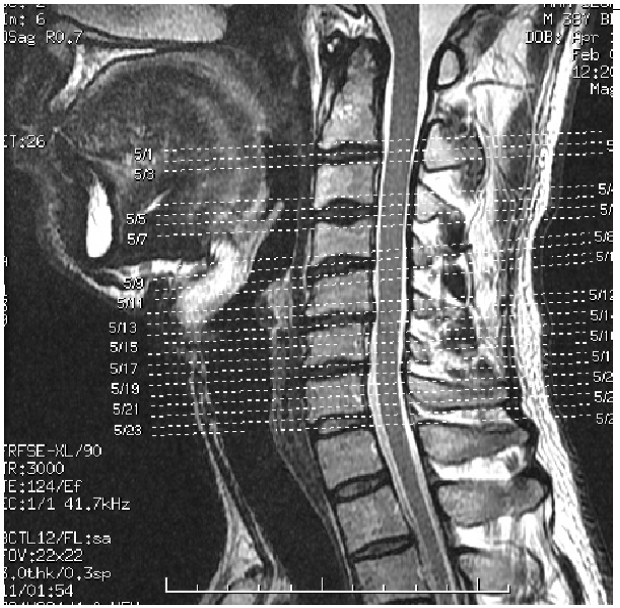
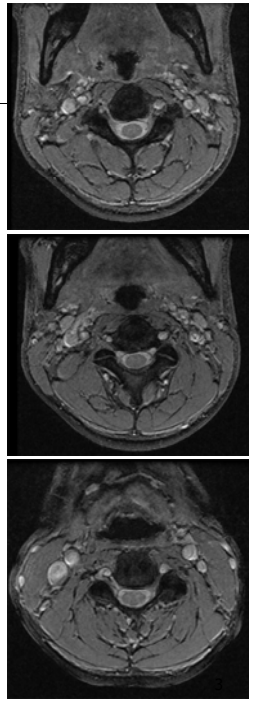
Outline

MRI



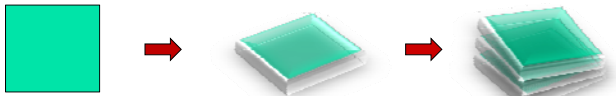


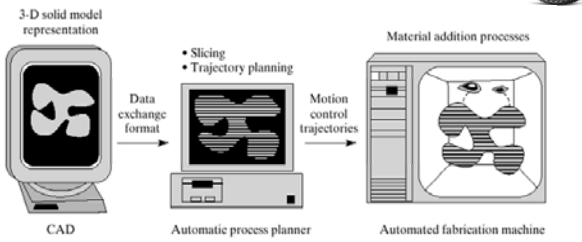
1

3

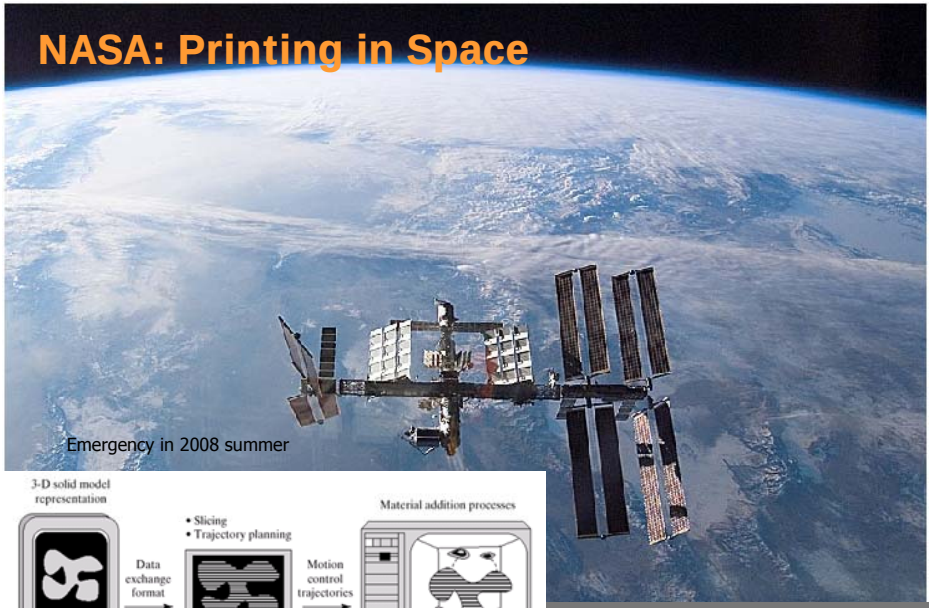
8

From 2D to 3D printing





NASA: Printing in Space



Emergency in 2008 summer

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

쾌속조형 (Rapid Prototyping, RP)

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

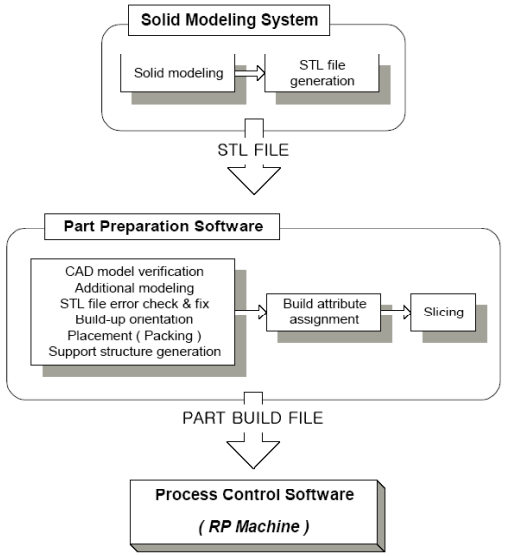
Introduction to RP

- 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

Advantages of RP

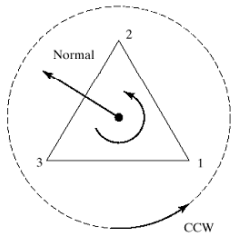
- No need to define a blank geometry
- No need to define set-ups and material handling
- No need to consider jigs, fixtures, and clamping
- No need to design mold and die

