Prototyping to Production:

3D Fabrication Applications, Opportunities & Hurdles

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TechConnect 2014

VCE Solutions & Solutions Group

- Provides technical & marketing consulting & planning services for digital & analog printing, imaging & fabrication system manufacturers & users
- Conducts market research & analysis, monitors & evaluates technological developments, facilitates printing technology implementation & business planning
- Focuses on industrial, textile & graphic arts printing & deposition solutions, markets & public relations issues

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Topics

This presentation will cover the hurdles to adoption, strengths, & opportunities that digital 3D Additive Manufacturing (AM) technologies present for:

- Prototype model making
- Functional model making
- Casting model making
- Custom production
- Short-run production
- Mass production

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Hurdles for 3D AM

- Visible Z-layer >30⌠m
- Interlayer adhesion
- Voids in builds
- Build speed
- Materials limited
- Multiple materials
- Free radical UV incomplete cure & oxygen inhibition
- Process obsolescence
- Capital cost
- Material cost
- Material performance
- Lower cost of volume analog production manufacturing
- Trained designers & technicians
- Limited color range

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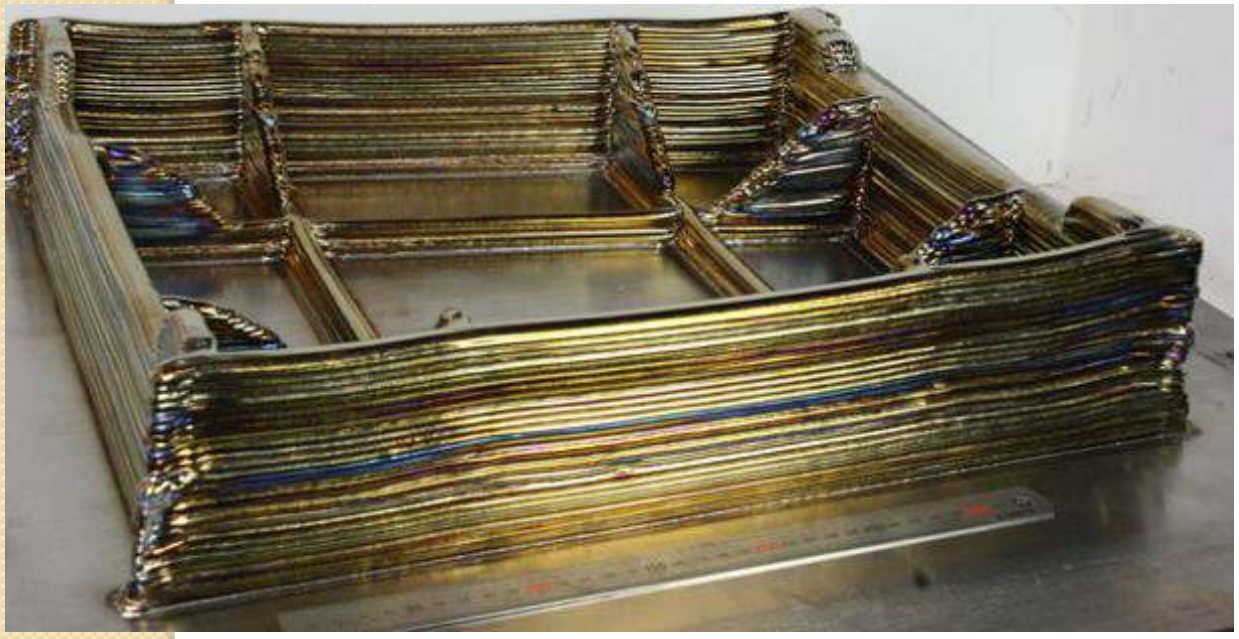
AMAZE

- The European AMAZE Project: Additive Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products



