

3D Printing (Additive Manufacturing) Ecosystem

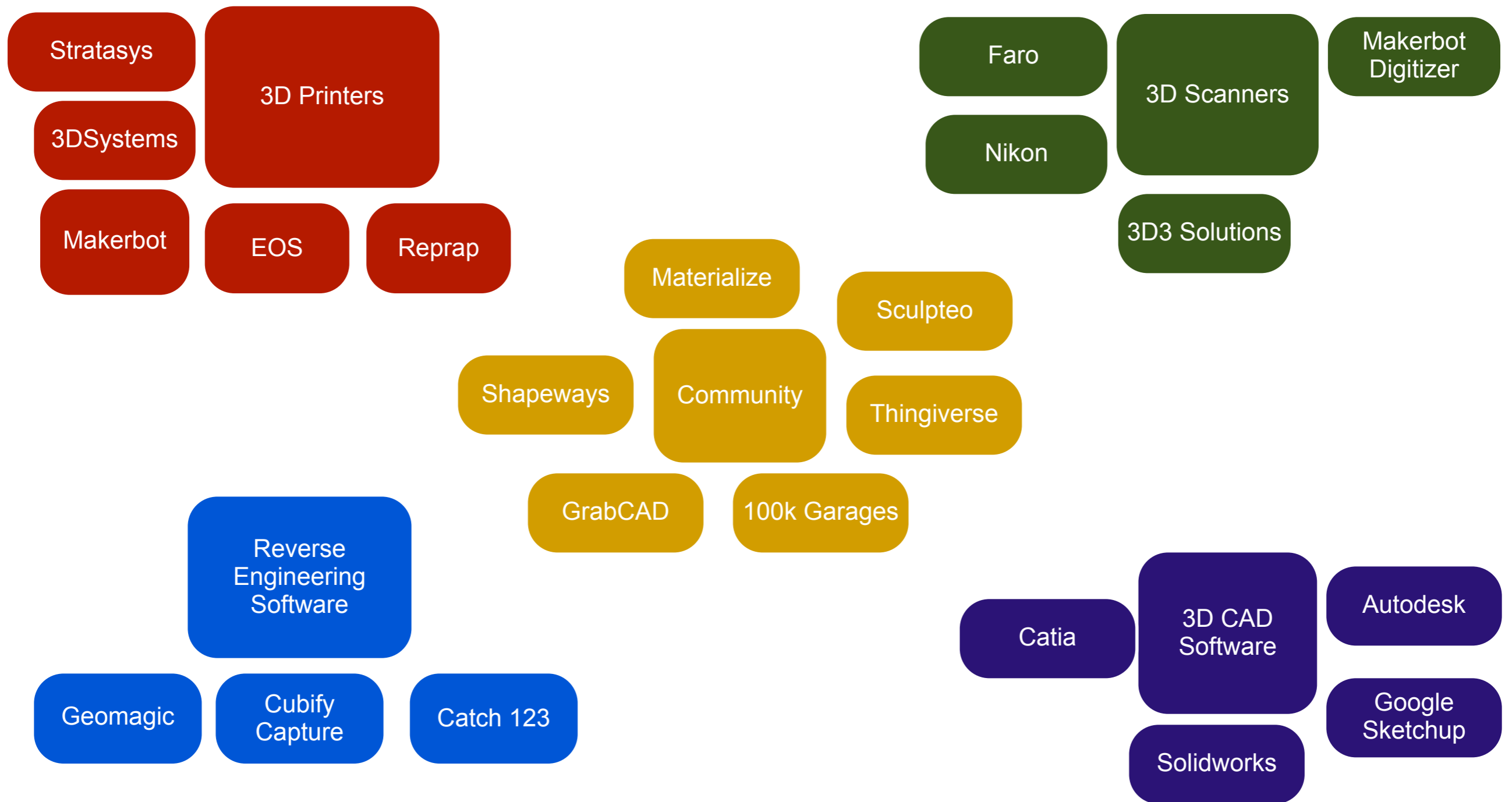
Onat Ekinci

Overview

- 3D Printing ecosystem
- 3D Printers: 3D printers and how they work
- 3D Scanners: Inspection and reverse engineering
- Reverse engineering software
- CAD software
- 3D Printing communities
- 3D Printing materials

3D Printing Ecosystem

Representative companies, list not exhaustive



3D Printing Market in the Future?

McKinsey “Disruptive Technologies” Report, 2013

We estimate that 3D printing could generate economic impact of **\$230 billion to \$550 billion** per year by 2025 in the applications we have sized. The largest source of potential impact among sized applications would be from consumer uses, followed by direct manufacturing and the use of 3D printing to create tools and molds.

Exhibit 11

Sized applications of 3D printing could have direct economic impact of \$230 billion to \$550 billion per year in 2025



Sized applications	Potential economic impact of sized applications in 2025 \$ billion, annually	Estimated scope in 2025	Estimated potential reach in 2025	Potential productivity or value gains in 2025
Consumer use of 3D printing	100–300	<ul style="list-style-type: none"> \$4 trillion in sales of consumer products that might be 3D printed 	<ul style="list-style-type: none"> 5–10% of relevant products (e.g., toys) could be 3D printable, assuming easy consumer access 	<ul style="list-style-type: none"> 60–80% value increase per 3D-printed product – 35–80% cost savings to consumers – 10% added value from customization
Direct product manufacturing ¹	100–200	<ul style="list-style-type: none"> \$300 billion spending on complex, low-volume items such as implants and tools 	<ul style="list-style-type: none"> 30–50% of products in relevant categories replaceable with 3D printing 	<ul style="list-style-type: none"> 40–55% cost savings to buyers of 3D-printed products
Tool and mold manufacturing	30–50	<ul style="list-style-type: none"> \$470 billion spending on complex, low-volume parts in transportation 		
Other potential applications (not sized)		<ul style="list-style-type: none"> \$360 billion global market for injection-molded plastics 	<ul style="list-style-type: none"> 30–50% of injection-molded plastics produced with 3D-printed molds 	<ul style="list-style-type: none"> 30% production cost reduction using superior 3D-printed molds
Sum of sized potential economic impacts	230–550			

3D Printing Market in the Future?

But, not everyone agrees...: Wired, 2013

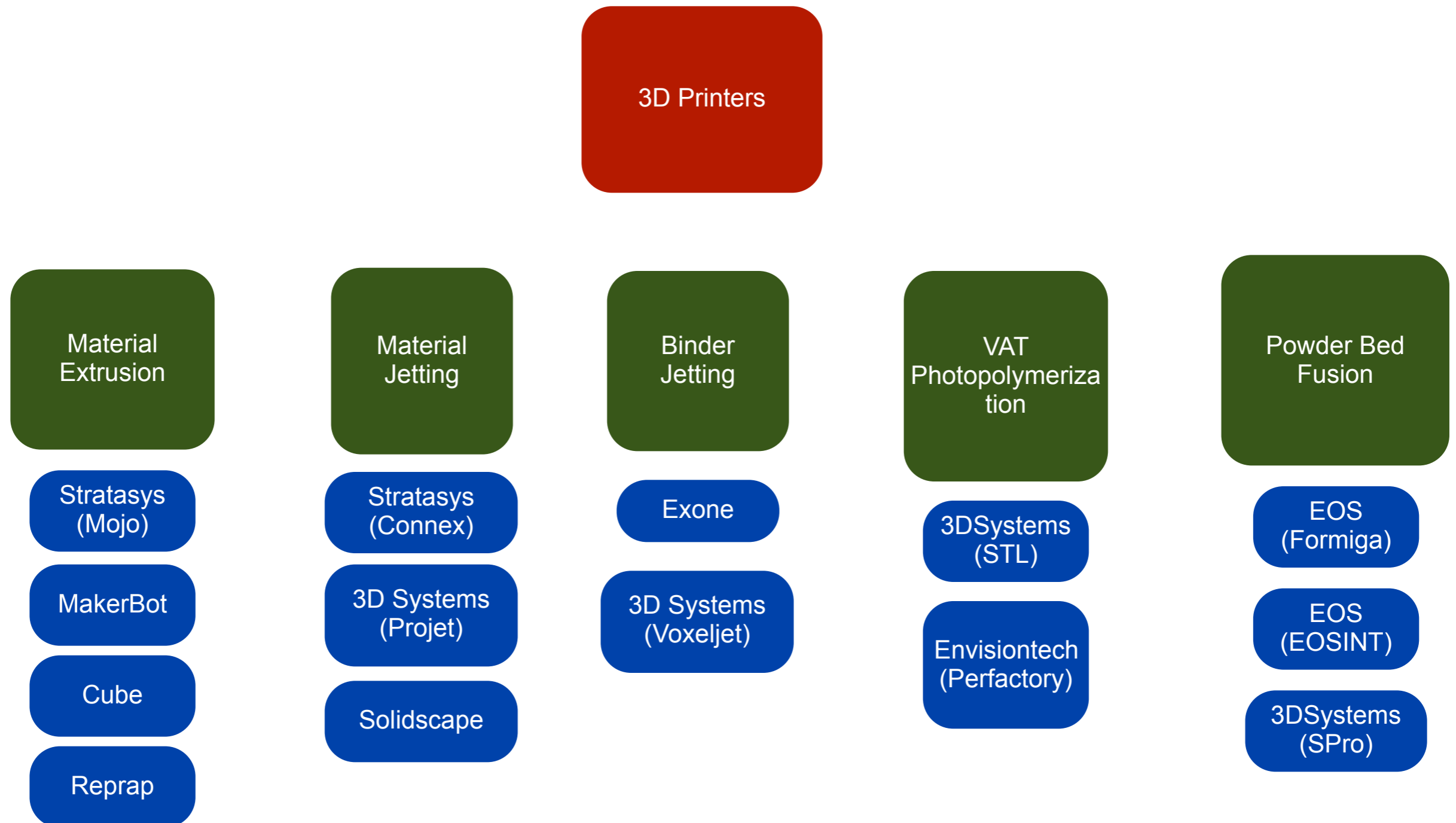
Part of the confusion (and the hype) around 3-D printing cranking out everything we desire from atop our countertops is this idea that it is somehow a gadget like any other in the tech world. If it is a device, it can therefore ride Moore's Law into a fast improving future. **But Moore's Law does not apply to 3-D printing, except perhaps for the chips that go inside the machines. 3-D printing is a combination of material science, precision mechanics, electronic controllers and software.**

Computing can hitch itself to Moore's Law, the notion that the number of transistors able to be crammed onto a given space of silicon approximately doubles every 18 months, because that single axis can account for much of the improvement in the computer world. 3-D printing has multiple axes. There are the raw materials fed into the printer, the speed of the machine, its reliability, its accuracy or resolution. Depending on the application – orthopedics or jewelry – different axes will matter more.

“I would describe the improvement curve we are on in 3-D printing as analogous to screen technology,” says Mark Hatch, CEO of TechShop. “It's been a gradual improvement over the last 20 years, and will continue to be gradual.”

3D Printers

Process categories according to ASTM F42 classification. Representative companies, list not exhaustive

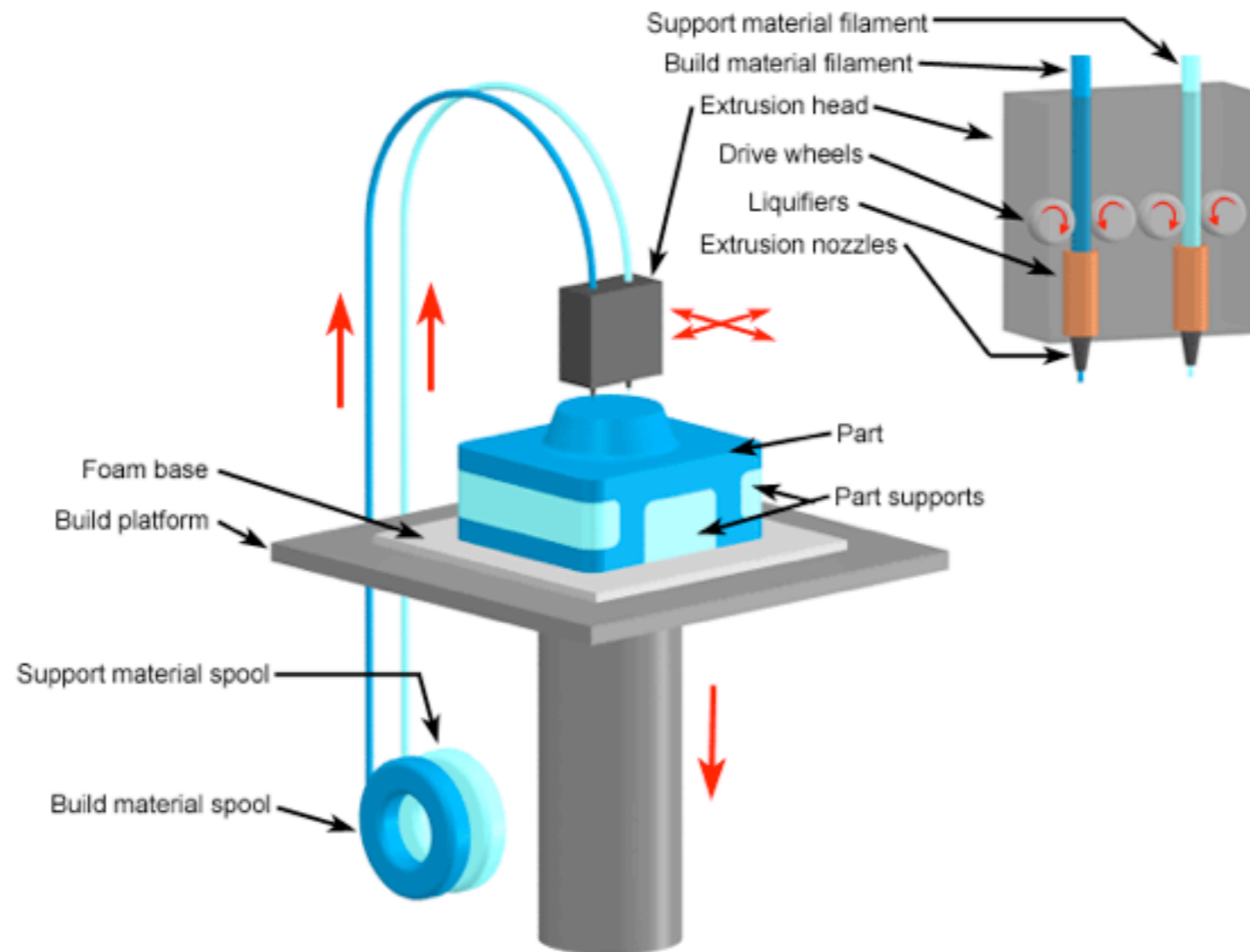


Material Extrusion

Technology summary: Material extrusion machines force the material through a nozzle.

The extrusion nozzle or the build platform moves in the x-y plane.

When a layer is completed the build platform moves down, and another layer starts to be formed.



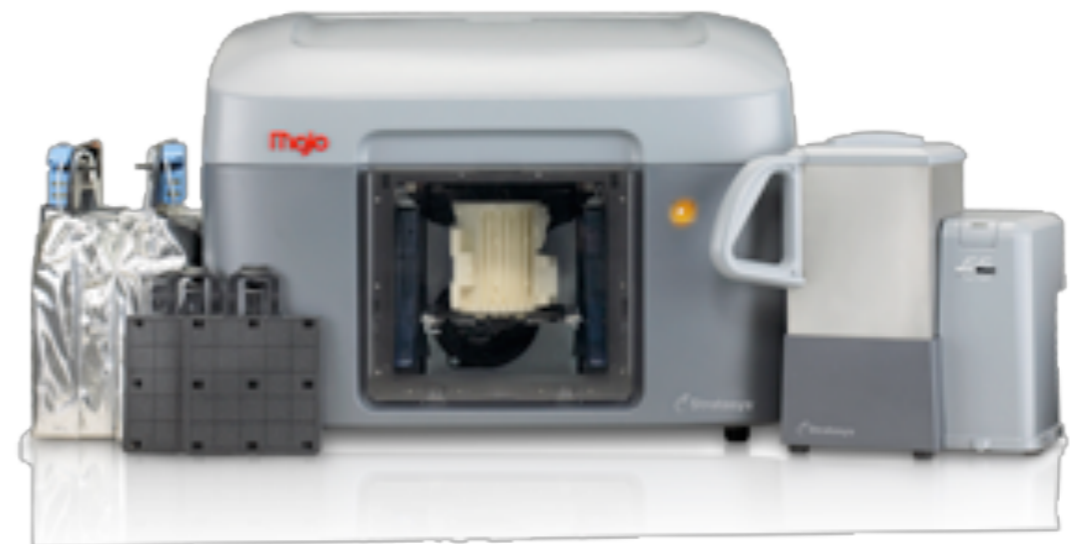
Material Extrusion

Companies - Prices:

Material extrusion is **the most popular 3D printing process**.

The first material extrusion process was patented by Stratasys (Fused Deposition Modeling). FDM based printer prices from Stratasys range from \$10K to \$500K.

Stratasys Mojo: \$9900



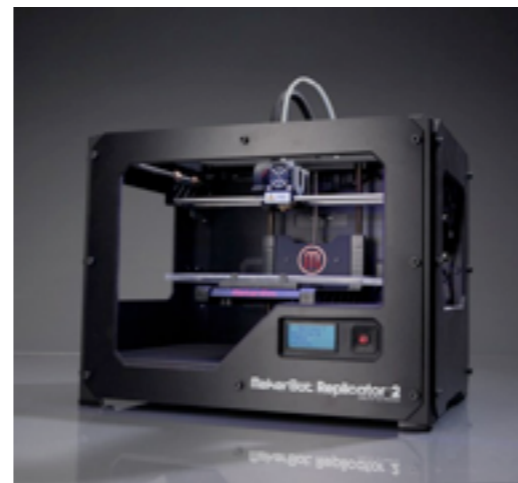
Material Extrusion

Companies - Prices:

Most of the popular low-cost personal printers belong to material extrusion category:

Makerbot (bought recently by Stratasys)

- Advantage: Designed for consumers, not hobbyists.
- Disadvantages: Product quality can be variable, probably depending on the complexity.



Makerbot Replicator 2: \$2200

Build Volume:	11.2 L x 6.0 W x 6.1 H in [28.5 x 15.3 x 15.5 cm]
Layer Resolution Settings:	High 100 microns [0.0039 in] Medium 270 microns [0.0106 in] Low 340 microns [0.0133 in]

Cube (by 3D Systems)

- Advantage: Designed for consumers,
 - Disadvantages: Cartridges self-destructs after emptying.
- No hobbyist tweaking allowed, too much of a closed system.



Cube : \$1299

Material Extrusion

Advantages:

- Personal desktop printers cheap enough for mass consumption (or production).
- Ideal for prototypes.
- Ideal for homes, offices, classrooms --> Maker movement.

Disadvantages:

- You have to buy the printing material from the manufacturer (as you would buy cartridges for your inkjet printer). So the lifecycle cost is higher than expected. (Each cartridge may cost \$400).
- There is a need for material standardization.
- The material should be plastic, because of heating requirements in extrusion (no metals).
- High in-plane properties, low out-of-plane properties (because of build line between layers).

Material Extrusion

Materials:

Thermoplastics = Cheese --> Melt when heated. Does not lose their internal composition when heated. So can be melted and remelted (thus also more environment friendly).

Example: Most personal printers use a thermoplastic dubbed ABS.

Thermosets= Eggs--> Solidify when melted. Like eggs, can be used only once; because their internal composition change when heated. They cannot be melted back into a useful liquid form.

Example: Most STL printers use thermoset style plastics.

Material Extrusion

Disadvantages - Materials:

Most thermoplastics for high quality 3D printing cost within \$175-\$250/kg. By contrast, thermoplastics for injection molding costs \$2-3/kg!

Thermoplastics used in personal 3D printers may cost within \$15-\$50/kg.

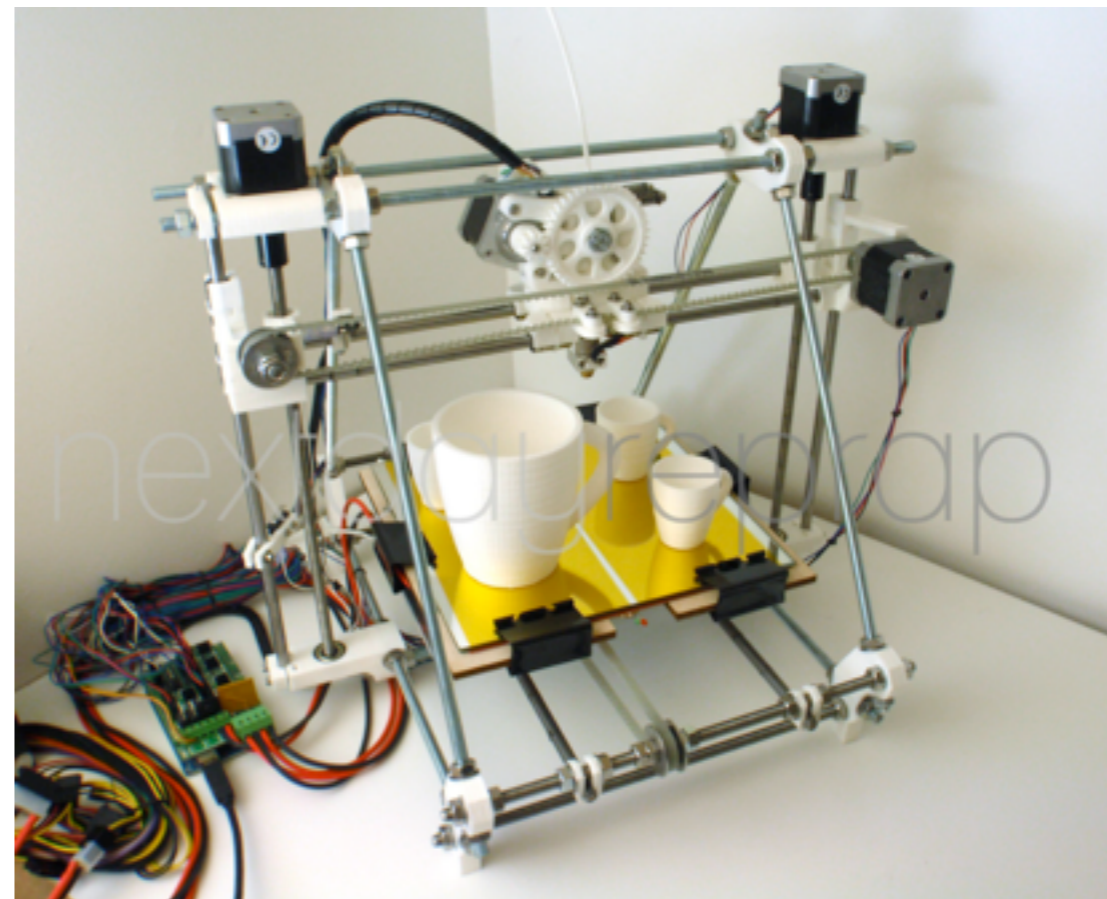
On the positive side, material waste per part can be much less than in injection molding.

Reprap

Open source project. A Reprap machine is ideally capable of printing other 3d printing machines.

Original project developed in Bath University in UK.

Reprap Mendel: 500 Euros



Material Extrusion Links

Stratasys:

<http://www.stratasys.com/3d-printers/idea-series/mojo>

<http://www.youtube.com/watch?v=M-bt7pyZr0s>

Makerbot:

<http://store.makerbot.com/replicator2.html>

<http://www.youtube.com/watch?v=AKTSdW7-H3Q>

<http://www.youtube.com/watch?v=13hXothTtaU>

Cube:

<http://cubify.com/cube/>

http://www.youtube.com/watch?v=-YXm3TK_rh8

Reprap:

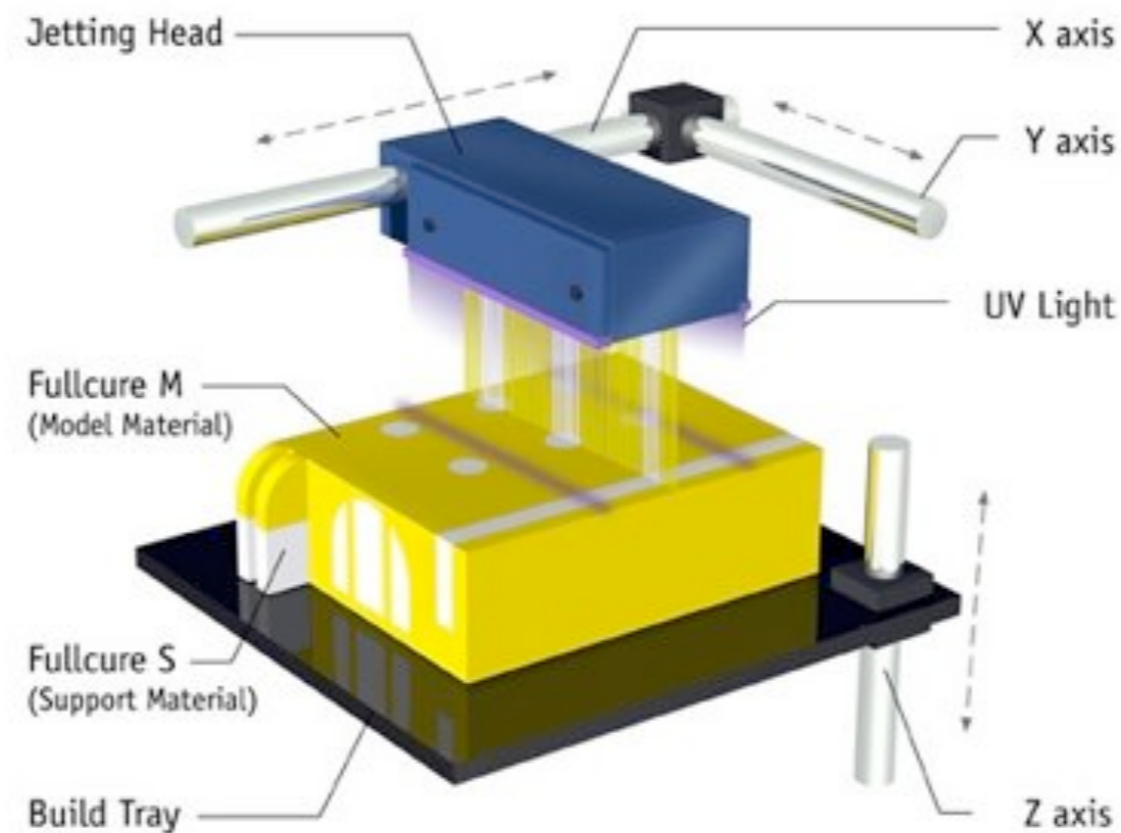
http://reprap.org/wiki/Main_Page

Material Jetting

Technology summary:

Material Jetting is the process where the 3D printer uses an inkjet head to selectively deposit product material like in normal inkjet printers. The layers are then cured with UV light.

Multi-nozzle print heads can be used to print different kinds of materials.



Material Jetting

Stratasys Connex:

Multiple material printers.

Prices range from \$160K to \$600K.

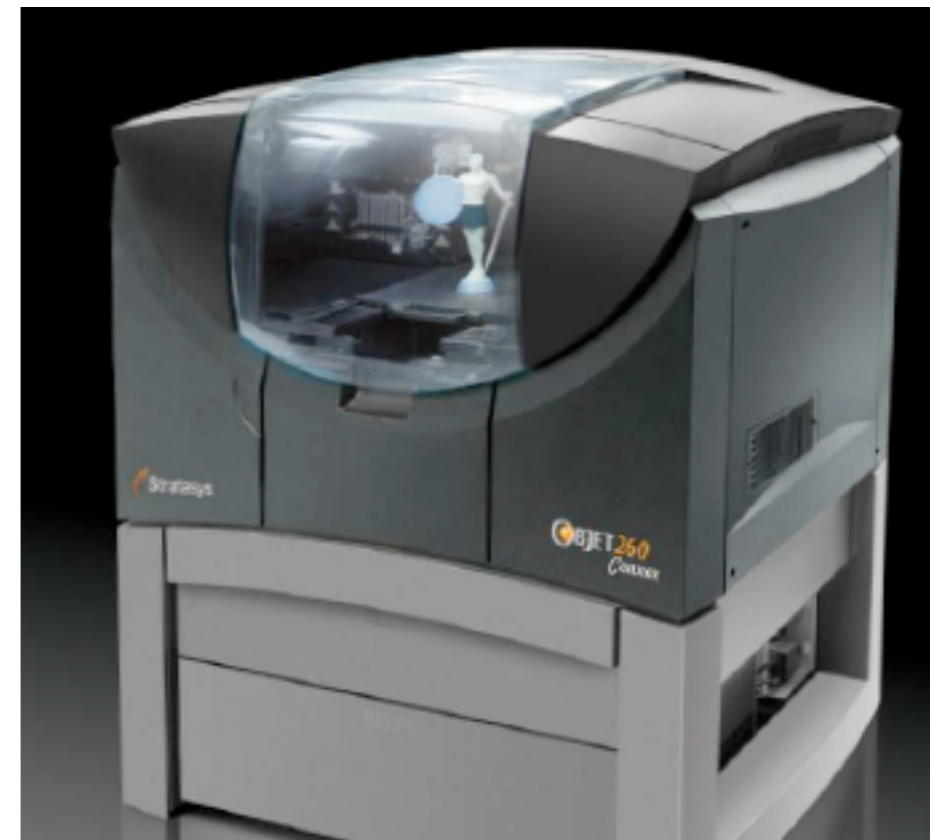
Objet260 Connex

Can print up to 14 different material properties within a single printed part.