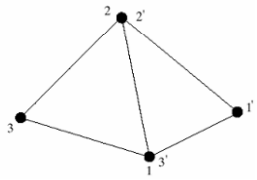
General System Configuration of RP



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

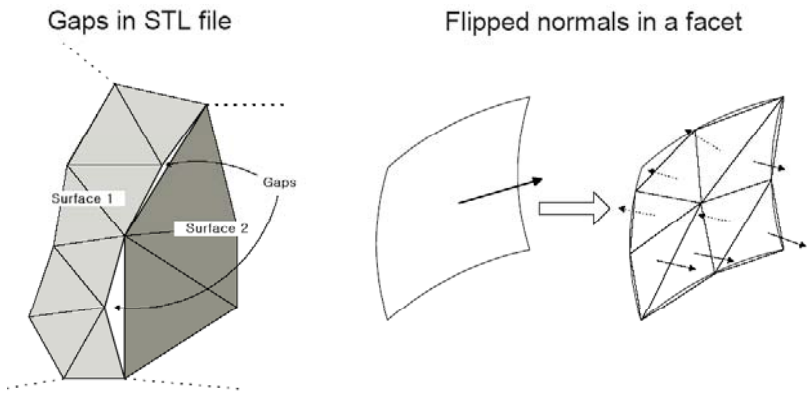
```
solid example
    facet normal 6.89114779E-02 -9.96219337E-01 -5.28978631E-02
    outer loop
        vertex 2.73239994E+01 1.08957005E+01 4.57905006E+01
        vertex 2.81019993E+01 1.09582005E+01 4.56250000E+01
        vertex 2.75955009E+01 1.09116001E+01 4.58456993E+01
    endloop
    endfacet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

(a) ASCII

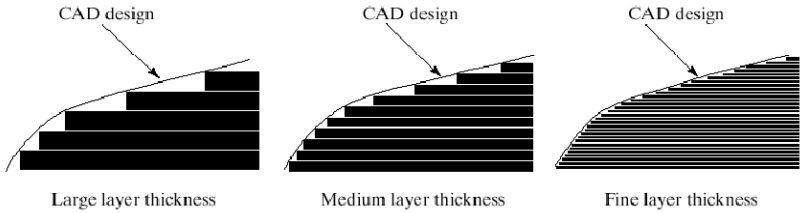
Byte	Type	Description
80	String	Head information such as the CAD system used
4	Unsigned long integer	Number of facets
First Triangle Definition		
4	Float	Normal x
4	Float	Normal y
4	Float	Normal z
4	Float	Vertex1 x
4	Float	Vertex1 y
4	Float	Vertex1 z
4	Float	Vertex2 x
4	Float	Vertex2 y
4	Float	Vertex2 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

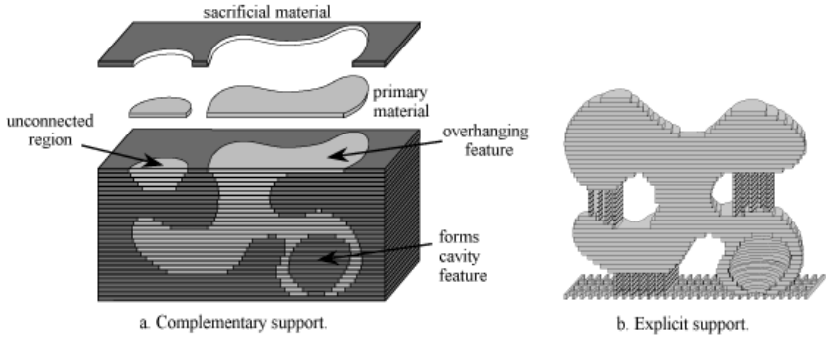


Stair-Step Effect



Surface roughness vs. build time

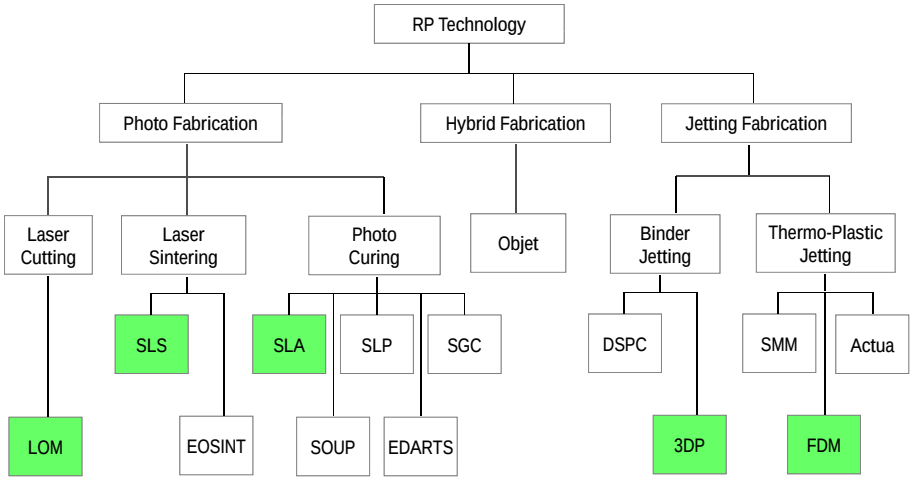
Support Structures



Issues in RP

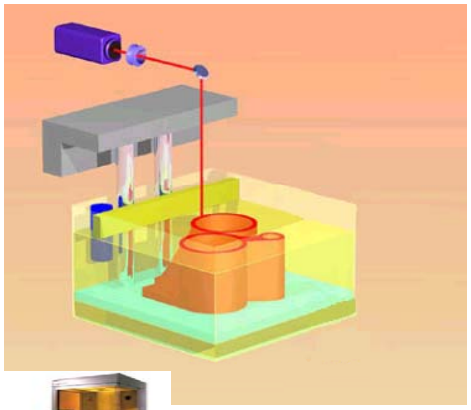
- Accuracy and Surface Finish
- Material
  - Stereo Lithography Resins
  - Metals
  - Ceramics and Paper
- Cost
  - Equipment
  - Maintenance
- Time

Classification of RP Technologies



1. Stereo Lithography Apparatus (SLA)

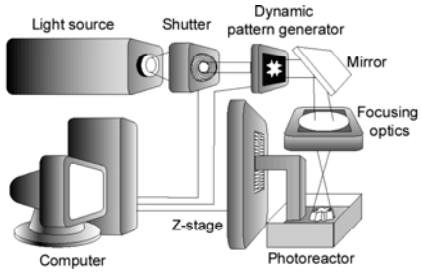
- Developed by 3D Systems, Inc.
- Laser beam will scan the surface following the contours of the slice



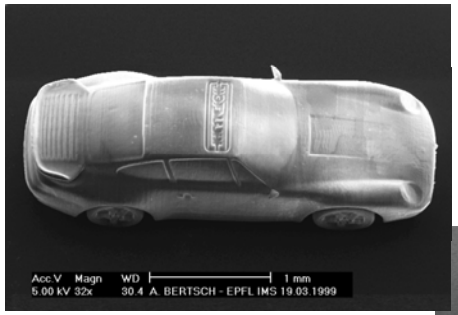
SLA-3500

1-1. Micro Stereo Lithography (MSL)

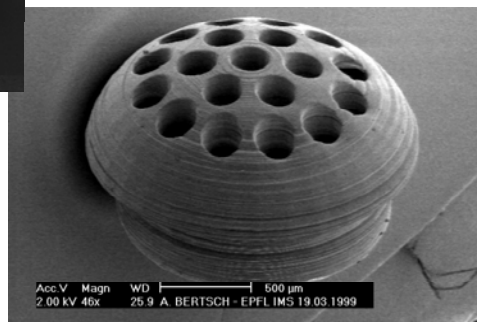
- Technique of fabricating true 3-D micro devices for various applications such as biosensors, 3-D micro-mechanisms.
- Creating true 3-D micro devices using layer-by-layer photopolymerisation
- Higher resolution (5micron ~) as well as 3D micro fabrication capabilities



Micro Structure of MSL Part

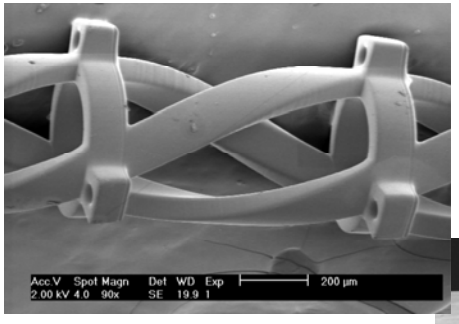