- Considerable artifact that could interfere with function

Titanium printed structure. / Photo: ESA

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How & Why 3D AM

- Layer by layer build
- Complexity is possible & virtually free
- Approach Nature's structural advantages
- Engineered structures: more with less
- STL file typical
- Some subtractive elements in some methods
- Maker control & network
- Enables closer to market manufacturing
- Cost effective prototypes & models
- Cost effective for custom & high value
- Replacement parts anywhere anytime
- Inventory control – Just in time – minimize warehousing & risk
- Reduce assembly
- Fast digital front end
- Production AM technologies emerging

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Opportunities for 3D AM

- High value, short run applications
- Fuel saving driven (aerospace, auto…)
- Custom
- Parts repair
- Biology & medicine
- Low tech deposition
- Food preparation
- Assembly process
- Construction
- Hybrid with CNC
- Hybrid with printed electronics, PV, displays & lighting
- 4D enabler for self assembly & sustainable intelligent materials deposition
- New deposition technologies
- Laser & e-beam

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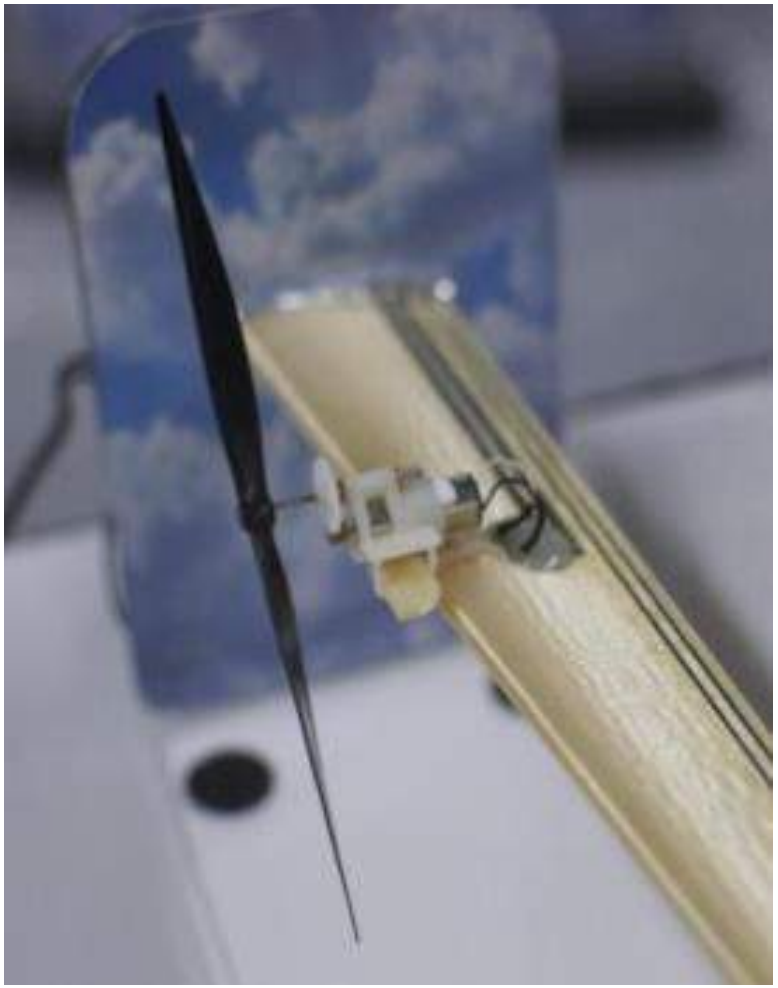
Stratasys & Optomec



- Additive manufacturing beginning: Optomec AerosolJet printed electronic circuitry onto a model of a UAV wing, which Stratasys FDM technology 3D printed.
- Minimizing & automating assembly

