RAPID PROTOTYPING TECHNIQUES

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Introduction

- In the development of a new product, there is a need to produce a single example, prototype, of a designed part or system before allocating large amounts of capital to new production facilities or assembly lines.

- The main reasons for this need:
  - Capital cost is very high
  - Production tooling takes considerable time to prepare
  - Design evaluation
  - Troubleshooting

Rapid Prototyping (RP) is also called as:
  - desktop manufacturing
  - digital manufacturing
  - solid free-form manufacturing
Introduction

- Developments in rapid prototyping began in the mid-1980s.

The advantages of RP:

- Physical models of parts produced from CAD data files can be manufactured in a matter of hours and allow the rapid evaluation of manufacturability and design effectiveness. In this way, rapid prototyping serves as an important tool for visualization and concept verification.

- With suitable materials, the prototype can be used in subsequent manufacturing operations to produce the final parts. This also serves as a manufacturing technology.

- RP operations can be used in some applications to produce actual tooling for manufacturing operations (rapid tooling).
Introduction

RP processes can be classified into three major groups:

1) **Subtractive**: material removal from a workpiece that is larger than the final part

2) **Additive**: built-up a part by adding material incrementally to produce the part

3) **Virtual**: uses advanced computer-based visualization technologies

Almost all materials can be used through one or more RP operations. However, polymers are the most commonly used material today, followed by metals and ceramics.
### Characteristics of Additive Rapid-Prototyping Technologies

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Introduction

- Almost all materials can be used through one or more RP operations.
- However, polymers are the most commonly used material today, followed by metals and ceramics.
- The objective of this lecture is to give a detail introduction to the most common RP operations, describe their advantages and limitations, and explore the present and future applications of these processes.
Subtractive Processes

- Making a prototype traditionally has involved a series of processes using a variety of tooling and machines.
- This approach requires skilled operators using material removal by machining and finishing operations until the prototype is completed.
- To speed up the process, subtractive processes increasingly use computer-based technologies such as:
  - Computer-based drafting
  - Manufacturing software: planning the operations required to produce the desired shape
  - Computer-numerical-control (CNC) machinery
- For the purpose of shape verification, a soft (polymer or wax) is used in order to reduce or avoid any machining difficulties.
Additive Processes

- Additive rapid-prototyping operations all **build part in layers**.
- All of the processes to be described **build parts slice by slice**.
- The main difference between the various additive processes lies in the method of producing the **individual slices**, which are typically 0.1 to 0.5 mm thick and can be thicker for some systems.
- All additive operations require **elaborate (complicated) software**.
- The first step is to obtain a **CAD file** description of the part. The computer then **constructs slices** of the 3D part.
- Each slice is analyzed separately, and a set of instructions is compiled in order to provide the **RP machine** with detailed information regarding the manufacture of the part.
(a) Three dimensional description of part.
(b) The part is divided into slices (only one in 10 is shown).
(c) Support material is planned.
(d) A set of tool directions is determined to manufacture each slice.
  Shown is the extruder path at section A-A from (c), for a fused-deposition modeling operation.
Additive Processes: RP Technologies

Prototyping technologies
Selective laser sintering (SLS)
Direct metal laser sintering (DMLS)
Fused deposition modeling (FDM)
Stereolithography (SLA)
Laminated object manufacturing (LOM)
Electron beam melting (EBM)
3D printing (3DP)

Base materials
Thermoplastics, metals powders
Almost any alloy metal
Thermoplastics, eutectic metals
Photopolymer
Paper
Titanium alloys
Various materials
(1) Fused-deposition modelling (FDM)

- In FDM process, a gantry robot-controlled extruder head moves in two principal directions over a table, which can be raised and lowered as needed.
- A thermoplastic filament is extruded through the small orifice of a heated die.
- The initial layer is placed on a foam foundation by extruding the filament at a constant rate while the extruder head follows a predetermined path.
- When the first layer is completed, the table is lowered so that subsequent layers can be superimposed.
Fused-deposition modelling (FDM)

- In some parts, the filament is required to support the slice where no material exists beneath to support it.
- The solution is to extrude a support material separately from the modelling material. The use of such support structures allows all of the layers to be supported by the material directly beneath them.
- The support material is produced with a less dense filament spacing on a layer, so it is weaker than the model material and can be broken off easily after the part is completed.
Fused-deposition modelling (FDM)

- The layers in an FDM model are determined by the *extrusion-die diameter*, which typically ranges from 0.050 to 0.12mm. This thickness represents the best achievable in the vertical direction.

