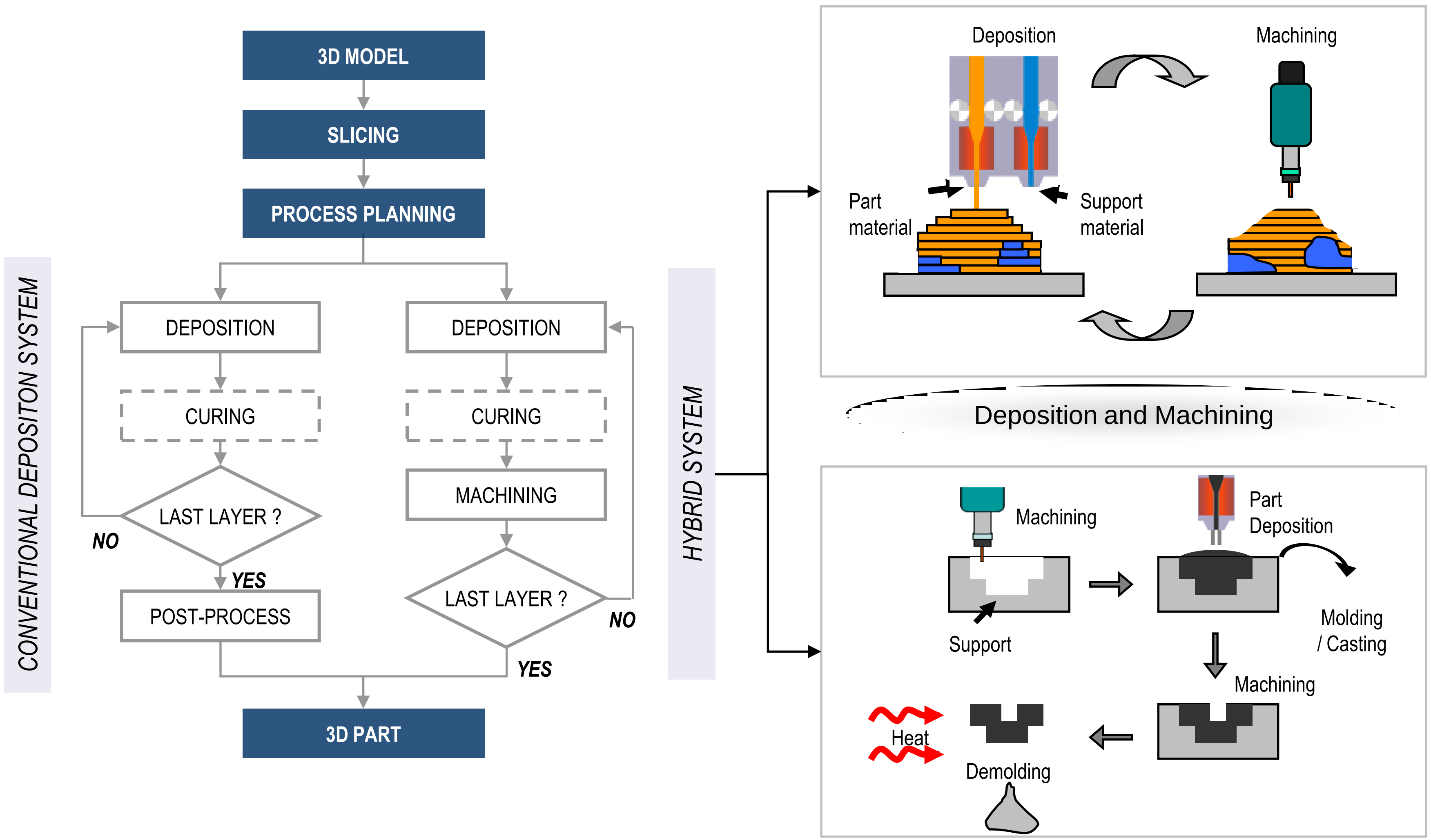




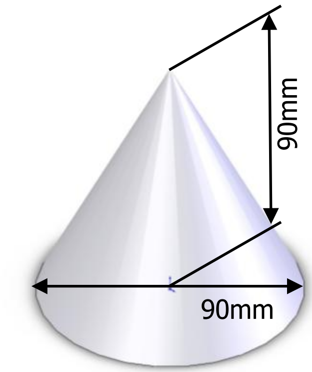
Conceptual process of NCDS

Hybrid RP System (cont.)