Allows users to simulate diverse mechanical and physical properties, from rubber to rigid; opaque to transparent; and standard to ABS-grade engineering plastics.

Net Build Size :

255 x 252 x 200 mm (10.0 x 9.9 x 7.9 inch)



Material Jetting

Advantages:

- Resolution is lower than the material extrusion (FDM), so surface quality is better. FDM can require smoothing stations.
- Printing of very fine features.
- Widest range of materials.
- Unique property: Several materials can be mixed during the process.

Material Jetting

Disadvantages:

There is no equivalent of high performance engineering materials, as in the case of FDM (Ultem, etc.).

Material Jetting Links

Stratasys Connex (Connex belonged to Objet which was merged with Stratasys in 2012):

<http://www.stratasys.com/3d-printers/design-series/precision/objet260-connex>

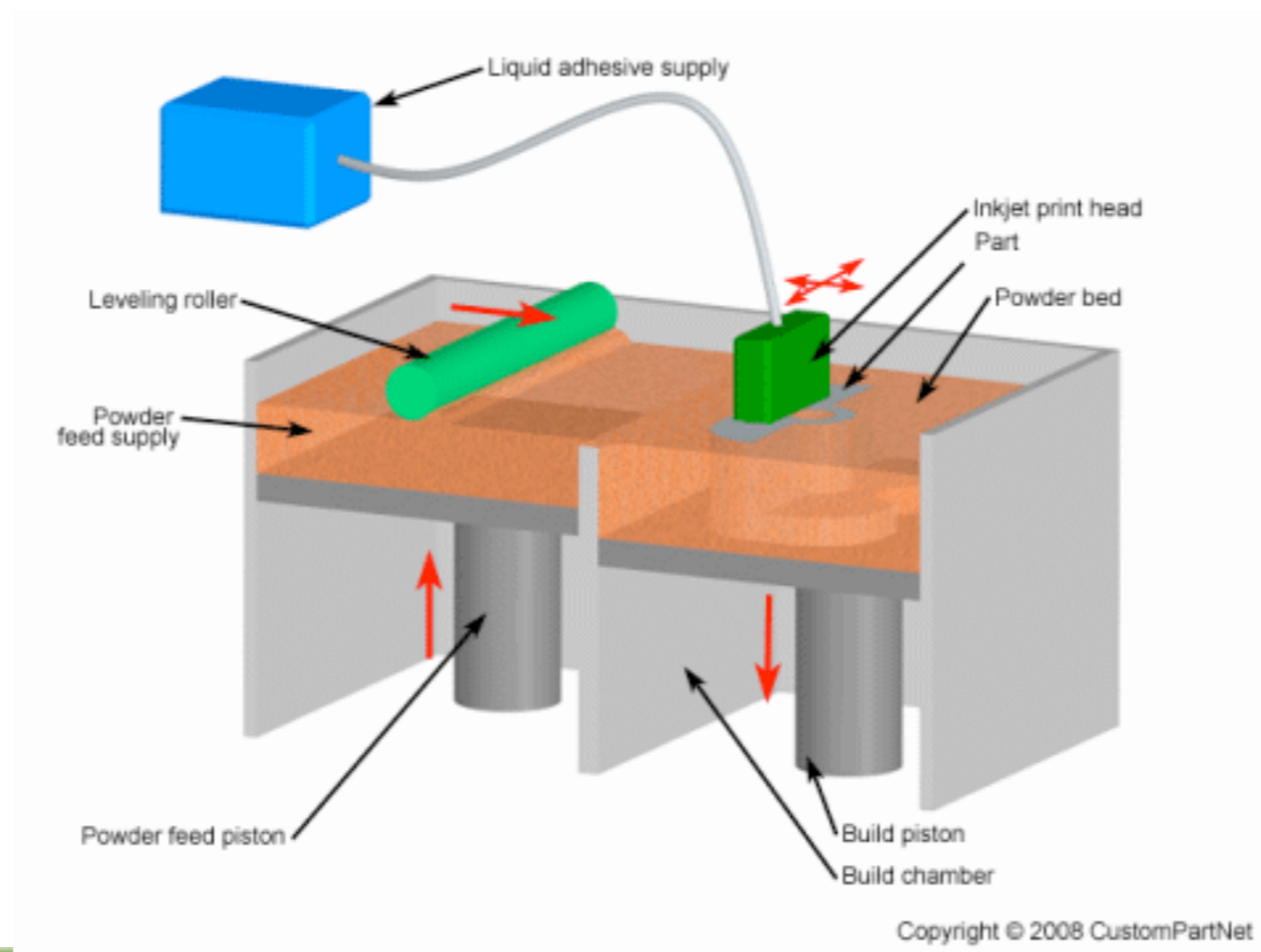
http://www.youtube.com/watch?v=L3jL_4Yhvhk

Binder Jetting

Technology summary:

A liquid binder is selectively deposited through inkjet nozzles to join powder materials in a powder bed.

Originally developed by MIT, then licensed to ZCorp (now part of 3D Systems) and Exone.



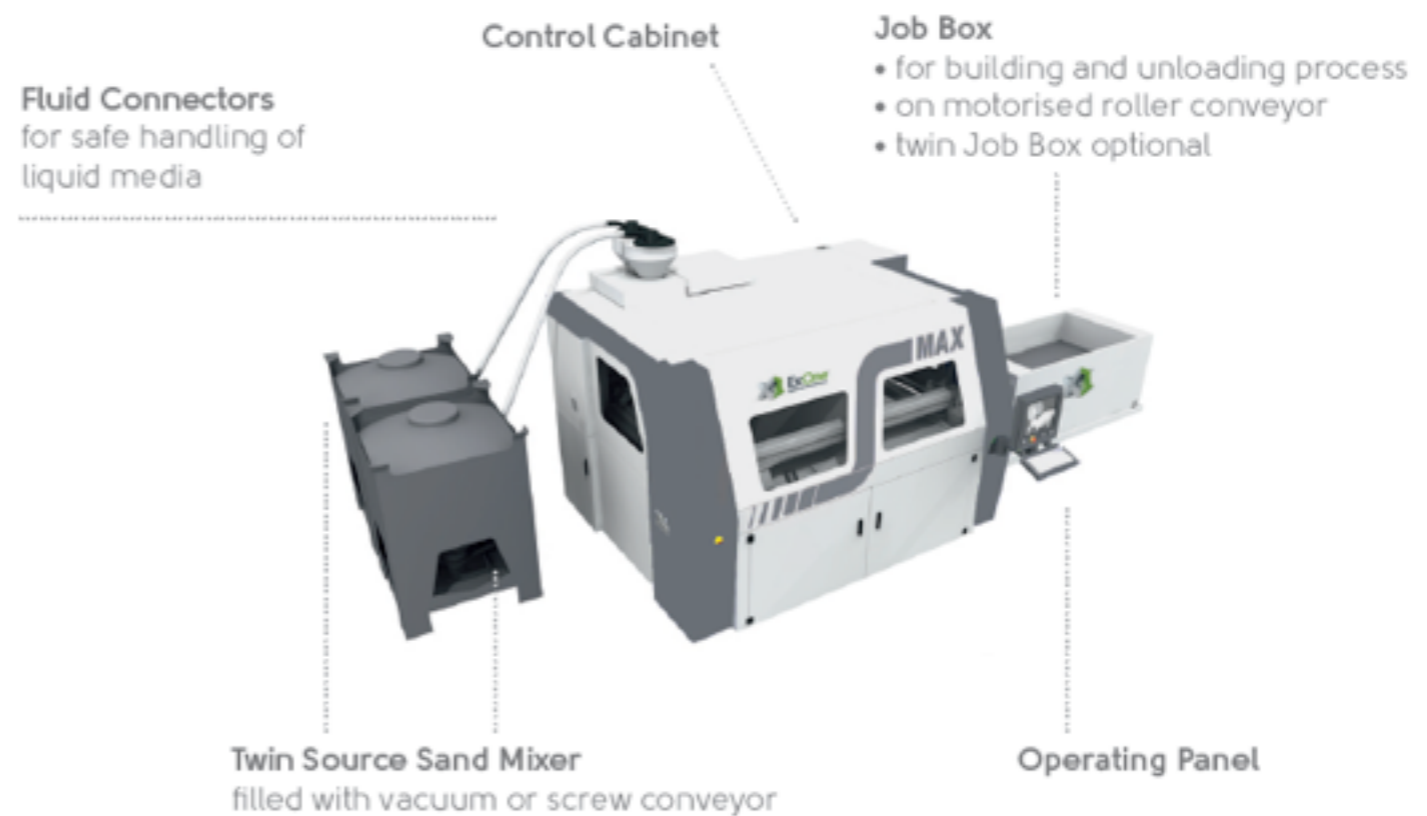
Binder Jetting

Exone:

Powder material is quartz and specialty sands.

Build Volume (WxDxH): 1800 x 1000 x 700 mm (70 x 39 x 27 in.)

Prices range from \$140K to \$1.4M.



Binder Jetting

Exone Processes

1. Metal systems:

- a. Jet a liquid binder into a bed of metal powder (stainless steel).
- b. Furnace cycle: Burn the binder out and infiltrate some bronze.

Exone metal systems are used for metal parts sold in Shapeways.

Alternative conventional system: Machining. Speed advantage?

Exone Processes

2. Sand systems:

Sand moles and cores for automotive and oil\gas customers.

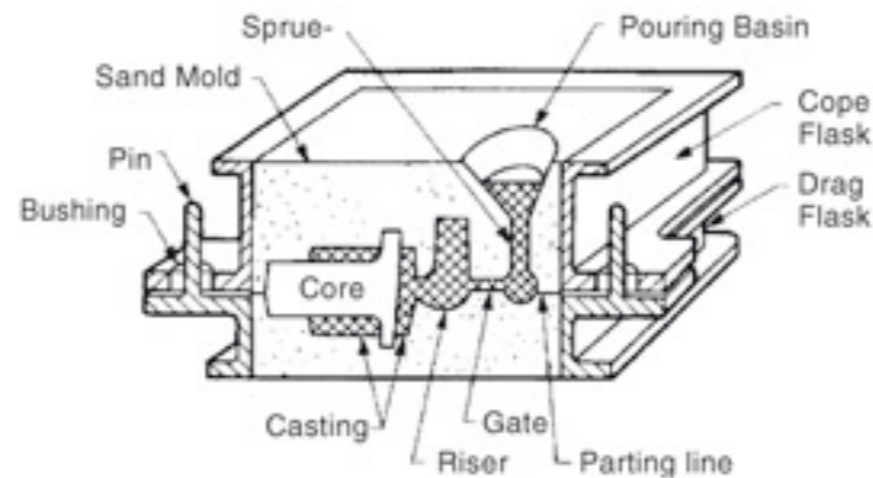
Ford motor is using many Exone sand systems in their processes. But they are mainly used in casting prototype parts.

Alternative conventional system: Sand Casting.

Binder Jetting

Sand Casting (Conventional Process)

In sand mold casting the mold is made of packed sand. Molten metal is poured into a cavity in the sand. When the metal cools and solidifies, it has the shape of the cavity. The sand is removed, normally by a shaking action that is vigorous enough to cause the mold to break apart. The casting is then cleaned of sand; flashing and sprues are cut off and any jagged or sharp edges are ground smooth.



The most common metal casting method.

Binder Jetting

Exone Competitors

Binder Jetting companies:

Voxeljet

Laser sintering companies:

EOS

Concept Laser

Electron beam sintering companies:

Arcam

Binder Jetting

VoxelJet (bought by 3D Systems):

Large build platform with large print heads.

Costs range from 140K Euros to 1.7M Euros.

PROCESS

Build space LxWxH	1060 x 600 x 500 mm
Print resolution x,y	600 dpi
Layer thickness	100-300 μm
Build speed	36 mm/h $\hat{=}$ 23 l/h



Binder Jetting Links

Exone s-Max:

<http://www.exone.com/materialization/systems/S-Max>

Exone metal printing:

<http://www.youtube.com/watch?v=2GI9Bw48liY&feature=c4-overview&list=UU2AGWEWI1iF0mCeggzUyqNA>

Exone sand printing:

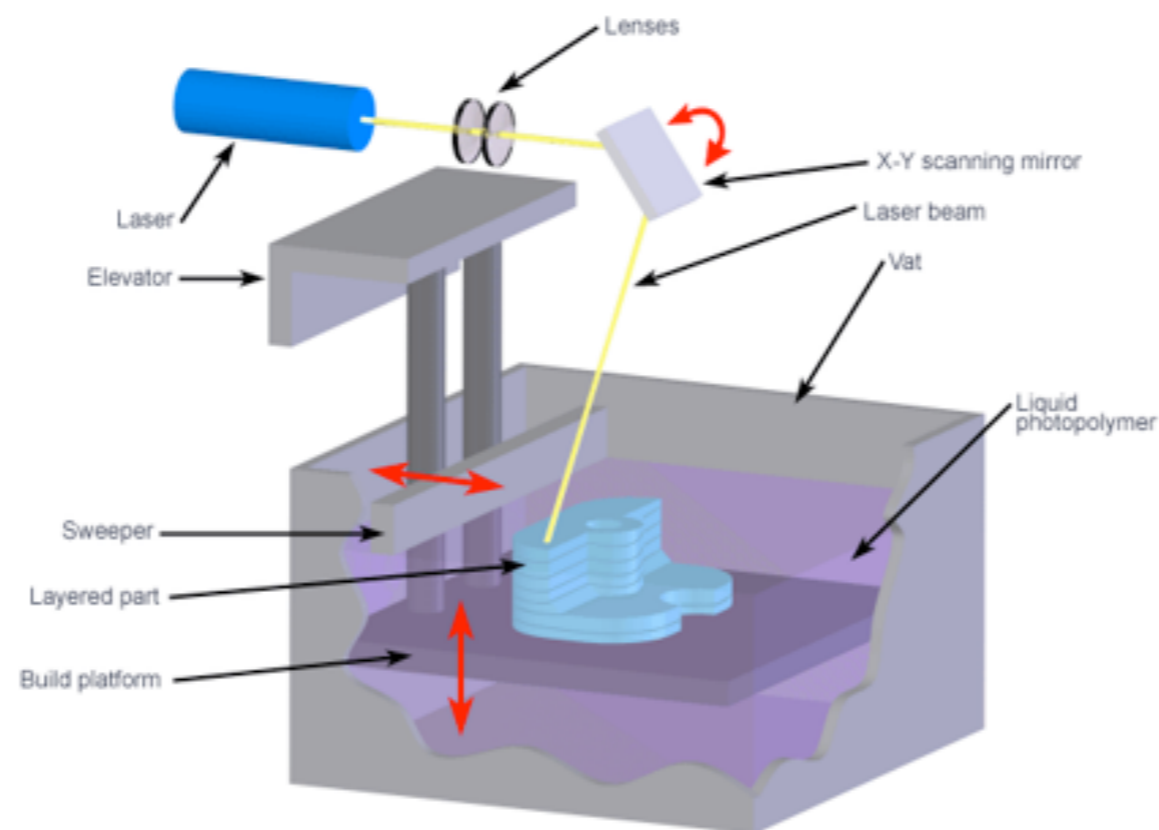
<http://www.youtube.com/watch?v=LFGnjkoedng&list=UU2AGWEWI1iF0mCeggzUyqNA>

VAT Photopolymerization (Stereolithography)

Technology summary:

VAT Photopolymerization is a process by which a photopolymer in vat is selectively cured by a light source.

Stereolithography was the first patented VAT Polymerization process using a UV light as source. It was commercialized by 3D Systems.



VAT Photopolymerization (Stereolithography)

3D Systems iPro:

Build envelope: 650 x 750 x 550 mm (25.6 x 29.5 x 21.65 in)

Weight: 1590 kg (3500 lbs)

Prices range from \$200K to \$800K.



VAT Photopolymerization (Stereolithography)

Form Labs:

Desktop STL machine.

Makerbot's counterpart, but in STL, thus resolution is higher.

Build envelope :4.9 x 4.9 x 6.5 inch
(Makerbot's 11.2 x 6.0 x 6.1 inch)

Price: \$3299 (Makerbot: \$2200)



VAT Photopolymerization (Stereolithography)

Disadvantages:

Photopolymers for STL cost within \$175-\$250/kg. By contrast, thermoplastics for injection molding costs \$2-3/kg!

Photopolymers may not be as strong as their counterparts in injection molding.

Fumes from photopolymers can be toxic.

Metals are not usable as process material in STL.

VAT Photopolymerization links

3D Systems iPro 8000:

http://www.3dsystems.com/3d-printers/production/ipro-8000#.UhkdkLwkIT_

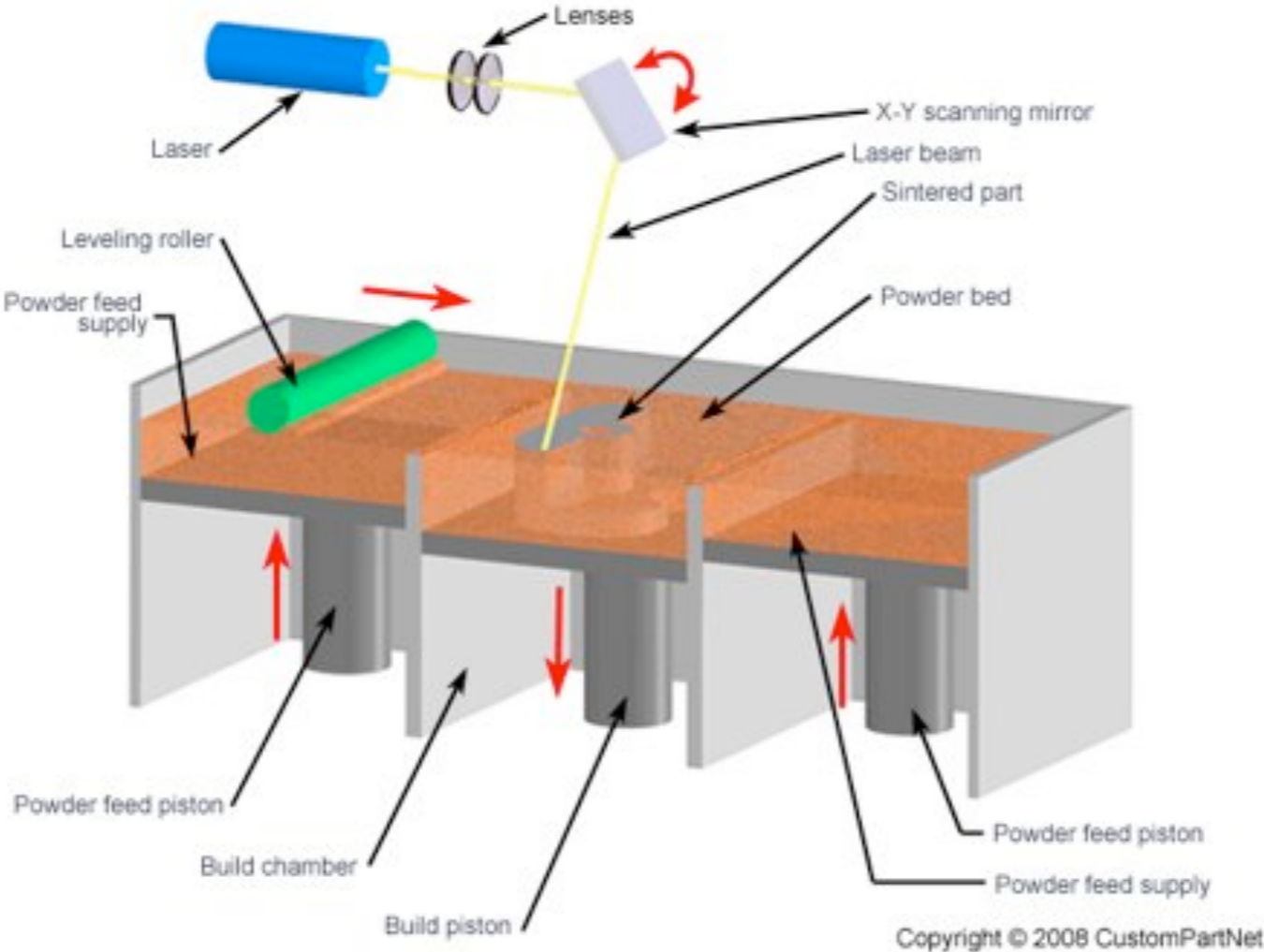
Stereolithography Process:

<http://www.youtube.com/watch?v=sTNUrFzHbxc>

Powder Bed Fusion

Technology summary:

Powder bed fusion is a process by which metal or plastic powder material in bed is selectively melted by a laser or an electron beam.



Powder Bed Fusion

EOS INT: Metal Fusion by Laser (Laser Sintering)

Build volume: 250 mm x 250 mm x 325 mm (9.85 x 9.85 x 12.8 in)

Price: \$550K



Powder Bed Fusion

Advantages

- Both metal and polymer manufacturing possible.
- Several metals can be used in this process: Steel, aluminum, titanium, etc.
- Produced part properties can approach those produced by casting.
- More uniform part characteristics with respect to casting. in the casting the part properties can be quite different as the part cools off from outside in.

Powder Bed Fusion

Disadvantages

- Like 3d printing plastics, 3d printing metals are also expensive with respect to conventional manufacturing counterparts. (Ex: stainless steel for 3d printing cost \$120/kg, vs \$10/kg for traditional one).
- Cooling after powder bed fusion process can take time (depending on the dimensions of the workpiece).

Powder Bed Fusion Links

EOS INT: Metal powder systems

http://www.eos.info/systems_solutions/metal/systems_equipment/eosint_m_280

EOS Technology:

<http://www.youtube.com/watch?v=onmbIKPKYvI>

EOS aluminum and titanium printing:

<http://www.youtube.com/watch?v=zApmGFDA6ow>

Important Companies

Stratasys merged with Objet in late 2012 and became the largest manufacturer in the field. The headquarters of the merged company is in Rehovot, Israel. Stratasys also acquired Makerbot in June 2013 for \$400M, which was offering popular consumer 3d printing machines.

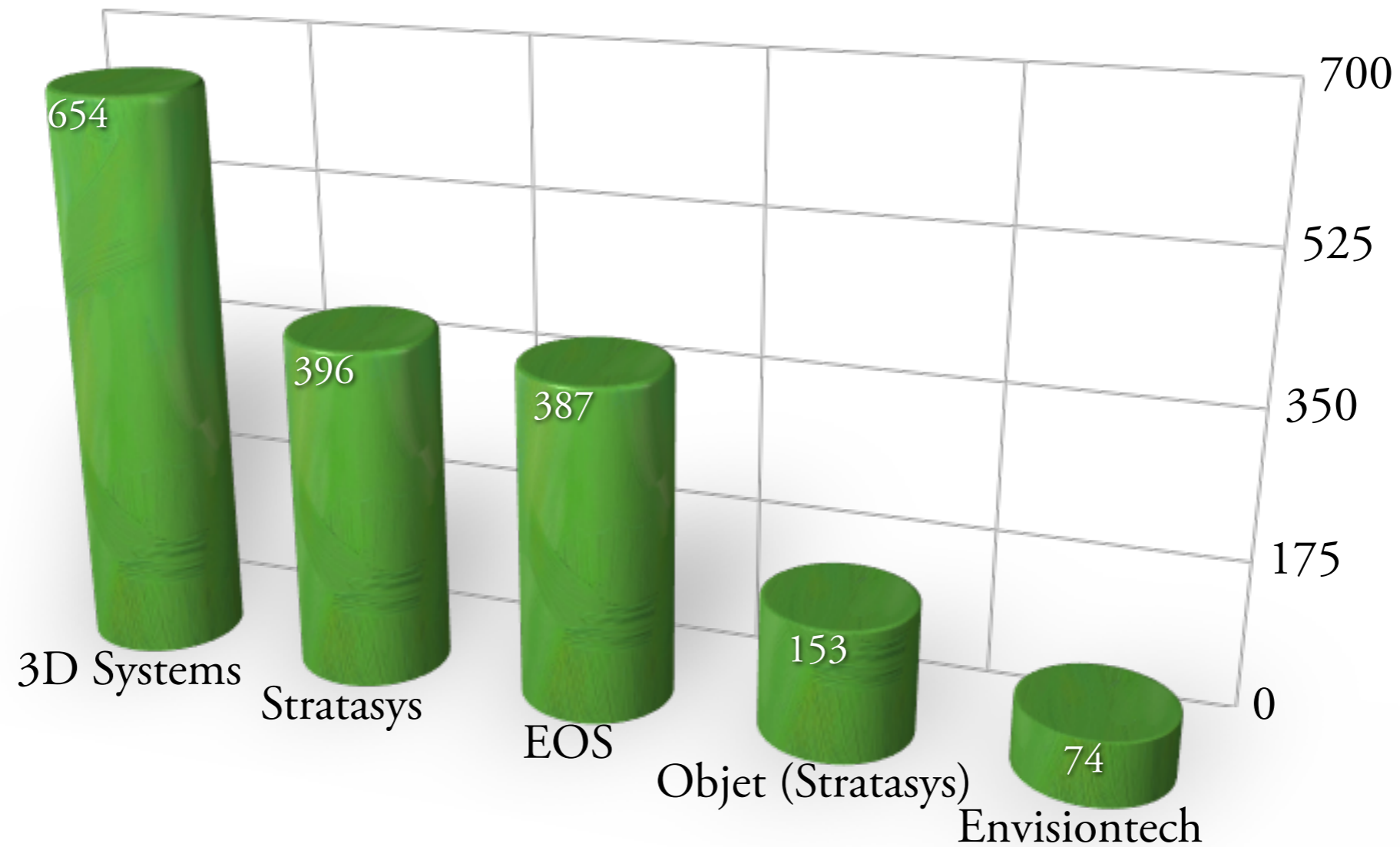
3D Systems gobbled down two dozen companies in the last two years. Presently it's a confederation of loosely connected small companies. The most important acquisitions were Z Corp, Rapidform, Geomagic and Phenix Systems.

These two companies also have the largest market share: Stratasys (40%), Objet (15%), 3D Systems (18%) (all 3d printing systems included).

So these two companies merit special attention.

Envisiontech (12% market share) and **EOS** (2%) from Germany are the two other important companies.