Small car, 673 layers of 5㎛ each

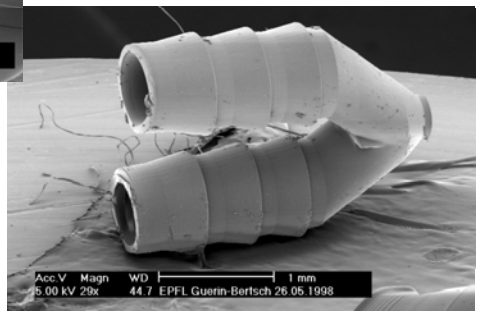


Hearing aid, 200 layers of 5㎛ each

Micro Structure of MSL Part

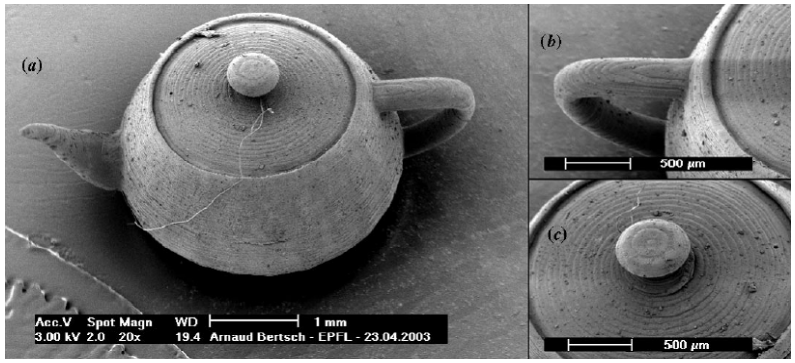


Spring, 1000 layers of 5㎛ each



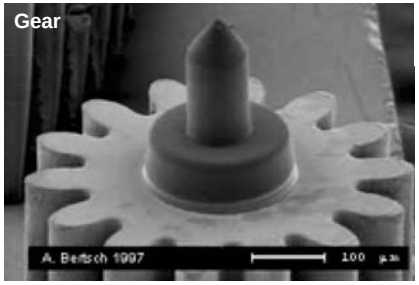
Micro pipe, diameter 500㎛

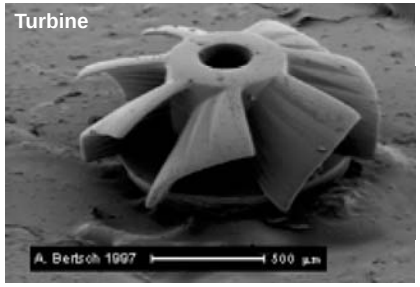
Micro Structure of MSL Part

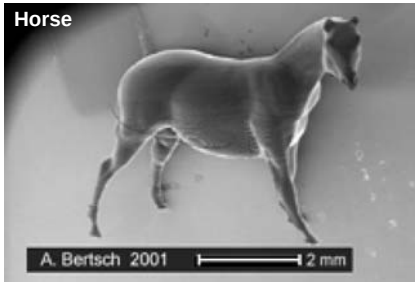


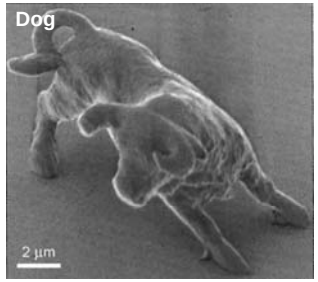
Teapot, 295 layers of 10㎛ each

Micro Structure of MSL Part



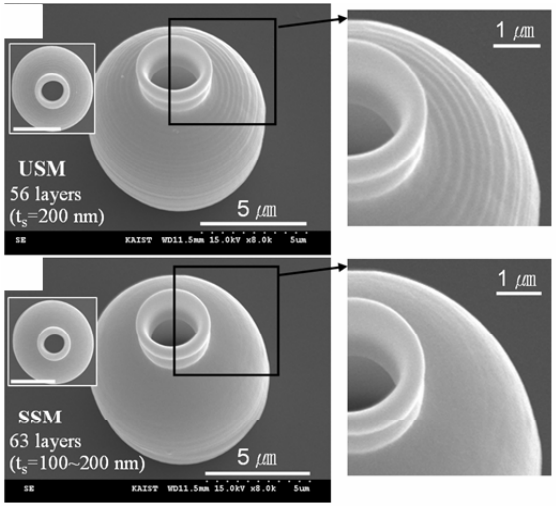




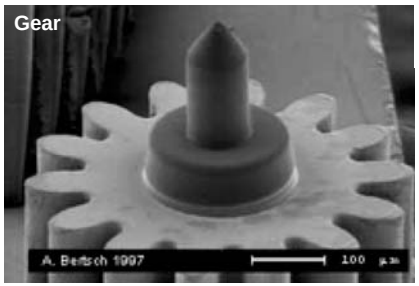


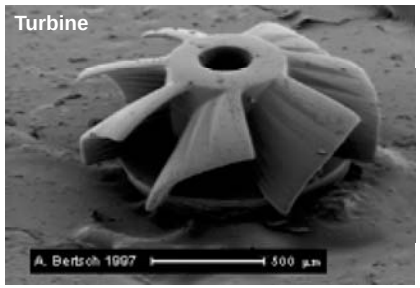
Subregional Slicing Method for MSL

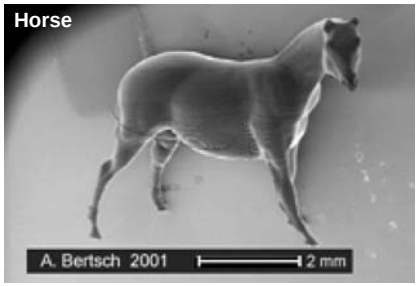
- D. Y. Yang, et al KAIST 2006

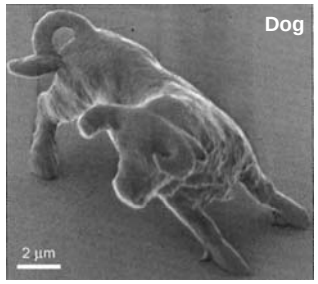


Micro SLA Part



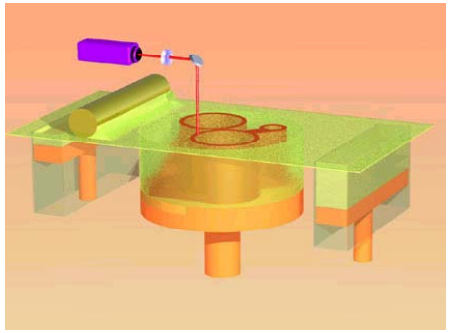






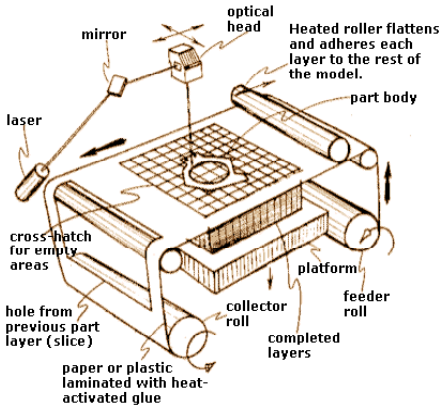
2. Selective Laser Sintering (SLS)

- 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)

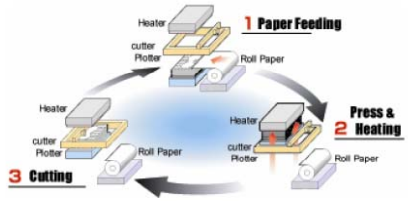
- Developed by Helysis
- The undersurface of the foil has a binder that when pressed and heated by the roller causes it to glue to the previous foil.
- The foil is cut by a laser following the contour of the slice



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

LOM based technique

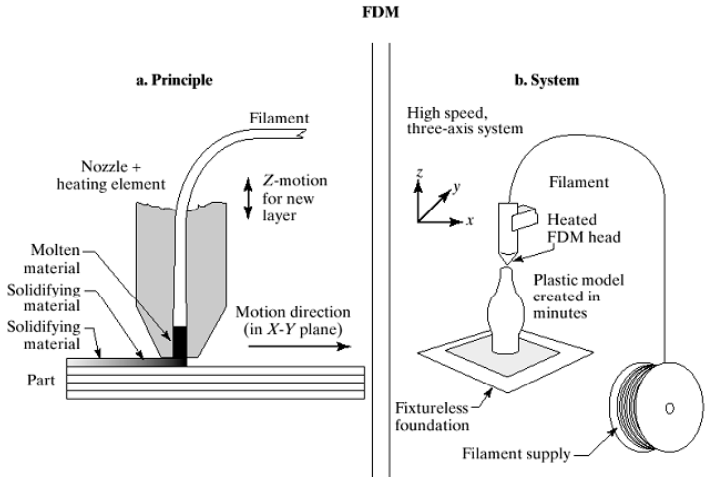
- Paper Lamination Technology(PLT) System



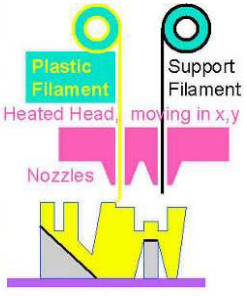
< Kira Solid Center >

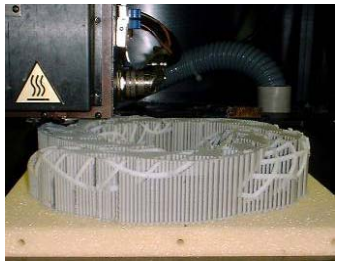
- Type: PLT-A4
- Model Material: Exclusive use sheet paper (280×190 ×200m)
- Paper Thickness: 0.08mm, 0.15mm
- Resolution: ±0.05mm (X, Y), ±0.1mm (Z)
- Accuracy: ±0.2mm

4. Fused Deposition Modeling (FDM)

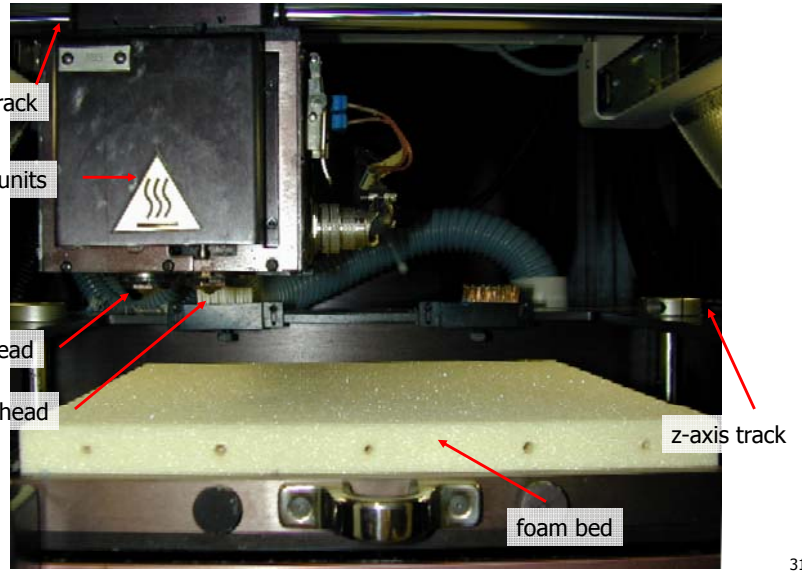


Fused Deposition Modeling (FDM)

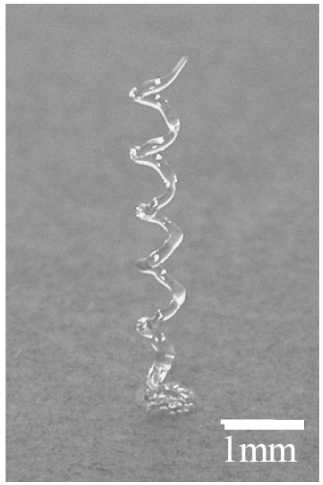




FDM Head



Structure of Micro FDM Part



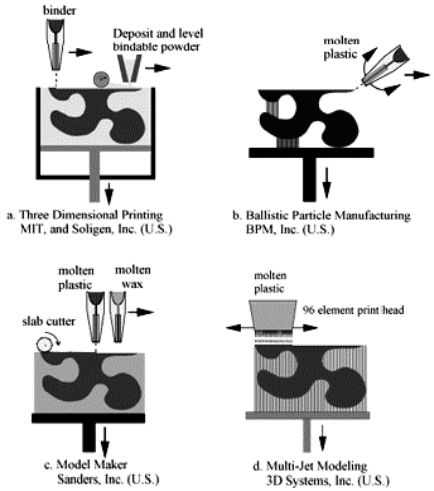
Coil spring, Line diameter 200㎛
5 turn