- Process planning

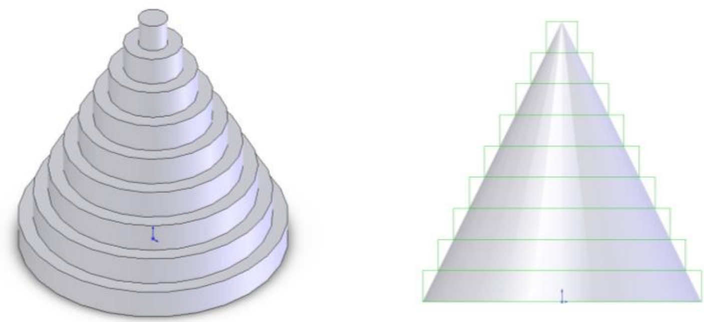


CAD Model and NC Codes



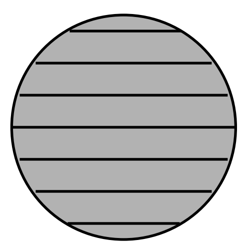
CAD design of a microcone

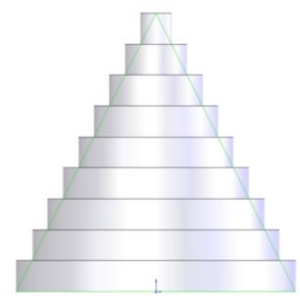
Slicing: Slice into 9 layers, layer thickness is 10mm



Layer model of a microcone

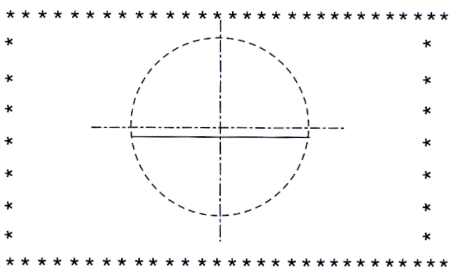
Hatching: Parallel line spacing, filling between lines is 10mm





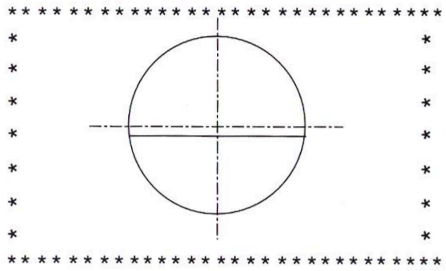
NC Codes for the Cone

```
;  cone_90.PRG, Layer 1
G92;  set software home, reset axes to 0
G71;  set as metric mode
G24;  set conditions the deceleration behavior ;
;     of a contour type move as corner
;     rounding off
OU 0;  No output to trigger the optical shuttle
;      (light off)
G1 F200.0;  G1: initiates motion where each axis
;           adjust its feedrate to keep a
;           contour path; F200.0: motion speed
;           definition.
G90;  set as absolute mode
G1 X-.0447 Y-.005;  Move to the position with
;                   x=-0.0447, y=-0.005
OU 1;  light on
G1 F10.0;  define motion speed
G1 X-.0447 Y-.005;  Move to the position with
;                  x=0.0447, y=-0.005
;
;
;
;
;
;
;
;
;
;
```



```
OU 0;  light off
G1 F200.0
G1 X.045 Y0;  Move to the position with x=0.045,
;             y=0
OU 1; light on
G1 F10.0
G3 X.045 Y0 C-.045,0; G3:  counterclockwise
;                     contouring of one to four
;                     axes; move from point ;
                      (0.045, 0) and draw a
;                     circle with radius of
;                     0.045.
```