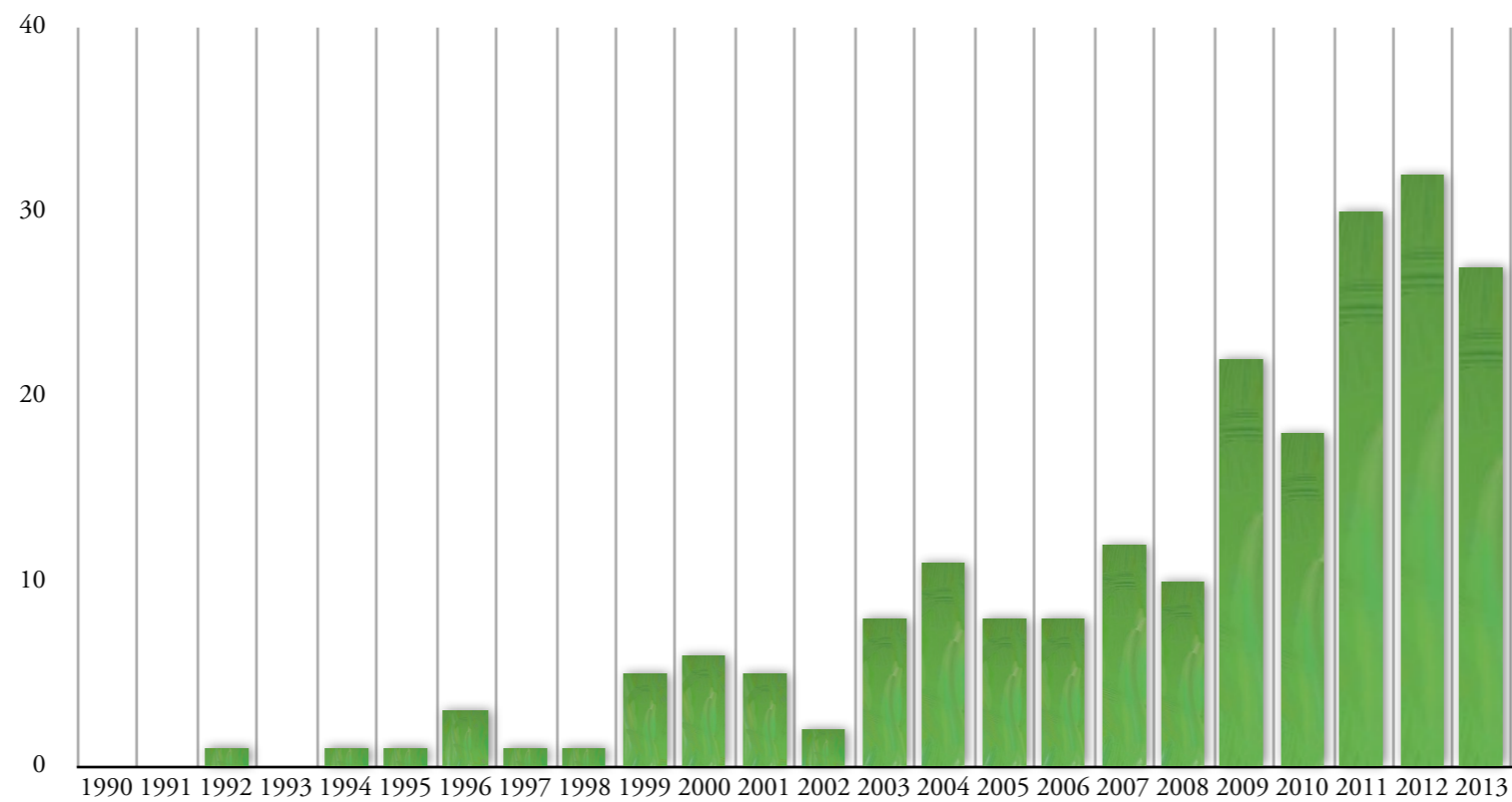
Main Stakeholders in Patents-Patent Applications (1990-2013)



(US-EP-WIPO-JP Patent offices)

Stratasys Patents-Patent Applications (1990-2013)

Stratasys Patents-Patent Applications (1990-2013) US Patent Office only



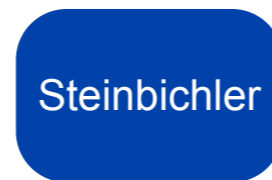
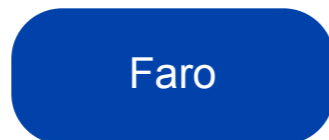
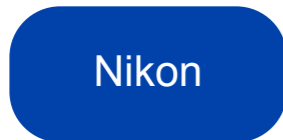
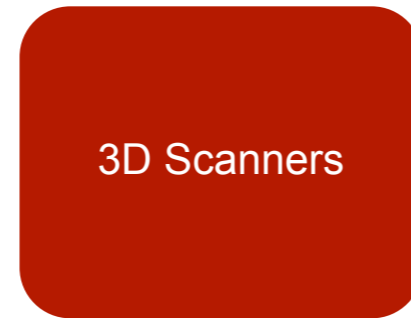


3D Scanners - Reverse Engineering

Onat Ekinici

3D Scanners

Representative companies, list not exhaustive



Industrial (High End)



Consumer (Low End)

Industrial Scanners



Large volume scanner (Lidar; Nikon)

- Laser-tracked line scanners
- Single-beam, direct ranging-systems



Laser triangulation scanners (Portable Arm; Faro)

- Spatially located by CMM arms and fixed-base cameras



Structured light scanners (White-light; Atos)

- Cameras combined with structured light projection (patterns, fringes)

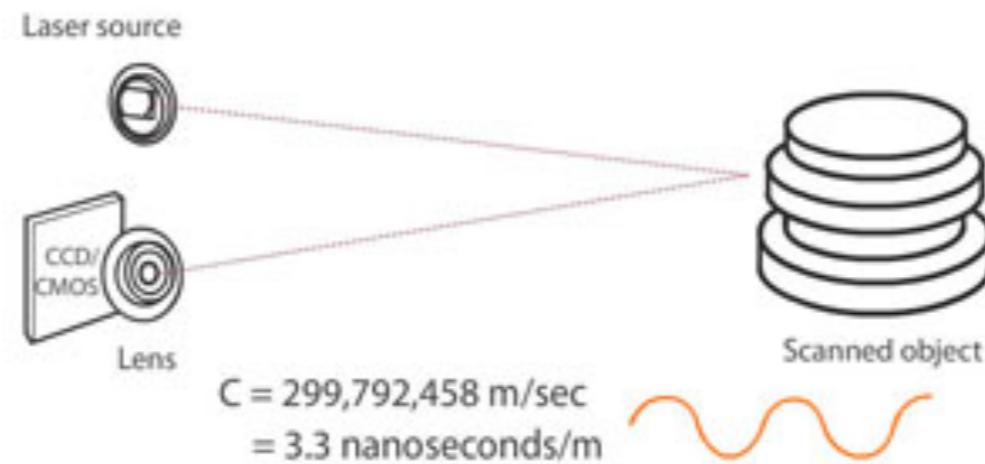
Large Volume Scanner (Lidar: Laser Radar)



The MetricVision system operates using a sensor to direct a focused invisible infrared laser beam to a point and coherently processes the reflected light. As the laser light travels to and from the target, it also travels through a reference path of calibrated optical fiber in an environmentally controlled module. The two paths are combined to determine the absolute range to the point. Huge laser-modulation bandwidth (100 GHz) makes precise measurement possible in a millisecond. The distance measurement is then combined with the positions of the two precision encoders to determine a point on a surface in space.

Laser Radar

- These systems pulse and modulate the power of the laser beam, and the scanner compares the phase of the laser being sent out and then returned to the sensor.



Laser Radar

Advantages:

- No need for a reflector.
- Needs a reflectivity of just 1% of the signal, and is able to measure directly on the surface of the object. This makes it possible to scan many points in a short period of time and eliminates the compensation for the retroreflector radius.
- LR provides automated non-contact measurement capability for a large volume application up to 60 meters.
- Rapid data collection up to 1000 points/second without photogrammetric targets.

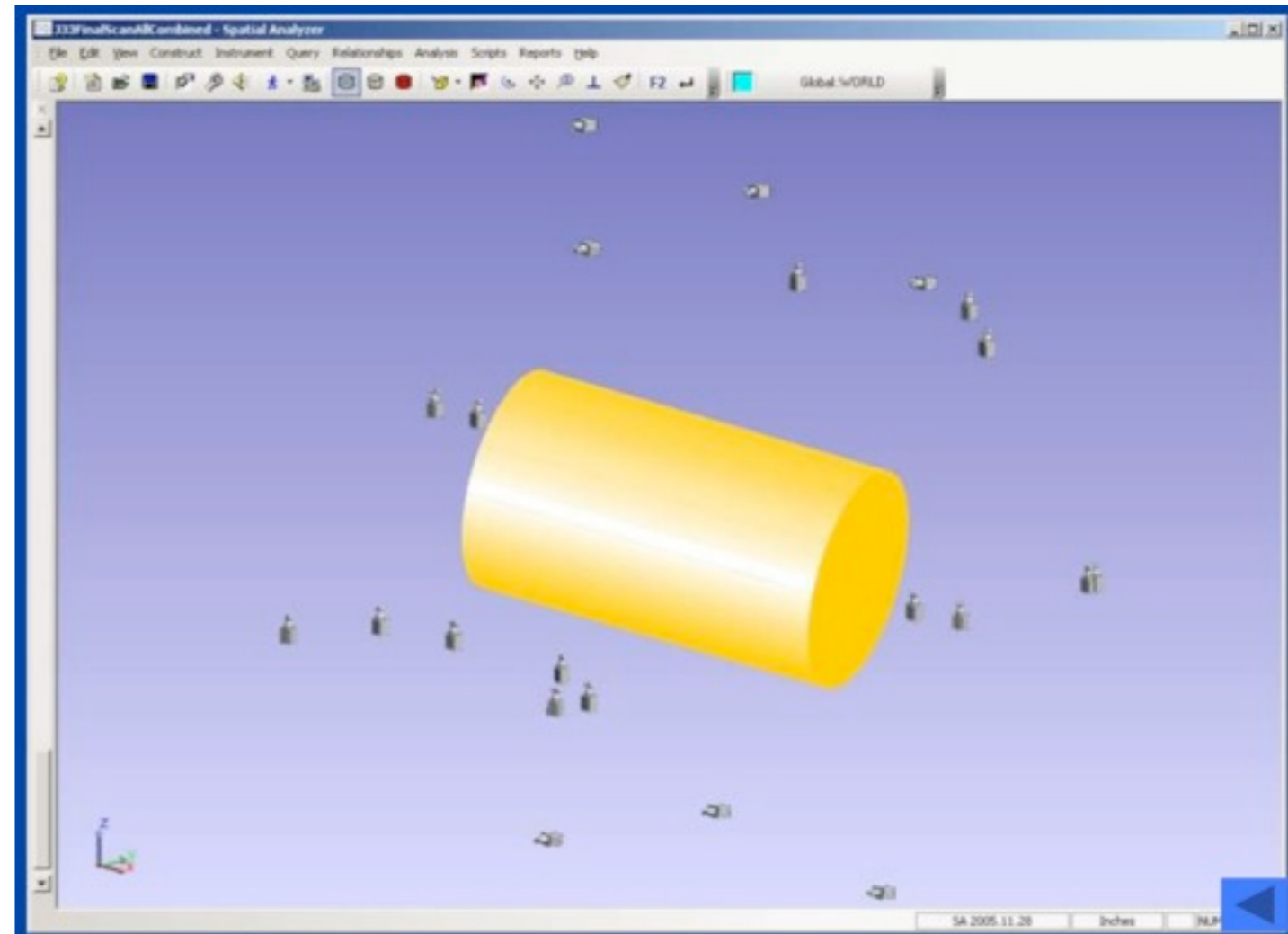
Disadvantages:

- Performance depends on surface reflectivity.
- Heaviness.
- Air turbulences, temperature variations in time and in space (affecting the refracting index of the air) can be an important source of perturbation.
- (From Vakil et al. :) Locating LR for a complete view of the structure can be challenging
 - – Top skins and panels are easily measurable. BUT:
 - – Bottom skins/panels & structures require special line of sight arrangement

Laser Radar

Aircraft Fuselage Measurement [Lazar, 2007]

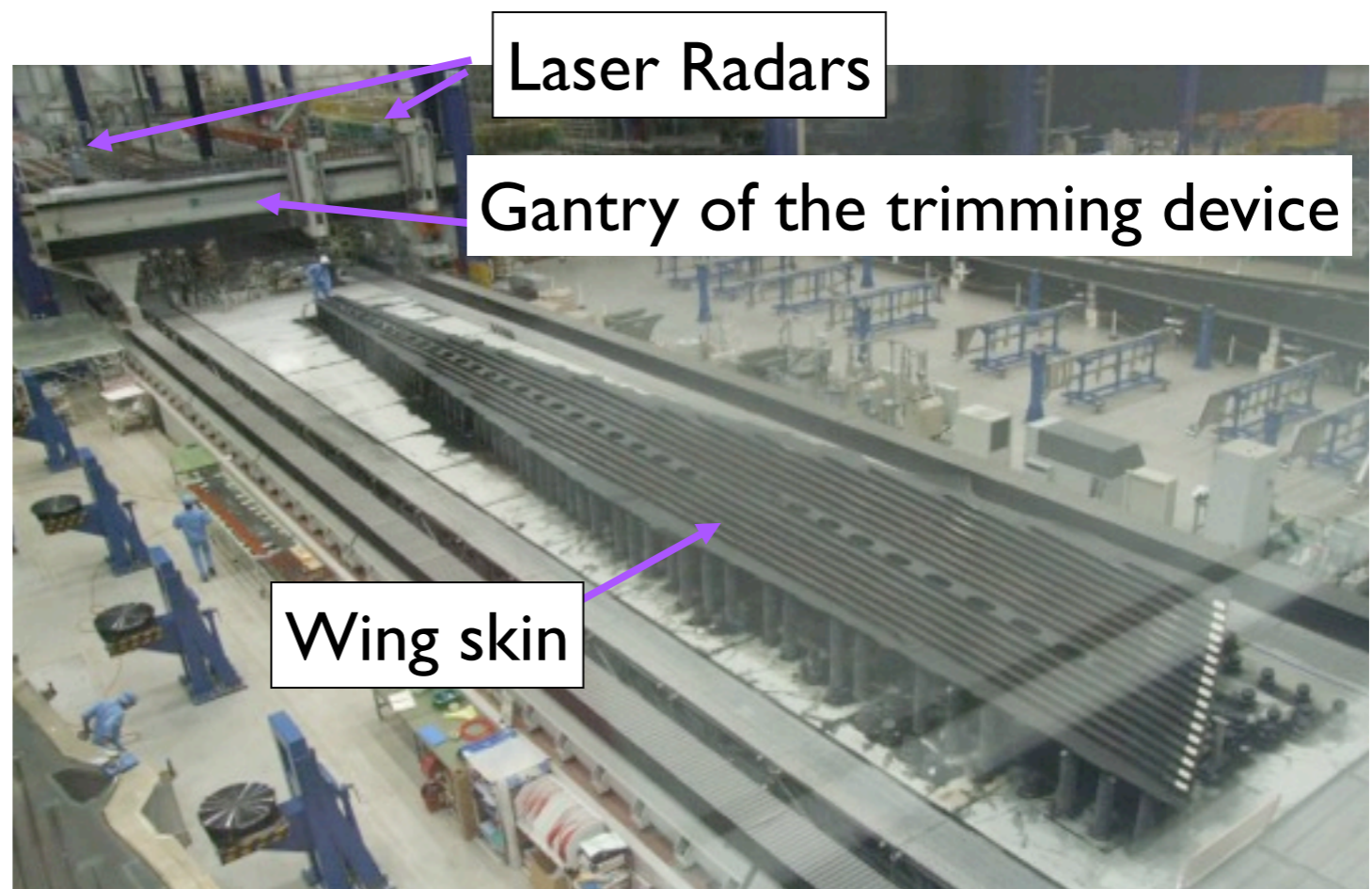
Comparison between photogrammetry and laser radar



Laser Radar

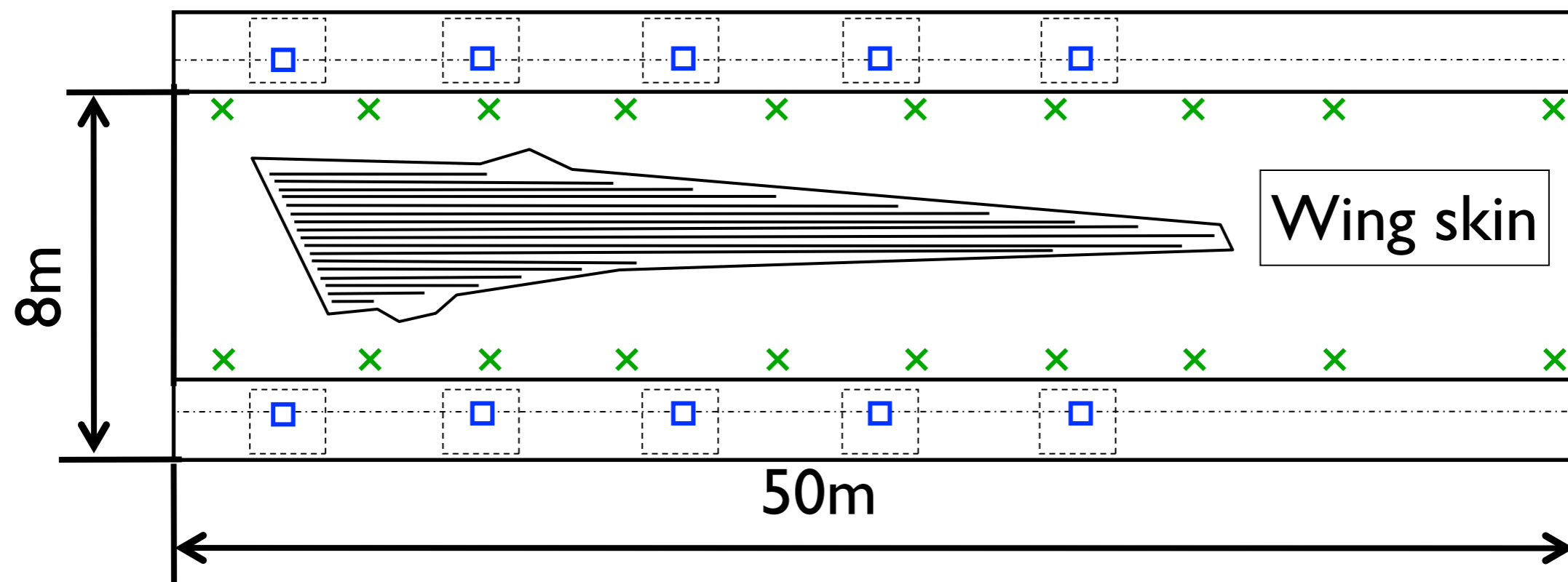
“3D Measurement” in the 787 wing skin manufacturing process [Mitsubishi-Hitachi, 2010]

- Two Laser Radars are installed on the gantry of the trimming device.
- The area of trimming and inspection is shared.



Laser Radar

“3D Measurement” in the 787 wing skin manufacturing process [Mitsubishi-Hitachi, 2010]

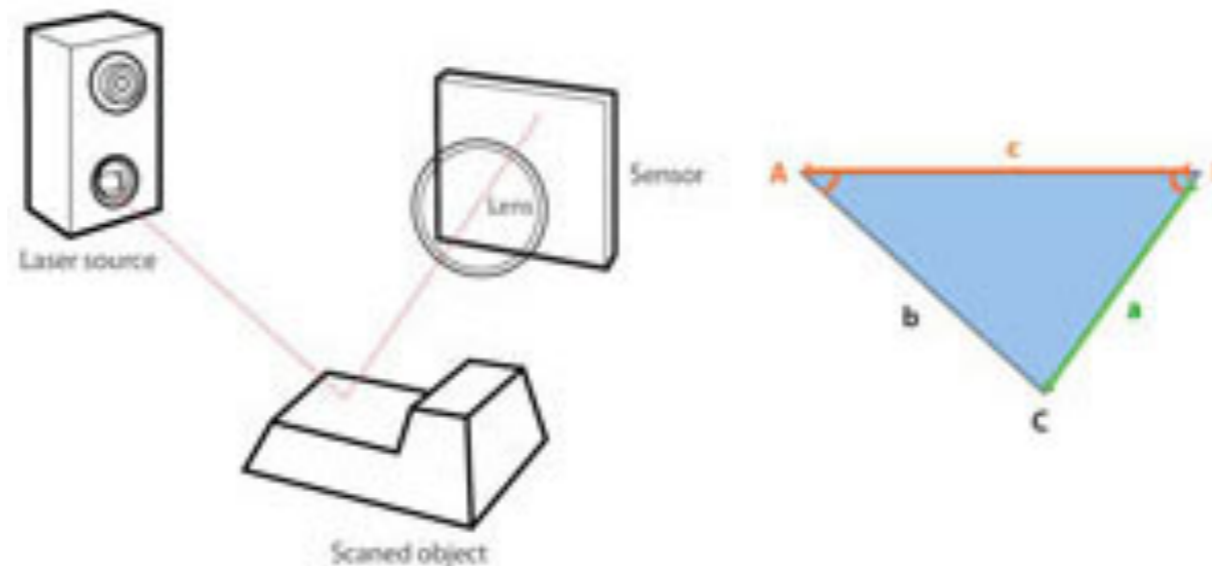


- × :Common point (fixed) Total of 20 points
- :LR position (unfixed)

Portable Arm (Laser Triangulation) Scanners

Laser triangulation scanners use either a laser line or single laser point to scan across an object. A sensor picks up the laser light that is reflected off the object, and using trigonometric triangulation, the system calculates the distance from the object to the scanner.

The distance between the laser source and the sensor is known very precisely, as well as the angle between the laser and the sensor. As the laser light reflects off the scanned object, the system can discern what angle it is returning to the sensor at, and therefore the distance from the laser source to the object's surface.



Portable Arm (Laser Triangulation) Scanners

1.8m to 3.7m (6 ft. to 12 ft.) spherical working volume

Accuracy from 0.024mm (0.0009 in.) to 0.064mm (0.0025 in.)



Portable Arm (Laser Triangulation) Scanners

Faro Arm Intro:

<http://www.faro.com/en-us/solutions/applications/cad-based-inspection>

A good intro with Jay Leno!

<http://www.youtube.com/watch?v=q3SVTBrKyZk>



Structured Light

Major players

Faro

Romer

Metronor

Creaform

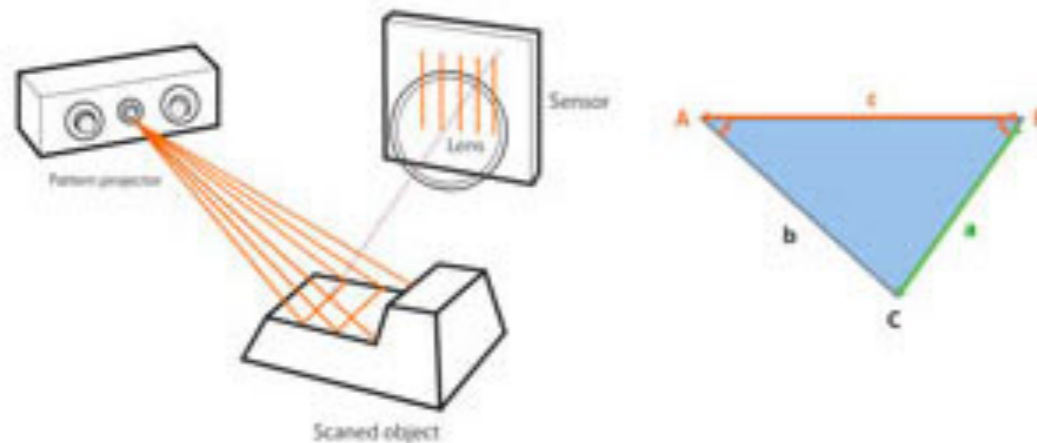
Aicon

Nikon



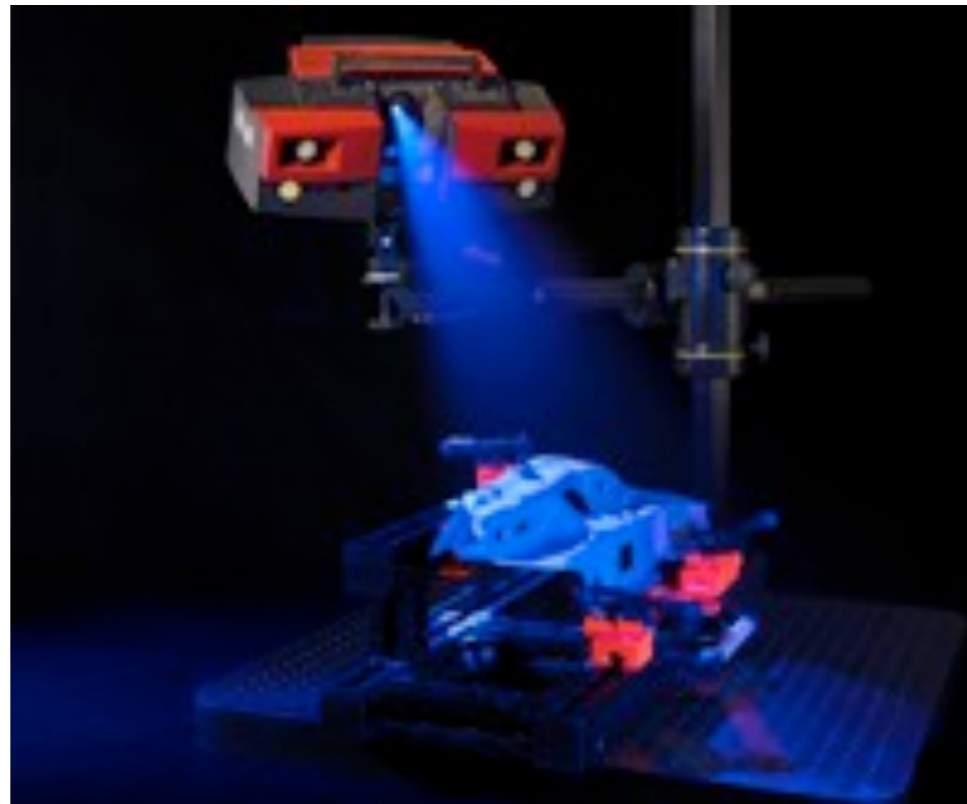
Structured Light

- Structured light scanners use trigonometric triangulation, but instead of looking at laser light, these systems project a series of linear patterns onto an object. Then, by examining the edges of each line in the pattern, they calculate the distance from the scanner to the object's surface.



Structured Light

- More accurate than laser-line scanner, lower noise, faster scanning
- Less portable, sensitive to surface finish and lighting
- Takes ~15 sec per each shot (8M or 16M of points) (45K pts/s FARO Edge arm scanner)
- Some systems need targets, others don't.
- With or without CAD (comparison to a master piece)



Structured Light

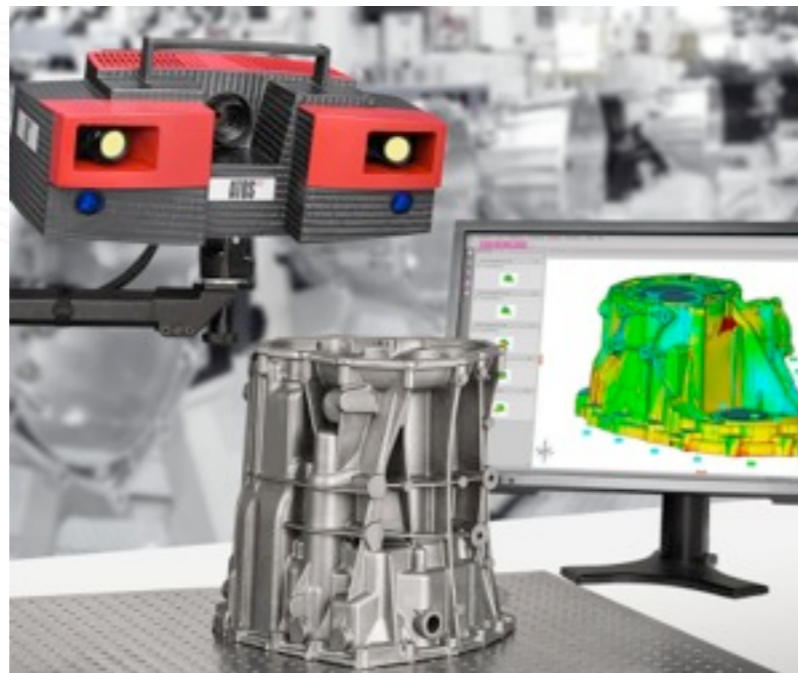
Major players

GOM Athos

Hexagon Cognitens

Steinbichler

Aicon



Structured Light

Videos

Steinbichler:

http://www.youtube.com/watch?v=jV1A_ItgPP8



X-ray Computed Tomography

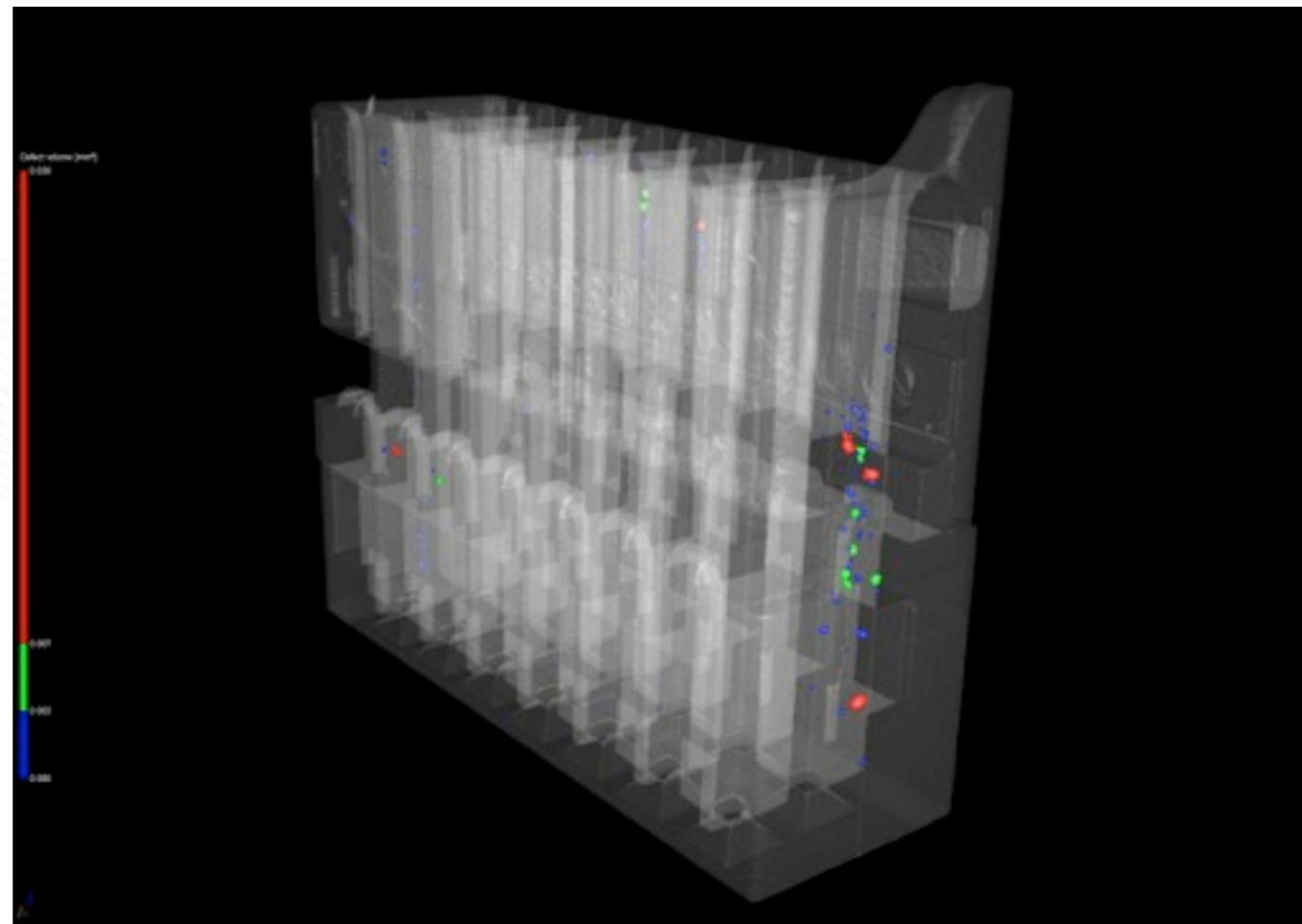
- Comes from medical industry
- Volumetric scanning
- Billions of points (GB of data)
- Precision: ~1 microns



