Indirect Rapid Prototyping
Indirect Rapid Prototyping (iRP)

• Molds realised with RP devices (CAD/CAM)
• Casting of the desired (bio-)material
• Extraction of the final object

DW Hutmacher et al., Trends in Biotechnology, 22(7):354 – 362, 2004
iRP – General concepts

- Wide range of (bio-)materials
- Known also as rapid tooling
- Less waste
- High fidelity
- Microporosity by:
  - critical point drying
  - free-drying
  - leaching
- Use in surgery room

DW Hutmacher et al., Trends in Biotechnology, 22(7):354 – 362, 2004
iRP – Stereolitography

<table>
<thead>
<tr>
<th>Casted Materials</th>
<th>Extraction method</th>
<th>Resolution (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoplastic Elastomer</td>
<td>Mechanical</td>
<td>≈1000</td>
</tr>
<tr>
<td>HA</td>
<td>Pyrolysis</td>
<td>400</td>
</tr>
<tr>
<td>PCL, PLLA, PLGA, Chitosan, alginate</td>
<td>Basic Solution</td>
<td>200-400</td>
</tr>
</tbody>
</table>

R Sodian et al., ASAIO Journal, 48(1), 2002
YJ Seol Microelectronic Engineering, 86(4-6):1443–1446, Apr 2009
iRP – Fused Deposition Modeling

<table>
<thead>
<tr>
<th>Casted Materials</th>
<th>Extraction method</th>
<th>Resolution (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina, TCP</td>
<td>Pyrolysis</td>
<td>300-500</td>
</tr>
<tr>
<td>Agarose, Alginate, PEG, Fibrin, Matrigel</td>
<td>Water dissolution</td>
<td>500</td>
</tr>
</tbody>
</table>
iRP – 3D printing

<table>
<thead>
<tr>
<th>Casted Materials</th>
<th>Extraction method</th>
<th>Resolution (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLGA</td>
<td>Calcium Reagent</td>
<td>800</td>
</tr>
</tbody>
</table>
iRP – Ballistic

<table>
<thead>
<tr>
<th>Casted Materials</th>
<th>Extraction method</th>
<th>Resolution (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA, TCP</td>
<td>Pyrolysis</td>
<td>300-400</td>
</tr>
<tr>
<td>Collagen, Silk, PLLA</td>
<td>Organic Solvent</td>
<td>200-400</td>
</tr>
</tbody>
</table>

E Sachlos et al., Biomaterials, 24(8):1487–97, Apr 2003
MJJ Liu et al., Med Eng Phys, Nov 2011
iRP – main problem

• Difficulty to extract the final object
  – Mechanical
  – Pyrolysis
  – (Organic) solvent

• IDEA:
  CASTING INTO LOW MELTING POINT MOLDS
Investment Casting Using Rapid-Prototyped Wax Parts

- Manufacturing steps for investment casting that uses rapid-prototyped wax parts as blanks. This method uses a flask for the investment, but a shell method also can be used. Source: Courtesy of 3D Systems, Inc.
PAM²

- Modular CAD/CAM system
- A 3-axes robotic stages:
  - position ±50 mm;
  - velocity 0-15 mm/s;
  - resolution 1 μm;
  - different extrusion modules;
  - layer-by-layer processing.

TCS extrusion module
Temperature Controlled Syringe
TCD module
Temperature Controlled Deposition plane

- Peltier Cell
- H-Bridge drivers
- Control algorithm based on step strategy
- ± 40°C respect to room temperature
Plotting low melting point waxes
Drop formation

\[
\frac{d(MV)}{dT} = \gamma(\pi D_0) \cos(\theta_c) \pm 2\pi \mu L \ln\left(\frac{D}{D_0}\right) - Mg
\]

Chang B et al., Commun Nonlinear Sci Numer Simulat 17 (2012) 2045–2051
Drop formation

- Just before drop detachment:

\[ \gamma \pi D_0 \cos(\theta) = \rho g \left( \frac{\pi D^3}{6} \right) \]

![Graph showing drop diameter vs. pressure at different temperatures](image)

\( \text{T=70°C, T=80°C, T=90°C} \)

\( \gamma, \pi, D_0, \theta, \rho, g \)
System calibration
preliminary tests

- Volumetric shrinking
  - Casting into an aluminium mold
- Contact angle
  - Several material tested