Wine glass, (1) Diameter 2mm
Height 3mm

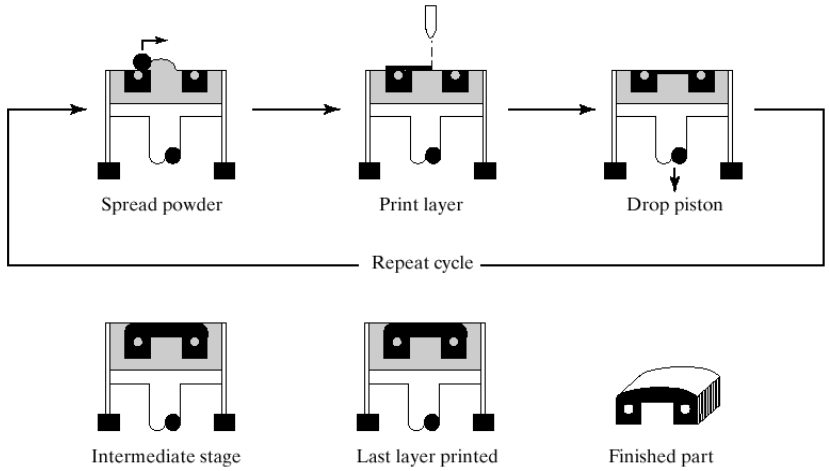
(2) Diameter 0.8mm
Height 1.5mm

5. 3D Printers

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



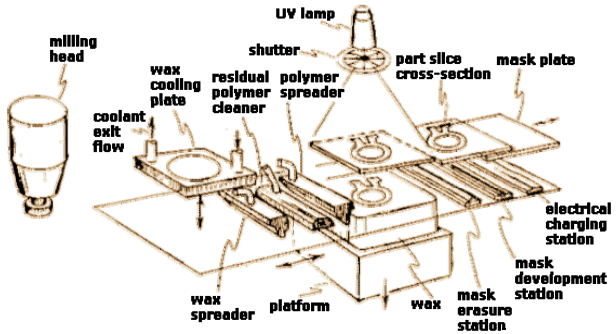
3D Printing Process



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

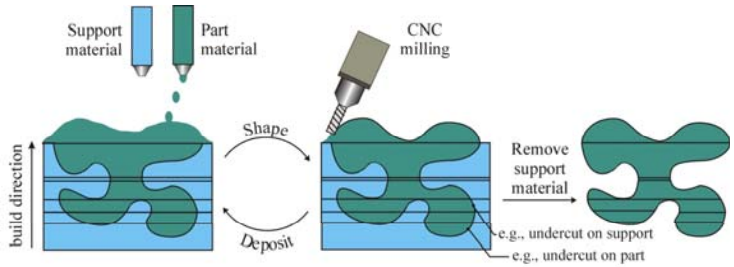
6. Solid Ground Curing (SGC)

- 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

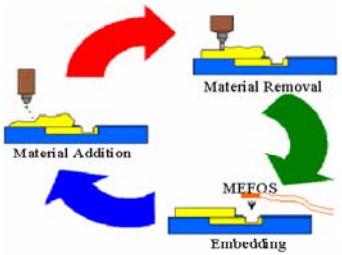


7. Shape Deposition Manufacturing (SDM)

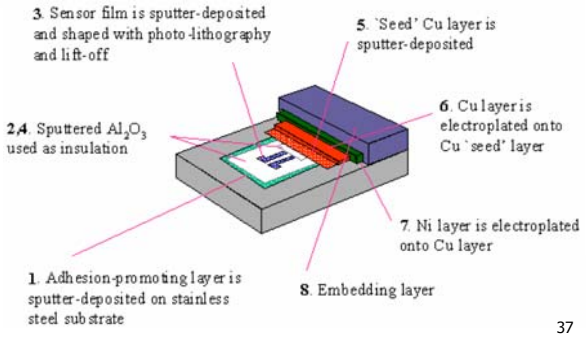
- Developed by Stanford University/CMU
- Uses deposition and milling
- Provides good surface finish



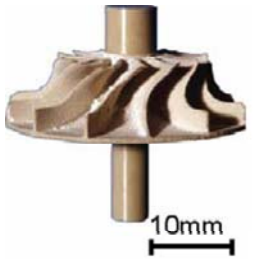
Embedded Sensor using Micro SDM



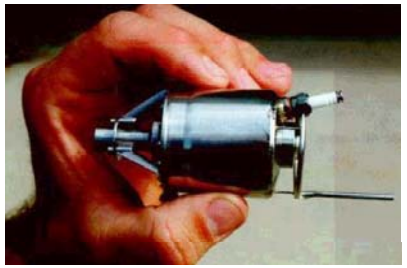
Embedding process



Meso Structure of SDM Parts



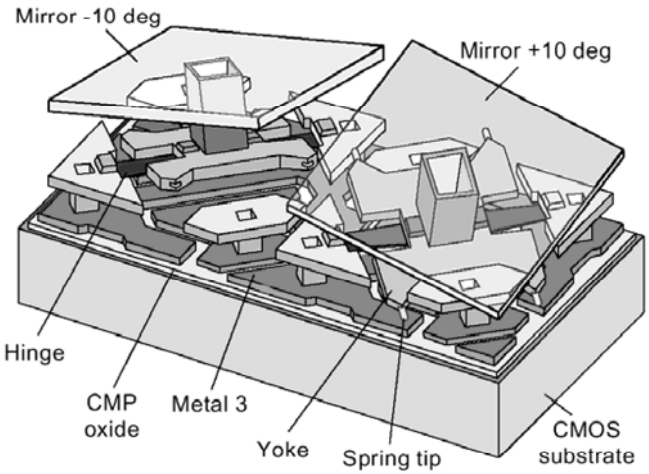
Ceramic turbine



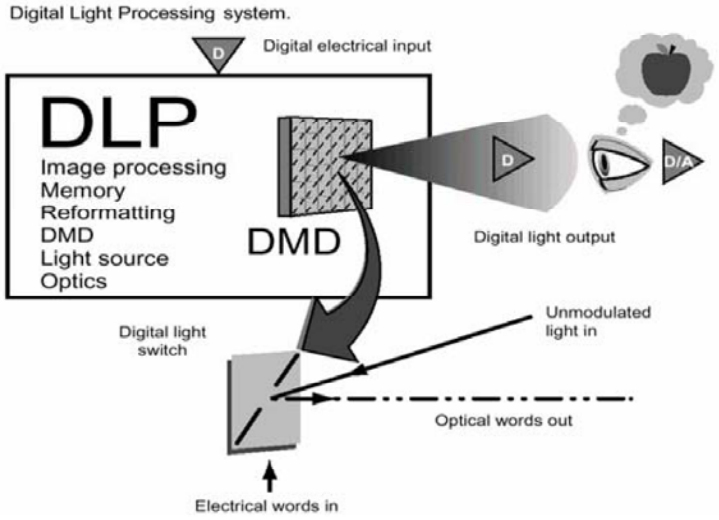
Miniature jet engine

Silicon nitride parts fabricated using mold SDM process

8. Digital Light Projection (DLP)



Application of DLP



Conventional RP Materials

Process	Materials
Stereolithography (SLA)	PMMA Styrene Methyl Methacrylate Copolymer
Fused Deposition Modeling (FDM)	ABS, ABS/PC PVC/PMMA, PES
Selective Laser Sintering (SLS)	PMMA Aromatic Polyamide
Laminated Object Manufacture (LOM)	Paper (Cellulose Based)
3D Printers	ABS, ABS/PC PVC/PMMA, PES
Solid Ground Curing (SGC)	PMMA Styrene Methyl Methacrylate Copolymer

Materials for SLA

- **UV-curable resins**

Chemistry type	Viscosity (cPs)	Preferred Laser
Acylate	1000 ~ 4000	He-Cd / Ar+
Urethane acylate	2000	He-Cd
Epoxy	180 ~ 190	He-Cd
Vinylether	200 ~ 230	He-Cd

- **Ceramic and metal resin**

Material	Photocurable resin viscosity (cPs)	Maximum cure depth (㎛)
Alumina	~ 30000	> 800
Silica	~ 500	> 600
Zirconia	-	~ 150
Si_3N_4	~ 5000	~ 100
Stainless Steel	< 1200	~ 75
Tungsten	-	~ 62

Comparison of Materials

- Profile of RP technologies and their potential application in 3D micro fabrication