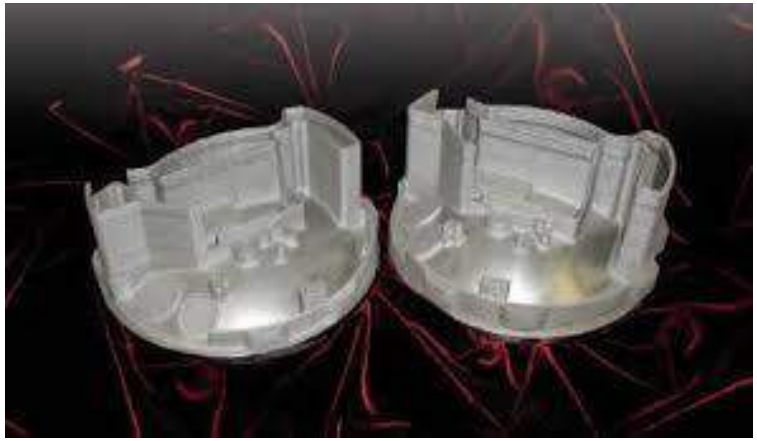
(Photo source: Optomec & Stratasys)

Hybrid Additive & Subtractive

- CNC + AM
- DMG Mori Seiki
- US Department of Energy ORNL & Cincinnati Inc.
- Sandia National Labs
- Popfab suitcase hybrid
- LOM, 3D Inkjet
- Matsuura Lumex Avance-25 laser sintering + milling
- Hybrid HSTM 1000

DMG Mori Seiki

ak Ridge National Laboratory:
rbon fiber reinforced ABS print



(Source: Sandia National Labs)

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AM Technologies

- Stereolithography (SLA) + (MSL), (FMSL) & (MLS)
- Film Transfer Imaging (FTI)
- Selective Laser Sintering (SLS)
- Selective Laser Melting (SLM)/ laser cladding (LC)
- Laser Engineered Net Shaping (LENS)
- Selective area laser deposition (SALD)
- 3D Inkjet (3DIJ), Polyjet Modeling (PJM) & Multijet Modeling (MJM)
- Inkjet Liquid Binding Powder (IJLBP)
- Aerosol Jet, AIST
- Syringe Deposit: Robo-casting (RC), Fab@home
- Electrostatic Inkjet
- LIFT & Photon-Jet (AMD)
- Fused Deposition Modeling (FDM)/ Fused Filament Fabrication (FFF)
- Electron Beam Melting (EBM)
- Electron Beam Freeform Fabrication (EBF^3)
- Cold metal transfer (CMT)
- Shaped Deposition Manufacturing (SDM)
- Laminated Object Manufacturing (LOM)
- Solid Ground Curing (SGC)
- Ultrasonic consolidation (UC) (UAM)
- Very high power ultrasonic additive manufacturing (VHP UAM)
- Integrated extrusion deposition (IED/PED)
- Near field electro-spinning (NFES)
- Bio-fabrication (BIO)

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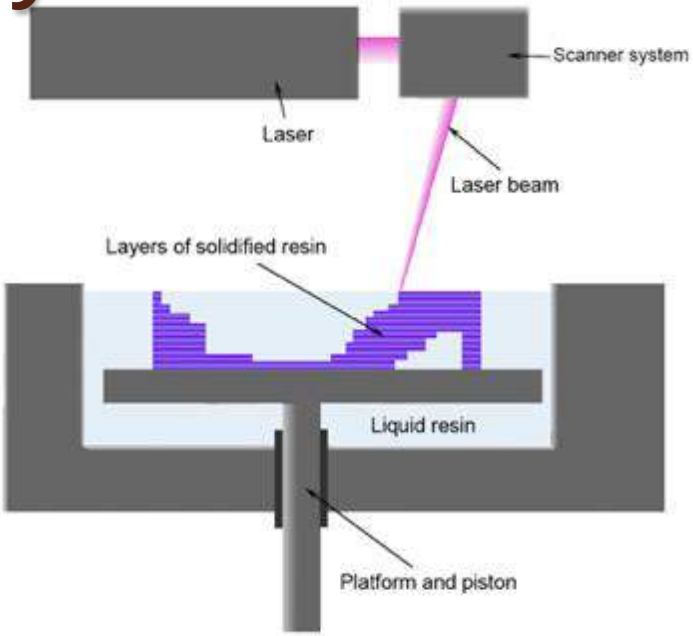
Types of Digital 3D Fab Methods