X-ray Computed Tomography

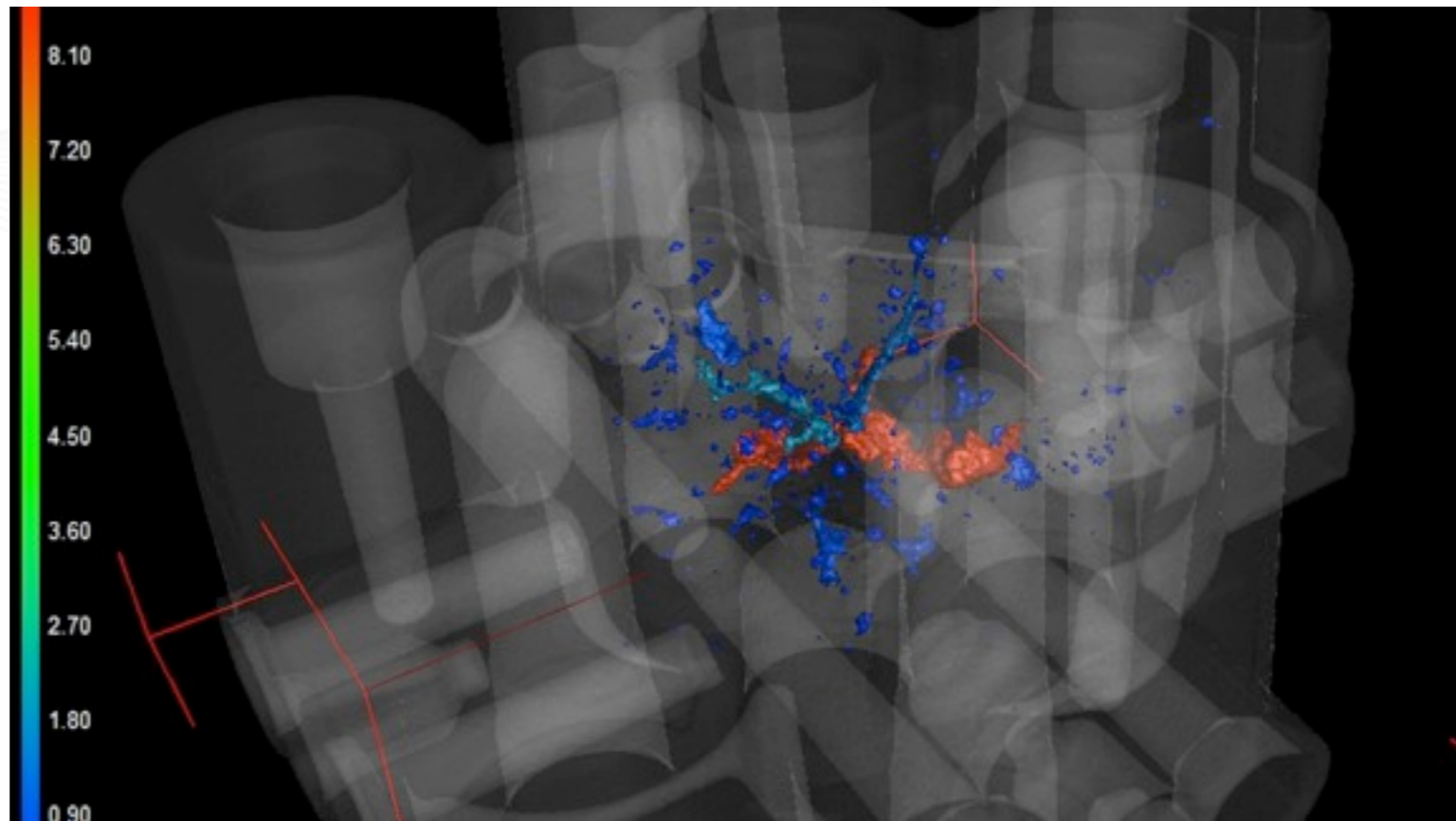
Detect failures in casting parts

- Air pockets



Computed Tomography

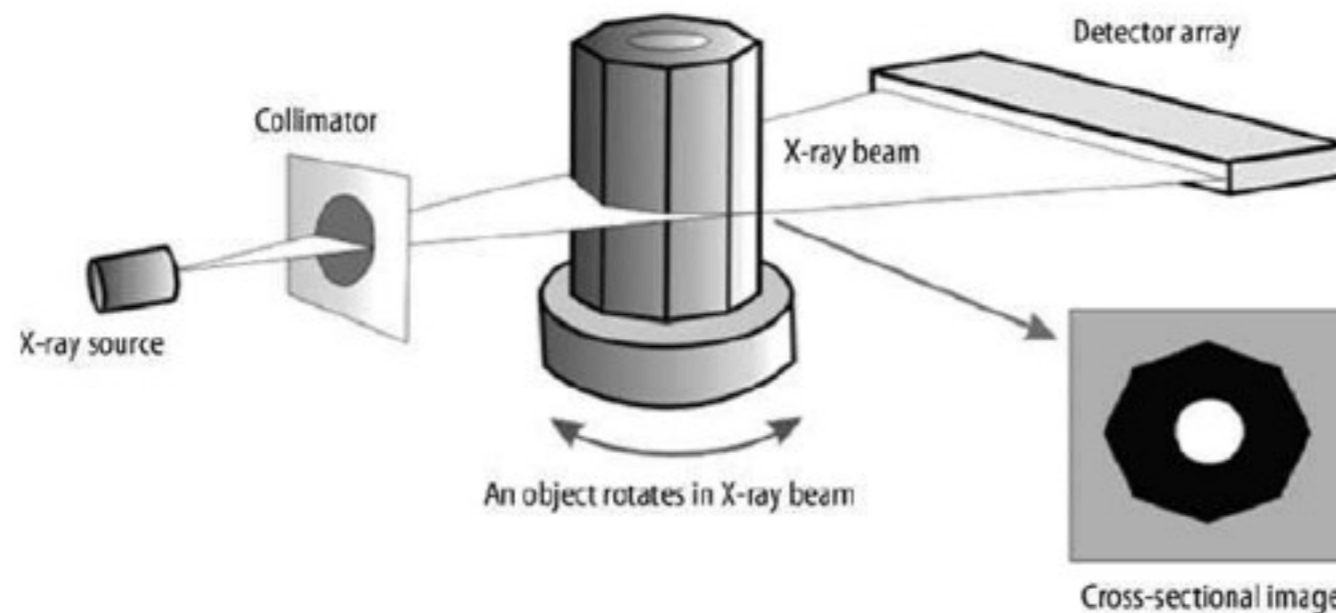
Detect failures in casting parts



Transitive Techniques (CT-MRI)

CT Advantages:

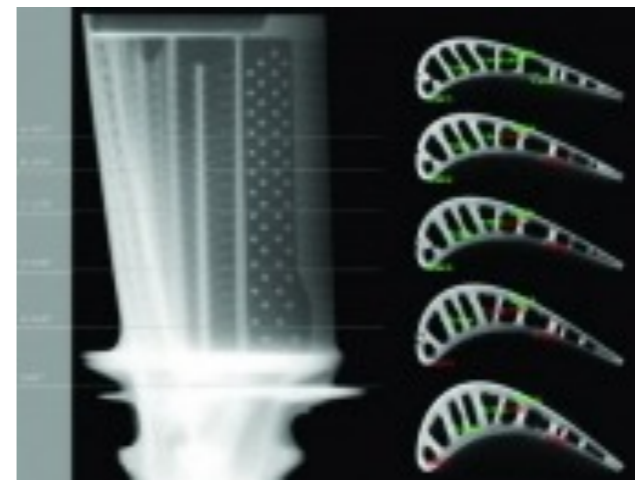
1. No need to place the pieces in various positions for their complete digitization
2. Internal inspection



CT working principle of generating 2-D cross-sectional images. By projecting a thin X-ray or Y-ray beam through one plane of an object from many different angles and measuring the amount of radiation that passes through the object along various lines of sight, a map of attenuation coefficients (a density map or cross-sectional image) for the scanned surface is reconstructed.

Nikon: XT H 450 LC for CT inspection

http://www.nikonmetrology.com/en_US/Products/X-ray-and-CT-Inspection/Computed-Tomography/XT-H-450-for-turbine-blade-and-casting-inspection



Applications

- **Automotive**

- Electrical connectors
- Injection nozzles
- Sensors (e.g. Lambda sensor)
- Translucent dashboard LED light pipes
- Small high-pressure die casting parts e.g. turbo compressor

- **Aerospace**

- Positioning of cores in wax for turbine blades
- Crack analysis in components
- Blade inspection

X-ray inspection of turbine blade with sections

Industrial Measurement Options

Gages+micrometers
+granite



Coordinate Measurement Machine
(CMM)

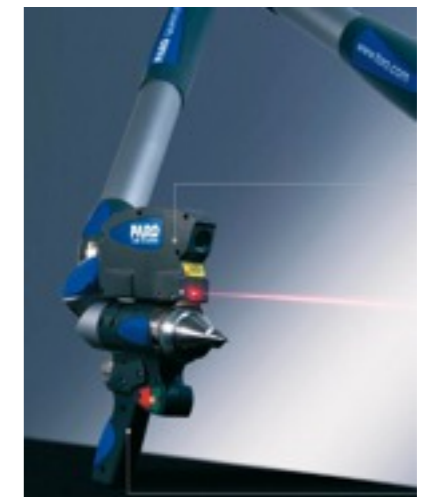


<http://www.mitutoyo.com/>

Portable Arm



Portable Arm + Scanner



Scanners for Industrial Metrology

FARO SCANARM

Accuracy $\pm 35\mu$ (± 0.0014 in.)

Scan rate up to 45,120 points/sec



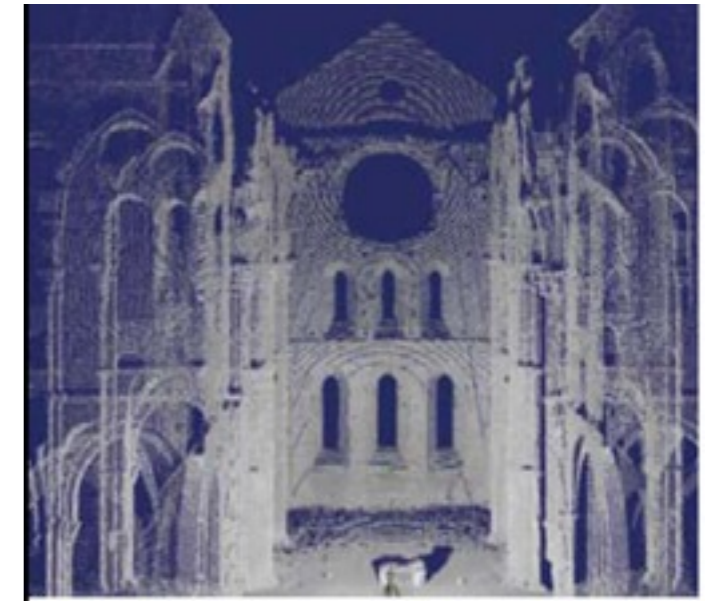
Scanners for Surveying

FARO FOCUS

Distance accuracy up to $\pm 2\text{mm}$

Range from 0.6m up to 120m

Measurement rate up to 976,000 points/sec



Commercial



Industrial



Residential



Manufacturing

WHAT IS REVERSE ENGINEERING?

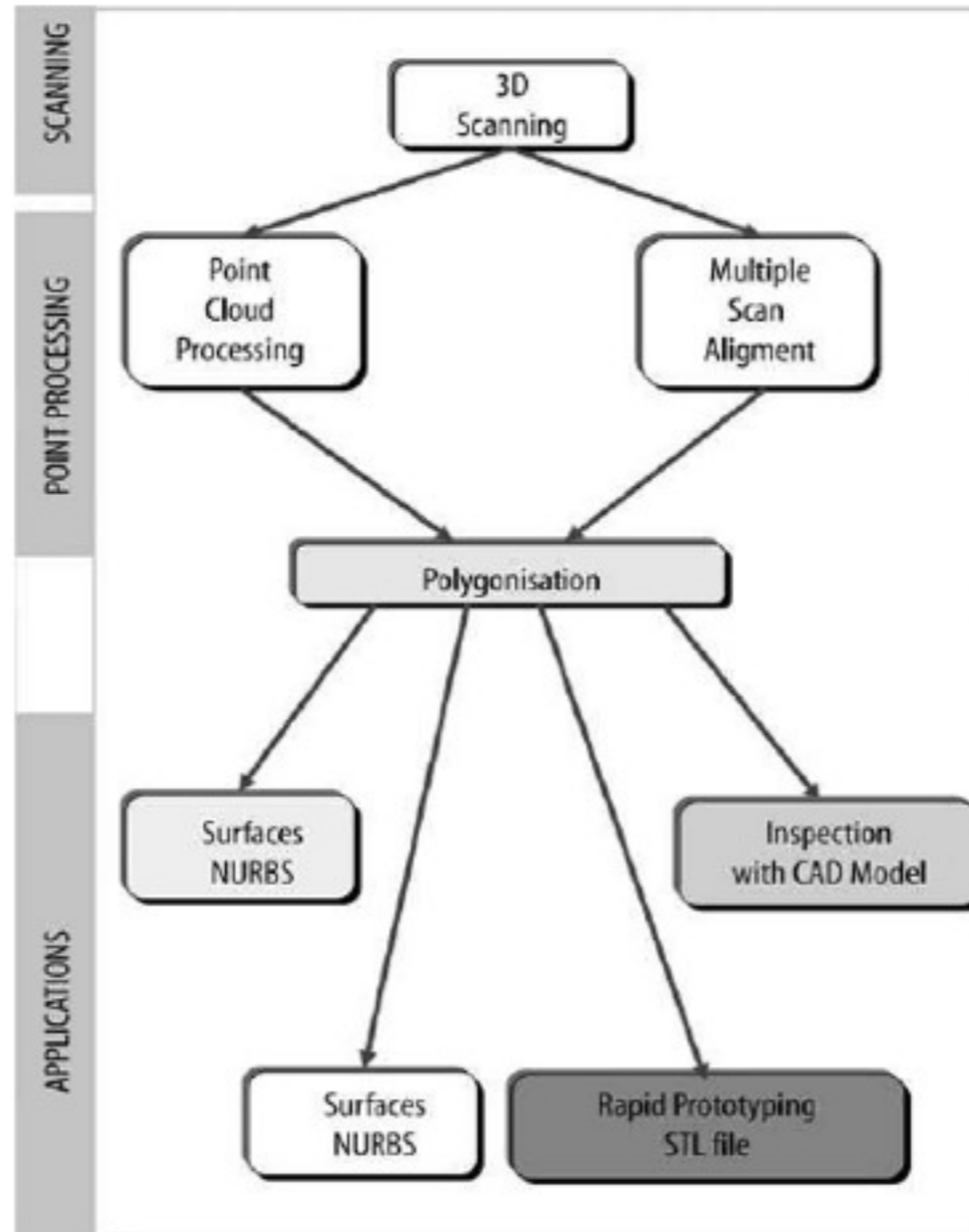
The process of duplicating an existing part, subassembly, or product, without drawings, documentation, or a computer model is known as reverse engineering.



WHAT IS REVERSE ENGINEERING?

- The original manufacturer no longer exists, but a customer needs the product, *e.g., aircraft spares required typically after an aircraft has been in service for several years.*
- The original manufacturer of a product no longer produces the product, *e.g., the original product has become obsolete.*
- The original product design documentation has been lost or never existed.
- Creating data to refurbish or manufacture a part for which there are no CAD data, or for which the data have become obsolete or lost.
- Inspection and/or Quality Control—Comparing a fabricated part to its CAD description or to a standard item.
- Strengthening the good features of a product based on long-term usage.
- Analyzing the good and bad features of competitors' products.
- Exploring new avenues to improve product performance and features.
- Creating 3-D data from a model or sculpture for animation in games and movies.

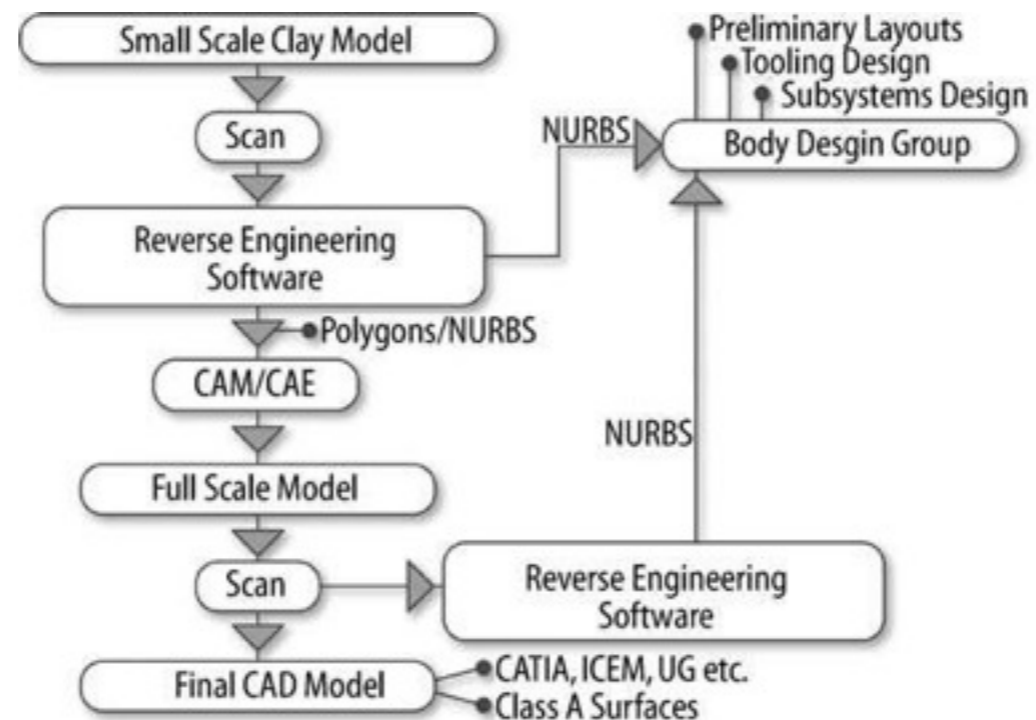
Reverse Engineering



Reverse Engineering

RE APPLICATIONS

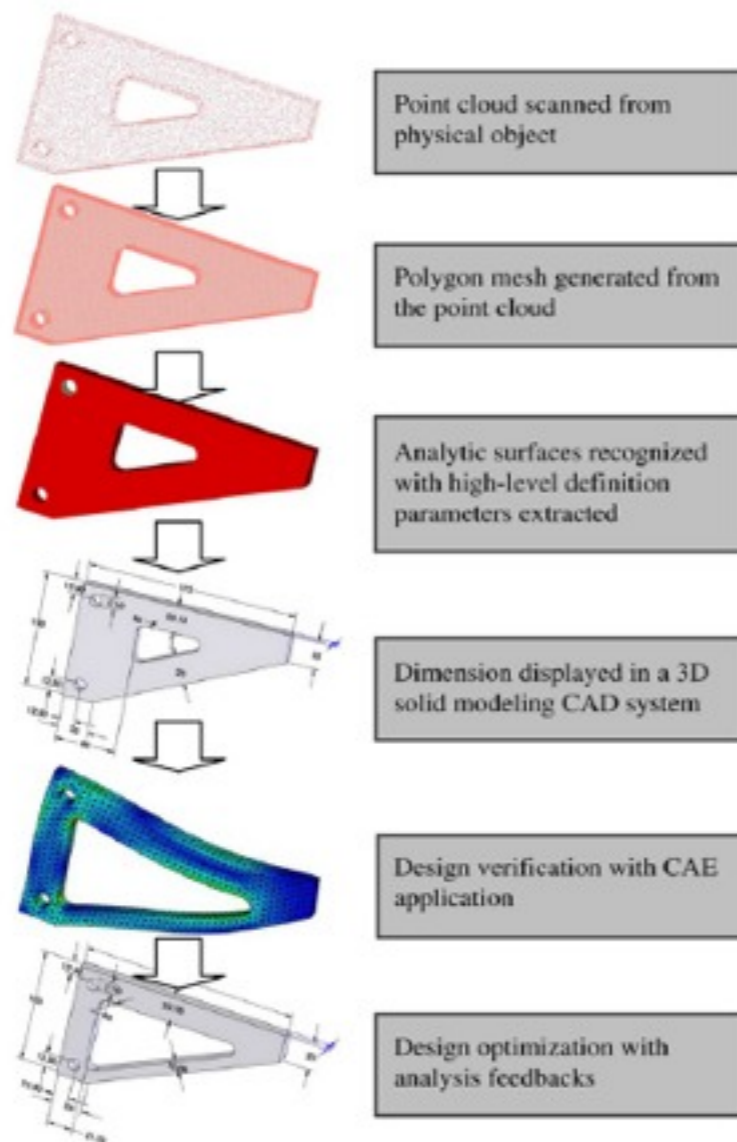
Automotive (Japanese companies)



Using traditional computer-aided design, engineering, and manufacturing processes, a typical full-scale car design takes more than 3 months to complete. This is not acceptable to Japanese auto companies, which are working to shorten the process to 3 days. The only way this can be done is through a drastic change in the design flow, such as the reverse engineering process illustrated below.

RE APPLICATIONS

Reverse Innovative Process [Ye, 2008]



Men's Style, Length = 264.9mm, Girth = 239.3mm
Basic Width = 88.3mm, Heel Height = 5.88mm



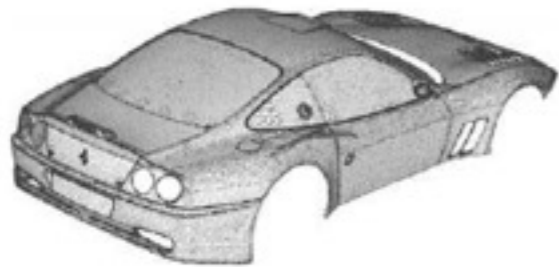
Men's Style, Length = 297.17mm, Girth = 239.3mm
Basic Width = 88.3mm, Heel Height = 25.69mm



Creation of design variations and product families by playing with parametrized models.

RE APPLICATIONS

Automotive (Ferrari-Geomagic)

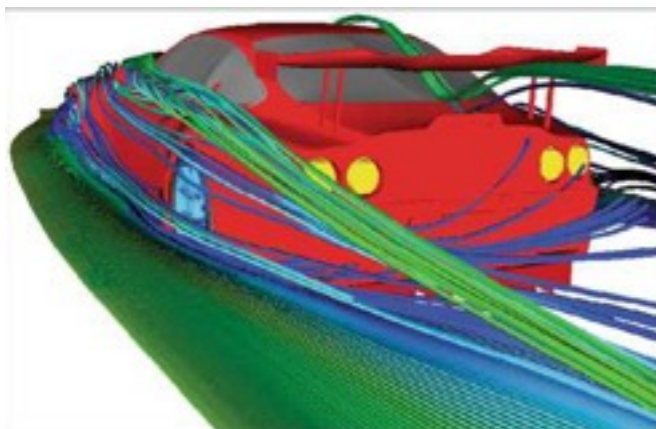


Aligned and merged point clouds of Ferrari 550

“The point cloud of the half car body contains 40 million points.”



Reverse engineered in Geomagic Studio



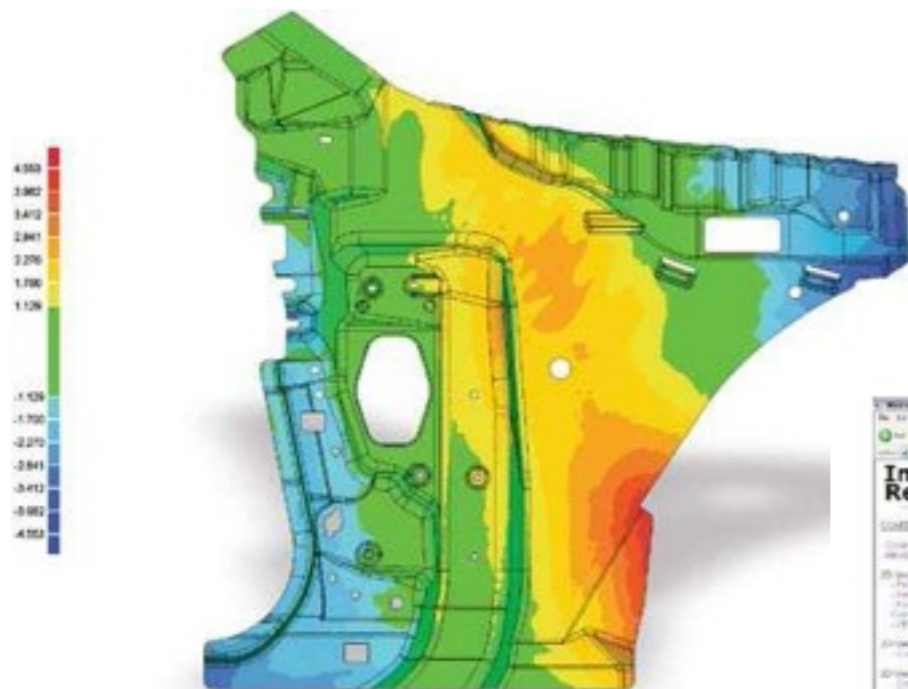
CFD Analysis for aerodynamics optimization

Reverse Engineering

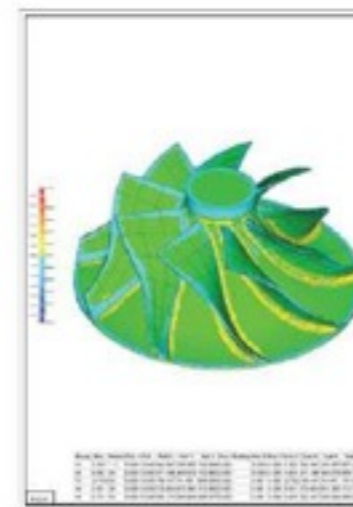
RE APPLICATIONS

Automotive (European automaker-Geomagic)

“The company is using reverse engineering to implement a new computer-aided inspection (CAI) process for a plant that builds nearly 600,000 engines a year.”



Sheet metal part reverse engineered in Geomagic Studio



RE APPLICATIONS

Aerospace *“A company is lucky if it has digital models of 1% of inventory”*

The modern aerospace industry uses reverse engineering for these key reasons:

1. to create legacy parts and hard tooling that do not have CAD models;
2. to overcome obstacles in data exchange and data integrity;
3. to resolve and correct problems arising from discrepancies between the CAD master model and the actual tooling or as-built part; and
4. to ensure quality and performance through computer-aided inspection and engineering analysis.

Legacy Parts: GM can leave obtaining a transmission for a 1968 Pontiac GTO to hobbyists and collectors, but the 1968 models of aircraft, with designs barely changed, are likely to be more prevalent in the air than models from the twenty-first century. This creates a huge inventory of legacy parts to be stored and maintained.

RE APPLICATIONS

Aerospace

“It would be a waste to capture a wing with a structured-light scanner that might generate a model with 40 million points”, said Brehm. “On the other hand, you might need 40–100 million points to capture the radii and complex shapes of an actuator.”