Process tradename	Materials	Light source	Potential for 3D microfabrication
Stereolithography (SL)	Photopolymer	He–Cd laser, Argon ion laser.	Good
Somos	Photopolymer	UV laser	Good
Optical fabrication	Photopolymer	Argon ion laser	Good
Mark 1000	Photopolymer	Argon ion laser	Good
Solider	Photopolymer	UV lamps	Good
Laminated object manufacturing	Sheet (paper, plastics, etc.)	CO_2 laser	Bad
Selective laser sintering (SLS)	Plastic, metal, and ceramic powders	CO_2 laser	Bad
Light Sculpting	Photopolymer	UV lamps	Good
Ballistic particle manufacturing	Thermoplastic ink	None needed	?
Fused deposition modeling (FDM)	Thermoplastic ink	None needed	Bad

Issues in RP Materials

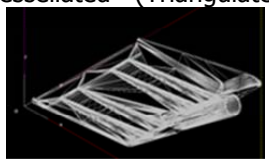
- Rapid Fabrication of functional parts
  - Structural
  - Optical
  - Surface Roughness
  - Electrical
  - Thermal
  - Color
  - … … …

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

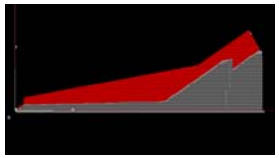
Case study: Collapsible Shovel Head

1. Tessellated (Triangulated) format

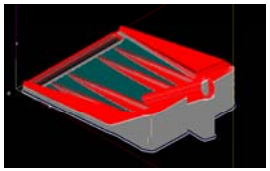


2. Vertically Sliced File

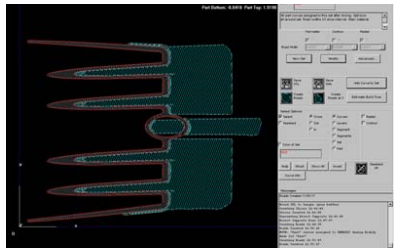
3. Support Calculation



4. Road Generation



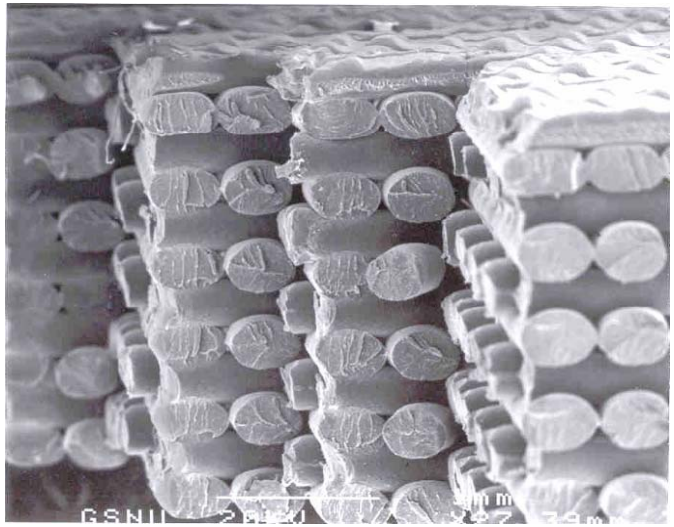
5. SML firle



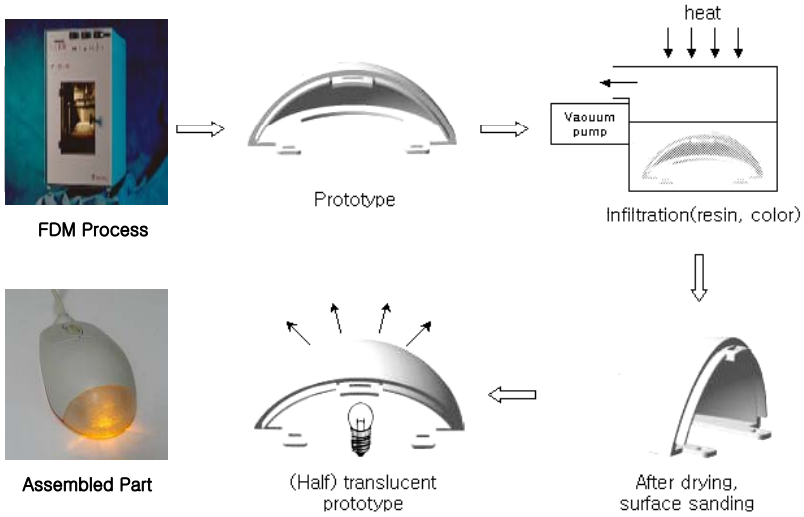
FDM Build Parameters - Software

- 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

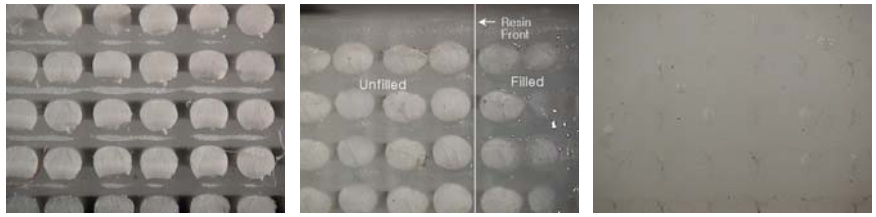
Micro Structure of FDM



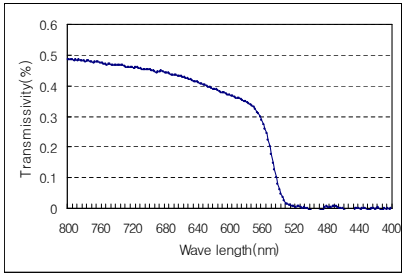
Part Post-process of FDM

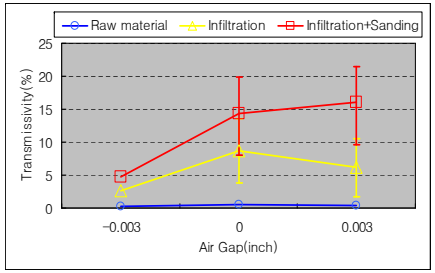


Resin Infiltration

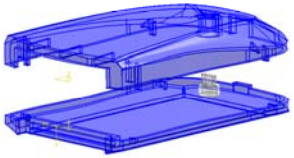


Raw FDM ABSi | **During Infiltration** | **After Infiltration**





Flash Memory Reader



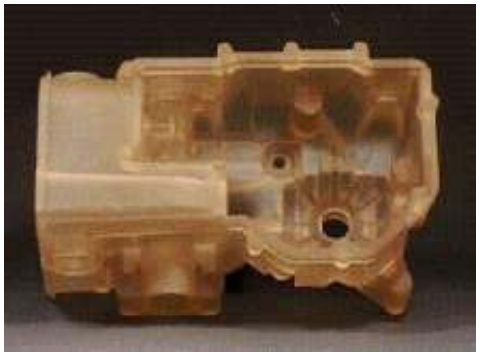
CATIA modeling:
5 hours

FDM process:
10 hours

Post-process : 24 hours
Total prototyping time : 39 hours

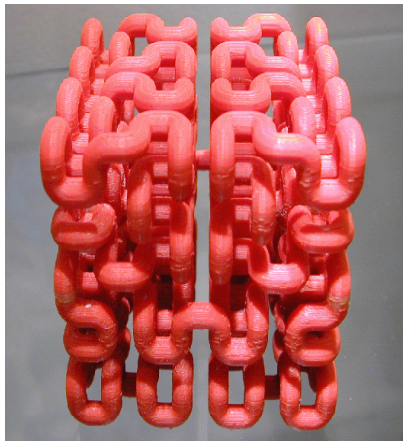
Gallery

- SLA



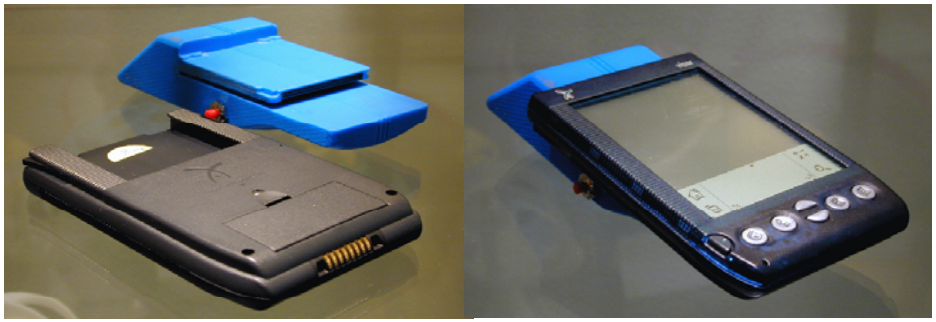
Gallery (cont.)

- FDM



Gallery (cont.)