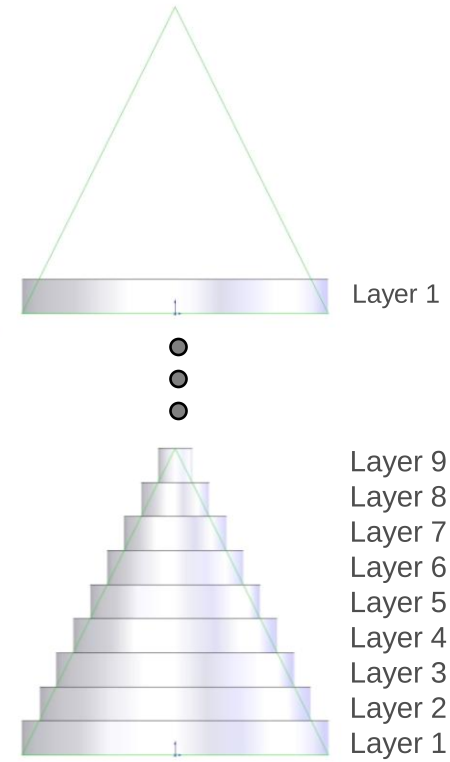
```
;
;
;
;
;
;
;
;
;
```



```
OU 0
G1 F200.0
G1 X.0447 Y.005
OU 1
G1 F10.0
G1 X-.0447 Y.005
OU 0
G1 F200.0
G1 X-.0424 Y.015
OU 1
G1 F10.0
G1 X.0424 Y.015
OU 0

G1 F200.0
G1 X.0374 Y.025
OU 1
G1 F10.0
G1 X-.0374 Y.025
OU 0
G1 F200.0
G1 X-.0283 Y.035
OU 1
G1 F10.0
G1 X.0283 Y.035
OU 0
G1 F200.0
G1 X.0424 Y-.015
OU 1
G1 F10.0
G1 X-.0424 Y-.015
OU 0
G1 F200.0
```

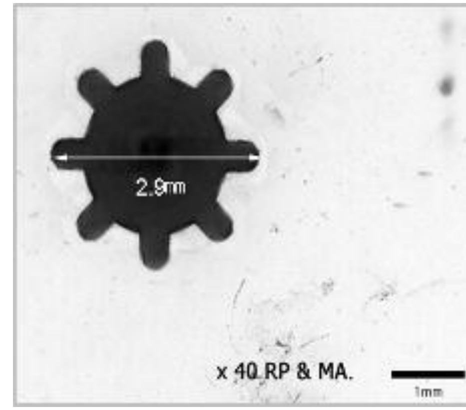
```
G1 X-.0374 Y-.025
OU 1
G1 F10.0
G1 X.0374 Y-.025
OU 0
G1 F200.0
G1 X.0283 Y-.035
OU 1
G1 F10.0
G1 X-.0283 Y-.035
OU 0
G1 F200.0
G1 X0 Y0;  Return to the position (0,0) and the
;          first layer fabrication is done.
```



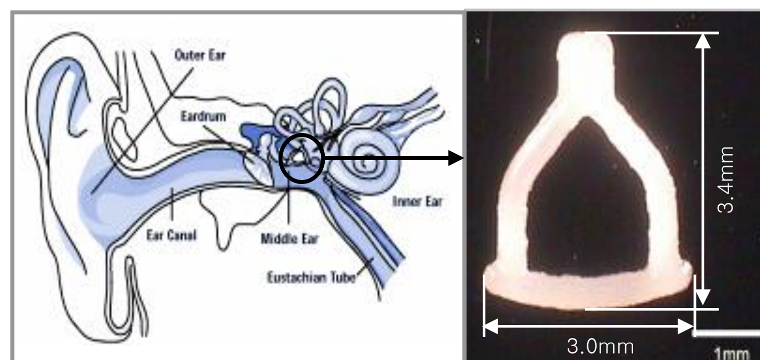
Nano Composite Parts

- Micro Gear
  - A gear geometry with ϕ 2.9mm was fabricated
  - 5wt% MWCNT + Acrylic resin
  - Dispensing process using ϕ 300㎛ needle
    micro milling using ϕ 100㎛ flat endmill
- Stapes
  - The smallest bone in human body, width 2.5mm / height 3.5mm
  - 40wt% Hydroxyapatite + Acrylic resin
  - Dispensing process using ϕ 140㎛ needle
    micro milling using ϕ 100㎛ flat endmill
  - Mold (using wax) machining → part deposition
    → surface machining → demolding
- Fabrication time