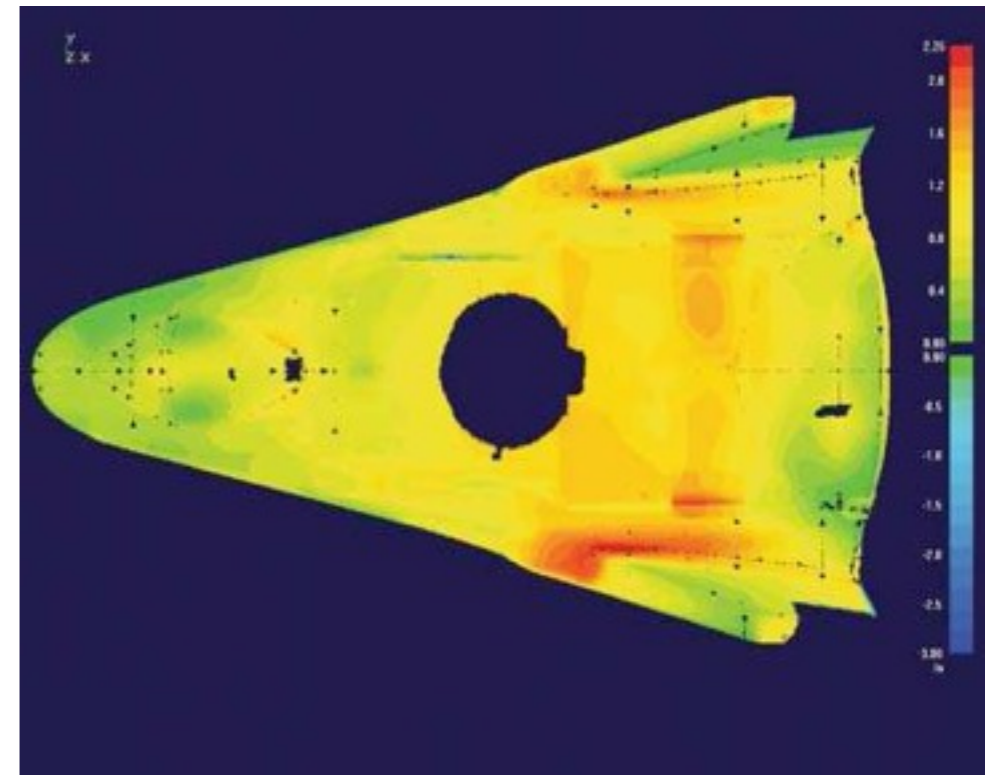
For master parts that require capturing a large shape, the cuts for the wings and fuselage of a 747, for example, a laser tracker is often used. Laser trackers can capture large surfaces fairly quickly, as long as high detail is not required. Complex parts with tight contours that require lots of data to generate an accurate model are captured by a structured-light or laser scanner. For small, intricate parts, a scanning arm with an integrated scanner head is likely to be used.

RE APPLICATIONS

Aerospace (NASA Space Vehicle)



Autonom Crew Return Vehicle X-38

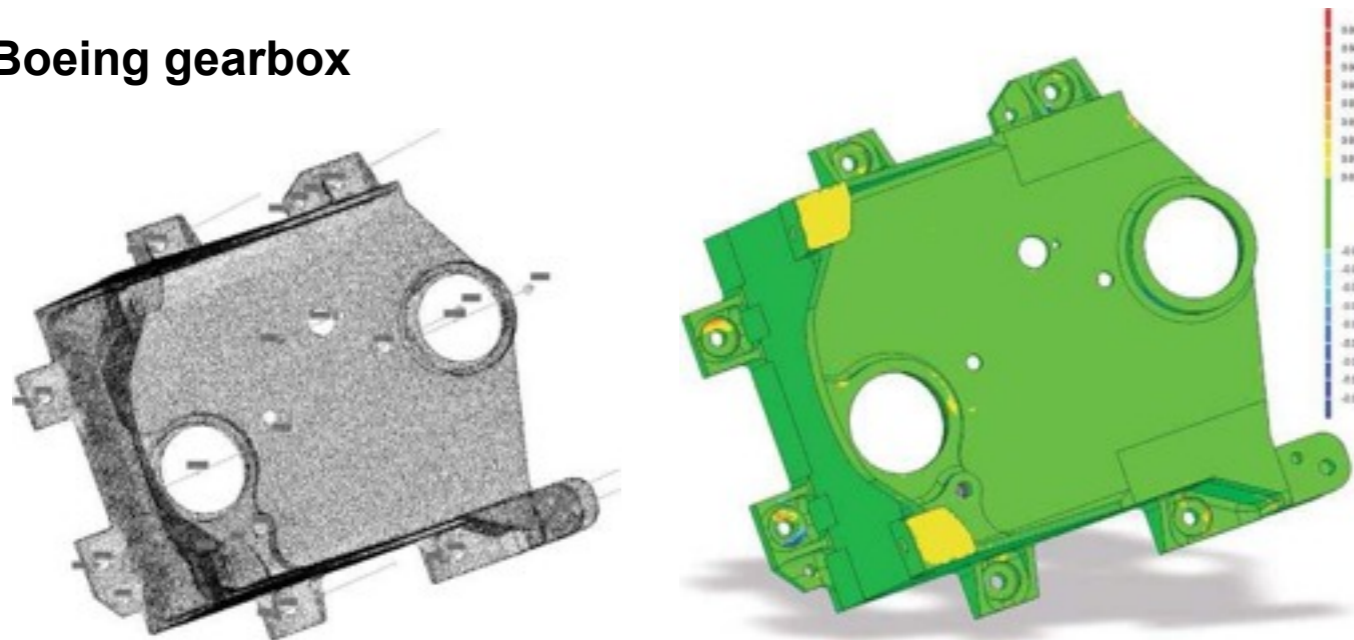


Previous efforts to capture the X-38 prototype with a laser tracker met accuracy requirements, but not the data density needed to recreate surface details for reverse engineering. To overcome these obstacles, NASA used a combination of a white-light scanner and a photogrammetry system.

RE APPLICATIONS

Aerospace (Gearbox-Boeing OEM)

Boeing gearbox



RE Advantages compared to CMMs:
1. High speed
2. No need for highly skilled labour

“Manufacturing has a fire-hose capacity, but quality inspection clamps it down to a drizzle.”

While CMMs are accurate, the high cost, slower speeds and difficulty correlating to 3-D CAD models make them less conducive to adjustments during the manufacturing process. Customers like Boeing are pressured by OEMs as they try to cut inventory, and we need to decrease the time involved in the inspection phase of manufacturing.

RE APPLICATIONS

Medical Devices (Misalignment of teeth- Invisalign)

Three major technologies drive the company's highly customized design, engineering, and manufacturing processes:

1. *high-resolution scanners that digitally measure the dental impression of an individual's upper and lower arches;*
2. *computer graphics technology to compute and visualize the movement of teeth during each treatment stage; and*
3. *advanced digital manufacturing systems such as stereolithography machines to make individualized molds for shaping aligners.*

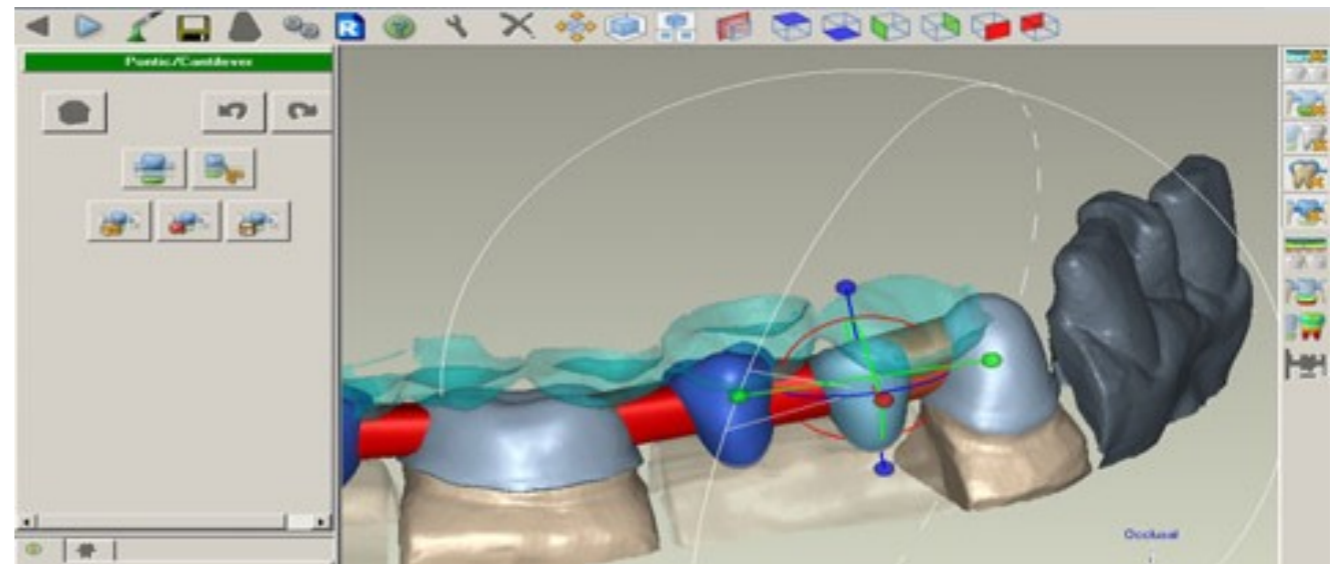


Reverse Engineering

Medical Devices (Dental Frameworks-KaVo Everest)



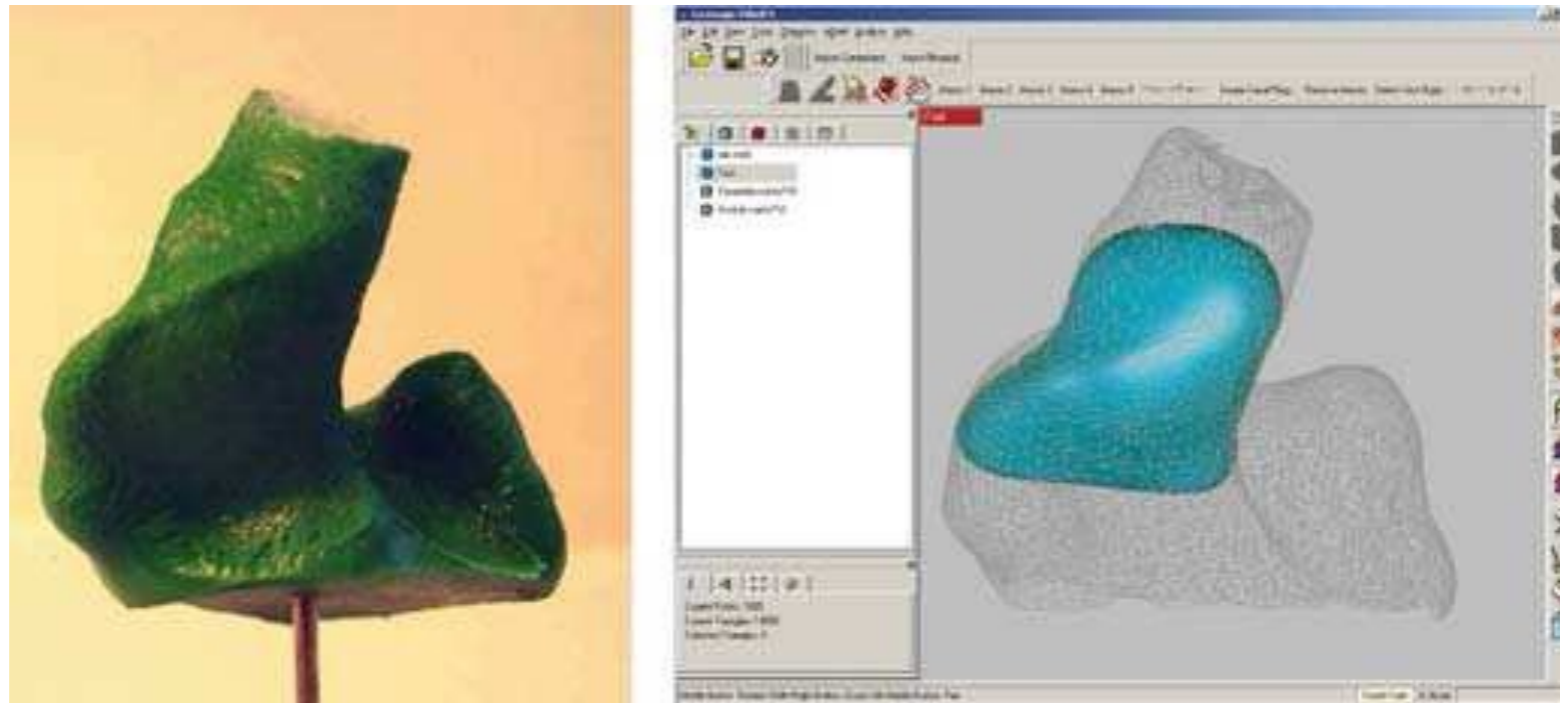
Manufacturing of inlays, onlays, veneers, coping, full crowns and bridge frameworks up to 14 components.



The KaVo Everest system is a complete reverse engineering system that combines all four technological advances described in the introduction: new 3-D scanners, automated reverse engineering software, a fabrication machine that produces one-of-a-kind custom devices in large quantities, and new medical grade fabrication materials.

RE APPLICATIONS

Medical Devices (Hearing Instruments-GN ReSound)



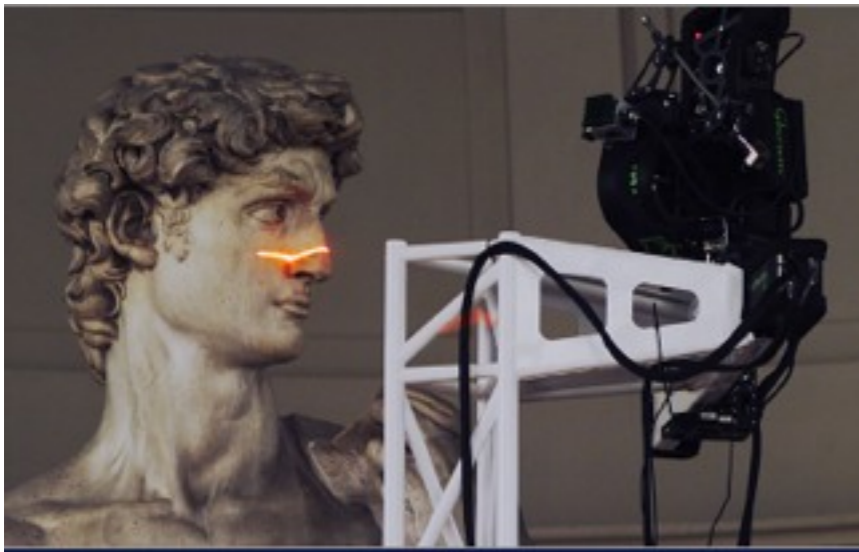
Impression of the inner ear → Scanning → Manufacturing of shells by SLA

Scan files from the impression are loaded into reverse engineering software to design the hearing instrument shell. This is the virtual sculpting step that replaces the old manual processes. The software simulates the traditional process and also provides visual feedback and automation, making the sculpting process easier and reducing human error.

RE APPLICATIONS

Art (Digital Michelangelo Project)

Create a long-term digital archive of important cultural artifacts.



- 480 individually aimed scans
- 2 billion polygons
- 7,000 color images
- 30 nights of scanning
- 22 people



RE APPLICATIONS

Architecture & Construction

When planning a future addition or alteration to a building an initial 3D laser scan survey will accurately document the current layout, this means that any future plans made are based on the exact current status of the building, not on previous plans made which may or may not be correct.



Basic Principles

Close Range Photogrammetry (*inside and outside the camera*)

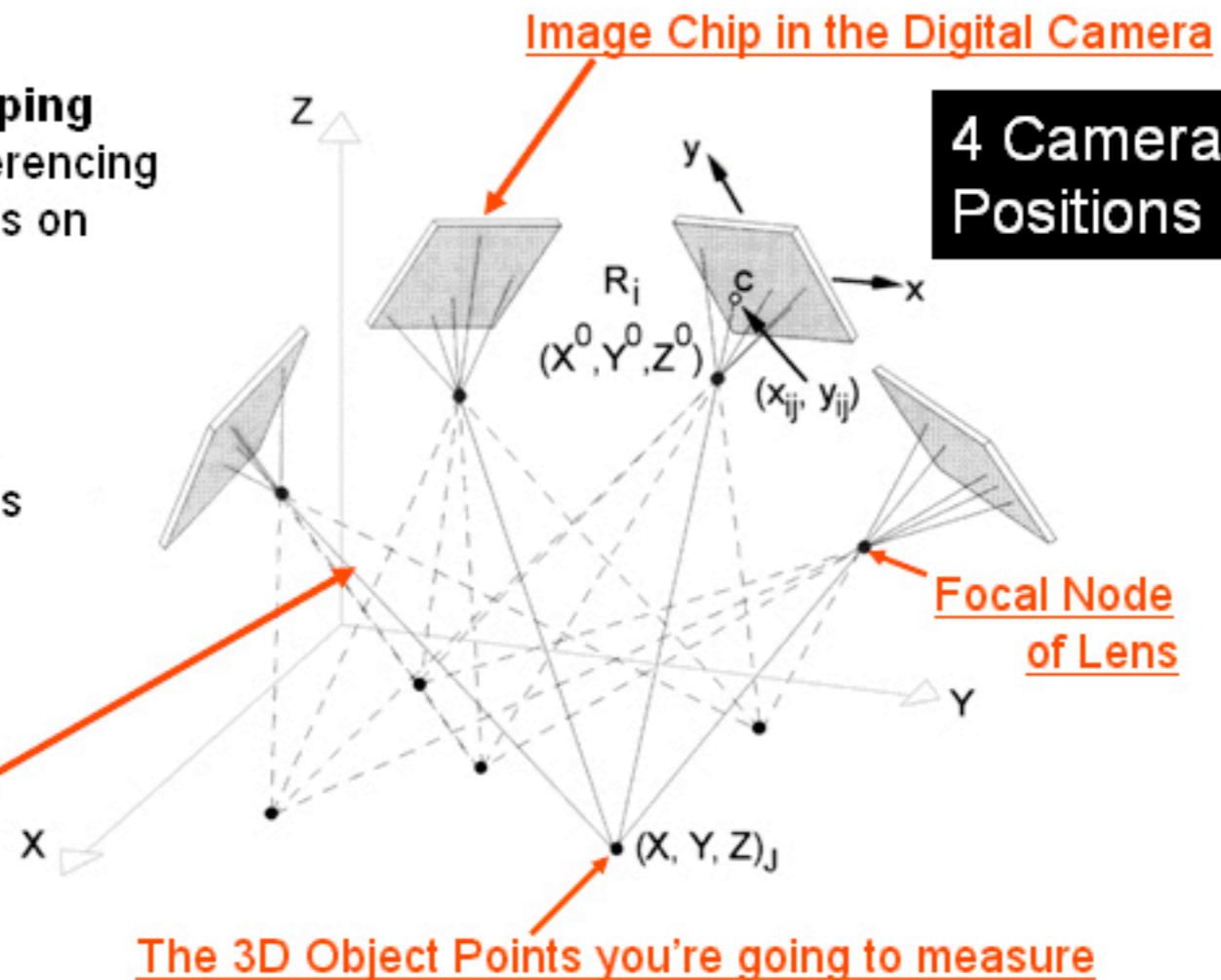
The Process:

1. Record **multiple overlapping images** of the scene by referencing 2D positions of feature points on two or more digital images.

2. The determination of 3D coordinates of these feature points happens via a process called "**Photogrammetric Bundle Triangulation**".

Spatial Intersections of Light Rays

The 3D Object Points you're going to measure



Photogrammetry

Representative companies, list not exhaustive

Photogrammetry

Calibrated
Camera +
Software
(Grade 1)

Geodetic

Calibrated
Camera +
Software
(Grade 2)

Photomodeler

iWitness

Smartphone+
Software

Catch 123D

Smartphone+
Open Source
Software

VisualFSM

Archeos

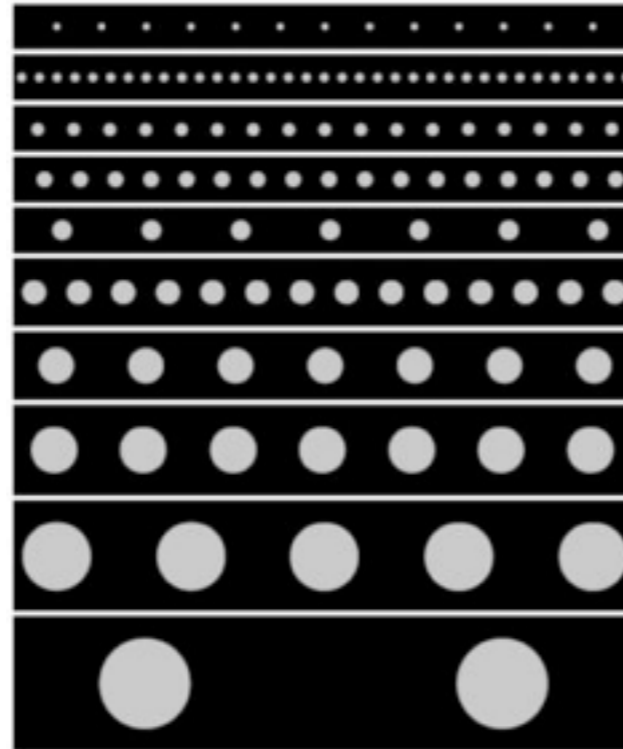
Industrial (High End)



Consumer (Low End)

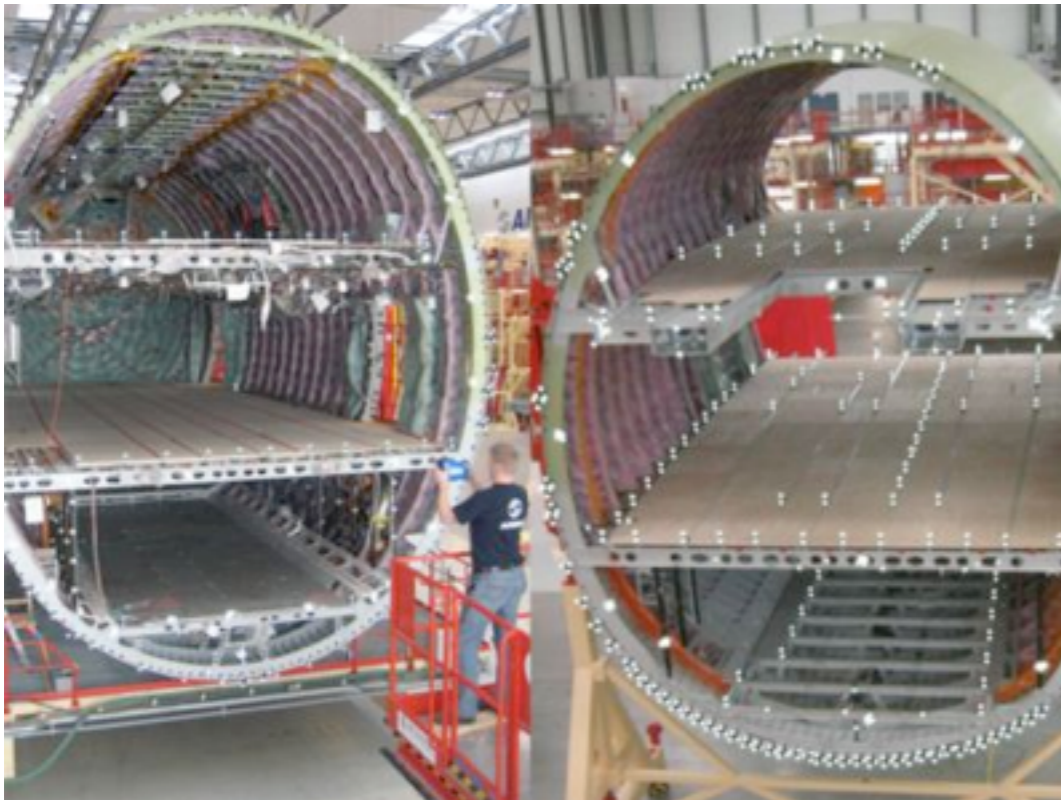
Photogrammetry

Calibrated Camera + Proprietary Software - Grade 1: Geodetic



Photogrammetry

Photogrammetry Aerospace Application (Geodetic)



Photogrammetry

Photogrammetry Automotive Application (Geodetic)



Photogrammetry

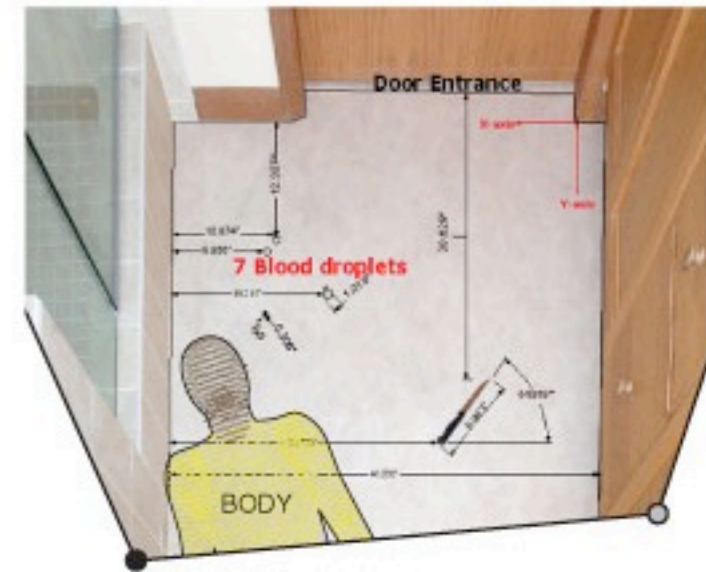
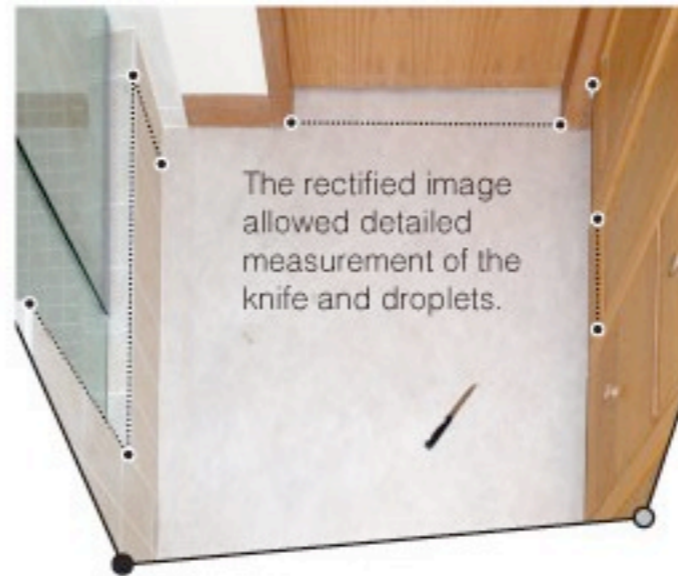
Forensics

3-D CONTROL POINT RECTIFICATION

The exact positions of blood droplets and a knife were called into question after this crime scene photo was taken.



Corners and other points in the photo were digitally marked, allowing a computer to rectify the floor with an accuracy of about 0.1 inch.



STEREO PHOTOGRAMMETRY can be used if a suspect is photographed or captured on video at a known location, as in the demonstration below.

A photographer goes to the scene, takes reference photos from several angles and measures one or more objects. Common points in the images are marked, allowing a computer to triangulate each point in three-dimensional space.

By correlating the suspect's photo with common points in the reference photos, the computer can make an accurate measurement of his height.