- Energy Fused Powder
  - Stereo Lithography (SLA)
  - Selective Laser Sintering (SLS) & Melting (SLM)
  - E-beam Melting
- Inkjet Binding Powder
  - 3D Systems (former Z Corp models), Voxeljet, ExOne
- Inkjet & Inkjet-like Direct Deposit
  - 3D Systems 3500-5000
  - Stratasys (former Objet models)
- Melt & Drop
  - Fused Deposition Modeling (FDM) & (FFF)

Stereolithography

- Chuck Hull invented Stereo-lithography (SLA) in 1983 & founded 3D Systems in 1986 (photo-polymer)
- Appropriate for fit/form prototypes & models



- UV cure free radical photopolymer

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Stereolithography (SLA): + & -

- Crisp detail & surface finish
- Minimal material waste
- Clear, clear amber, grey, white, black, blue build photo-polymers
- Material supports extended build elements
- Z-layer 150⌠m to min. 50⌠m

- UV degradation
- Expensive materials
- Low grade tensile strength & mechanical properties
- Free radical polymerization incomplete
- Max. build volume: 1.5m x .76m x .56m (59”x 30”x 22”) – iPro 9000

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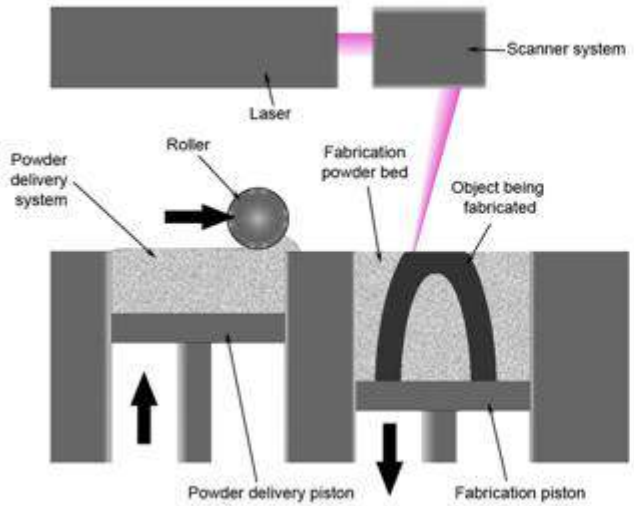
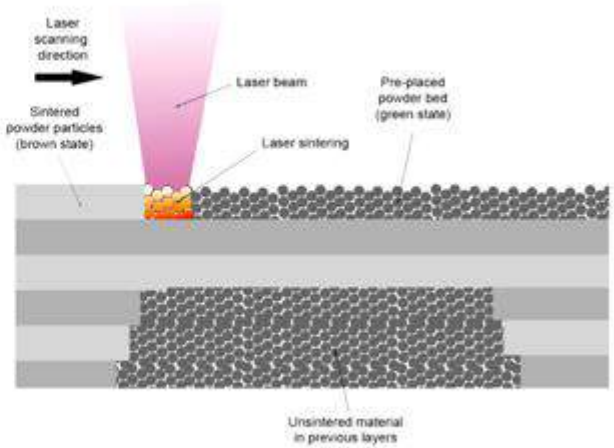
Accura® SLA Material Mimicry

Accura Product	Material / Mimic	Tensile Strength (MPa)	Elongation at Break (%)	Impact Strength (J/m)
25	Polyproplyene-like	38	13-20	19-24
PP White (SL 7811)	Polyproplyene-like	40-42	7-13	42-59
Xtreme	Tough/Durable	33-44	14-22	35-52
Xtreme White 200	Tough/Durable	45-50	7	55
55	ABS-like	63-68	5-8	12-22
ABS Black (SL 7820)	ABS-like	45-47	6-13	39-56
ClearVue	Clear Material	46-53	6-13	40-58
60	Clear Material	58-68	5-13	15-25
CastPro	Cast build model	52-53	4.1-8.3	43-49.5
CastPro Free (SL 7800)	Cast build model	45-48	9-19	35-50
48 HTR	High Temp & Composite	64-67	4-7	22-29
CeraMAX	High Temp & Composite	78-87	1.0-1.5	14.5-17.9
Bluestone	High Temp & Composite	66-68	1.4-2.4	13-17