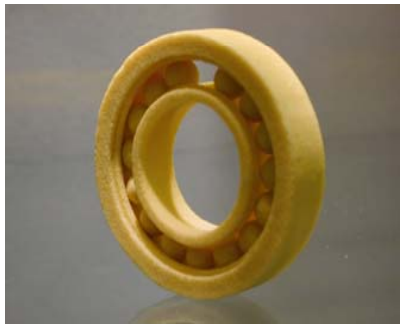
- FDM

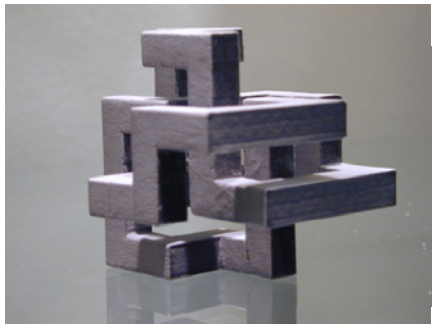


GPS module for PDA

Gallery (cont.)

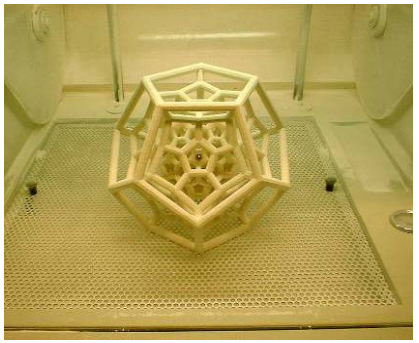
- Z- corp (3D Printer)
- SLS





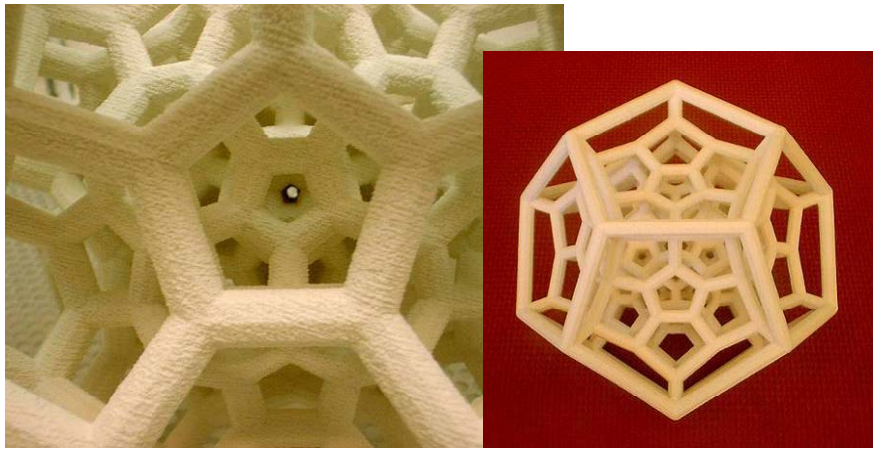
Gallery (cont.)

- Z- corp (3D Printer)



Gallery (cont.)

- Z- corp (3D Printer)

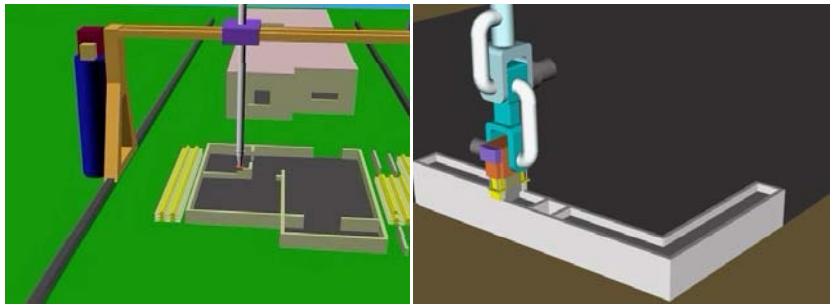


Gallery (cont.)

- 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

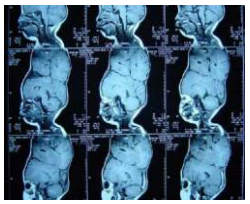
The original Volomandra Kouros and the SLA replica

Applications (cont.)

- Medical Domain

Before surgery

After surgery



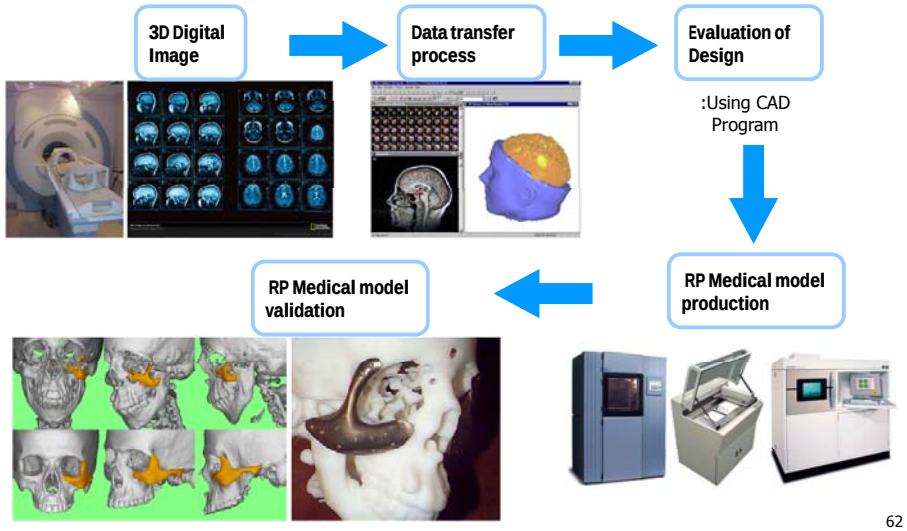
CT Scan

Virtual surgery

RP part

MRP (Medical rapid prototyping)

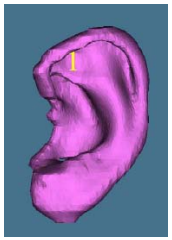
- 3D model creation process



Tissue Engineering

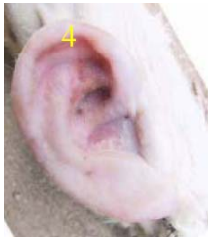
Vacanti, et al

Yan, et al



CAD modeling

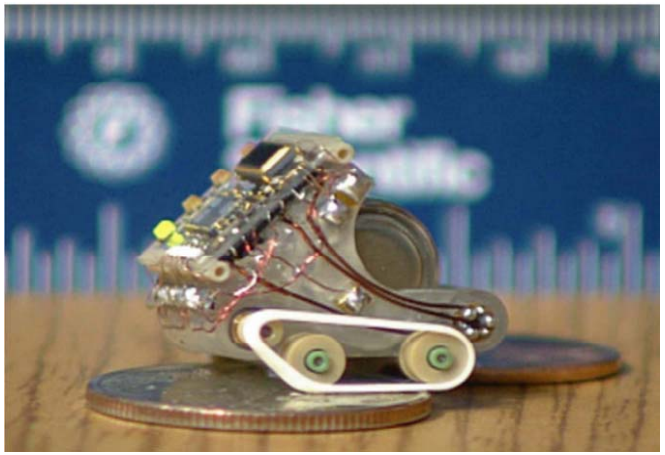
RP part



Rehabilitated ear

Applications (cont.)

- Micro component



Micro robot by Sandia Lab

Applications (cont.)

- Rapid Tooling (RT)

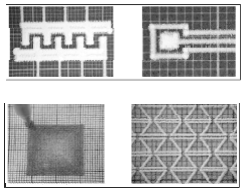
DTM's RapidTool™ process for rapid mold making

Core and cavity sets produced by RapidTool ™

Applications (cont.)

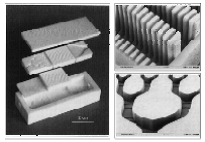
- Other Examples

Patterning with Ceramic



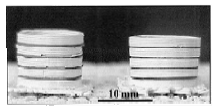
P. Kumar *at al,* Ann Arbor

Microreactor

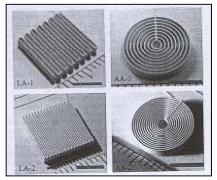


R. Knitter *at al.* RP Journal

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

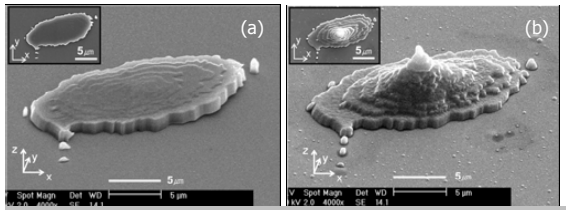
Y. Tan *et al.* Am. Ceram. Soc.

Artificial ear

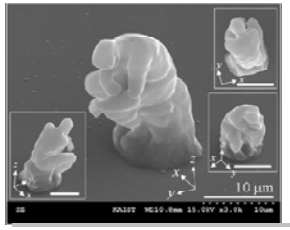
Bio-compatible Material

3D Nano / Micro Parts

- Two-photon Stereolithography

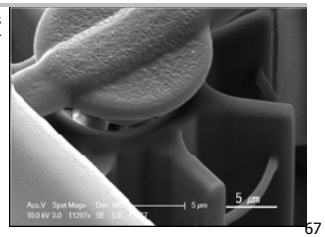


SEM images of fabricated islands with (a) actual and (b) exaggerated ratio of height vs. width by controlling both exposure time and laser power simultaneously. Inset is top view of the structure