- In the x-y plane, dimensional accuracy can be as fine as 0.025mm as long as a filament can be extruded into the feature.

- **A variety of polymers** are available for different applications.

- *Flat wire metal deposition* uses a metal wire instead of a polymer filament, but also needs a laser to heat and bond the deposited wire to build parts.
i.materialise
presents

Fused Deposition Modeling

by
Stratasys
**FDM Materials**

- **ABS (Acrylonitrile Butadiene Styrene)**
  A strong, durable industrial-grade ABS plastic in a wide variety of colors. Its strength is 60 to 80% that of injection molded ABS plastic.

- **ABSi (Methyl methacrylate Acrylonitrile Butadiene Styrene)**
  Its strength is superior to ABS and the translucent nature of ABSi is beneficial for monitoring material flow and light transmission, most commonly used for medical and automotive applications. When combined with FDM systems, ABSi gives you Real Parts that are visually unique, dimensionally accurate, durable and hold shape over time.
FDM Materials

- **ABS-M30**
  25-70% stronger than Standard ABS and with a greater tensile, impact and flexural strength.

- **Polycarbonate**
  Arguably the strongest plastic rapid prototyping material available. Its strength is 60 to 80% that of injection molded polycarbonate plastic.
FDM Materials

• Polycarbonate/ABS

Blend of Polycarbonate (PC) and ABS plastic. This blend combines the strength of PC with the flexibility of ABS. PC/ABS blends are used in production of parts for the automotive, electronic, telecommunications, and toy industries, among others. This blend has excellent thermal and mechanical properties. It is significantly stronger than ABS, and feature detail is similar to that of ABS modeling material.
FDM Materials

ABS-ESD7

- ABS-ESD7 is a durable and electrostatic dissipative material suited for End-use components, Electronic products, Industrial equipment and Jigs and fixtures for assembly of electronic components.

PC-ISO

- PC-ISO blends are widely used throughout packaging and medical device manufactures. The PC-ISO material used to build the FDM parts is USP Class VI approved and also ISO 10993-1 rated.

ULTEM 9085

- ULTEM 9085 is a pioneering thermoplastic that is strong, lightweight and flame retardant (UL 94-V0 rated). The ULTEM 9085 material opens up new opportunities for the direct additive construction of production grade components.
FDM Materials

ABS application

- Automotive body parts,
- Dash boards, components and housings,
- Electronic enclosures for business machines and consumer products; sporting goods;
- Handles and enclosures for power tools;
- Prototypes and end-use parts in other industries such as aerospace, medical, toys and industrial goods.
FDM Materials

Application Areas of Polycarbonate

- Pharmaceutical material handling, processing, and packaging systems;
- Surgical instruments;
- Food handling and processing systems;
- Automotive lighting;
- Rapid manufacturing of end-use products
Advantages and Disadvantages

• The main advantage to using FDM is the very durable parts that can be made using waxes and various engineering plastics.

• The drawback to using the FDM method is that the parts generally take much longer to build and the layering is clearly visible because of the extrusion type process.
(2) Stereolithography

- A common RP process developed prior to FDM is **stereolithography** (SLA).
- This process is based on the principle of **curing** (hardening) a liquid **photopolymer** into a specific shape.
- A vat containing a mechanism whereby a platform can be **lowered and raised** is filled with a photocurable liquid-acrylate polymer.
- The liquid is a mixture of acrylic monomers, oligomers (polymer intermediates), and a photoinitiator (a compound that undergoes a reaction upon absorbing light).
(2) Stereolithography

- At its highest position (depth $a$), a shallow layer of liquid exists above the platform.
- A laser generating an ultraviolet (UV) beam is focused upon a selected surface area of the photopolymer and then moved around in the x-y plane.
- The beam cures that portion of the photopolymer and thereby produces a solid body.
- The platform is then lowered sufficiently to cover the cured polymer with another layer of liquid polymer, and the sequence is repeated.
- The process is repeated until level $b$ is reached. Thus far, we have generated a cylindrical part with a constant wall thickness. Note that the platform is now lowered by a vertical distance $ab$. 
(2) Stereolithography