Source: 3D Systems

Selective Laser Sintering





- Dr. Carl Deckard & Dr. Joe Beaman at UT Austin invented Selective Laser Sintering (SLS) in the mid-1980s (DARPA Sponsored) (polymer or metal)
- Sintering forms a mass of material at the points of particulate contact with energy from laser, heat and/or pressure without melting it to a liquid

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Selective Laser Sintering (SLS): + & -

- Good mechanical properties
- Acceptable aging
- Preferred modeling

Direct Laser Metal Sintering (DMSL)

- Build can be fully dense without infiltration
- No plastic binder

- Material Selection limited to stainless steel/bronze matrix & polymer particles
- Limited build volume
- Require bronze infiltration for full density metals
- Low energy laser, binder needed

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LENS & EBM

LENS 850-R

- Melted metal shielded from atmospheric oxygen for better interlayer adhesion
- Materials: stainless steel, inconel, copper, aluminum & titanium alloys
- Multiple compositions possible in each build
- High-energy laser

- Fast production
- Minimal residual stresses
- Eliminates voids
- Limited maximum part size
- EBM: Building internal elements difficult
- EBM: Rough surface finish

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Fused Deposition Modeling (FDM): + & -
a.k.a. Fused Filament Fabrication (FFF)

- Large build volumes
- Cost effective
- Affordable for home & hobbyists
- Polymeric materials reasonably strong

- Visible Z step, usually rough surface finish
- Slow production
- Materials directional anisotropic
- Materials limited to a few thermoplastics
- Toxic vapors

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Fused Deposition Modeling (FDM)
Fused Filament Fabrication (FFF)

- Thermoplastic melt deposited through extrusion head
- ABS plastic (5,000+ psi)
- Relatively low cost of printers & materials ($250 / 56inch^3)
- Polycarbonate (PC), Polyphenylsulfone (PPSF/PPSU) & high temp. Ultem 9085 (10k psi)
- Scott Crump FDM 1989 patent expired in 2009
- 100+µm z-layer limitation = visible artifact, 50 µm z-layer devices available
- Machine-able, paintable