Parts	Average Time (min)
Micro Gear	2
Stapes	15



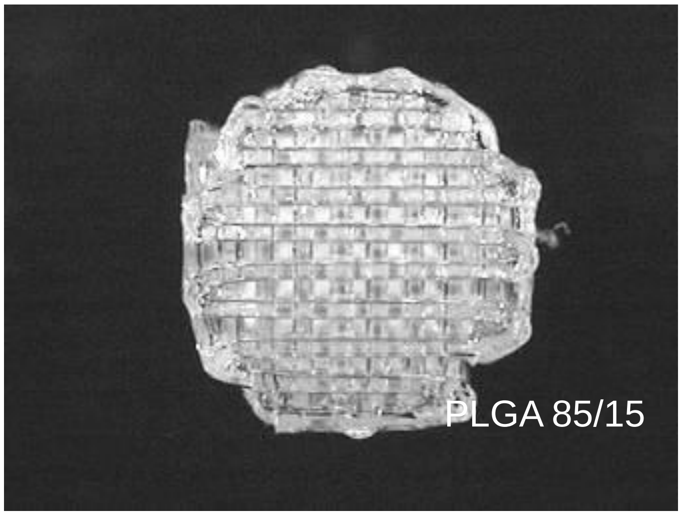
Microscope picture of microgear

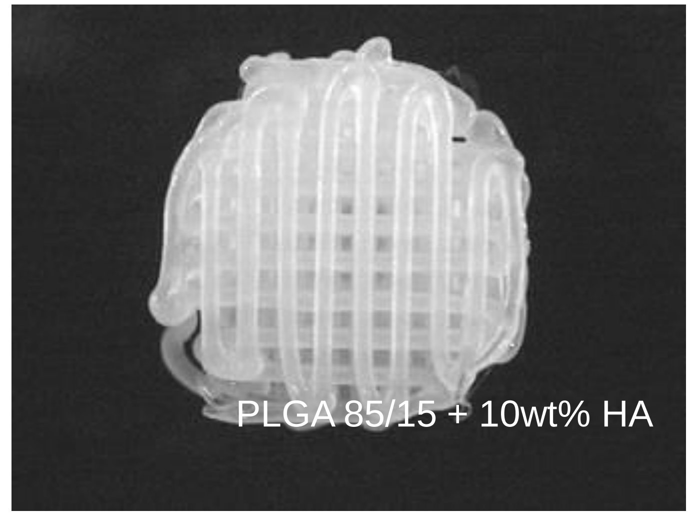


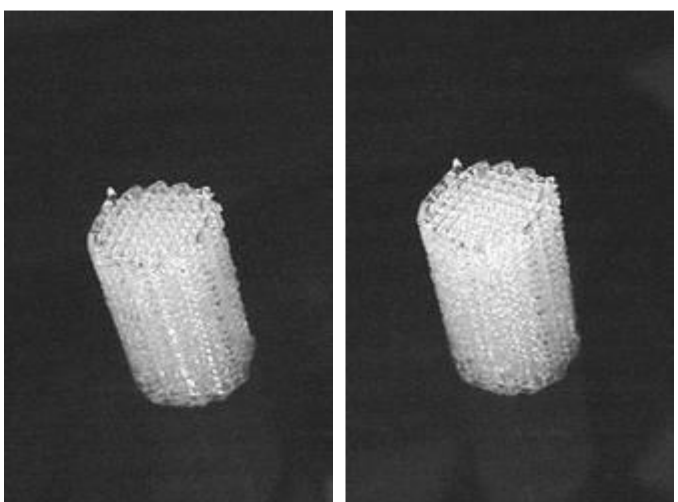
Geometry of stapes