- At level $b$, the x-y movements of the beam define a wider geometry, so we now have a flange-shaped portion that is being produced over the previously formed part.
- After the proper thickness of the liquid has been cured, the process is repeated, producing another cylindrical section between levels $b$ and $c$.
- Note that the surrounding liquid polymer is still fluid (because it has not been exposed to the ultraviolet beam) and that the part has been produced from the bottom up in individual ‘slices’. The unused portion of the liquid polymer can be used again to make another part or another prototype.
(2) Stereolithography

- Stereolithography comes from the facts that the movements are three-dimensional and the process is similar to ‘lithography’ (is a method for printing using a stone (lithographic limestone) or a metal plate with a completely smooth surface), in which the image to be printed on a flat surface is ink receptive and the blank areas are ink repellent.

- Note also that, like FDM, SLA can utilize a weaker support material. In SLA, this support takes the form of perforated structures. After its completion, the part is removed from the platform, blotted, and cleaned ultrasonically and with an alcohol bath.

- Then the support structure is removed, and the part is subjected to a final curing cycle in an oven.

- The smallest tolerance that can be achieved in SLA depends on the sharpness of the focus of the laser; typically, it is around 0.0125mm.

- Oblique surfaces can also be of very high quality.
(2) Stereolithography

- Total cycle times in SLA range from a few hours to a day – without postprocessing such as sanding and painting.
- Depending on their capacity, the cost of the machines is in the range from $100,000 to $400,000.
- The cost of liquid polymer is on the order from $80 per litre.
- The maximum part size that can be produced is 0.5x0.5x0.6m.
- SLA has been used with highly focused lasers to produce parts with micrometer-sized features (micro-STL).
(2) Stereolithography Materials

- **Somos 7120** - A high speed general use resin that is heat and humidity resistant. Its a liquid photopolymer.
- **Somos 9120** - A robust accurate resin for functional parts. The material offers superior chemical resistance. It is a thermosetting polymer.
- **Somos 9920** - A durable resin whose properties mimic polypropylene (Thermoplastic Polymer). Offers superior chemical resistance and fatigue properties.
- **Accura 50 White** - A durable, accurate material for producing functional prototypes with the look and feel of molded ABS.
- **RenShape 5260** - A durable white resin that closely simulates ABS plastic.
(2) Stereolithography Materials

- **Somos 10120 WaterClear** - A general purpose resin with mid range mechanical properties. Transparent parts are possible if finished properly.

- **Somos 11120 WaterShed** - Produces strong, tough, water-resistant parts. Many of its mechanical properties mimic that of ABS plastic.

- **Somos 14120 White** - A low viscosity liquid photopolymer that produces strong, tough, water-resistant parts.

- **Somos ProtoTool** - ProtoTool is a high density material that transcends currently available stereolithography resins by offering superior modulus and temperature resistance.
(2) SLA support structures

• Support usually need for liquid-based and solid-based RP systems in order to anchor the part to the platform hence the part can be seperated from the platform thus preventing floating layers and make removal of the part become simple.
• Support can be classified according to the support structure and the type of the surfaces being supported. Support types include solid, box, web and finepoint supports.
(2) SLA support structures

Desired part or model geometry

Without supports, overhanging areas of part may peel away and damage the whole model

Result of missing supports for overhanging areas

SLA Fine-point support

Down-facing Region

Up-facing Region

Projection

Stand
(2) Stereolithography Interface

- Stereolithography was first commercial Solid Freeform Manufacturing process, released in 80’s by 3-D Systems

- 3-D Systems developed interface between CAD systems and their machine

- STL files (*.stl) allow CAD systems to interface with 3-D system machines

- Virtually all subsequent SFM (solid free-form manufacturing or RP) processes can use this same format (SFM industry standard)

- Many CAD programs now can export the *.stl file for easy conversion from CAD to part
(2) Stl files (*.stl)

- STL files were based on a program called Silverscreen CAD
- Silverscreen CAD represent boundary with all surfaces being approximated by polygons or groups of polygons.
- *.stl files use triangles or groups of triangles to approximate surfaces
- Accuracy depends on the triangle sizes
- Triangles assigned normal vectors for outward surface normal
- Parts are defined by representing all their bounding surfaces as faceted surfaces, using the triangular patches
(2) Stl representation