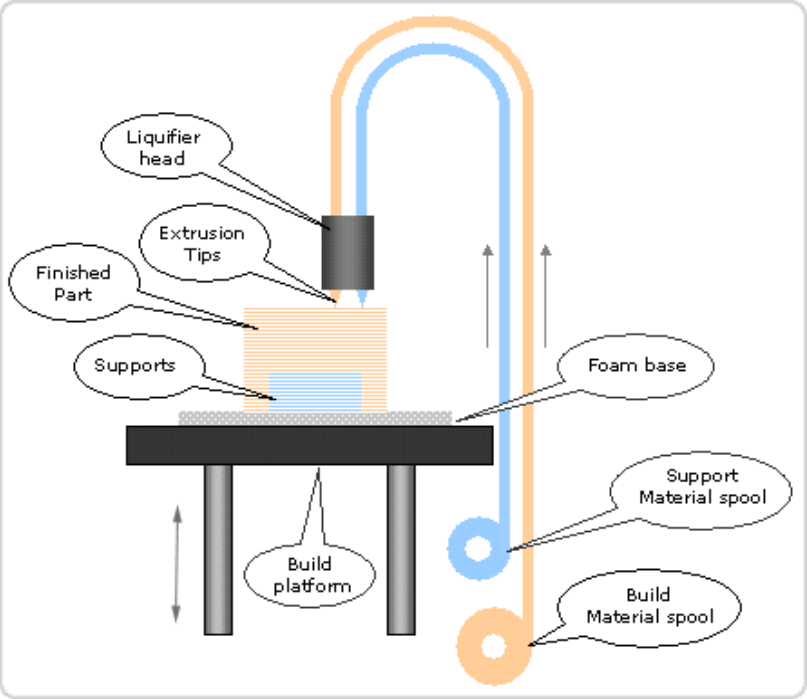

Diagram source: Arptech

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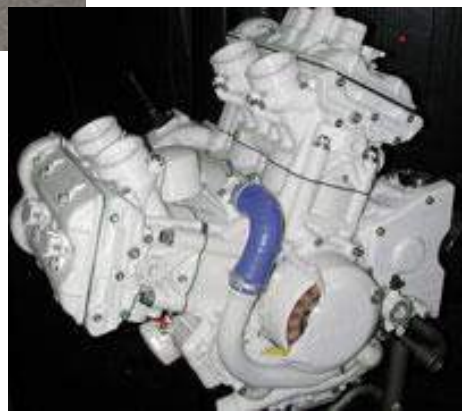
3D Printing for Prototyping

Ducati Desmosedici motor prototype
(cut 20 months off development)



- Architectural modeling
- Products & parts prototyping
- Casting forms
- Automotive prototyping
- Aerospace prototyping
- Pre-surgery

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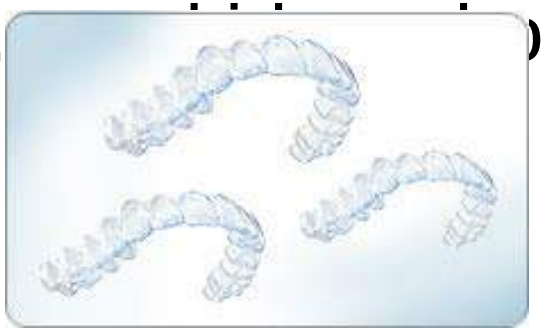
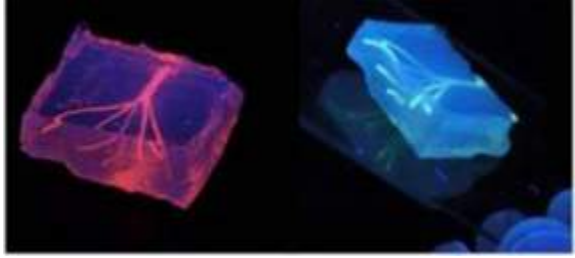
Custom & Small Run Applications

- Metal copings for dental crowns & bridges
- Orthopaedic implants
- Orthodontics (Invisalign)
- Parts replacement (file & scan)
- Biology (skin, one, bladder)
- Jewelry
- Food
- Restoration
- Machining Jigs



Stratasys Solidscape IJ Phase Change

3D+ Biology



- Anthony Atala, MD & his team developed printed organs, particularly bladders, with patient's DNA, skin for treating burn victims & is now working to build kidneys
- Cornell University Bioengineers print ears
- Unit of Pennsylvania & MIT printing blood vessels
- Washington State University 3D printing bones
- Organova

- Researchers at Brigham and Women's Hospital created artificial blood vessels using hydrogel constructs that combine advances in 3-D bio printing technology and biomaterials.
- "In the future, 3D printing technology may be used to develop transplantable tissues customized to each patient's needs or be used outside the body to develop drugs that are safe and effective," said Ali Khademhosseini, PhD bio-medical engineer.