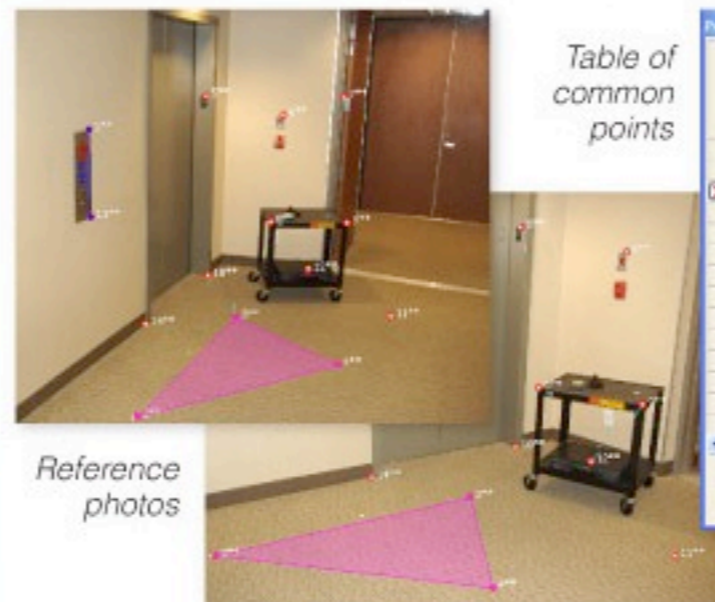
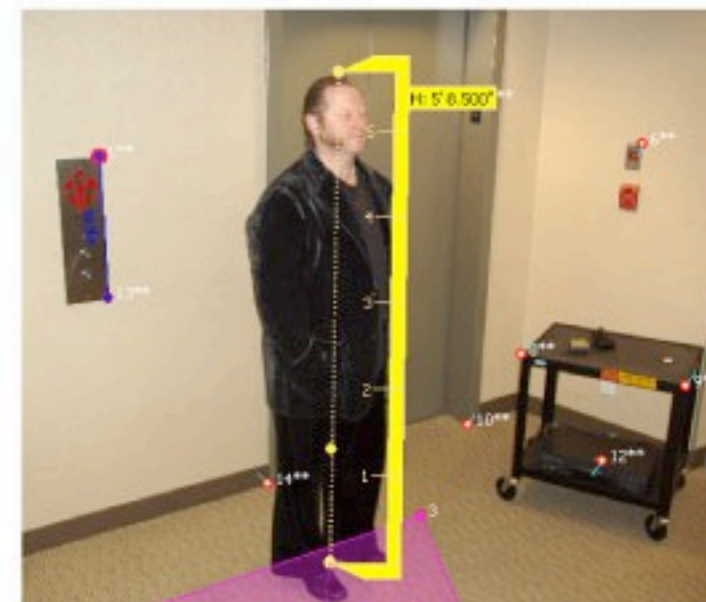


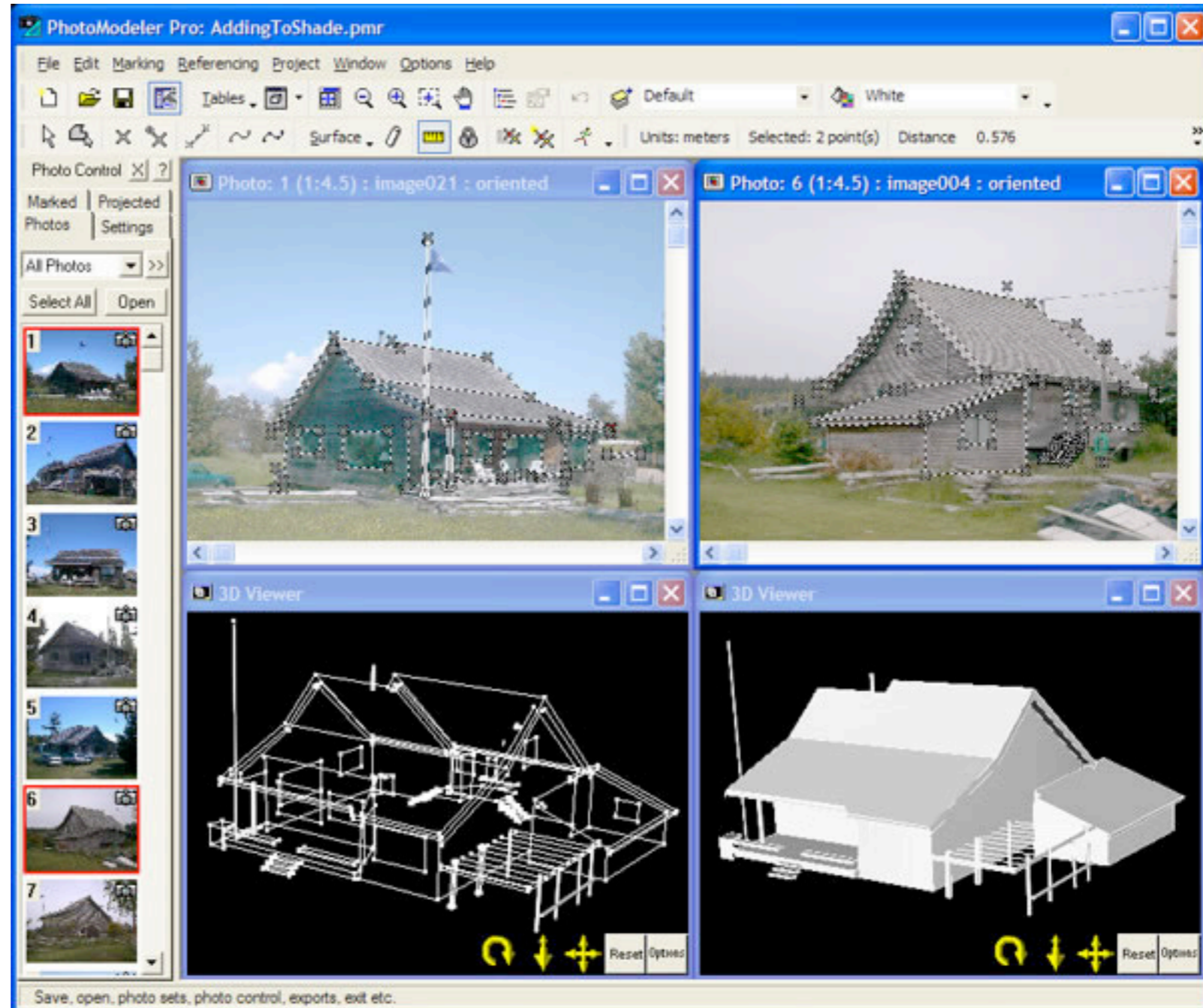
Table of common points

ID	Model	X	Y	Z	error (µm)
1	1	-2.286	1.495	13.965	0.011
2	2	-1.225	3.560	13.252	0.100
3	3	0.664	2.602	14.472	1.420
4	4	2.674	3.195	12.250	0.604
5	5	-0.074	-3.113	16.162	0.235
6	6	2.125	-2.732	16.886	0.385
7	7	3.888	-3.252	17.052	0.434
8	8	1.542	0.292	14.949	0.665
9	9	3.619	0.310	15.108	0.207
10	10	-0.010	1.885	17.259	0.559
11	11	-4.526	2.637	14.786	0.377
12	12	2.589	1.531	15.529	0.137
13	13	-2.262	0.125	11.352	0.086
14	14	-1.495	2.665	13.965	0.397



Photogrammetry

Calibrated Camera + Proprietary Software - Grade 2: Photomodeler



Photomodeler: How it works?

02

LOAD IMAGES INTO PHOTOMODELER SOFTWARE ON YOUR COMPUTER

03

CHOOSE YOUR METHOD

MARKING & REFERENCING

MANUALLY MATCH COMMON FEATURES BETWEEN PHOTOS

OR

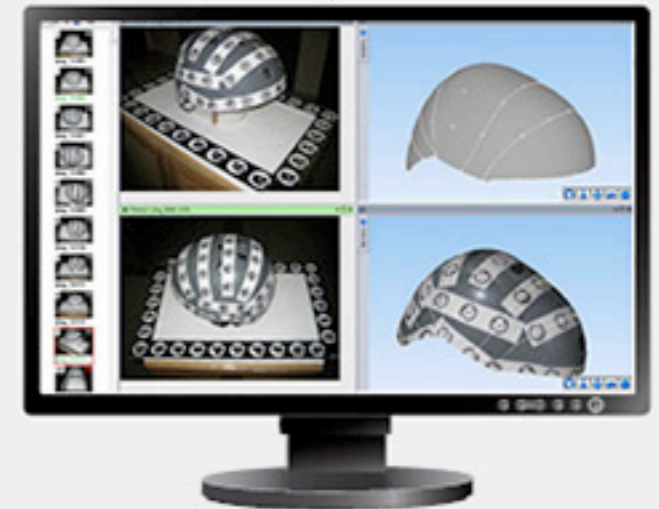
SMARTMATCH / DSM

GENERATE DENSE POINT CLOUDS FROM PAIRS OF PHOTOS

OR

CODED TARGET DETECTION

AUTOMATICALLY MARK CODED TARGETS; MODELS SOLVE QUICKLY AND AUTOMATICALLY

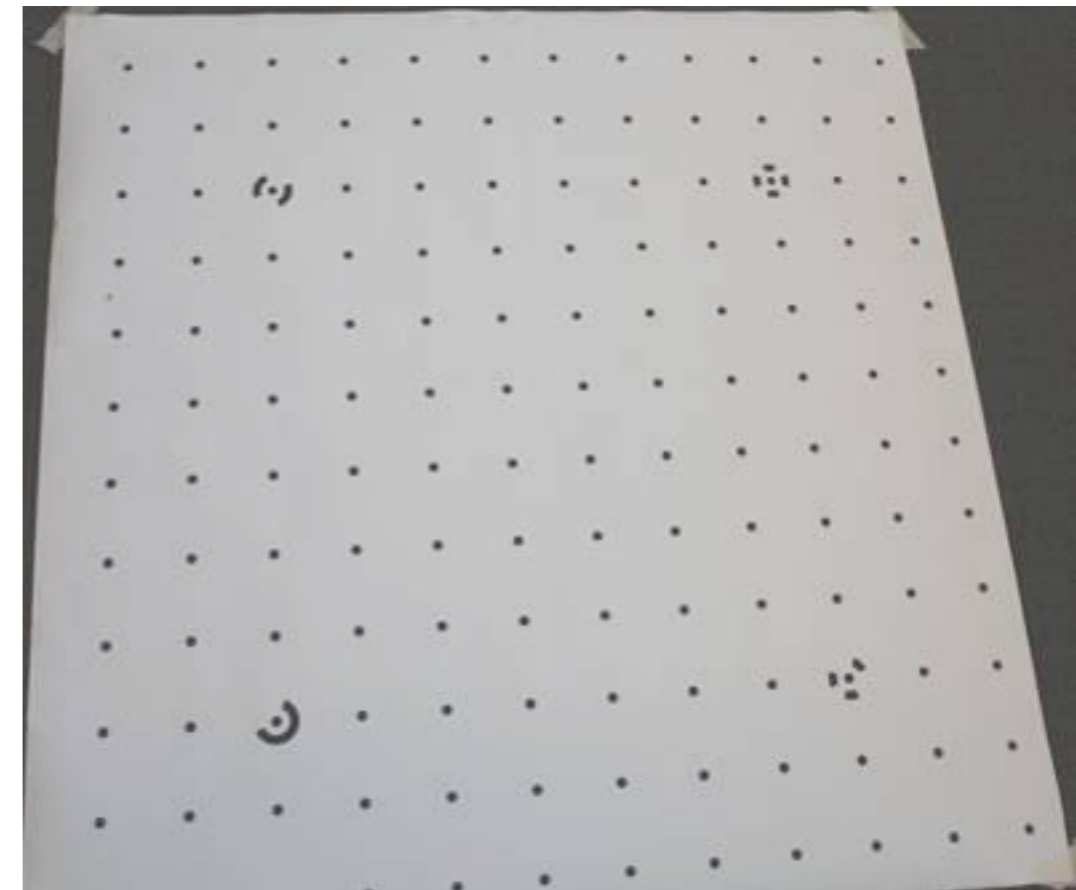
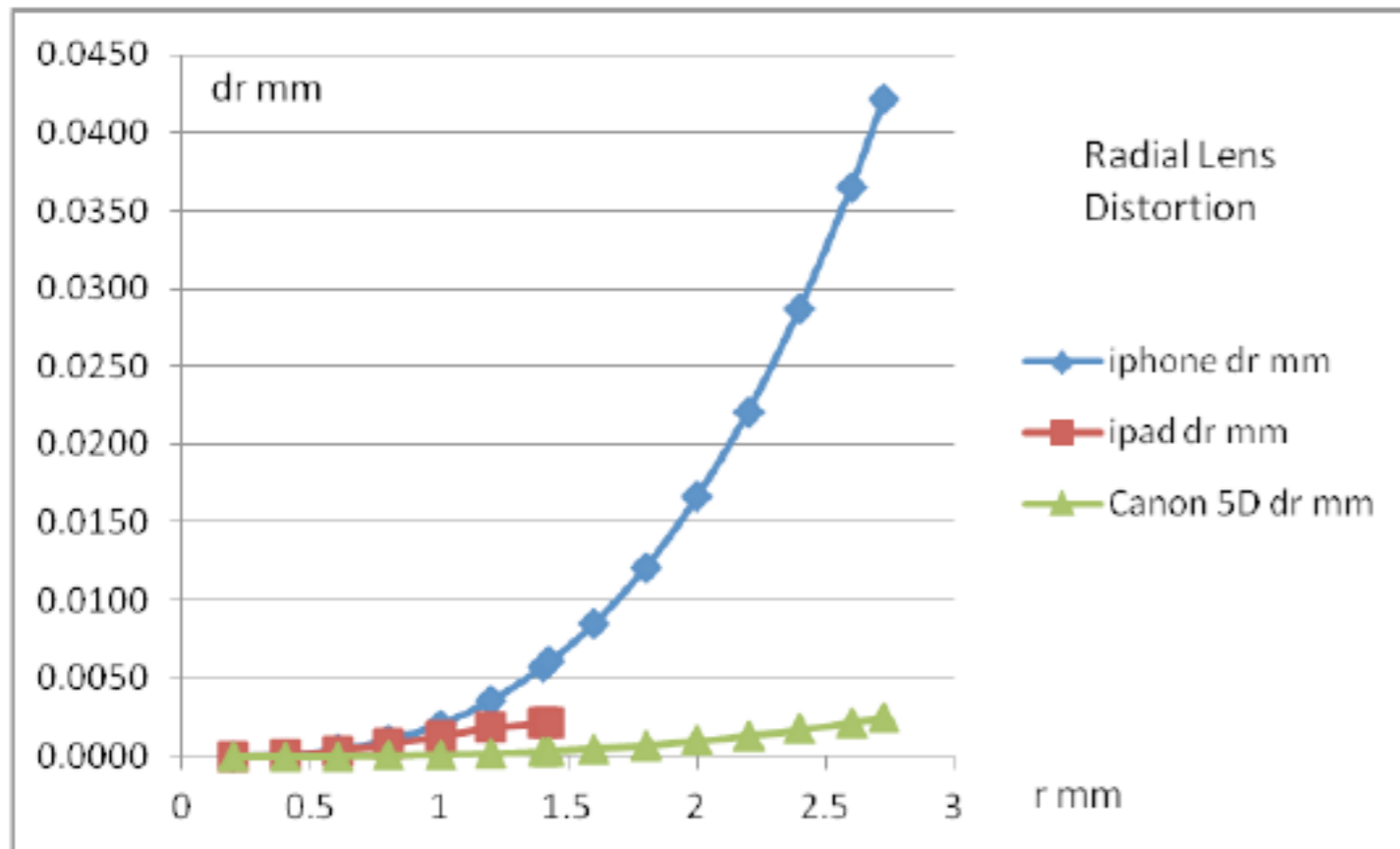


04

REVIEW, VISUALIZE, ANALYZE, MEASURE, EXPORT TO YOUR CAD OR DESIGN SOFTWARE

Photogrammetry

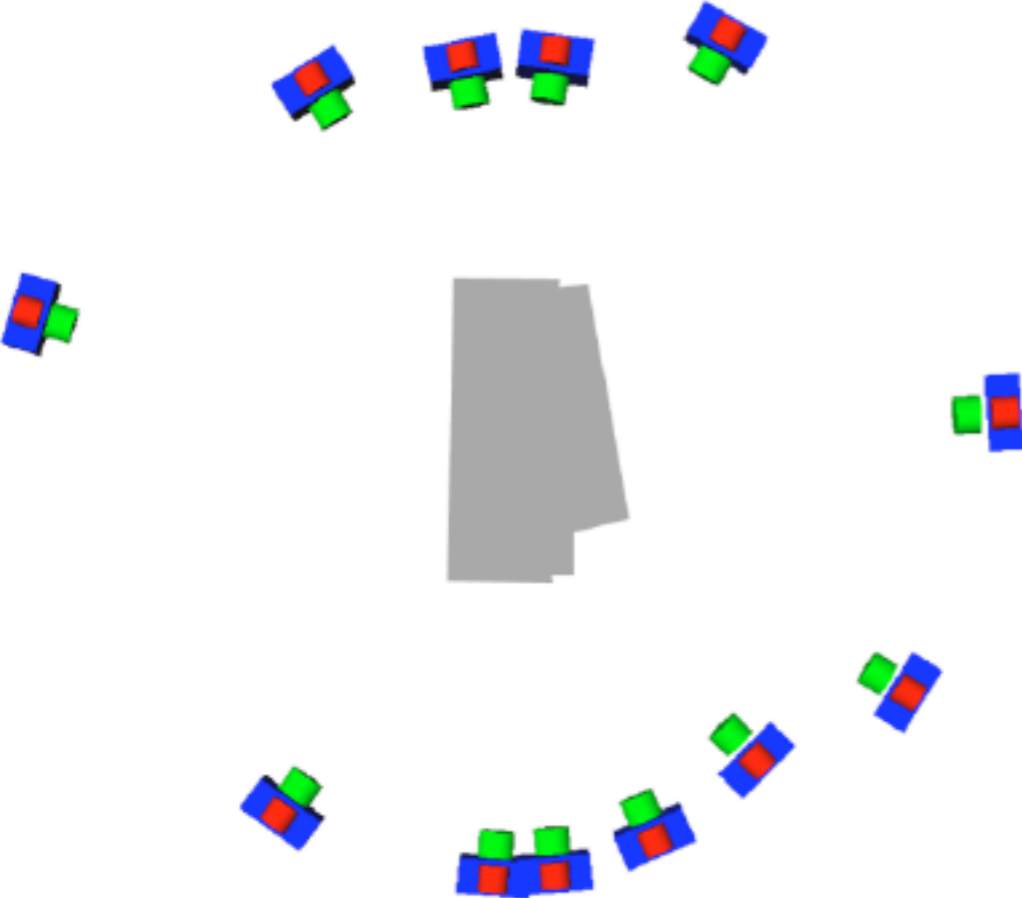
Camera Calibration:



Parameter	Value mm	Standard deviation mm
Focal Length	4.198	0.010
Xp - principal point x	2.195	0.001
Yp - principal point y	1.632	0.004
Fw - CCD format width	4.372	0.001
Fh - CCD format height	3.265	0.001
K1 - radial distortion	0.002078	0.00011
K2 - radial distortion	0.000e+000	0
K3 - radial distortion	0.000e+000	0

Photogrammetry

Photomodeler + iPhone



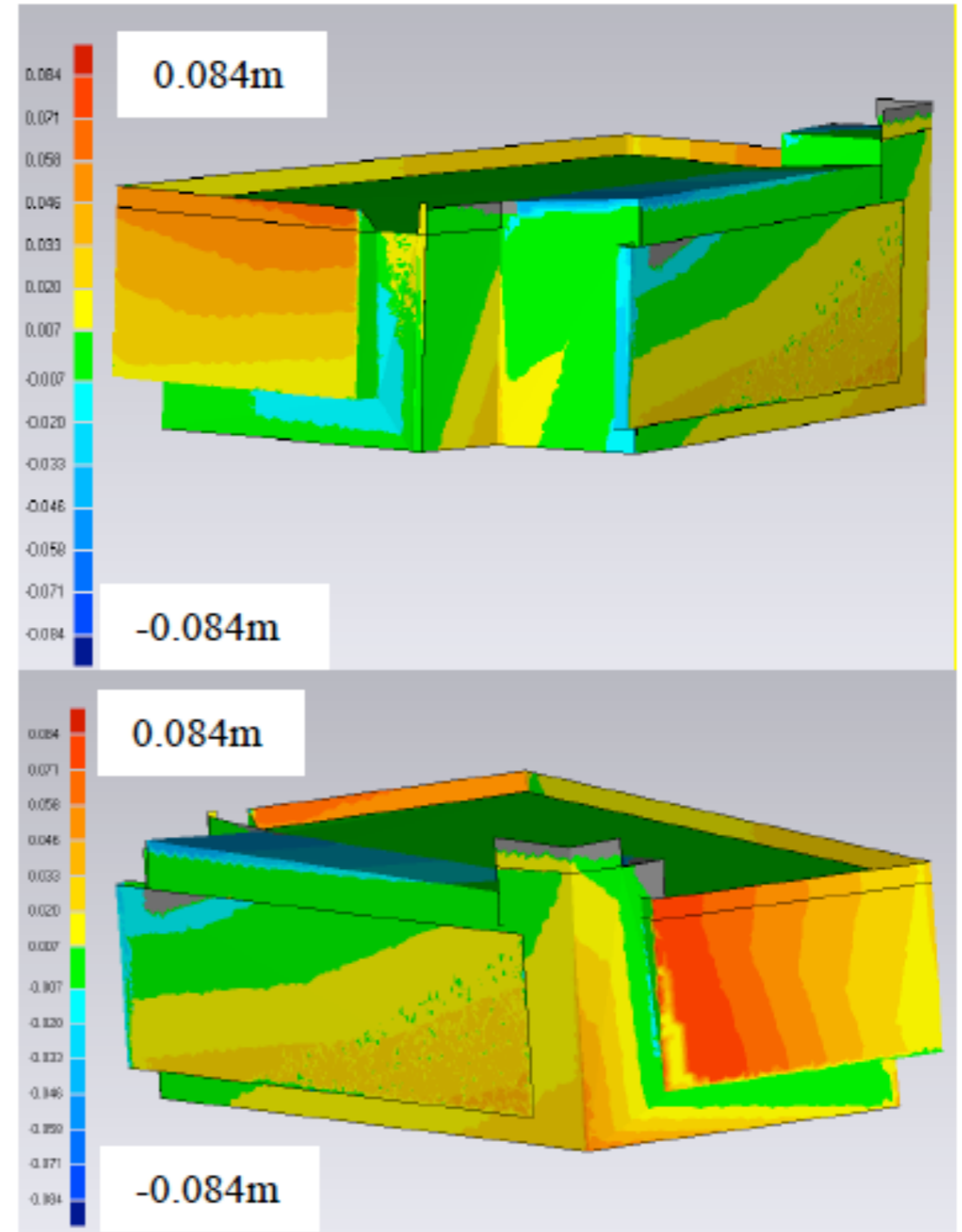
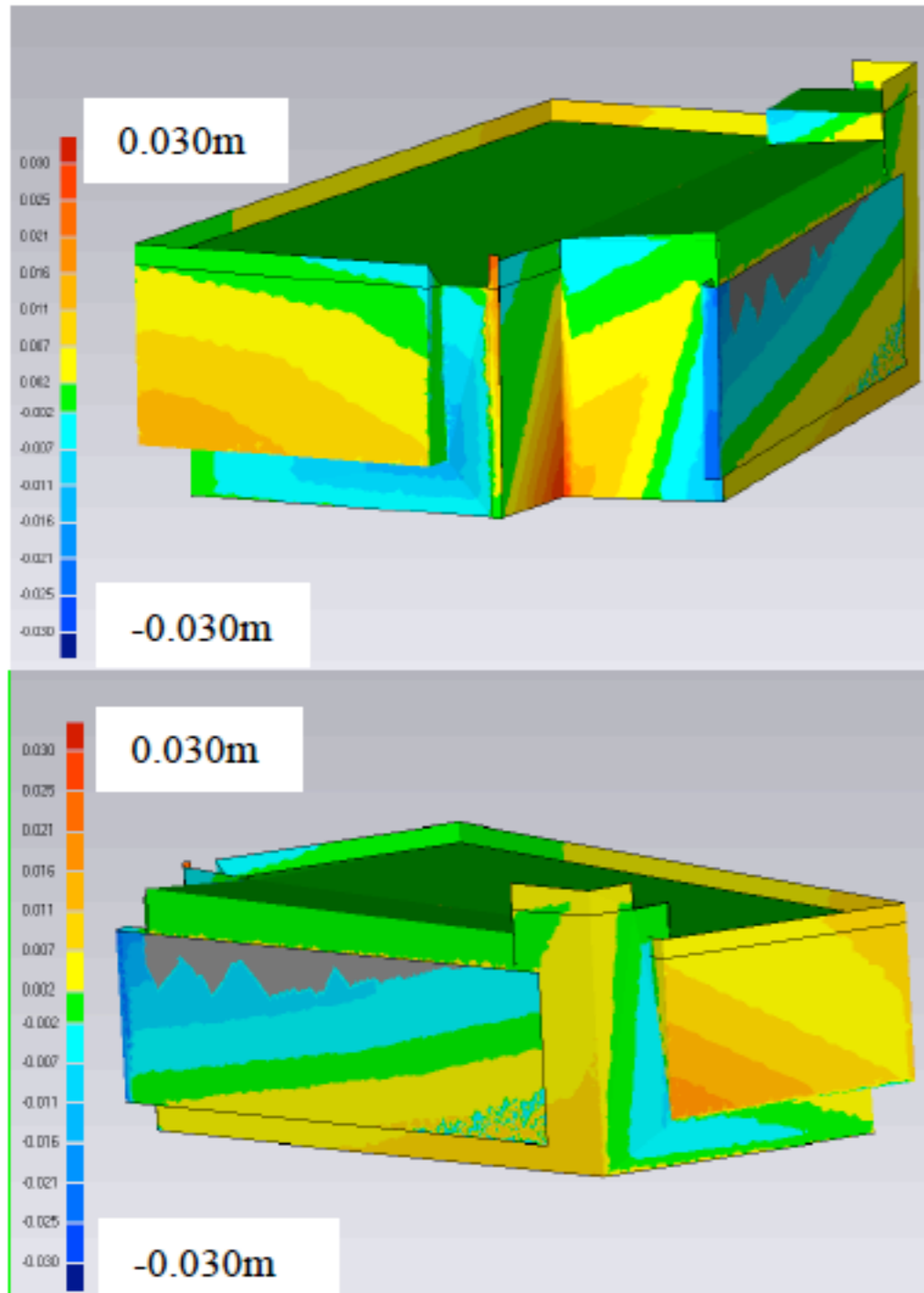
Photogrammetry

Photomodeler + iPhone vs. iPad



Photogrammetry

Photomodeler + iPhone vs. Canon + iPad vs. Canon












Photogrammetry

Catch 123D

AUTODESK 123D Apps Explore Fabricate Learn gallery // 49074 results for 123D Catch

sort by featured ▾

 <p>Theegu Chandra Subramanian 11 MB</p>	 <p>wolf from flotsam colin jones 1.9 MB</p>	 <p>Dannyboy2 Benjamin Rayner 9.0 MB</p>
 <p>pumpkin Jamin Shou 12 MB</p>	 <p>Capture Name Gines Navaro 26 MB</p>	 <p>Statue1 Berkeley Art M... Michael Green 11 MB</p>
 <p>Egyptian hieroglyphics Jasper Renow-Clarke 18 MB</p>	 <p>Assyrian palace relief Jasper Renow-Clarke 9.5 MB</p>	 <p>Carli Terepka james cook (574) 5.2 MB</p>

SEARCH
search for... 🔍

MADE WITH...

- 123D Catch
- 123D Creature
- 123D Design
- 123D Make
- 123D Sculpt

SHOW...

- all models
- free models
- premium models

POPULAR TAGS

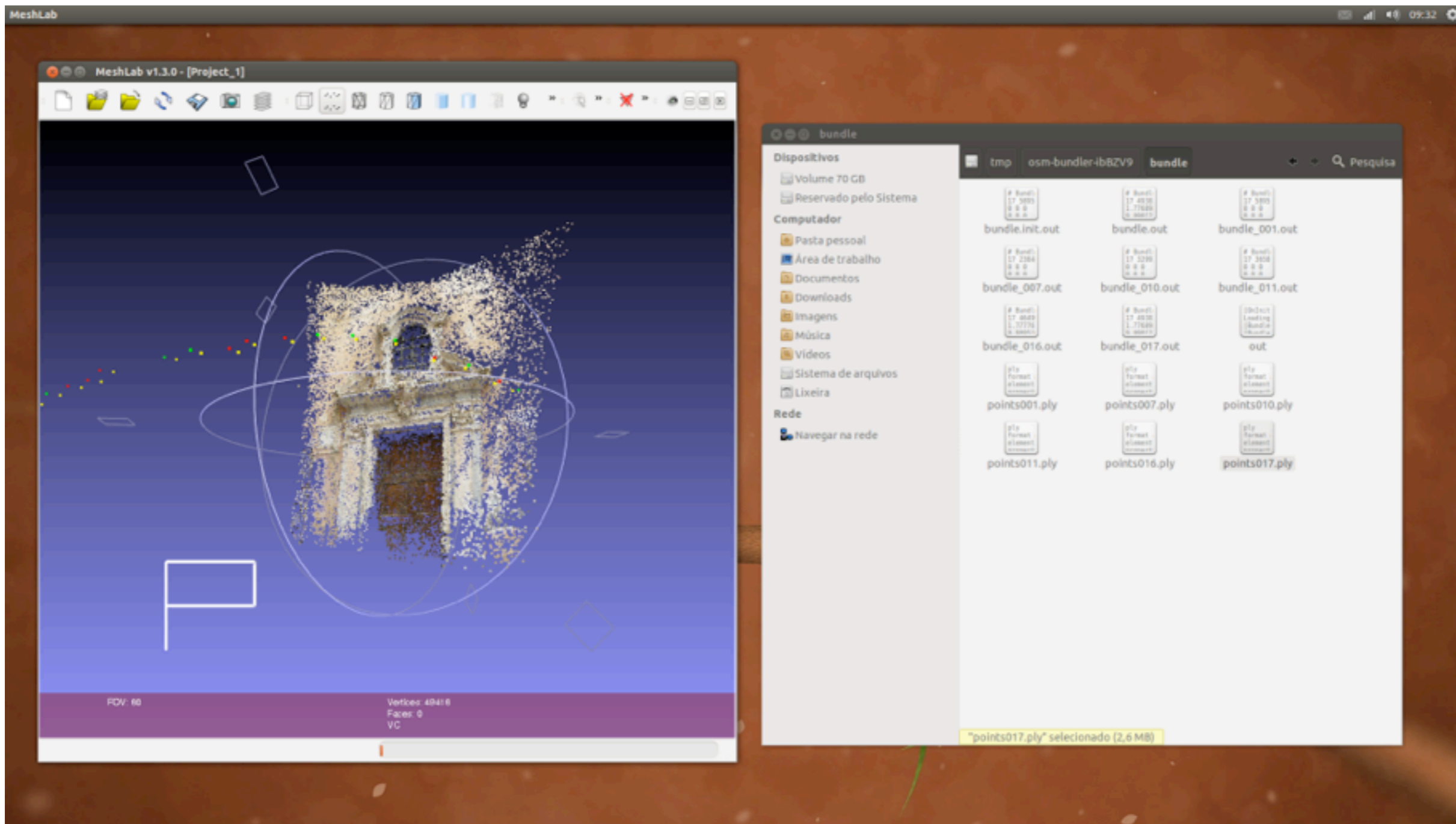
- collection
- capture
- name
- characters
- architecture
- animals
- food
- electronics

Catch 123D: Disadvantages (wedidstuff blog)

- **Photo limits:** the iphone app seems to allow a maximum of 40 images. (the non-mobile version for Windows is limited to 70.) There's no technical reason why there should be any limit. Plus, capturing larger 3d scenes like detailed environments will require more than 70 pictures pretty quickly.
- **Down-rezed photos:** pretty sure in order to speed the photo's "ascent" into the cloud, the pictures are scaled down limiting their detail and use as a high-rez texture during the projection phase.
- **Limited texture map size:** in my few tests, the texture maps returned from 123D Catch's automatic processes are returned at a given size...you have no control over how big a map you want.
- **Total blackbox:** no controls to guide the 3D reconstruction or manipulate the results. This process is pretty intricate and having no controls seems a little scary.
- **Lightweight output by design:** Autodesk's 123D line (Catch included) isn't meant to be a professional solution: this is meant to 3D-ize trinkets and give you something to 3D print with, not create high-rez models.