Representing a sphere

solid obj1
  facet normal 1.457591e-01 -9.885599e-01 -3.877669e-02
  outer loop
    vertex 9.614203e+00 4.757629e+00 0.000000e+00
    vertex 7.875000e+00 4.501190e+00 0.000000e+00
    vertex 9.483117e+00 4.764183e+00 -6.598330e-01
  endloop
endfacet
  facet normal 1.161178e-01 -9.870778e-01 -1.104267e-01
  outer loop
    vertex 9.483117e+00 4.764183e+00 -6.598330e-01
    vertex 7.875000e+00 4.501190e+00 0.000000e+00
    vertex 9.109818e+00 4.782848e+00 -1.219212e+00
  endloop
endfacet
  facet normal 6.134766e-02 -9.843393e-01 -1.652652e-01
(3) Solid Base Curing

- Cross section shape is “printed” onto a **glass mask** and this glass mask is **positioned above photopolymer tank**.
- **UV lamp shines** through mask onto photopolymer- light only can pass through clear part, polymer solidifies there, polymer in masked areas remains liquid.
- All excess polymer is removed- part is again hit with UV light.
- Melted wax is spread over workpiece, filling all spaces.
- **Workpiece is precisely milled flat**.
- Glass is erased and re-masked, workpiece is placed slightly below surface in photopolymer, process repeats.
- After fabricating part, wax is melted and removed.
- **Accurate, no support or post cure needed, but expensive & toxic.**
(3) Solid Base Curing Cycle

Remove excess polymer, and fill gaps with liquid wax. Chill to solidify wax.

Shine UV Lamp through mask to solidify photopolymer

Generate glass mask

Coat with photopolymer

Mill wax & workpiece

Milling Cutter
Ballistic particle manufacturing (BPM)

- BMP uses CAD-generated three-dimensional solid model data to direct streams of material (waxes, plastics, photocurable polymers, ceramics, or metals) at a target, building three-dimensional objects in much the same manner an ink jet-printer produces two-dimensional images.

- An object is built by a three-axis robotic system controlling a piezoelectric ink-jet mechanism "shooting" particles of the material, producing multiple cross-sections, onto a target.

- There are different ink jet techniques (deposition systems), but all rely on squirting a build material in a liquid or melted state which cools or otherwise hardens to form a solid on impact.
Ballistic particle manufacturing (BPM)

- Employs a technology called Digital Microsynthesis
- Molten plastic is fed to a piezoelectric jetting mechanism, similar to those on inkjet printers.
- A multi-axis controlled NC system shoots tiny droplets of material onto the target, using the jetting mechanism.
- Small droplets freeze upon contact with the surface, forming the surface particle by particle.
- Process allows use of virtually any thermoplastic (no health hazard) & offers the possibility of using material other than plastic.
(4) BPM advantages & disadvantages

**Advantages**

- Requires minimal post-processing.
- Low toxicity.
- Minimal power consumption.
- Low cost and materials.
- Ability to perform in microgravity and vacuum environments.
- BPM has no size constraints.
- The process allows use of virtually any thermoplastic. Because of this, there are no health hazards involved.

**Disadvantages**

- Parts produced lack strength and durability.
(4) Future of BPM

- Developed system similar to BPM’s
- System focuses on metal materials rather than plastic
- There have been successful fabrications out of tin and aluminum
- Major advantage of this product is the ability to produce large metal parts
(5) Selective Laser Sintering (SLS)

- SLS is a process based on the sintering of nonmetallic or (less commonly) metallic powders selectively into an individual object.

The bottom of the processing chamber is equipped with two cylinders:

1. A powder-feeder cylinder, which is raised incrementally to supply powder to the part-build cylinder through a roller mechanism.
2. A part-build cylinder, which is lowered incrementally as the part is being formed.
First, a thin layer of powder is deposited in the part-build cylinder.

Then, a laser beam guided by a process-control computer using instructions generated by the 3D CAD program of the desired part is focused on that layer, tracing and sintering a particular cross-section into a solid mass.

The powder in other areas remains loose, yet it supports the sintering portion.