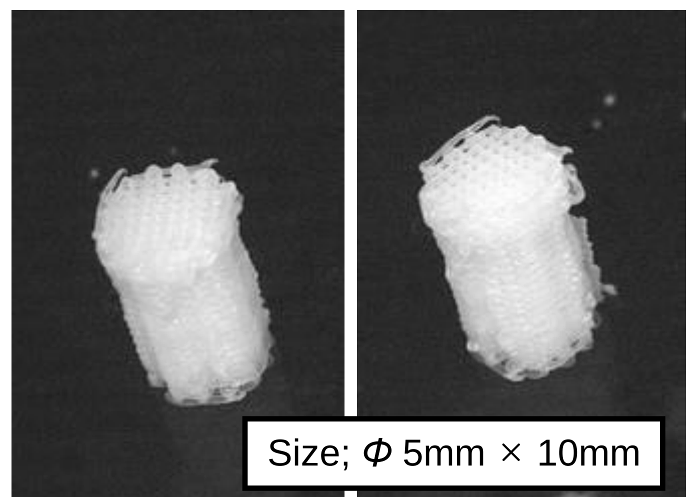
Scaffold for Bone Growth

- Bio-degradable polymer



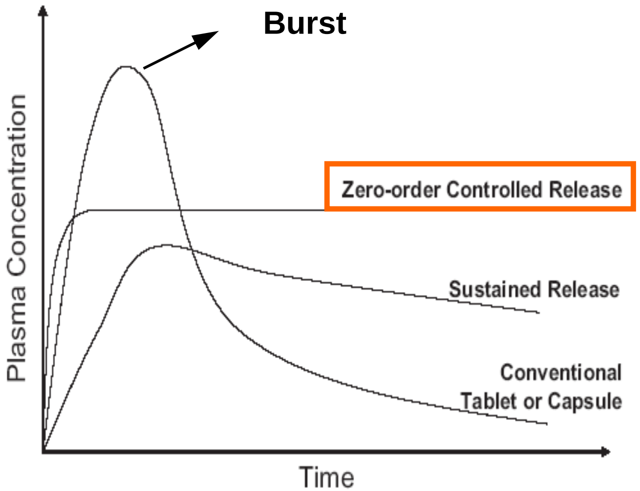


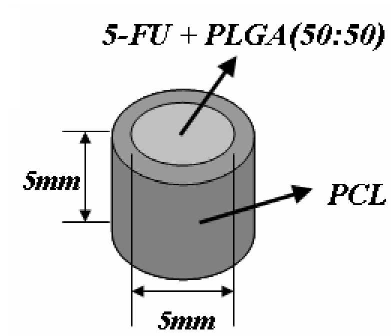


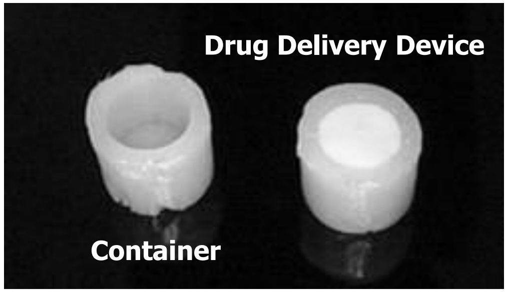


Drug Delivery System (DDS)