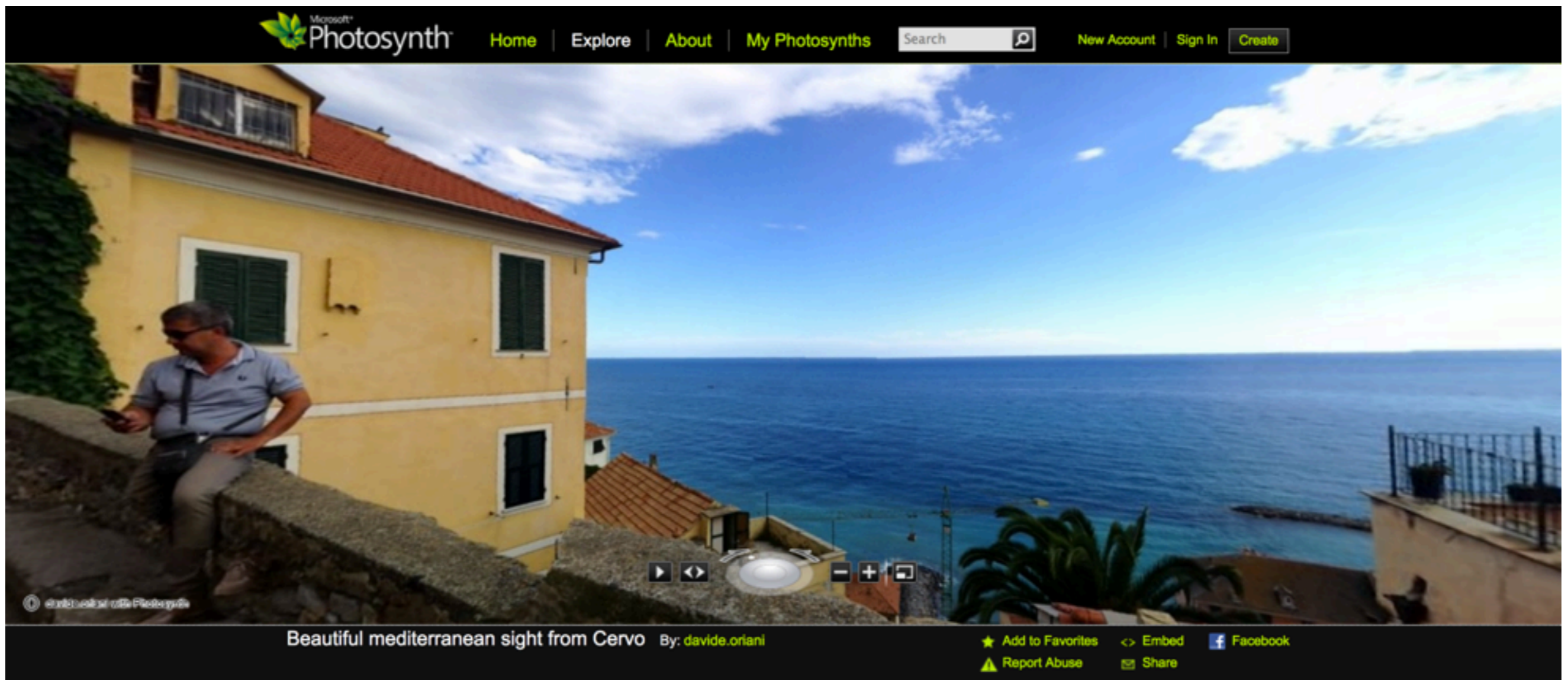
Photogrammetry

Open Source Alternatives: Archeos



Photogrammetry

Panorama Stitching: Photosynth (Microsoft)



<http://photosynth.net/view.aspx?cid=a16ca1d6-503b-46f0-87b7-79677121be69>

CAD\CAE Software

Representative companies, list not exhaustive

3D CAD Software

CAD \ CAE
\CAM

Catia

NX

Creo

CAD \ CAE

Solidworks
(Dassault)

Autodesk

CAD
(Low cost)

TinkerCAD
(Autodesk)

CAD
(Free)

FreeCAD

Google
Sketchup

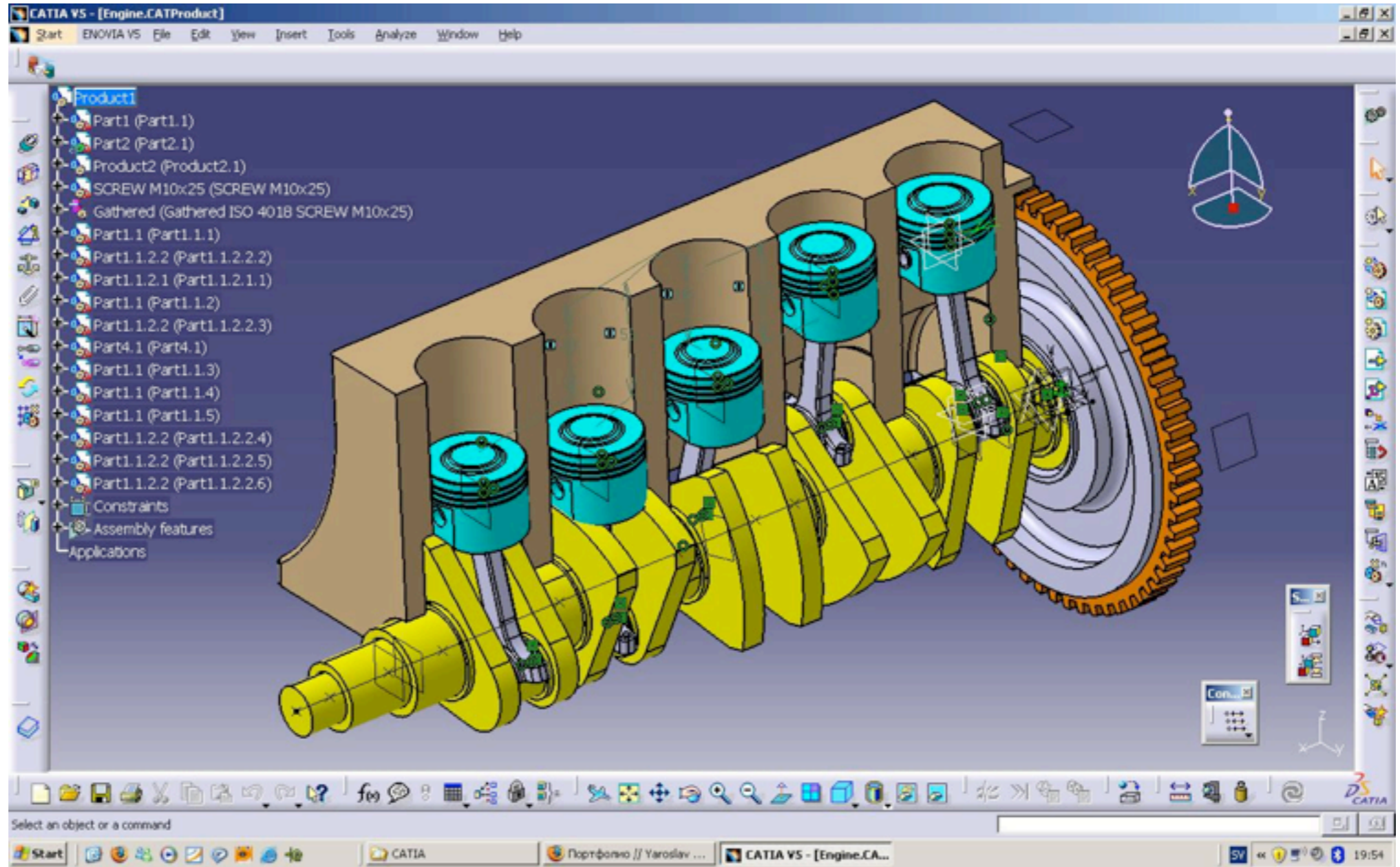
Industrial (High End)



Consumer (Low End)

CAD Software

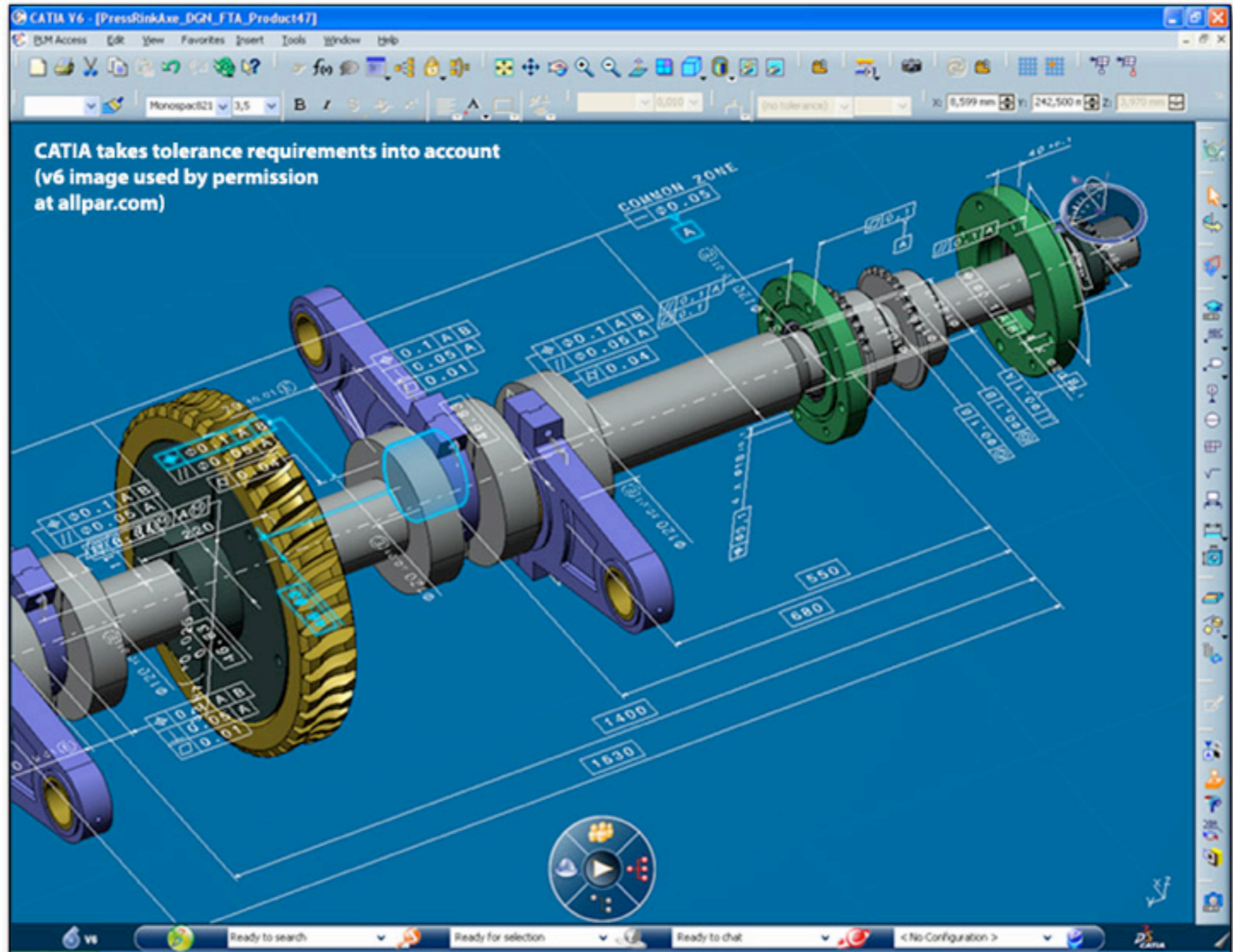
Catia V5



<http://www.youtube.com/watch?v=jEx0emcnuj4>

CAD Software

Catia V5



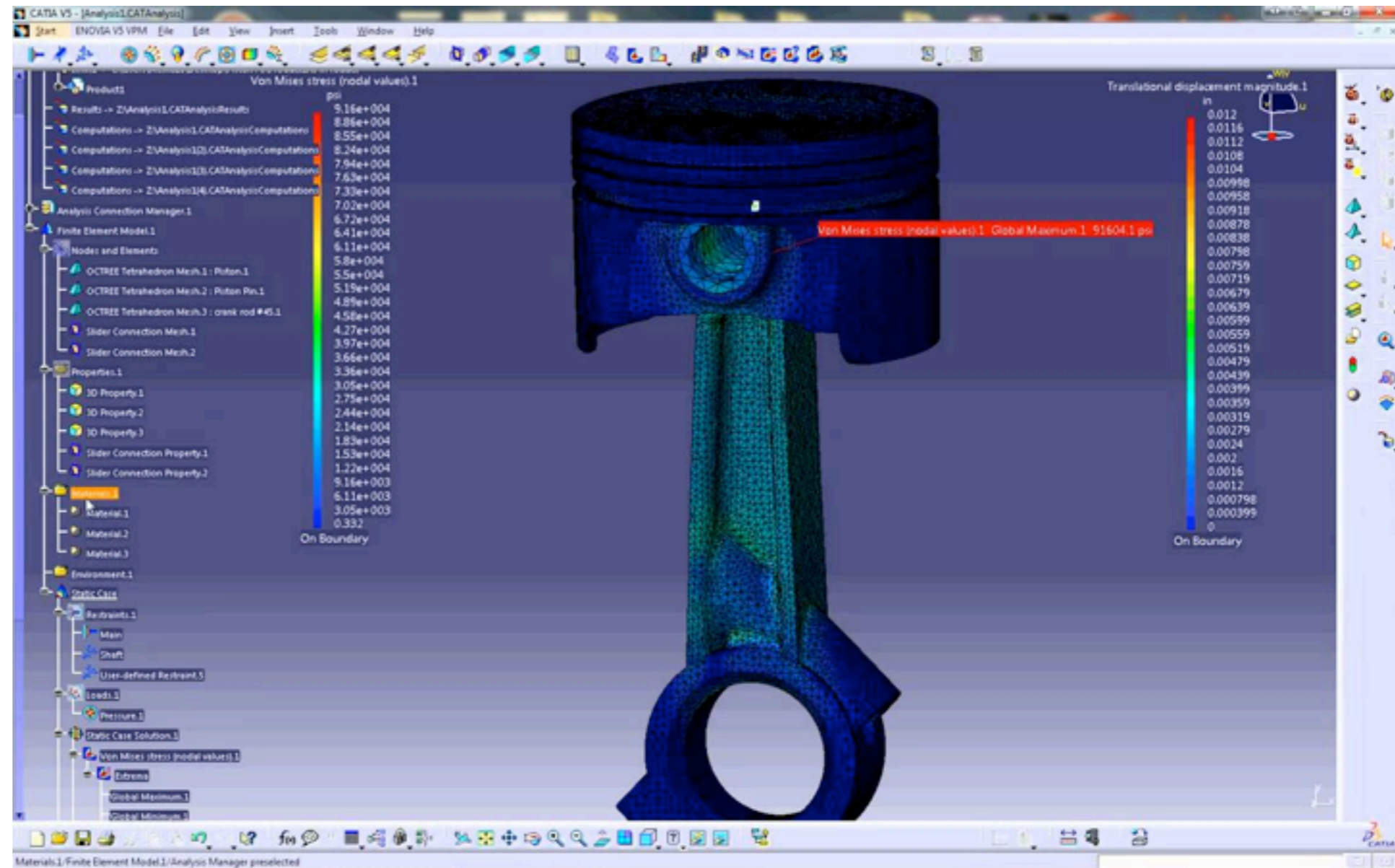
CAD Software

Catia V5

Computer Aided Engineering:

Finite Element Analysis
Thermal Analysis
Simulations

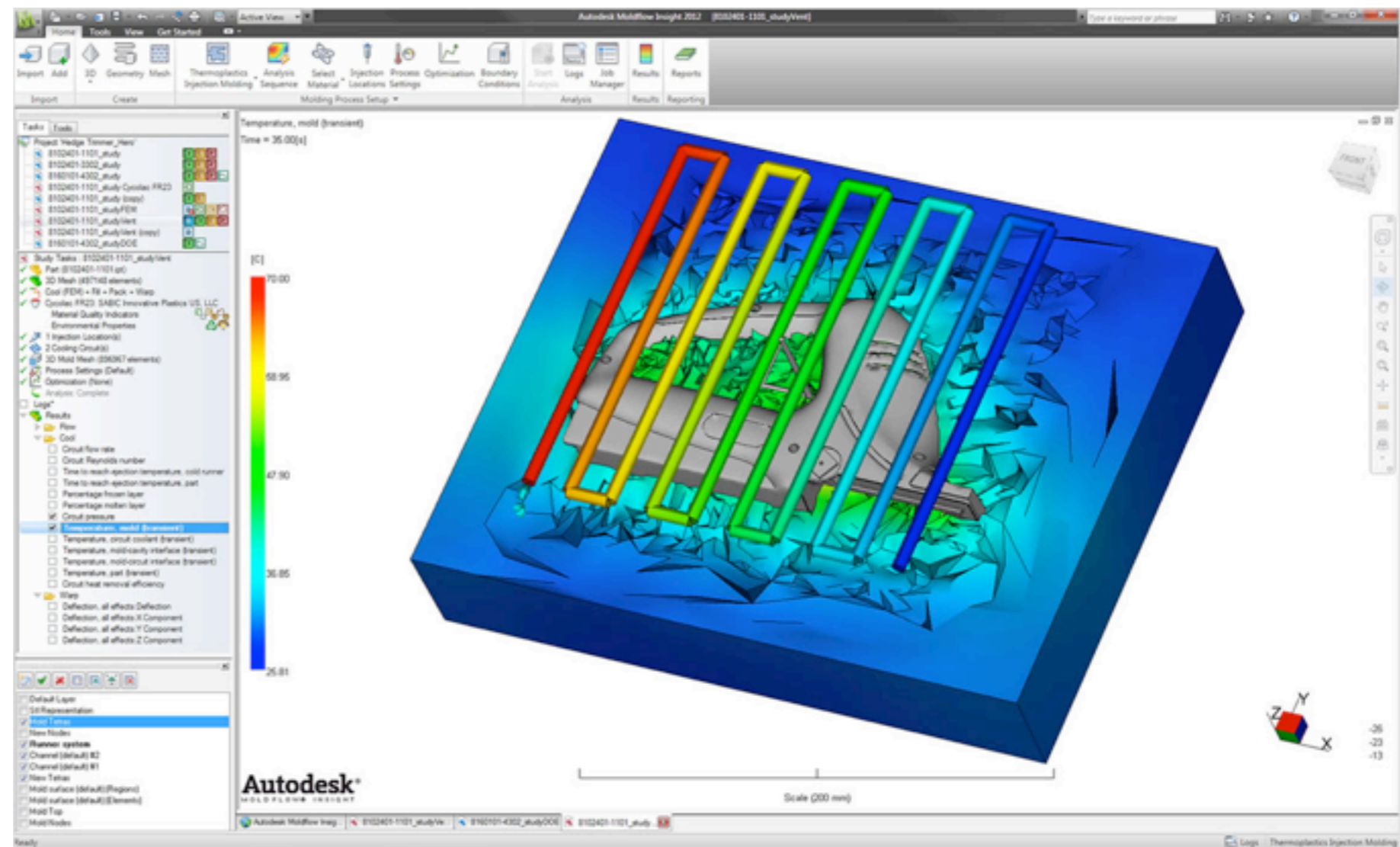
Design Optimization
Sheet Metal Design
Mold Design



CAD Software

Autodesk (Moldflow)

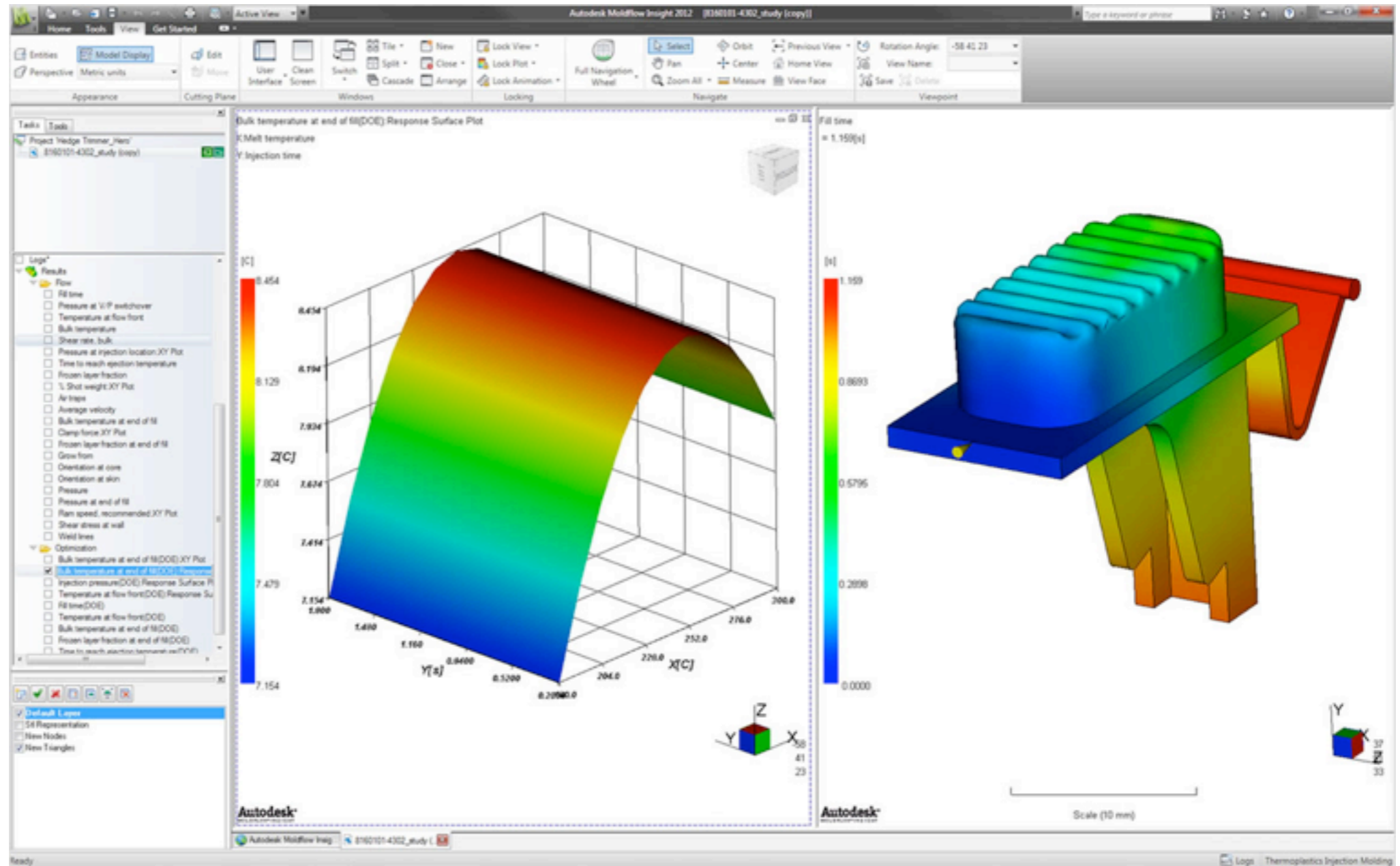
Injection Molding Simulation



CAD Software

Autodesk (Moldflow)

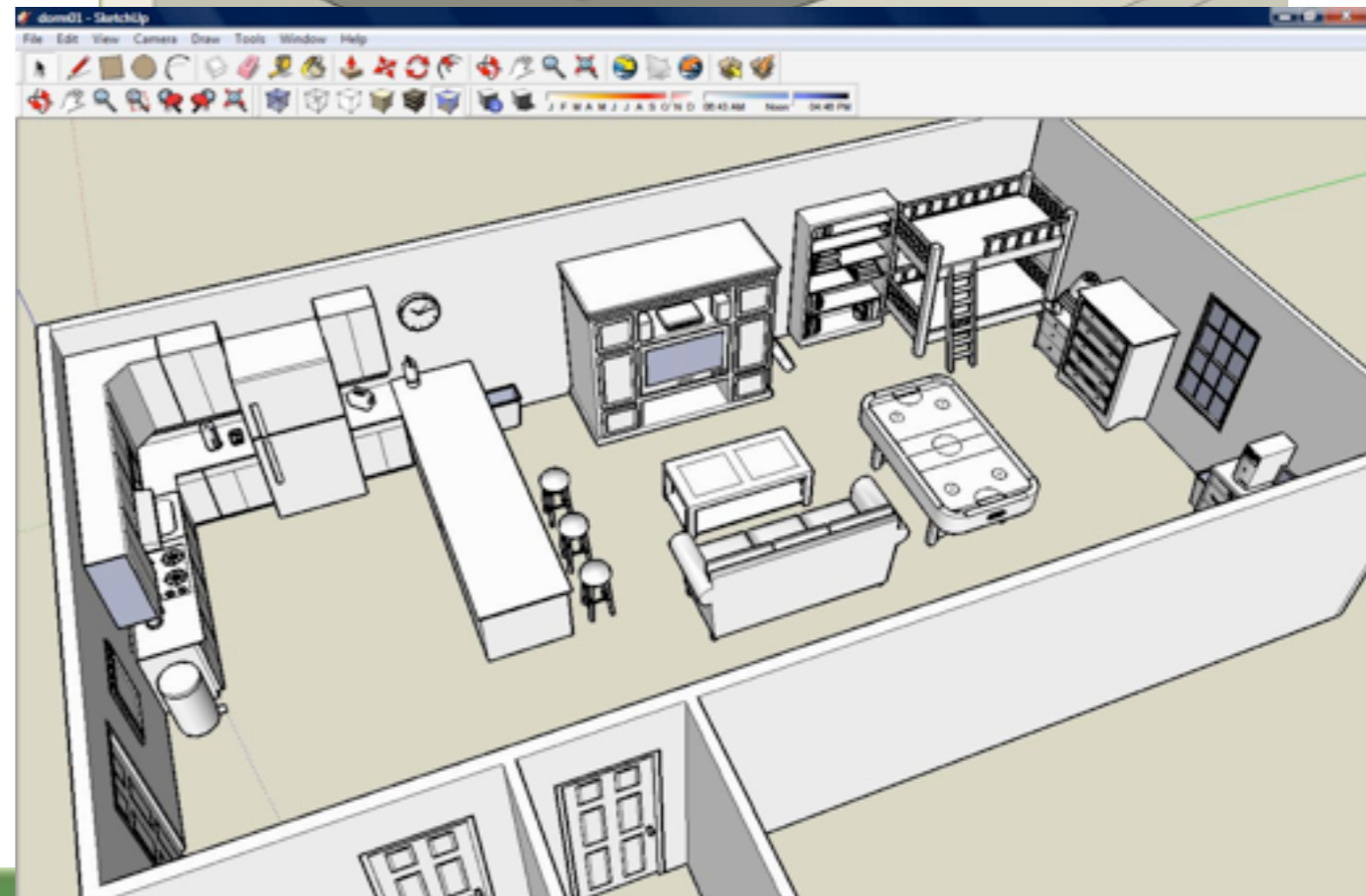
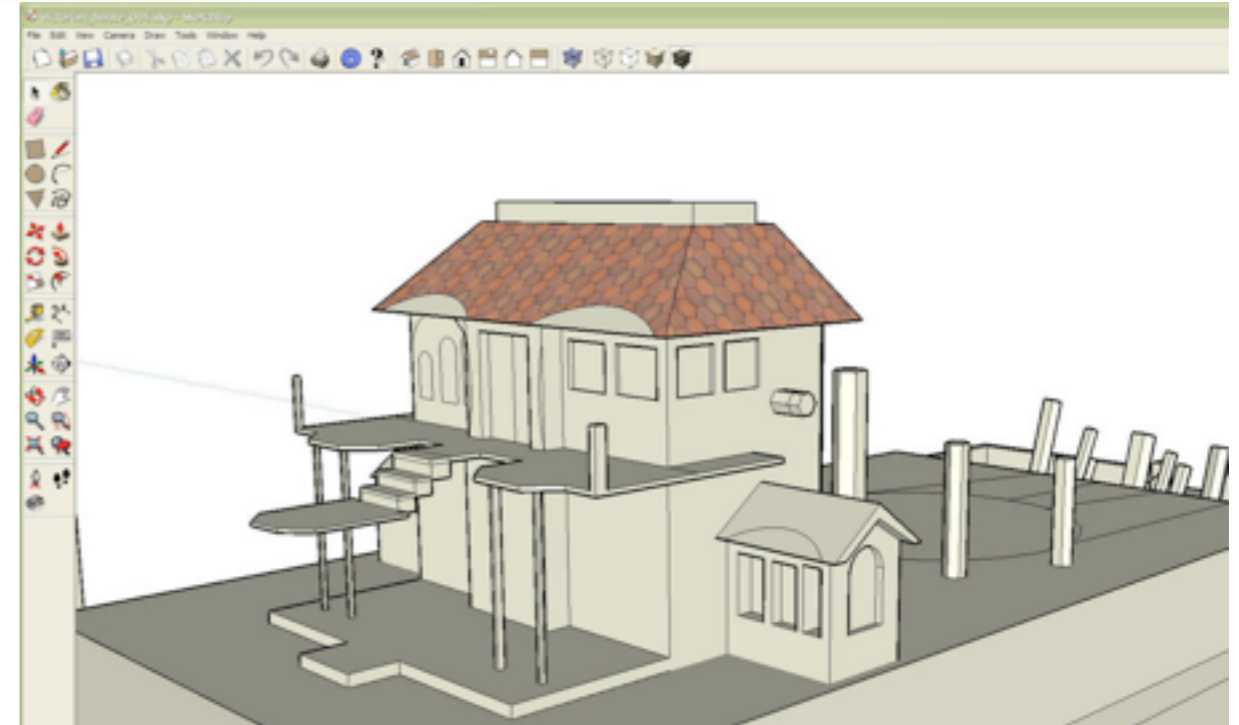
Design Optimization