Image courtesy of Khademhosseini Lab, from article in Science Daily May 30, 2014

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3D Printing Food

- Natural Machines – Foodini – Pump System $1K (Kickstarter)
- 3D Systems – Stainless steel inkjet - ChefJet 1-head $5K, Pro 4-head $10K

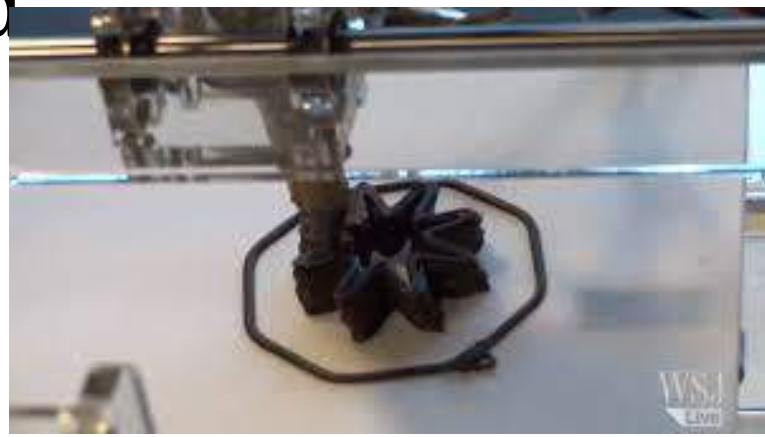

Photo sources: 3D Systems, Natural Machines

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3D Inkjet

Direct Print

- 3D Systems ProJet 3500-5000 (UV)
- 3D Systems ChefJet
- Stratasys Objet, Eden, Connex (UV)
- Solidscape

Inkjet Binder → Powder

- fcubic AB: inkjet binder +laser metal or ceramic powder
- Ex-One M-Print, S-Print & S-Max
- 3D Systems (Z-corp)
- Voxeljet

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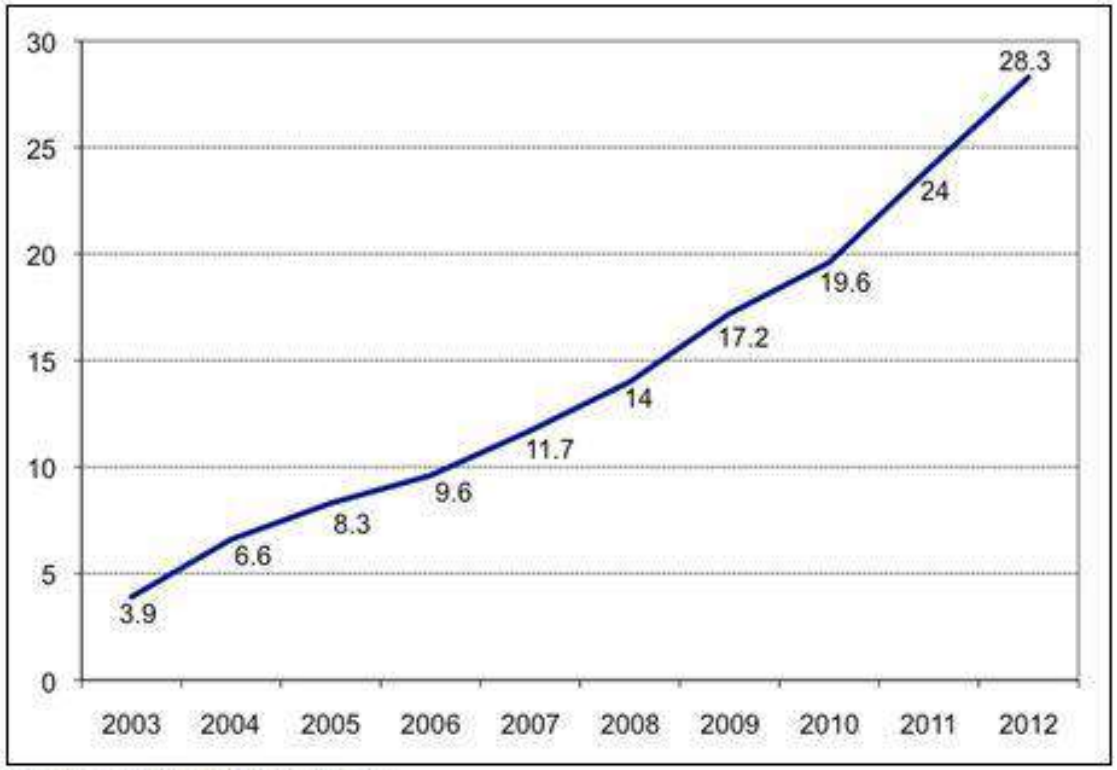
3D Printing for Making Parts for Products