- Specimen for Zero-order Release Test

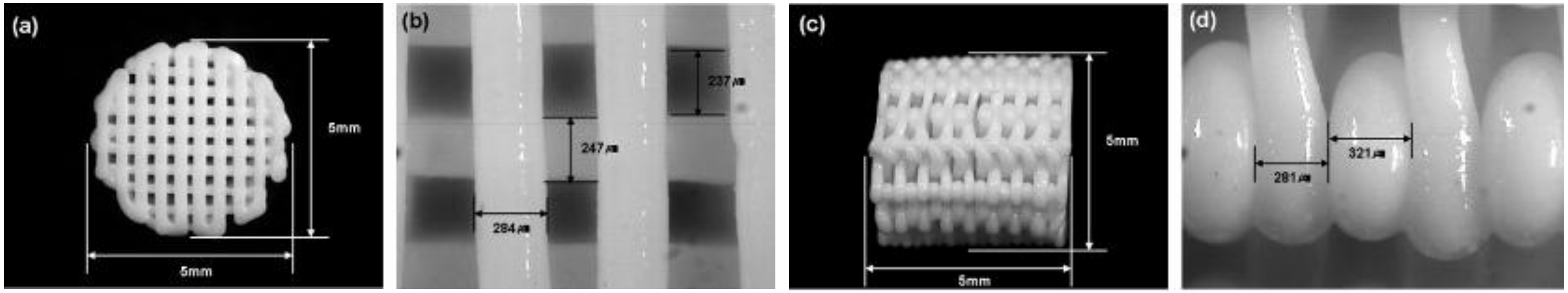






Fabricated container and drug delivery device

- Scaffold Shape of DDS (Controlled Pore Size)

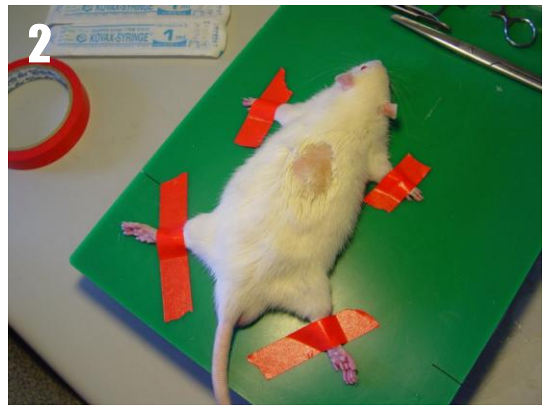


Fabricated drug delivery device of scaffold shape (15 layers, $[0°_8/90°_7]$, 5mm$\times$5mm)

DDS (cont.)

- *In vivo* test with Sprague-dawley Rat

Anesthetize mouse



Remove hairs

Incise back skin

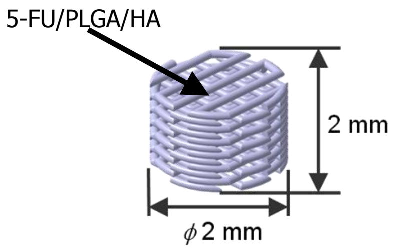
Anesthesia

When implantation (100㎎/㎏ for Sprague-dawley Rat)
- 25㎎ of Ketamine(90vol%)+Xylazine(10vol%)
- 1 ㎖ needle

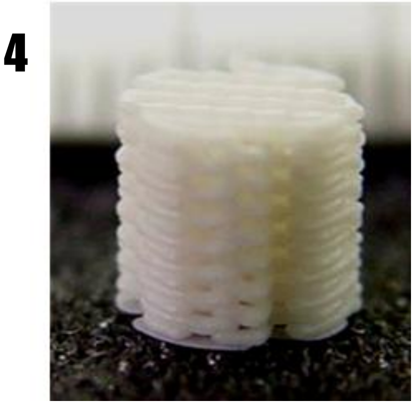
When picking the specimen
- Inhale anesthetize using ether

DDS (cont.)

- Implantation of DDS
  - Scaffold type of DDS
  - ϕ2mm × 2mm size of DDS for implantation
  - 5-FU(10wt%)/PLGA(85:15)(85wt%)/HA(5wt%)