CAD Software

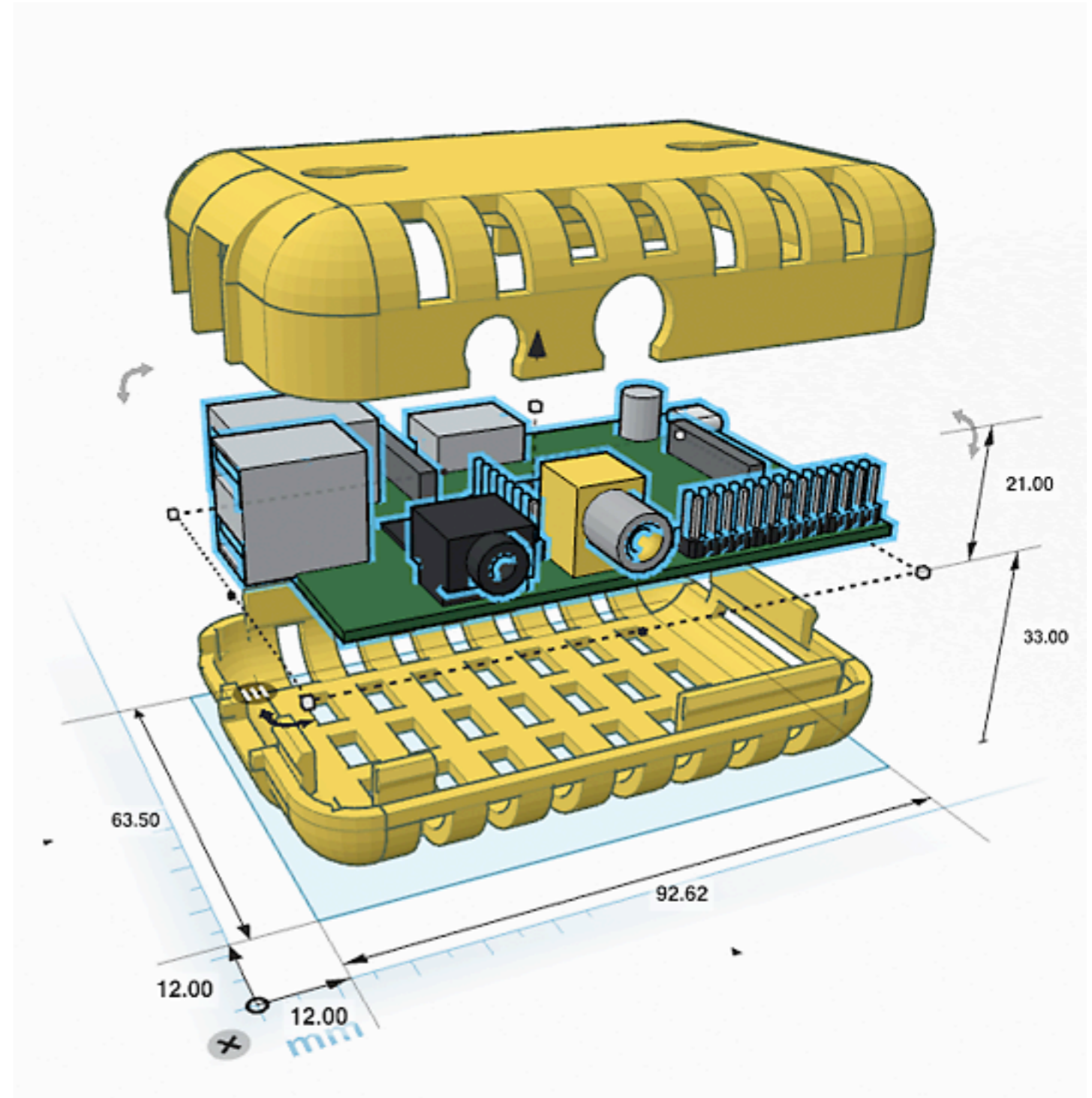
Google Sketchup

<http://www.sketchup.com/>



TinkerCAD

<https://tinkercad.com/about/>

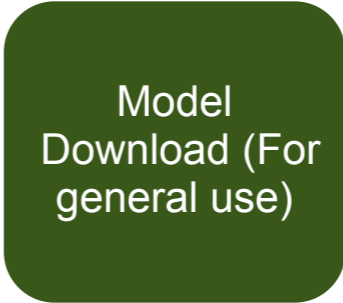
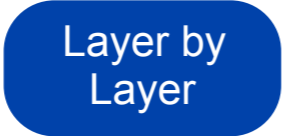


3D Printing Communities

Onat Ekinci

3D Printing Communities

Representative companies, list not exhaustive



3D Printing Communities

Cubify

3D printing services +
you can download
some of the models.

<http://cubify.com/>

The screenshot shows the Cubify website homepage. At the top left is the Cubify logo with '3D SYSTEMS' underneath. To the right is a navigation menu with links for 'Shop', '3D Printers', 'Cloud printing', 'Create', 'How it works', and 'Community'. Further right are links for 'Log in', 'Sign up', and 'My Cart (0)', along with a search bar. Below the navigation is the main heading 'Cubify: your home for all things 3D'. Three main promotional tiles are displayed: 'SHOP' featuring various 3D printed objects, '3D PRINT at home' showing a 3D printer, and 'NEW: Cubify Sculpt' featuring a computer monitor displaying a 3D shoe model. Below these tiles is a section titled 'FEATURED ON CUBIFY' with four featured items: 'Leaf Shoe' (FREE), '3DMe App' (\$64.99), 'Cloud printing: Cubify Ceramix' (with a 'Learn more' link), and 'SPARKLII'.

3D Printing Communities

Cubify

Free files...

The screenshot shows the Cubify website interface. At the top, there is a navigation bar with the Cubify logo (BOSYSTEMS) and a menu with items: Shop, 3D Printers, Cloud printing, Create, How it works, and Community. A search bar is located on the right side of the navigation bar. Below the navigation bar, there are several category tabs: ALL, ACCESSORIES, ART & COLLECTIBLES, FASHION, HOME, JEWELRY, LIGHTING, MUSIC, and TOYS & GAMES. The main content area displays a grid of 3D printed models, each with a heart icon, a name, and a 'Free file' link. The models include: Sunflower TDW_2..., Brainiac TDW_1924, FatGator TDW_1913, Smashface TDW_..., PenguinCat TDW_..., and Sad Doggy TDW_... Below the grid, there are three more items: Line Ring, heart cookie cutter, and DesignerfredTOP. On the right side, there is a 'SHOP BY' section with 'ARTISTS' and 'PRICE' filters. The 'ARTISTS' section lists: cubify (95), marcellerice (26), METMuseum (21), DesignerFred (9), and jannekyttanen (8). The 'PRICE' section lists: All, \$0 - \$1, \$1.01 - \$10, \$10.01 - \$20, \$20.01 - \$50, and More than \$50. At the bottom right, there is a 'YOU MIGHT ALSO LIKE' section with several small images of 3D printed objects.

3D Printing Communities

Shapeways

Designer files...(you can't download the models, they will print them for you).

<http://www.shapeways.com/jewelry?li=nav>

shapeways* Shop Make + Sell Search Join Sign in

Art Fashion Home Gadgets Games Jewelry Maker/DIY Miniatures Make Your Own Feed Shops Gifts Blog

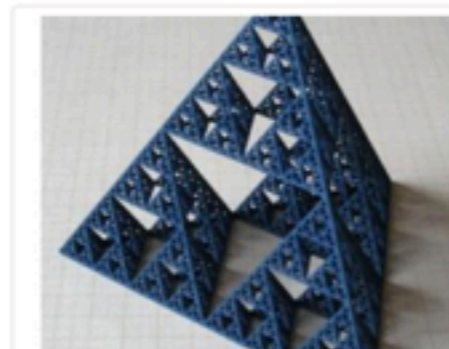
Art > Mathematical Art

Thought you would never be able to see möbius strips and klein bottles in the real world? Think again.

Shop for:
[Mathematical Art](#) [Memes](#) [Sculptures](#)

Klein Bottle Opener

Shapeways Picks



Sierpinski tetrahedron
\$48.94 by Wahtah



Triple gear
\$40.00 by henryseg



SILVER BUCKY
Silver Bucky
\$65.00 by vertigopolka

Best Sellers

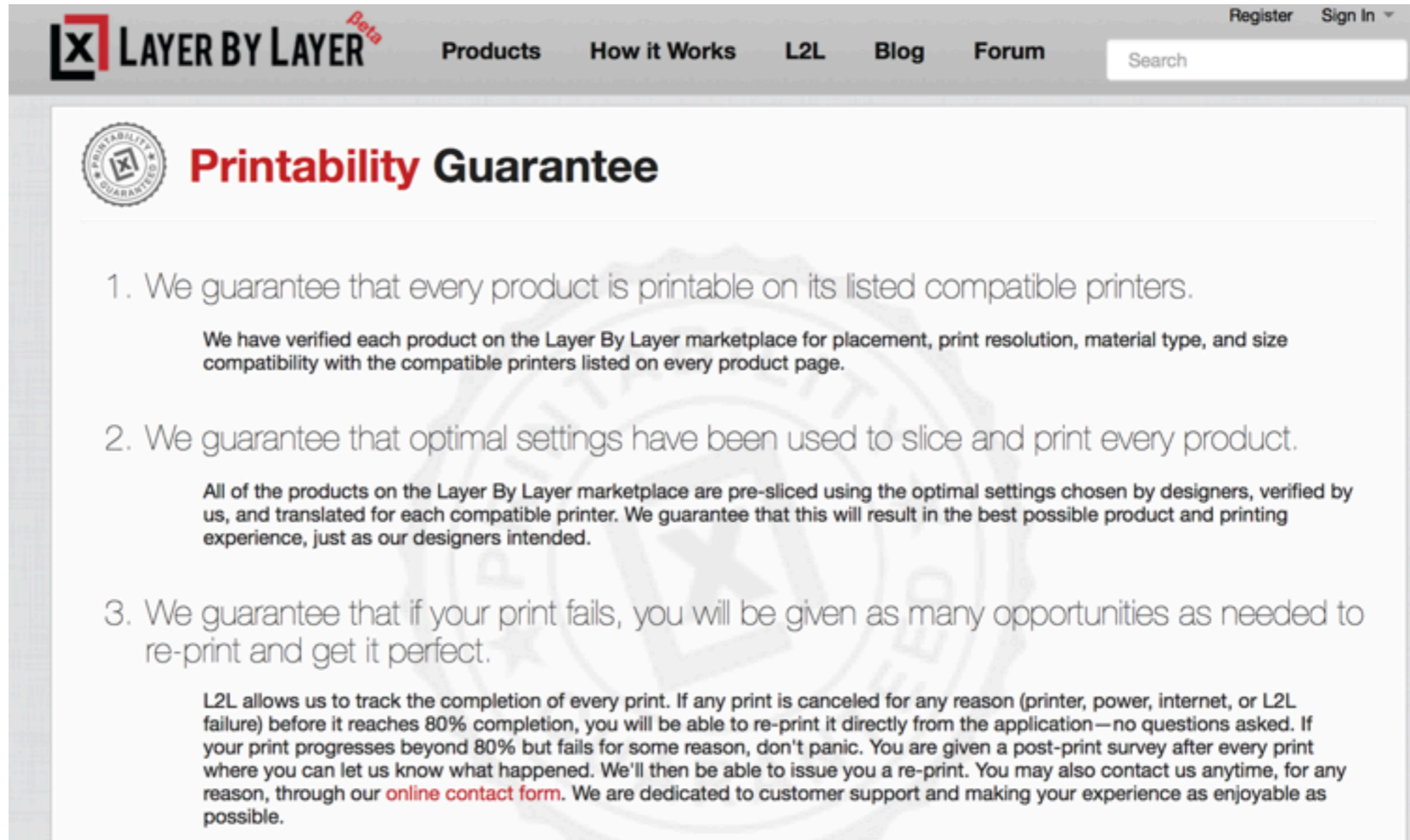


3D Printing Communities

Layer by Layer

(you can't download the models, they will print them for you).

[https://
www.layerbylayer.com
/guarantee](https://www.layerbylayer.com/guarantee)



The screenshot shows the top navigation bar of the Layer By Layer website. The logo is 'LAYER BY LAYER' with a red 'X' icon and a 'Beta' tag. Navigation links include 'Products', 'How it Works', 'L2L', 'Blog', and 'Forum'. There are 'Register' and 'Sign In' links on the right, and a search bar.

The main content area features a circular seal with 'PRINTABILITY GUARANTEE' and the text 'Printability Guarantee' in large red and black font. Below this, there are three numbered points:

1. We guarantee that every product is printable on its listed compatible printers.
We have verified each product on the Layer By Layer marketplace for placement, print resolution, material type, and size compatibility with the compatible printers listed on every product page.
2. We guarantee that optimal settings have been used to slice and print every product.
All of the products on the Layer By Layer marketplace are pre-sliced using the optimal settings chosen by designers, verified by us, and translated for each compatible printer. We guarantee that this will result in the best possible product and printing experience, just as our designers intended.
3. We guarantee that if your print fails, you will be given as many opportunities as needed to re-print and get it perfect.
L2L allows us to track the completion of every print. If any print is canceled for any reason (printer, power, internet, or L2L failure) before it reaches 80% completion, you will be able to re-print it directly from the application—no questions asked. If your print progresses beyond 80% but fails for some reason, don't panic. You are given a post-print survey after every print where you can let us know what happened. We'll then be able to issue you a re-print. You may also contact us anytime, for any reason, through our [online contact form](#). We are dedicated to customer support and making your experience as enjoyable as possible.



Fully assembled 3D printable wrench




by barspin, published Aug 24, 2013



- ♥ Like 506
- 📁 Collect 473
- 💬 Comment 66
- 📄 I Made One 29
- 🔄 Remix It 3
- 🔗 Share

[Download This Thing!](#)

Thing Info | Instructions | **Files** | 66 Comments | 29 Made | 473 Collections | 3 Remixes

File Name	Downloads	Size
 Printable_Wrench.A.15.stl Last updated: 13-08-28	2775	8mb
 Printable_Wrench.A.15.stp Last updated: 13-08-28	1350	1mb
 Printable_Wrench_w_more_gap.A.0.stl Last updated: 13-08-30	2363	7mb



Fully assembled 3D printable wrench by barspin is licensed under the Creative Commons - Attribution license.

By downloading this thing, you agree to abide by the license: Creative Commons - Attribution

[Download All Files](#)

(2 mb zip file)

Thingiverse

Only files to download.
Not a printing service.
Belongs to Makerbot
(Stratasys)

<https://www.thingiverse.com>

3D Printing Communities

GrabCAD

3D model repository.
Not specific to 3D printing.
Trying to build the “App Store” for 3D CAD models.
Partnership with Autodesk.

Their workbench can build and edit files.
<http://grabcad.com/>

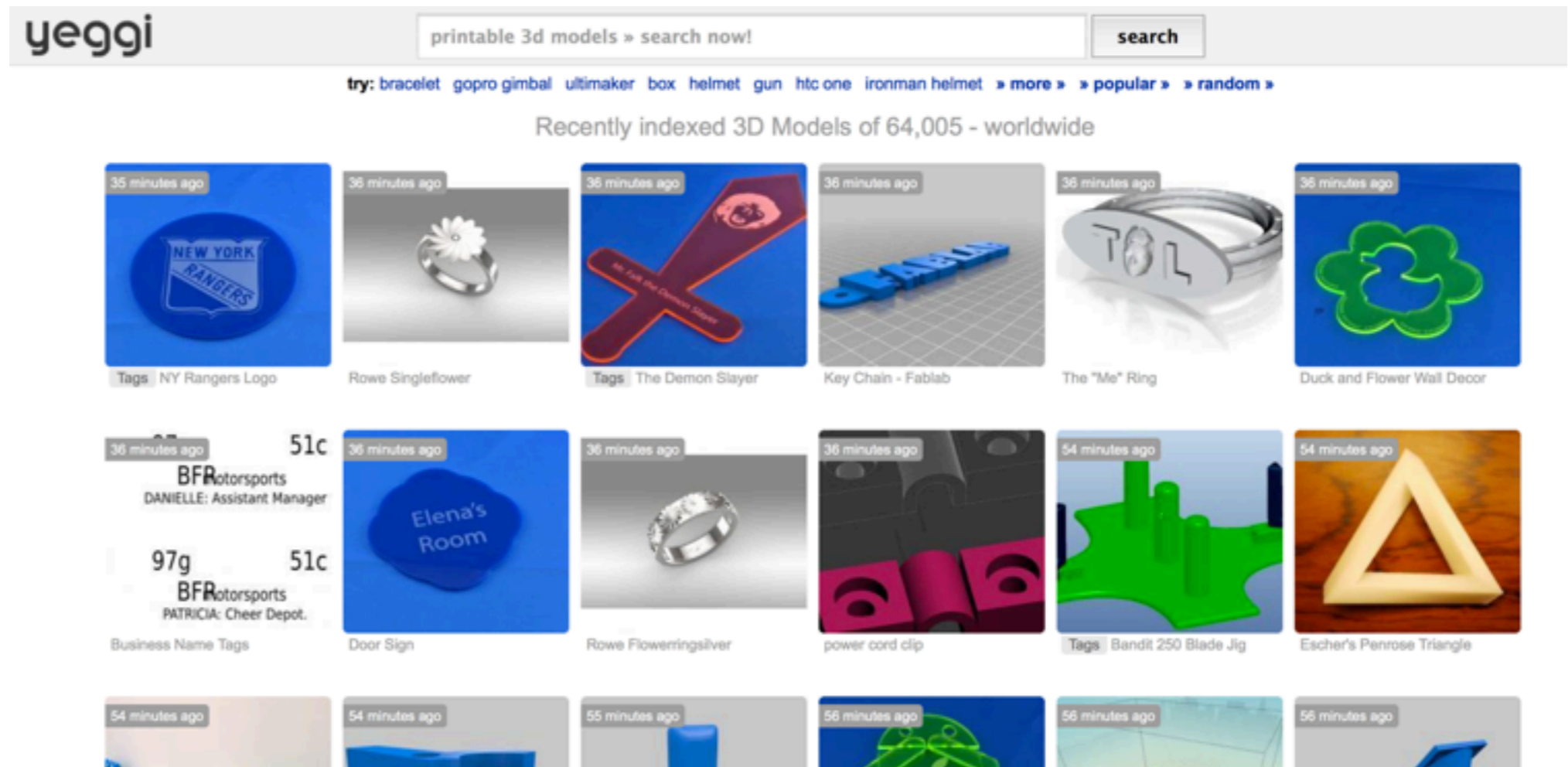
The screenshot displays the GrabCAD website interface. At the top, there are navigation tabs for 'GRABCAD', 'Community', 'Workbench', and 'Toolbox'. To the right, there are links for 'Search community', 'Log in', and 'Register'. A prominent red banner below the navigation contains the text 'Get access to thousands of free CAD projects' and 'Join our community of over 822,618 engineers and 278,681 CAD files', with a 'Register' button on the right. Below the banner, the section is titled 'Most downloaded models' and includes an 'Upload library model' button. A search bar with the placeholder text 'Search CAD models' and a 'Search' button is present. Below the search bar, there are sorting options: 'Sort by: Recently added', 'Most liked', 'Most downloaded', and 'Most commented'. On the right side, there are options for 'Models per page: 20 40 100'. The main content area features a grid of model thumbnails. The first row includes: 'AUDI R8' (328 likes, 52775 downloads), 'Oblivion copter' (40 likes, 31101 downloads) with metadata: 'SOFTWARE: Available in 55 versions', 'RENDERINGS: 10', 'ENGINEER: Ondřej Novák', 'Aerospace, Aviation, Military'; 'Apple iPhone 4' (120 likes, 25582 downloads); and 'Colt 1911-A1 Model Government Pistol' (101 likes, 19103 downloads). The second row shows a wireframe horse model, Brembo brake discs, a dark sports car, and a white drone.

3D Printing Communities

Yeggi

Meta search engine to find 3D Printable models all over the 3D Printing model universe.

www.yeggi.com



3D Printing Communities

Ebay



[DOWNLOAD](#) [CONTACT](#) [FAQ](#)

Unleash your creativity by customizing select products to create exactly what you want with eBay Exact. Simply select a product, choose a design, and add your own personal flair to create a unique item for yourself or someone special!

With our first foray into 3D printing technology, we have partnered with Sculpteo, MakerBot, and Hot Pop Factory who are leaders in 3D printing technology to hand-select a range of special products including, iPhone cases, figurines, and jewelry.

Take the power of creation into your own hands and [download the app now](#) to start customizing right away.

Bring your style to life. Choose from a variety of materials, including plastics, wood and metals. Use the engraving feature to further customize your product.

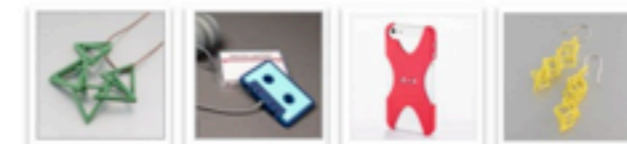
Be the first to use new technology to create one-of-a-kind iPhone cases, jewelry, and figurines based on self-portraits.

Build your collection. Whether you love jewelry or figurines, eBay Exact allows you to create as many unique products, exactly as you like, based on your personal desires and preferences.



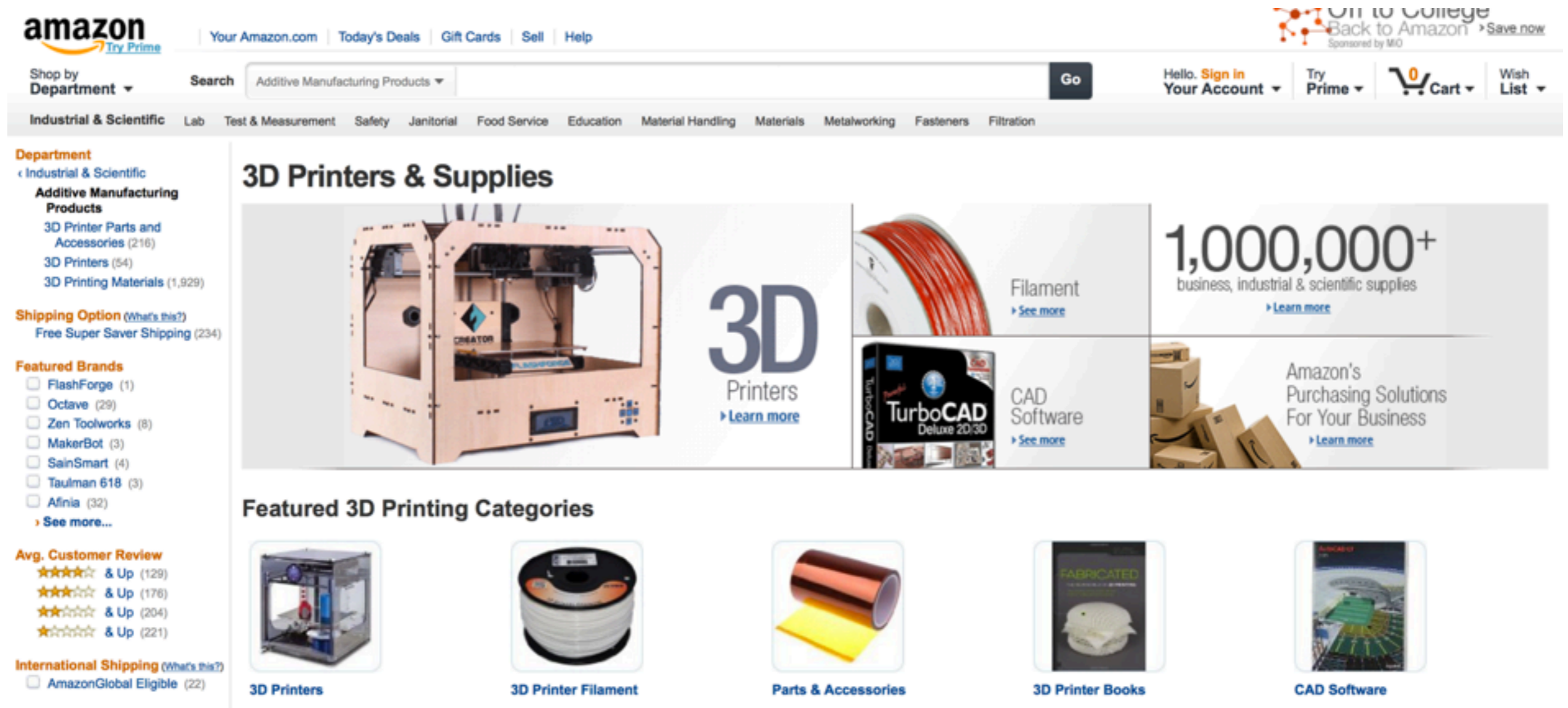
[DOWNLOAD NOW](#)

Available on the iPhone
[App Store](#)



3D Printing Communities

Amazon



The screenshot shows the Amazon.com website interface for the '3D Printers & Supplies' category. At the top, the Amazon logo is on the left, and navigation links for 'Your Amazon.com', 'Today's Deals', 'Gift Cards', 'Sell', and 'Help' are in the center. On the right, there are links for 'Hello, Sign in Your Account', 'Try Prime', 'Cart', and 'Wish List'. Below the navigation bar, a search bar contains the text 'Additive Manufacturing Products'. A horizontal menu lists various departments: Industrial & Scientific, Lab, Test & Measurement, Safety, Janitorial, Food Service, Education, Material Handling, Materials, Metalworking, Fasteners, and Filtration.

Department
Industrial & Scientific
Additive Manufacturing Products
3D Printer Parts and Accessories (216)
3D Printers (54)
3D Printing Materials (1,929)

Shipping Option (What's this?)
Free Super Saver Shipping (234)

Featured Brands
 FlashForge (1)
 Octave (29)
 Zen Toolworks (8)
 MakerBot (3)
 SainSmart (4)
 Taulman 618 (3)
 Afinia (32)
[See more...](#)

Avg. Customer Review
★★★★★ & Up (129)
★★★★☆ & Up (176)
★★★☆☆ & Up (204)
★★☆☆☆ & Up (221)

International Shipping (What's this?)
 AmazonGlobal Eligible (22)

3D Printers & Supplies

3D Printers [Learn more](#)

Filament [See more](#)

1,000,000+ business, industrial & scientific supplies [Learn more](#)

CAD Software [See more](#)

Amazon's Purchasing Solutions For Your Business [Learn more](#)

Featured 3D Printing Categories

- 3D Printers**
- 3D Printer Filament**
- Parts & Accessories**
- 3D Printer Books**
- CAD Software**

3D Printing Communities

Maker Sites - Distributed Manufacturing

<http://www.100kgarages.com/about.php>

<http://www.ponoko.com/make-and-sell/how-it-works>

<http://www.sculpteo.com/en/help/>