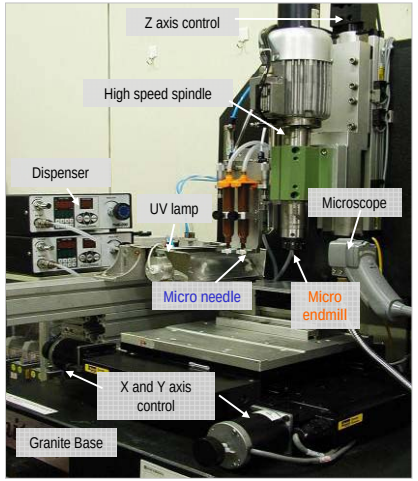
SEM images of fabricated micro-Thinker by double-scanning path. The insets are the same micro-Thinker with various view angles, and the scale bars are 10 ㎛

Fabricated micro-prototypes of a micro rotor

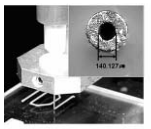


Hybrid RP System

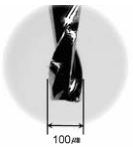
- Hardware



- ✓ ***Deposition; Rapid Prototyping***
- ✓ ***Cutting; Milling***
- ✓ ***Hybrid; Both***



Micro needle



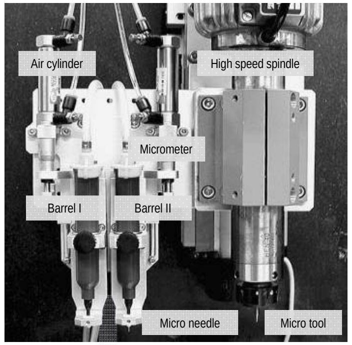
Micro endmill

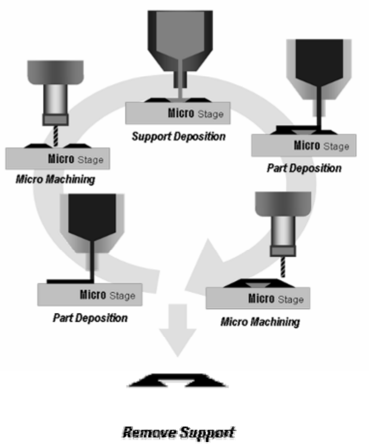
SPECIFICATIONS

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 ㎚
Controller	PMAC (Multi-tasking board)

Hybrid RP System (cont.)

- Hybrid process: depositing + machining

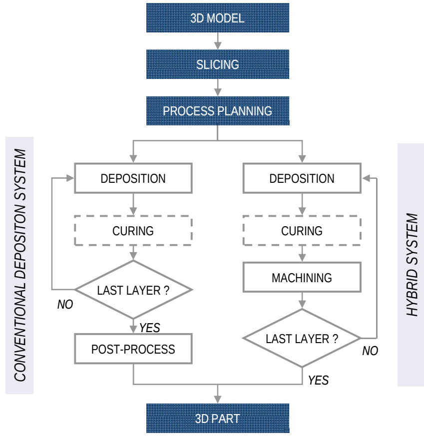


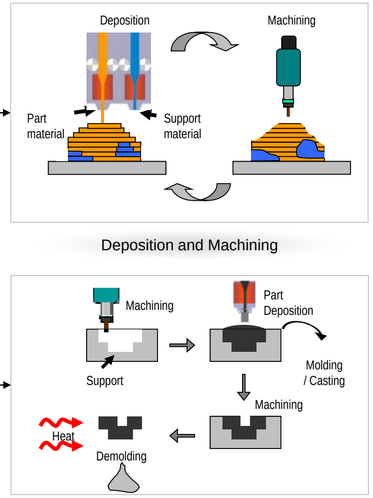


Conceptual process of NCDS

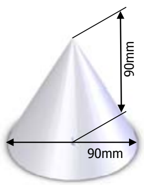
Hybrid RP System (cont.)

- Process planning



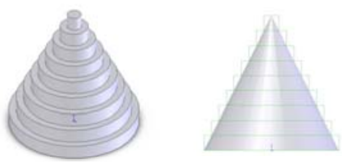


CAD Model and NC Codes



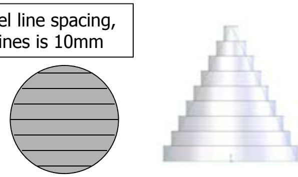
CAD design of a microcone

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



Layer model of a microcone

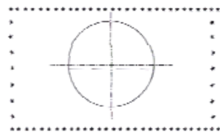
Hatching: Parallel line spacing, filling between lines is 10mm



NC Codes for the Cone

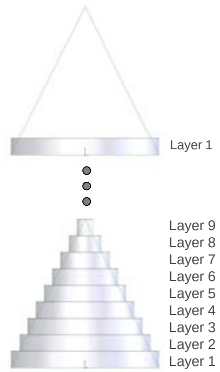
```
;  cone.90.PRG, Layer 1
G92;  set software home, reset axes to 0
G71;  set as metric mode
G24;  set conditions the deceleration behavior ;
;     of a contour type move as corner
;     rounding off
OU 0;  No output to trigger the optical shuttle
;      (light off)
G1 F200.0;  G1: initiates motion 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
```

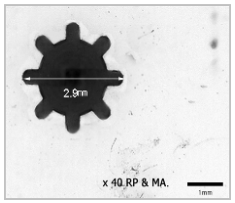
```
G1 X-.0374 Y-.025
OU 1
G1 F10.0
G1 X.0374 Y-.025
OU 0
G1 F200.0
G1 X.0283 Y-.035
OU 1
G1 F10.0
G1 X-.0283 Y-.035
OU 0
G1 F200.0
G1 X0 Y0;  Return to the position (0,0) and the
;          first layer fabrication is done.
```