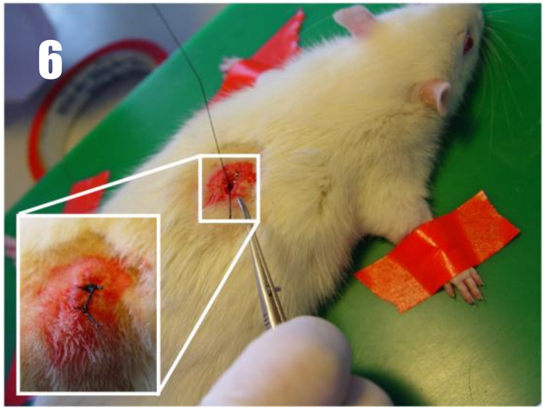


Schematic diagram of scaffold shape of DDS for *in vivo*



Prepare scaffold DDS

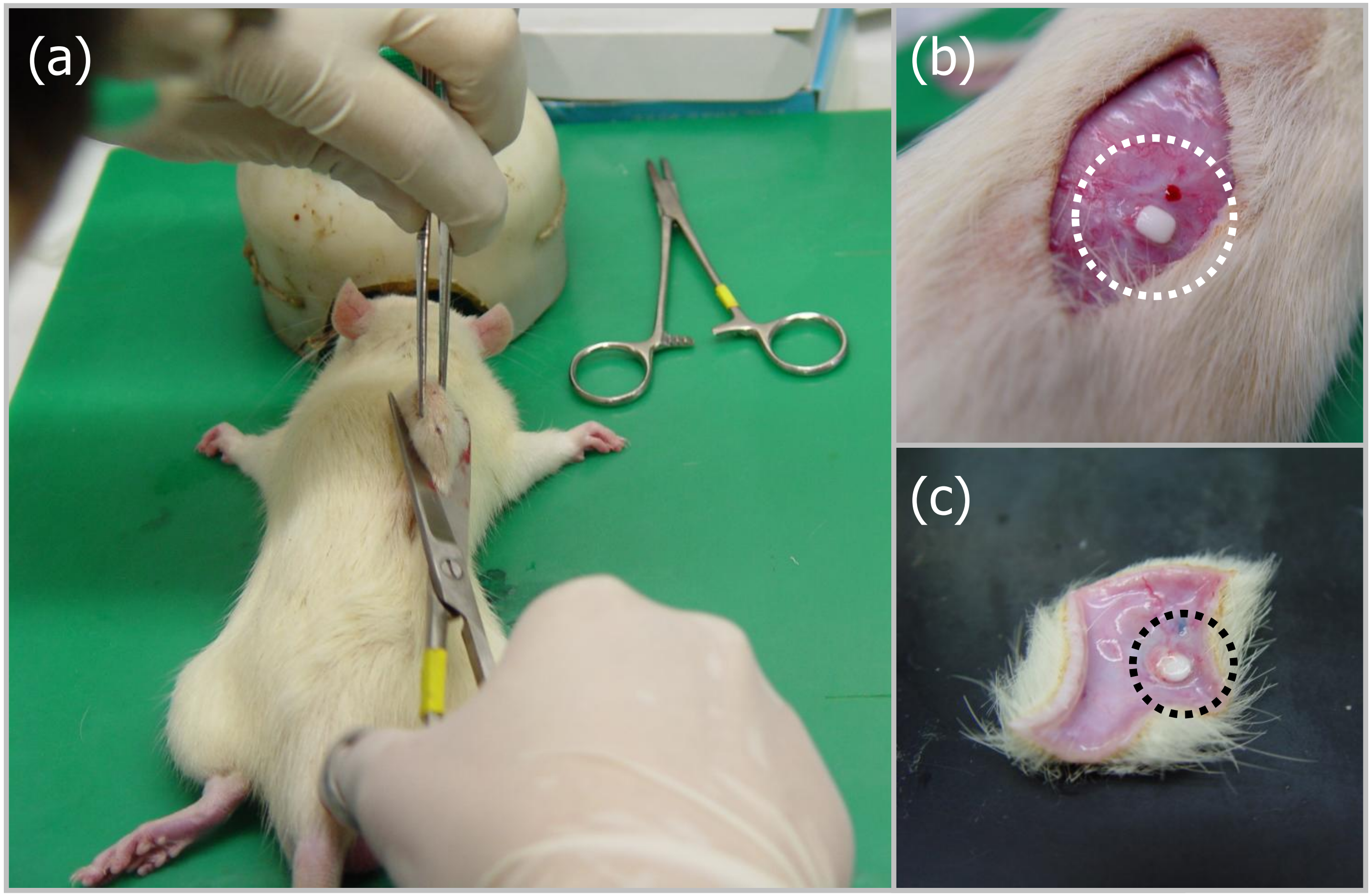
Insert the scaffold



Suture the skin

DDS (cont.)

- Collecting implanted DDS form Sprague-dawley rat



(a) Resection of back skin of the rat, (b) DDS in the back of the rat, and (c) DDS in resected skin