- $2.2 billion spent worldwide in 2012
- Projected to $4 billion by 2015; $10.8 billion by 2021

Annual Rate of Growth



Source: Wohlers Report 2013

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Product Manufacture

Lockheed Martin, Launched 2011

- Hugh Evans, 3D Systems VP, “Today, the 3D printing market is worth $3 billion.” He predicts it would increase tenfold to $30 billion over the next decade.
- 12 E-beam melt titanium alloy brackets on board Juno
- Boeing uses 3D printed polymer-based air ducts on the F/A-18

Juno spacecraft

A 3D-printed bracket onboard the Juno

F/A-18 Super Hornet

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GE Aviation: AM Fuel Injectors

- Fuel injectors made with laser metal (titanium) melting
- Weigh ~ 25% less than previous injectors
- Last 5 times as long
- Plan to print 40,000 per year
- Made as one piece
- Engine scheduled 2016
- LEAP could save airlines up to $1.6 million per airplane per year in fuel costs. They also generate fewer carbon and nitrogen emissions
- Also includes 3D printed ceramic matrix composite (CMC) parts

GE LEAP Jet Fuel Injector

GE LEAP Jet Engine

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Airbus-EADS -

- Gregor Dirks, Airbus Corporate Innovator, “Parts of the vision are already being implemented in the current fleet. Titanium brackets used in the cabin have been made using 3-D printing, reducing the weight of the parts, and allowing the manufacture of "organic" shapes that would otherwise be too expensive to produce.”

A350 XWB Bracket

- Rolls Royce: engine brackets & fuel nozzles
- Chinese military: J-20 & J-31 fighter jet titanium parts
- Boeing, Northrup, Grumman, Raytheon, SpaceX, Lockheed-Martin

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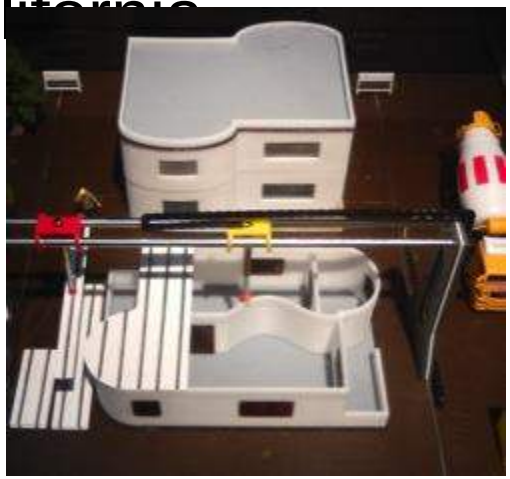
Contour Crafting & Monolite

- Dr. B. Khoshnevis, Univ. of Southern California



- Automated construction technology
- “Potential to build housing units in a single day, at a quarter of the cost of existing manual methods.”
- Enrico Dini
- Netherlands house project
- ESA Moon base

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3D Fabrication Without Hype

- The modulus of UV cured polymers is much lower than that of thermoforming polymers.
- UV cured polymers typically achieve about 70 to 90% polymerization
- Migrating photo initiators offer potential product hazard
- Visible artifacts with most 3D
- Slow Build process for most 3D
- Software still developing to use of 3D's potential to create even greater engineered complexity
- Health & safety issues with venting & nanoparticle handling
- 3D realized & cost effective for prototypes, some custom manufacture & high value metal applications
- Need for 3D design, software & operations training
- On-line maker community
- Kick-starter entrepreneurs
- 3D scanning
- 3D growing from its infancy
- Printed organs: skin soon, others much later
- 3D Service Bureaus
- At home applications for food & hobbyists

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Thank You

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