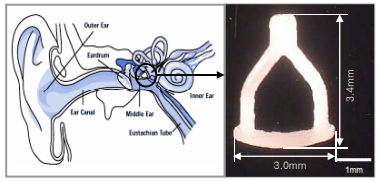
Nano Composite Parts

- 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



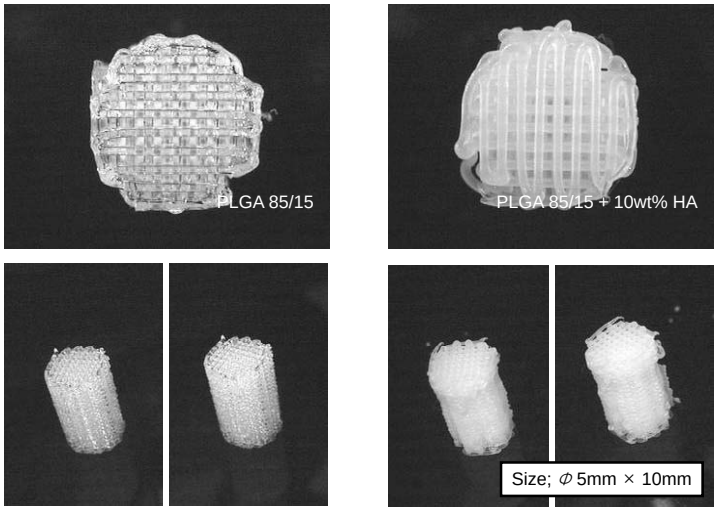
Microscope picture of microgear



Geometry of stapes

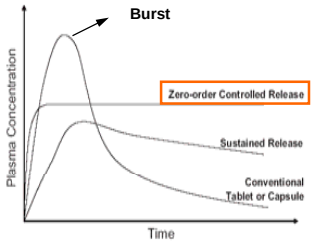
Scaffold for Bone Growth

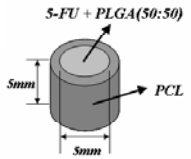
- Bio-degradable polymer



Drug Delivery System (DDS)

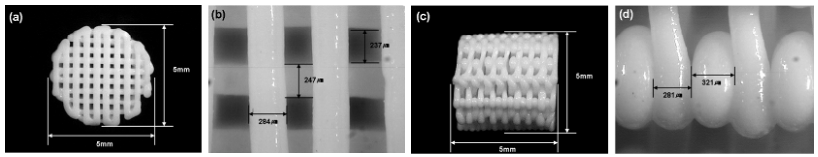
- Specimen for Zero-order Release Test





Fabricated container and drug delivery device

- Scaffold Shape of DDS (Controlled Pore Size)

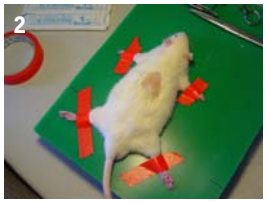


Fabricated drug delivery device of scaffold shape (15 layers, [0°$_8$/90°$_7$], 5mm×5mm)

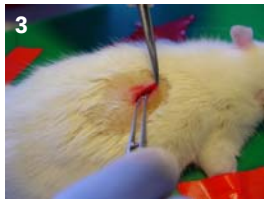
DDS (cont.)

- *In vivo* test with Sprague-dawley Rat

Anesthetize mouse



Remove hairs



Incise back skin

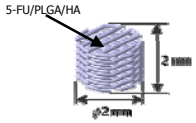
Anesthesia

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.)

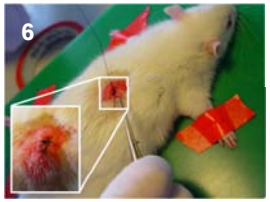
- Implantation of DDS
  - Scaffold type of DDS
  - ϕ2mm × 2mm size of DDS for implantation
  - 5-FU(10wt%)/PLGA(85:15)(85wt%)/HA(5wt%)



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

Prepare scaffold DDS

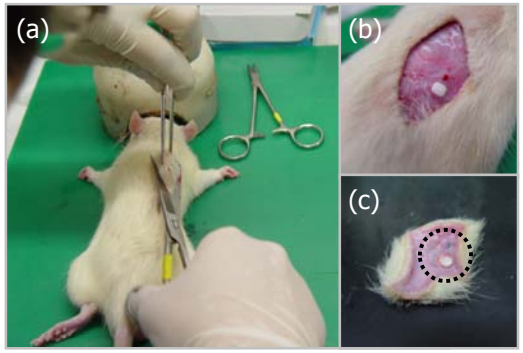
Insert the scaffold

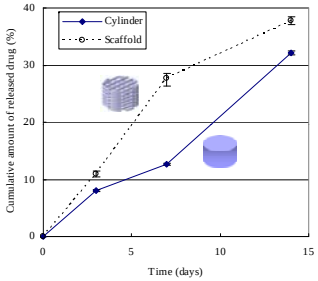


Suture the skin

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

Conclusions

- **Rapid Prototyping is used for product development, sculptures, and functional prototypes**
- **RP has advantages over other fabrication technologies in terms of fabrication time part's complexity**
- **Various new RP processes are under development and commercialized**
- **Some RP processes may fabricate 3D parts in micro scale**
- **Functional materials and precision of parts are important issues in RP**
- **Various bio-medical applications using RP are under investigation**
- **Multi-material and multi-functional parts made by RP will broaden the applications of RP technology**