Processing parameter in PAM²
Low melting point mold – 2D

• Hexagonal path:
  – Side 2 mm, linewidth 400 μm
  – Side 1 mm, linewidth 300 μm
• 60% W/V HA in gelatin gel (5% W/V), crosslinked with genipin 0.5 W/V
• Volumetric change < 1%
Low melting point mold – 2D

- Hexagonal path:
  - Side 2 mm, linewidth 400 μm
  - Side 1 mm, linewidth 300 μm
- Pentagonal path:
  - Side 2 mm, linewidth 300 μm
- 5% gel-collagen 1:1 + 0.2% GP
- Volumetric change < 6 %
Low melting point mold for microfluidic devices

- Serpentine path
  - Length 20 mm, height 2
- Casting with 5% w/v gelatin gel crosslinked with genipin

Huang et al., Biofabrication, 2011 vol. 3 (1) pp. 012001
Low melting point mold for microfluidic devices

- Hexagonal path
  - Side 2 mm, linewidth 400 um
- Casting with PDMS
SHAPE DEPOSITION MANUFACTURING (SDM)
Shape Deposition Manufacturing

- Rapid production method with repetitive addition and selective removal of materials.
- It uses conventional machining facilities, hence also achieves the same order of machining tolerances.
- Multi-material parts can be created to compose functional mechanisms, also with embedded functional parts such as sensors and actuators.
- Cross-boundary embedding is the key for realizing highly integrated structures.

http://www-cdr.stanford.edu/biomimetics
Motohide Hatanaka: motohat@cdr.stanford.edu
Shape Deposition Manufacturing

- Developed at Stanford & Carnegie Mellon
- Is it a pure SFM process?

1. Deposition - material is added by plasma or laser based welding techniques
2. Filler material is deposited around part and Material is shaped using conventional CNC
3. Solid is stress relieved
4. Components can be embedded
5. Filler is removed to leave only finished part
Why not add material in bulk and then selectively remove?
Why not add material in bulk and then selectively remove?
Comparison between common RP methods and SDM

<table>
<thead>
<tr>
<th>RP</th>
<th>SDM</th>
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<tbody>
<tr>
<td>Limited material variation</td>
<td>Wide variety of materials</td>
</tr>
<tr>
<td>Limited fabrication tolerance</td>
<td>Fabrication tolerance comparable to</td>
</tr>
<tr>
<td>Requires special equipment</td>
<td>conventional machining</td>
</tr>
<tr>
<td></td>
<td>Conventional machining tools used.</td>
</tr>
<tr>
<td></td>
<td>Can embed parts (sensors, actuators,</td>
</tr>
<tr>
<td></td>
<td>reinforcement)</td>
</tr>
</tbody>
</table>
SDM capabilities

Multi-material molding

Component embedding
Fabric-reinforced flexural hinges

- Left: Kinematic prototype of stroke extension linkage with 31 parts
- Center: Single component SDM linkage with thick flexures
Biology is a target for complex integrated structures manufacturing
SDM is suited for complex integration

• Material properties can be locally altered by multi-material fabrication.

• Components can be assembled without fasteners, hence easier and more room for complex integration.

• Semi-automated process allows detailed fabrication.
Cross-boundary embedding

- Selectively adding, removing or otherwise processing material around the flexible strands without damaging them or being hindered by them.
Selective deposition

- Embedded component
- Selective deposition of part material
- Partially embedded
- Cross-boundary embedded
- Sacrificial material

Selective deposition of sacrificial material
Capillary effect for selective deposition

Example:

Small string-suspended gimbals with two rotational degrees of freedom. Developed for attitude control of solar panels on a small satellite (100mm-side cube).
Selective deposition
Selective removal

Selective removal of part material

Excessive deposition

Selective removal

Selective removal of sacrificial material
Manual Selective Removal

Example:

Spring-loaded hinge with partially embedded coil-spring and fiber-reinforced flexure. Developed for deploying solar-panels for a small satellite.
Selective removal
Material property alteration by post-processing.

Material property alteration. E.g. by heat treatment, light exposure, or material addition.
Selective removal by photo-lithography

Example:

A small flexural hinge with embedded electrical wires.
Selective removal by photo-lithography