Another layer of powder is then deposited; this cycle is repeated again and again until the entire 3D part has been produced.

The loose particles are shaken off, and the part is recovered.

The part does not require further curing—unless it is a ceramic, which has to be fired to develop strength.
A variety of materials can be used in this process, including polymers (such as ABS; PVC, nylon, polyester, polystyrene, and epoxy), wax, metals, and ceramics with appropriate binders.

It is most common to use polymers because of the smaller and less expensive, and less complicated lasers are required for sintering.

With ceramics and metals, it is common to sinter only a polymer binder that has been blended with the ceramic or metal powders.

The resultant part can be carefully sintered in a furnace and infiltrated with another metal if desired.
(6) Electron-beam Melting (EBM)

- A process similar to SLS and electron beam welding, EBM uses the energy source associated with an electron beam to melt titanium or cobalt-chrome powder to make metal prototypes.
- The workpiece is produced in a vacuum; the part build size is limited to around 200x200x180 mm.
- EBM is up to 95% efficient from energy standpoint (compared with 10-20% efficiency for SLS), so that the titanium powder is actually melted and fully dense parts can be produced.
(6) Electron-beam Melting (EBM)

- A volume build rate of up to 60 cm³/hr can be obtained, with individual layer thicknesses of 0.050-0.200 mm.
- Hot isostatic pressing also can be performed on parts to improve their fatigue strength.
- Although the process is mainly applied to titanium and cobalt-chrome to date, the process is being developed for stainless steels, aluminum, and copper alloys.
(7) 3D Printing

- In 3D Printing (3DP) process, a **print head** deposits an inorganic binder material onto a layer of polymer, ceramic, or metallic powder.
- A piston supporting the powder bed is lowered incrementally, and with each step, a layer is deposited and then fused by the binder.
3DP allows considerable **flexibility** in the materials and binders used.

Commonly used powder materials are blends of **polymers** and fibers, foundary sands, and metals.

Furthermore, since multiple binders printheads can be incorporated into a machine, it is possible to produce **full-color prototypes** by having different-color binders.

The effect is a 3D analog to printing photographs using **three ink colors** on an ink-jet printer.

A common part produced by 3DP from **ceramic powder** is a ceramic-casting shell, in which an aluminum-oxide or aluminum silica powder is fused with a silica binder.

The molds have to be postprocessed in two steps:

1. **curing at around 150ºC** and
2. **firing at 1000º to 1500ºC**.
3D Printing

- The parts produced through the 3DP process are somewhat porous and therefore may lack strength.
- 3DP of metal powders can also be combined with sintering and metal filtration to produce fully dense parts, using the sequence.
- The part is produced as before directing the binder onto powders. However, the build sequence is then followed by sintering to burn off the binder and partially fuse the metal powders, just as in powder injection molding.

3DP using:
(a) part-build,
(b) sinter,
(c) infiltration steps to produce metal parts.
(7) 3D Printing

- Common metals used in 3DP are **stainless steels, aluminum, and titanium**.
- Infiltrating materials typically are **copper and bronze**, which provide good heat-transfer capabilities as well as wear resistance.
Lamination implies a laying down of layers that are bonded adhesively to one another.

Several variations of LOM are available.

The simples and least expensive versions of LOM involve using control software and vinyl cutters to produce the prototype.

Vinyl cutters are simple CNC machines that cut shapes from vinyl or paper sheets.

Each sheet then has a number of layers and registration holes, which allow proper alignment and placement onto a build fixture.

LOM systems are highly economical and are popular in schools and universities because of the hands-on demonstration of additive manufacturing and production of parts by layers.
(8) Laminated-object Manufacturing (LOM)

(a) Schematic illustration of the laminated-object-manufacturing process.
(b) Crankshaft-part example made by LOM.
(8) Laminated-object Manufacturing (LOM)

- LOM systems can be elaborate; the more advanced systems use layers of paper or plastic with a heat-activated glue on one side to produce parts.
- The desired shapes are burned into the sheet with a laser, and the parts are built layer by layer.
- On some systems, the excess material must be removed manually once the part is completed. Removal is simplified by programming the laser to burn perforations in crisscrossed patterns.
- The resulting grid lines make the part appear as if it had been constructed from gridded paper (with squares printed on it, similar to graph paper).